ASSESSING THE UNDERWORLD

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Assessing The Underworld

An Integrated Performance Model of City Infrastructures

ATU research team:

UNIVERSITY OF BIRMINGHAM · UNIVERSITY OF BATH · British Geological Survey NATURAL ENVIRONMENT RESEARCH COUNCIL · UNIVERSITY OF LEEDS · Newcastle University · The University Of Sheffield. · UNIVERSITY OF Southampton

Foreword

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Humans have buried things in the ground for all sorts of reasons. We bury things to hide them or keep them safe and secure; we bury things to protect them from the environmental stresses (heat, cold, wind, wetness) that may damage them; and we bury things to get rid of them – waste in landfill, for example. For not dissimilar reasons, we bury utility pipes and cables in the ground for protection from damage by surface activities, vehicles and the weather, to provide support to resist differential movements, to keep the unsightly arteries of civilised life hidden from view, and so on. The ground is therefore our friend in this endeavour, and in fact this is where I started my research career – researching flexible pipe support.

Flexible pipes require support from the ground in order to act structurally. However the ground also provides a disturbance to this structural equilibrium, at least to some degree, by loading the pipes, and of course the ground transmits loading from above – such as traffic loading. Flexible pipes therefore provide a classic example of a soil-structure interaction system that for stability needs to be in equilibrium.

This model of a stable structural system is very much an ideal when it comes to considering the reality of buried utility infrastructure in towns and cities. The location of the buried utility infrastructures is usually dictated by the pattern of roads and streets, since this is the common land in urban areas that is available for burying pipeline and cables. One point, and it is an important point, concerns the need to access the buried utilities for maintenance, repair, replacement, or simply to install additional service lines to complement the existing. If the utility services were buried beneath buildings or structures, this access would create a considerable difficulty.

While the ground is our friend in protecting and supporting the buried infrastructure, we do not treat our friend well at all! For example we repeatedly disturb the ground when installing new, or looking after existing, pipelines and cables and once we have finished these construction activities, we expect the ground to become stable and function as it had done before. Moreover, we expect these pipelines and cables to criss-cross beneath the surface so that the services can be delivered to where they are needed from what is often a major linear supply route. When infrastructures criss-cross in this way they start to become complicated, as do the stresses in the ground, because they have to be woven together in the space that is available – as I have stated repeatedly when discussing the Mapping The Underworld project: our city streets are congested, and this is equally true below ground as it is on the surface.

A fine example of such complexity in terms of road infrastructures exists close to the centre of Birmingham. Known formally as the Gravelly Hill Interchange, this road system has become known as spaghetti junction, and not without good reason – it is an impressive sight and with its smooth curves does look like spaghetti. This road interchange has several levels and many connections, and while it looks like a complex jigsaw puzzle, it is not all that complicated when compared with certain buried infrastructures!

The conclusion from all this is that the ground is expected to provide support to roads, and the traffic that the roads accommodates, as well as providing support for the buried spaghetti of pipes and cables. Moreover, it is expected to do this even though it is not infrequently disturbed and its properties therefore compromised – put another way: it deteriorates.

The buried pipes and cables might also be expected to deteriorate with time, commensurate with the degradation of the materials from which they are constructed, while the chemical makeup of the ground can accelerate this material degradation. Deterioration can also occur as a result of physical loading and/or physical displacement – one obvious example being the repeated loading from heavy vehicles transmitted through road structures and into the ground that surrounds the buried infrastructure. Since the infrastructure exists below the roads and pedestrian areas, and trenching is the most common construction operation used to access the buried infrastructure, then the road / pavement structures are also repeatedly disturbed – material cut out and replacement materials patched in.

The question this discussion raises is: how deteriorated are the existing buried pipes and cables, the existing road structures which have been repeatedly disturbed, and the ground which has likewise been repeatedly disturbed? This is the question that Assessing The Underworld has set out to answer. Knowing the answer, we will be in a far better position to decide on the engineering works that should be undertaken when dealing with surface and buried infrastructures, more colloquially known as streetworks.

The team assembled to answer this question draws on the original Mapping The Underworld consortium, yet it is greatly augmented by several leading researchers from allied disciplines. It has been a joy to lead this talented team of researchers, who have come together to tackle what is a complex interdisciplinary challenge. The way to tackle such a challenge is to assemble a multi-disciplinary team, and then learn how to work effectively together so that we move towards transdisciplinarity. Such research is truly inspiring.

However the Assessing The Underworld team is in no sense only formed from academics: the research was co-created with, and has been carried out with, a stunning array of professional practitioners – our project partners – and it is a testament to this wider collaboration that the very many scientific and engineering advances listed herein have been achieved.

Acknowledgements

The authors gratefully acknowledge the following grants awarded by the Engineering and Physical Sciences Research Council, all of which have supported the Assessing the Underworld initiative:

Assessing The Underworld - An Integrated Performance Model of City Infrastructures (EP/K021699, £5.8m, 2013-18)

Balancing the impact of City Infrastructure Engineering on Natural systems using Robots (EP/N010523, £4.2m, 2016-21)

TWENTY 65: Tailored Water Solutions for Positive Impact (EP/N010124, £4.0m, 2016-21)

i-BUILD: Infrastructure BUsiness Models, Valuation and Innovation for Local Delivery (EP/K012398, £3.5m, 2013-18)

Transforming the Engineering of Cities to Deliver Societal and Planetary Wellbeing (EP/J017698, £6.3m, 2012-17)

UKCRIC – PLEXUS: Priming Laboratory EXperiments on Infrastructure and Urban Systems (EP/R013535, £1.0m, 2018-19)

UKCRIC – National Buried Infrastructure Facility (EP/P013635, £21.6m, 2017-20)

UKCRIC – National Water Infrastructure Facility: Distributed Water Infrastructure (EP/R010420, £3.7m, 2016-19)

UK Quantum Technology Hub for Sensors and Metrology (EP/M013294, £35m, 2014-19)

Smart Leak Detection Pipes (EP/K504191, £241k, 2013-17)

FINDIT: Finding Infrastructure with Non-Destructive Imaging Technologies (82352-509379, £533k, 2017-18)

GG-TOP: Gravity Gradient – Technologies and Opportunities Programme (EP/I036877, £2.5m, 2011-16)

iSMART (EP/K027050, £1.7m, 2013-16)

Future Infrastructure Forum (FIF) – a network for resilient and sustainable infrastructure (EP/J004251 & EP/J004294, £147k, 2011-12)

Mapping The Underworld: Multi-Sensor Device Creation, Assessment, Protocols (EP/F065965 and its 4 partner grants, £3.5m, 2009-13)

Mapping the Underworld: Buried Asset Location, Identification and Condition Assessment using a Multi-Sensor Approach (EP/C547365, £500k, 2005-09)

Mapping the Underworld: Knowledge and Data Integration (EP/C014707, £158k, 2005-09)

Mapping the Underworld: Network (EP/C547330, £63k, 2005-09)

Network In Trenchless Technology (NETTWORK; GR/R14064, £63k, 2001-04)

The authors also acknowledge the very many individuals who have supported and guided the research team. There are too many to list, but the following deserve special mention:

Alan Dymock (Bristol Water)
Andy Rhoades (Buried Asset Protection Consultancy Ltd)
Arie Verwoert (Movares)
Bob Gallienne (Street Works UK)
Brian Murtagh (Corehard Limited)
Christina Jackson (Jacobs)
Dave Francis (University of Southampton)
Erica Carrick Utsi (EMC Radar Consulting)
Fionn Wardrop (Linesearch BYD)
Frank van der Kleij (Bristol Water)
Frans Taselaar (Hompe en Taselaar)
George Tuckwell (RSK)
Giles Fox (Bristol Water)
Ian Dabson (Infrastructure and Projects Authority)
Ian Jenkinson (The Stilwell Partnership)
Jim Anspach (Cardno & ASCE)
Jo Parker (UKWIR)
John Guest (JK Guest)
John Robinson (Malcolm Hughes Land Surveyors Ltd)
Jon Russell (formerly TfL)
Joshua Moran (Staffordshire County Council)
Lance Truckle (Bristol Water)
Leon Olde Scholtenhuis (University of Twente)
Les Guest (Les Guest Associates)
Marcel Van Driel (Arnhem Municipality)
Margaret Sackey (TfL)
Mark Koningen (Movares)
Martyn Stonecliffe-Jones (Dynatest)
Mike Page (Malcolm Hughes Land Surveyors Ltd)
Nick O'Riordon (Arup)
Nick Zembillas (Subsurface Utility Engineering LLC)
Pat Spain (STW)
Peter Barker (StratascanSUMO)
Richard Broome (Linesearch BYD)
Richard Ploszek (Infrastructure and Projects Authority)
Richard Van Ravesteijn (Hompe en Taselaar)
Robert Armitage (formerly AECOM)
Robert Burns (Costain)
Robert Huxford (Urban Design Group)
Sam Roberts (MetGeoenvironmental)
Stephen Ashton (University of Birmingham)
Steve Crossland (Balfour Beatty)
Steve Walker (CSTA-SU UK)
Tony Andrews (formerly Bentley)
Tony Rachwal (Independent Consultant)
Wil Kovacs (Rotterdam Municipality)
Wout Broere (Technical University Delft)

Finally the authors wish to acknowledge the very many organisations who have supported the research as project partners:

American Society of Civil Engineers (ASCE)
AMEY
ATI Projects Ltd
Balfour Beatty Plc
Bristol Water Plc
Cardno TBE
CH2M HILL
CH2M Hill (Halcrow)
Colorado School of Mines
Corporation of the City of London, ON
Costain
Defence Science & Tech Lab (DSTL)
Energy and Utilities Alliance
Exova
Globe Performance Solutions
Hydrosave UK Limited
IDS Ingegneria Dei Sistemi S.p.A,
Infotec Consulting
Institution of Civil Engineers (ICE)
J Murphy & Sons Limited
Keller Ltd
Leica Geosystems
Louisiana Tech University
Macleod Simmonds Ltd
Morrison Utility Services
MWH UK Ltd
National Grid
National Underground Assets Group Ltd
Network Rail
Ordnance Survey
OSYS technology limited
Peter Brett Associates
Pipehawk Plc
Pipeline Industries Guild
Primayer Ltd
Radiodetection Ltd
Robosynthesis Limited
RSK Group Plc
Sao Paulo State University UNESP
SBWWI
Site Vision Surveys Ltd
Skanska UK Plc
Stratascan Ltd
Subscan Technology
T2 Utility Engineers Inc
Technology Strategy Board (Innovate UK)
UK Society for Trenchless Technology
UK Water Industry Research Ltd (UKWIR)
Underground Imaging Technologies (UIT)
United Utilities
University of Auckland
University of Wollongong
URS Corporation
US National Academy of Sciences
UTSI Electronics Ltd
Watershed Associates
Yorkshire Water

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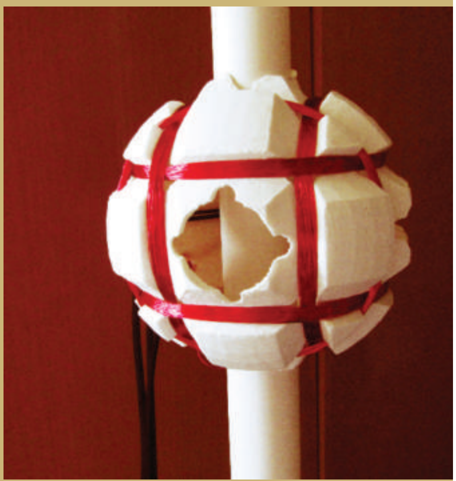

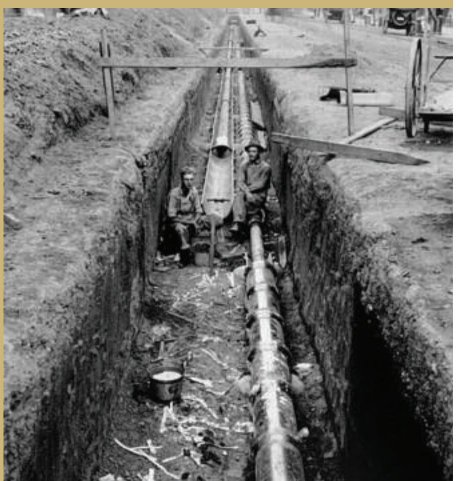

A Brief History of the Underworld

CDF Rogers and CG Overton
(University of Birmingham and UKWIR)

Mankind has used buried infrastructure for eight millennia, perhaps more. A supply of clean water and safe disposal of sewage have been prerequisites for civilisation's development, so it is not surprising that the earliest, and much of the subsequent, buried infrastructure involved water, sewage and drainage.

Traces of drains and primitive cess pits dating back to 6000 BC have been found in the Indus Valley, together with copper water pipes (estimated to be 5,500 years old) and streets drained by covered sewers made of moulded bricks cemented with a mortar of mud. Earthenware pipes, made from clay and chopped straw, dating back to the same period have been found in Mesopotamia; these were made by jointing bottomless pots end-to-end, and sealing them with bitumen.

Large brick drainage systems, some with access holes similar to today's manholes, were in use 4,000 years ago in Babylon, together with earthenware and stone water pipes. At the same time, the Egyptians used clay and straw and copper pipes for both irrigation and sewage systems.

Between 3000 and 1500 BC, the island of Crete had elaborate sewage disposal and drainage systems resembling those of today and extending up to 3.5m below ground. Tapered clay pipes were used for drainage, fitting together to form the first spigot and socket pipes. Many houses in ancient Greece were equipped with a closet or a latrine that drained into sewers beneath the streets, while the Greeks buried fresh water aqueducts up to 20 m below ground level to protect their drinking water supplies from their enemies.

Around 800 BC the Romans built enormous sewers, including the *Cloaca Maxima* which was built to drain the Forum, and some of these sewers still form part of today's sewerage system in Rome. Moreover to satisfy demand for water for drinking and bathing, the Romans laid vast underground systems using wooden and lead pipes. Bronze pipes carried water from the mainland to the island city of Tyre.

In the thousand years after the collapse of the Roman Empire, development of the underground was much more limited. This was in part due to an apparent aversion to cleanliness and, where infrastructure was built, water was generally conveyed in wooden and lead pipes.

Figure 1 – An early wooden pipe, or trunk main

The use of lead pipes was recorded in London in 1235, and in the 16th century, when piped water supplies were reintroduced to London, it was found cheaper to use wooden pipes (Figure 1) for all but the smallest sizes, for which lead continued to be used; this became standard practice for two centuries. Sewage was dumped on the street, or ran in open channels. Where covered sewers existed, these were crude brick walls topped with flat stones.

The first authentically recorded cast-iron pipe was laid in Germany in 1455 and carried water to the Dillenberg Castle. In 1664 King Louis XIV ordered the construction of a cast-iron main to carry water to fountains at Versailles. The Chelsea Water Works Company first used butt-jointed cast-iron water pipe in about 1746, but it was the introduction in 1785 by Thomas Simpson, Engineer of the Chelsea Company, of an effective spigot and socket joint that allowed the development of pressurised water supply systems.

The 19th century saw unprecedented growth of the underground infrastructure in the UK. The Metropolitan Paving Act of 1817 required water companies to lay cast-iron pipes – a response to the continual excavation of roads to find and stop leaks from wooden pipes. By 1850 nearly all of the old wooden pipes in London had been replaced by cast iron.

William Murdoch and Frederick Winsor's pioneering work on gas lighting in the early 1800s led to the installation of gas supply networks in major towns and cities across the land. In some areas, surplus rifle barrels from the Crimean War of 1854-1856 were screwed together to make gas pipelines. The introduction of pre-payment gas meters in the 1880s extended the network to many millions of poorer households.

The second half of the 19th century saw the introduction of electricity to the UK. The first public supply, along with street lighting, was introduced in Godalming in 1881, and by the end of the 19th century an underground distribution network of insulated cables was being installed. Electricity also powered the rapid expansion of the tram network between 1805 and 1905.

The introduction of the telephone in 1877 added further growth, with the first underground trunk cable laid in the 1880s.

Figure 2 – Congestion at a New York interchange circa 1900

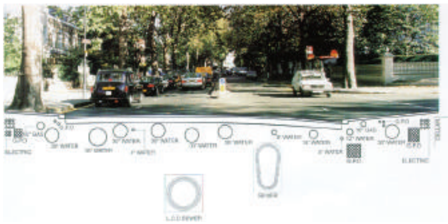

Figure 3 – Congestion beneath Holland Park Avenue, a space said to be "full" (courtesy of Dr M Farrimond)

Figure 4 – An unhappy marriage between the old and the new

In 1848, Parliament passed the Public Health Act, mandating sanitary arrangements in every house. The Government also allocated five million pounds for sanitary research and engineering, helping promote a major expansion of buried sewerage systems. A second Act in 1875 required local authorities to ensure adequate water supplies, while a growing need to provide firefighting capabilities for factory owners additionally led to further expansion of the underground water supply network.

This pattern of underground infrastructure provision was replicated, though generally somewhat later, in other major cities around the world and congestion beneath our city streets often matched that above them. Although the example from New York shown in Figure 2 might be superficially discounted as extreme, the fact that this photograph was taken more than one hundred years ago is sobering and, while many examples of such interconnectedness (and physical inter-dependency) are routinely exposed, there is a second issue: we now have cases of pipes of very different age (up to 200 years, and very occasionally more) and condition.

The 1950s and 1960s saw the introduction of ductile iron, PVC and polyethylene pipes in the UK and, in 1975, the first cable TV system was installed in Hastings. In 1980, the first optical fibre link was laid between Brownhills and Walsall in the West Midlands.

Since then our demand for newer and more modern methods of communication, such as broadband internet and television, has meant that many additional services have been laid beneath our streets. This mixture of the old and the new has meant that our urban streets have become congested to the point of exhaustion (Figure 3), but it also means that there are different types of utility service lines requiring different support conditions lying in close proximity. This situation is complicated further by pipes and cables that are aged and vulnerable to damage or loss of functional life if disturbed and the inevitability of disturbance as the new services are installed or the existing services are maintained or repaired (Figure 4).

In 2006 it was estimated that the UK utility industry spent £1.5 billion a year to carry out street works and another £150 million to repair damage to other services those works cause[1]. Moreover, it was estimated that the cost to society and the economy amounted to an additional £5.5 billion due to the manifold impacts of street works – such as traffic congestion and delays. While there are more up to date estimates of this disruption and its costs, and we present new findings later in this report, the situation has not changed – indeed it has worsened – since then. This is a problem in urgent need of a solution.

In the early days of pipe laying, even though the works were evidently disruptive (Figure 5), the complexities of dealing with adjacent buried infrastructure were largely absent. Nowadays the situation shown in Figures 2 and 4 is closer to what we find beneath the streets, and thus knowing what is present in the ground before digging is vitally important if damage to the existing network of pipes and cables is to be avoided and surface disruption is to be minimised. However, knowing the location and type of utility services buried beneath the streets is not enough to guide those responsible for streetworks – the physical condition of the pipelines and cables, and the ground that supports them, needs to be understood, or at least anticipated, if damage, either immediately or in the future, is to be avoided. Moreover, there are health & safety concerns to streetworks operators when working in close association with live services.

Figure 5 – Pipe laying in 1880, unencumbered by a proliferation of other buried utility services, and health and safety legislation

The underworld is therefore a complex place with a set of complex challenges for those who have to engineer in this space.

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A Brief History of Mapping and Assessing the Underworld

CDF Rogers
(University of Birmingham)

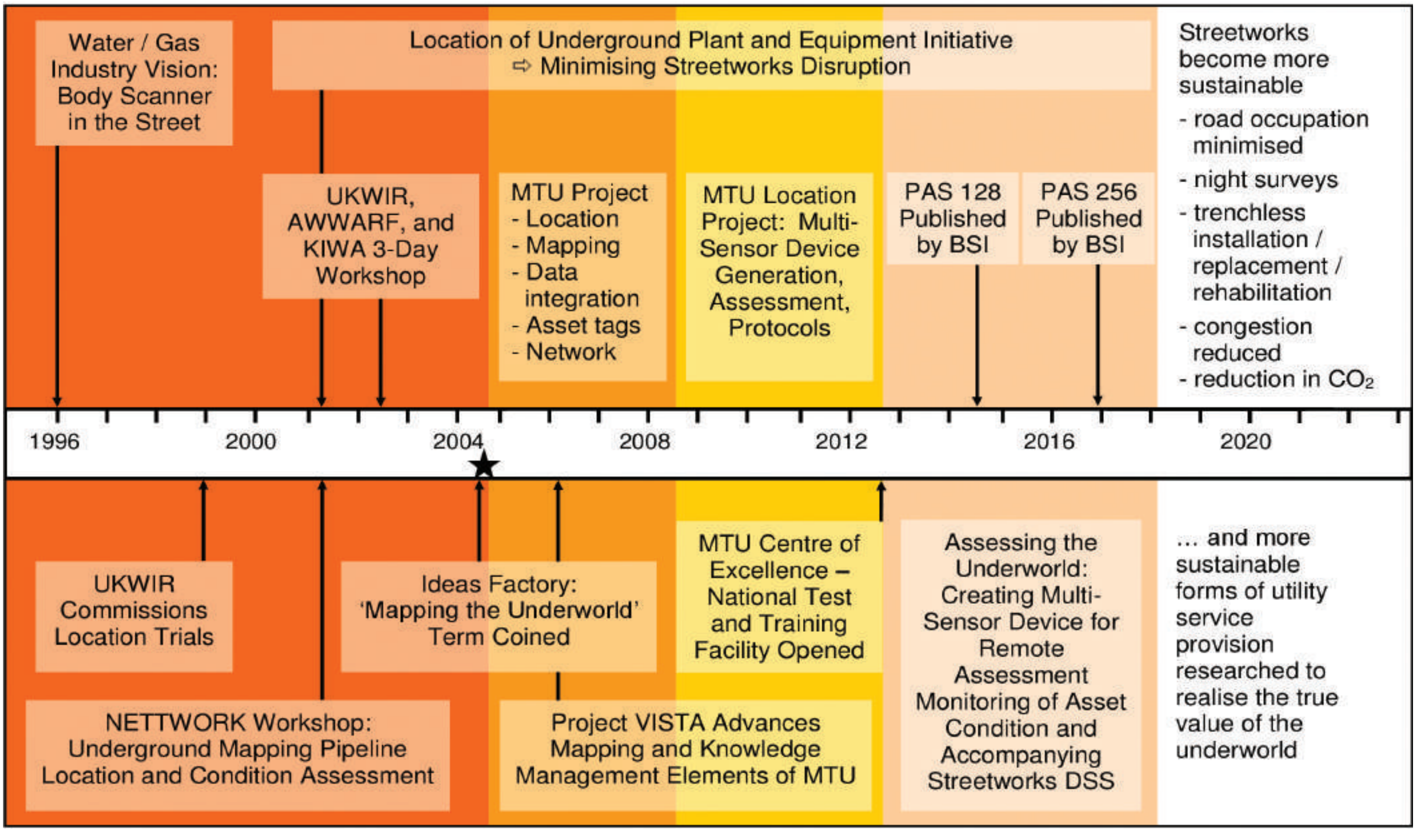

Figure 1 – The Mapping The Underworld timeline showing its 25 year Vision

Mapping The Underworld started with the problem of buried asset location – we must know what is where below the surface if we are to engineer in the space below the streets effectively and safely – a problem that has been articulated by UK urban professionals for as long as the built environment has needed servicing.

However, the problems associated with the location of existing buried utilities are emphatically not unique to the UK, and have been presented for example at the International No-Dig (or Trenchless Technology) conferences ever since they started in 1986. Indeed, they are reflected in the discussions of any worldwide gathering of those engaged in trenchless technology and pipeline engineering. It was in 1996 that Tony Rachwal, then Director of Research at Thames Water, crystallised the arguments by stating that we needed a 'bodyscanner for the street' (Figure 1).

Initially this essential problem was tackled by the industries involved in streetworks, but it was wholly reasonable that industry should seek help from academia: could advances in science and engineering that, for example, allow us to look below the surface of the moon not allow us to understand better what is buried shallowly below the surface of our urban streets and pavements?

Indeed, it was a parallel activity in academia, albeit guided by practitioners that reinforced the research need. This occurred as a result of an EPSRC Engineering Programme Network in trenchless technology (NETTWORK[1]) hosted at the University of Birmingham.

NETTWORK was established as an academe-industry forum to help shape the UK's research programme in trenchless technology and deliver better-focussed outputs in terms of industry and society need. The issues of inadequate utility location were introduced, debated and collectively agreed to be of major importance to the trenchless industry, and hence one of the foremost research priorities, at the first of the workshops hosted by NETTWORK early in 2001. The interest was sufficiently great that the topic formed the subject of a report commissioned by UKWIR[2], which was then used to prime the discussions at an international workshop on the topic. Following significant lobbying by UK industry and an acknowledgement of the importance of the issue by the UK government, EPSRC chose this topic to be the subject of its first sandpit (or IDEAS Factory).

A sandpit is a means of awarding funding to the UK academic community based on the outcomes of a week-long residential interactive workshop involving 30–40 participants, essentially academics or other research providers and a number of independent stakeholders. One of the founding principles of the sandpit concept is that the researchers should consist of a highly multi-disciplinary mix to facilitate lateral thinking and novel or radical approaches to addressing the particular research challenge in question.

The Mapping the Underworld sandpit identified the need for a combination of different sensing technologies if all buried services in all ground conditions were to be detected, thus yielding the concept of a multi-sensor location device[3]. A feasibility study to explore this idea was therefore funded. Parallel funded research included precise and accurate mapping in urban canyons[4] where sightlines to satellites, the basis of global positioning systems, could not be guaranteed, and establishing a common basis for the creation and sharing of records between utility service providers (data and knowledge mapping). These two projects combined to create Project VISTA[5]. The final research project funded by the sandpit concerned 'asset tagging' – the inclusion of a remotely detectable label fixed to a pipe or cable so that new or repaired utilities can be subsequently located and identified. This addressed the question of "what would we do now if we were starting again?" and, via follow-on EPSRC funding, has resulted in a commercially available system[6] marketed by OXEMS.

The IDEAS Factory also identified the need for a new Engineering Programme Network dedicated specifically to the topic of Mapping the Underworld (MTU). The primary purpose of the MTU Network was to facilitate the development of a community of streetworks practitioners, those governing streetworks and the academic community that seeks to support them. It has long been recognised by EPSRC that the research that it funds should be both co-created and carried out with those that the research seeks to support and benefit, and such networks provide an excellent vehicle for this.

The initial investment in Mapping The Underworld – to prove the concept that a multi-sensor surveying device would be feasible and to define the detailed avenues of research needed to bring such a device to fruition – it was always recognised that considerable further support, much deriving directly from the stakeholder community via an academe–practitioner partnership, would be required to complete the research.

The multi-sensor feasibility study not only proved the concept, but also helped to define a rigorous and detailed four-year programme of work termed the MTU Location Project, or Multi-Sensor Device Project, which was funded by a grant of £3.5 million by EPSRC along with in-kind funding of £1.36 million from 34 formal practitioner project partners. This stage of MTU started in 2008, was completed in the summer of 2013 and is reported in its own brochure[7] and numerous journal and conference papers, practitioner articles and other outputs.

It was always understood, however, that MTU formed part of a 25 year vision (Figure 1) that would be complete only when streetworks engineers could be supplied with as much prior knowledge of the environment in which they are required to engineer and a comprehensive picture of the likely consequences of their engineering actions. Accordingly the academic and practitioner community proposed, and was duly awarded funding for, an ambitious follow-on programme of research entitled Assessing The Underworld. Its vision was to create an integrated streetworks assessment framework encompassing the three interdependent infrastructures that co-exist in our urban streets – the surface transport, buried utility and geotechnical infrastructures – to evaluate the condition of these infrastructures, and to support coherent, intelligent and sustainable management of streetworks[8].

This four-year EPSRC-funded, cross-disciplinary, multi-university research project, which started in June 2013 and finishes in May 2018, aims to prove the concept of a single integrated model for subsurface utility and surface transport infrastructures. These infrastructures are supported by or hosted within the ground (termed herein the 'geotechnical infrastructure'), and thus it can be contended that their performance is controlled to a large degree by the performance of the geotechnical infrastructure. This inter-dependent relationship has significant implications for the performance of all three infrastructures, where deterioration of one infrastructure can compromise the performance of the others, hence only an integrated assessment, combined with deterioration models, will provide reliable information on the performance of these integrated, interdependent infrastructures now and into the future.

Put more simply, for reasons of minimising direct costs and to address uncertainties (of what is buried beneath the streets and its physical condition), trenching is often used in urban streets to install or maintain buried pipes and cables. Such excavations inevitably cause lateral stress relief displacements and therefore weaken the ground, cause differential movements in the pipes and cables that lie adjacent to or cross the excavation (accelerating their deterioration, sometimes to the point of immediate failure) and weaken road structures by cutting through the slab, loosening the unbound foundation layers and patching in replacement materials. All of this is done while disrupting traffic, damaging the economy, society (inconveniencing people and the social systems that operate in cities) and the environment (e.g. exacerbating pollution)[9].

This report covers the findings of the Assessing The Underworld Project, the majority of the research for which is now complete. As with all such programmes, the full findings will appear in print, and its impacts realised, in the months and years after the programme has formally ended. Nevertheless this report provides a detailed overview of the combined efforts of the team, academics and practitioners alike.

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Advanced Sensing Technologies Vibro Acoustics

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Vibro-acoustics, or structural acoustics, is the study of mechanical waves in structures and how they interact with and radiate into adjacent fluids and media. In the context of ATU (and formerly MTU), the structures of interest are buried pipes (water, oil, gas) along with trees and their root systems, and the adjacent fluids/media are the fluid contained within the pipes and the ground/soil/fluid in which they are buried or immersed.

The principle behind all of the vibro-acoustic techniques that have been explored in both ATU and MTU is that when one part of the structure/soil system is mechanically excited in a controlled manner, waves will propagate away from the excitation point, interact with the surrounding structure or fluid and be subsequently measurable at some remote location(s) on the structure itself or at the ground surface. By analysing the nature of the measured response(s), not only the location of the buried structure can be inferred but also, potentially some assessment of its condition or state can be made.

In MTU, a range of vibro-acoustic techniques were developed[1]. The intention in ATU was to build on the successful outcomes of MTU to expand the scope of the techniques to incorporate some measure of condition assessment. Furthermore, two additional avenues of inquiry were included namely: to explore a tree excitation method to determine the location of tree roots in order to identify areas of pipe network at risk of damage; and to develop vibro-acoustic methods to measure relevant soil wavespeeds in situ.

(a) Vibration excitation applied directly on a pipe. This is applicable when a buried pipe can be accessed from the surface (e.g. a fire hydrant). The exposed pipe is mechanically excited at low frequencies (<1kHz) resulting in waves that propagate along the pipe and in any fluid contained within the pipe. The energy of these waves then radiates to the ground surface where it is measured, using geophones, and from which the location of the remainder of the pipe can be inferred.

Recent research has revealed a number of important details about this process which open up exciting possibilities for condition assessment: the first is that the wavespeed of the dominant wave in the pipe is mainly controlled by the physical properties of the pipe (radius, wall thickness, pipe wall elasticity), regardless of the condition of the soil[2,3]; secondly, the attenuation of this dominant wave is significantly affected by the soil type; and thirdly, that the wave propagation behaviour within the pipe is mirrored at the ground surface above the pipe4.

By measuring the ground surface response resulting from a specific form of pipe excitation, examining the wavespeed and attenuation, and by monitoring changes in these over time, changes in, for example, pipe wall thickness (due to pipe wall deterioration) or elastic modulus (due to embrittlement) could be picked up remotely[5]. Moreover, reflections from discontinuities in the pipe wall, such as holes or cracks, or in the soil, will be manifest as peaks in the magnitude of the response.

These features are seen clearly in Figure 1, in which the pipe end and a small hole are evident (1a) along with the run of the pipe (1b). Figure 2 shows two measurements of the magnitude of the ground surface response due to exciting a pipe at a test facility. Here, the boundaries between the 'bays' containing different soil types are clearly visible in the response.

Finally, investigation of the fundamental torsional wave has shown that this mode too shows promise, particularly for cast iron pipes, in which spiral fracture is one cause of pipe failure[6].

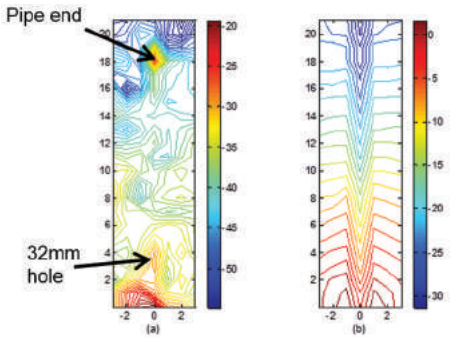

Figure 1 – Ground Surface Response above an MDPE Water Pipe: (a) Magnitude (b) Phase

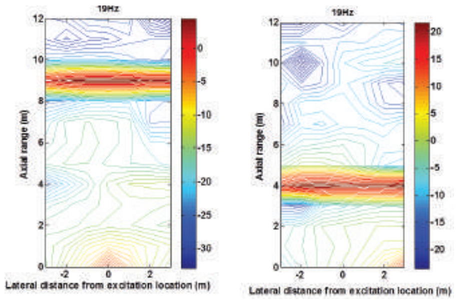

Figure 2 – Magnitude of Ground Surface Vibration Response

(b) Vibration excitation applied at the ground surface: detection of road surface cracks

Assessment of the location and of the extension of cracking in road surfaces is important for determining the potential level of deterioration in the road overall and the infrastructure buried beneath it. Damage in a pavement structure is usually initiated in the tarmac layers, making the Rayleigh wave ideally suited for the detection of shallow surface defects.

Two novel methods for crack detection have been investigated in ATU. In the first, a wave decomposition approach is developed. By decomposing the measured response at the ground surface into outgoing and reflected components, the location of discontinuities can be inferred[7]. By using multiple receivers, the system is overdetermined so an optimal solution can be found in the least squares sense. The resonant peak frequencies of the reflection coefficient and the cut-off frequencies of the transmission coefficient are used for assessing the depth of the crack; the phase of the reflection coefficient gives the information about the location of the crack. The second method exploits two standard seismic techniques for examining the near-surface: MASW (multi channel analysis of surface waves) and MISW (multiple impact surface waves). In homogeneous soils, the two methods are exactly equivalent. Here, the differences between them are utilized to detect the presence of discontinuities[8,9]. Figure 3 shows frequency-wavenumber spectra obtained from numerical simulations of a crack using the two different methods. The main dark red band in each image corresponds to the Rayleigh wave, with the periodic dark red spots on Figure 3b revealing the presence of a crack.

(c) Remote detection of tree roots. Tree roots are well known disruptive to underground pipe and cable networks. Detecting the extent of root development would identify areas of infrastructure which are particularly at risk of damage. The contention here is that a similar rationale as for the pipe excitation method may be applied to woody roots and an analogous technique developed. Preliminary research, showed that if a tree trunk is vibrationally excited, a significant proportion of the vibrational energy does indeed propagate down into the soil and the root structure[10].

However, in order to tailor the method specifically for tree root detection, additional knowledge about wave propagation in root-like structures was required. With this in mind, analytical and numerical models, supported by laboratory experiments have been developed[11,12].

Figure 4 shows the root model which was used for investigations into wave propagation in root-like structures together with the sandbox to emulate buried conditions. Results demonstrating how waves propagate along the free root and how the response at the root varies with position when in the sandbox are also presented.

(d) In situ measurement of soil properties. Central to all the ideas presented here is the ability to analyse the ground vibration data effectively. In order to achieve this, the relevant wavespeeds (shear & compressional) need to be known a priori. Here, one specific of research is particularly promising. Normally, when undertaking seismic surveys, only one component of vibration (e.g., the vertical) is exploited. Research in ATU suggests that by combining two components (e.g. vertical and horizontal), modal separation can be improved, along with an increase in global resolution.

Progress in all the areas of research are extremely encouraging. Together they have the potential to realise an entirely new mode of assessing the condition of buried assets and their surroundings.

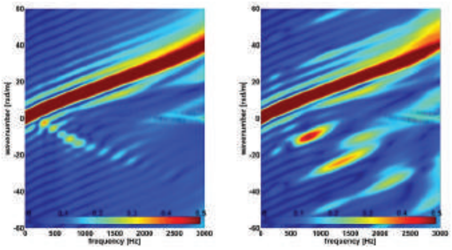

Figure 3 – F-k Spectrum Obtained with (a) MASW (b) MISW Technique

"The intention in ATU was to build on the successful outcomes of MTU to expand the scope of the techniques to incorporate some measure of condition assessment".

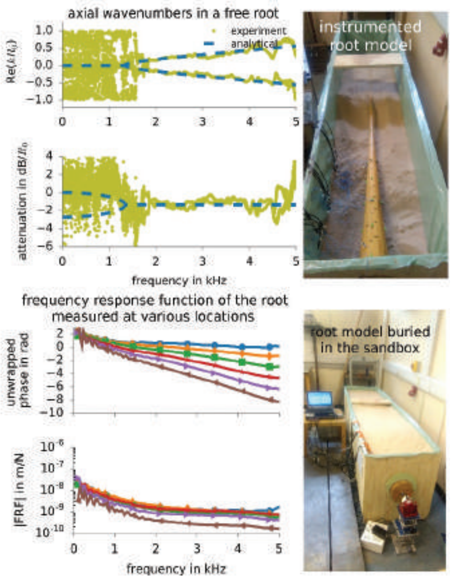

Figure 4 – Experimental Investigation into Wave Propagation in Root-like Structures

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Advanced Sensing Technologies Passive Electromagnetic Detection

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(University of Southampton)

It is essential to ensure the smooth operation of a large distribution network that consists of underground power cables. Furthermore, it is necessary to avoid unwelcome catastrophic failures in the systems that can have negative impact on customers, businesses, the environment, commuters and other utilities.

A catastrophic electrical failure is closely related to degradation within the insulation of the cable system including the joints and terminations. The signs of degradation can be predicted through the detection of preceding sequential partial discharge (PD) in the cable system insulation.

PD is the source of very brief electrical pulse that generate broadband electromagnetic signal. Hence, PD is considered as one of the most important quantities in assessing the condition of power assets[1]. For electric power cables, this means detecting and locating incipient fault(s) to allow for rapid remedial action before a catastrophic failure occurs.

PD signals are usually small and difficult to distinguish from background noise. They travel along the cable and usually propagate near the joints or termination through the ground. This results in the rapid attenuation of the highest frequency components of the PD signal[2].

Traditional techniques need access to the underground cables at the substation end. However, there is an increasing need for a mobile detection system to locate the PD source above ground along the cable path.

Assessing the Underworld (WS3a Team) aims to assess the condition of underground power cables using optimised multi-sensors approach whilst moving above ground along the path of the cable to detect the weak electromagnetic signals produced by PD.

The aim is to develop hardware (Antennas) in conjunction with the development of software that utilises special techniques to distinguish the weak PD signals from the surrounding background noise.

To achieve this, testing rigs were used along with a PD simulator source. This has helped to evaluate the performance of various types of antennas to help selecting the best antenna in terms of sensitivity and frequency bandwidth. Also, it will help with writing the code for the required software.

Figure 1 shows one of the test rigs. The source is positioned in the ground inside a vertical pipe with the signal detecting antenna at some distance at ground level. A selection of antennas used at the test site are shown in Figure 2.

Various antennas were used to detect the weak PD signals. The detected signals contain significant background noise. The largest of those are narrow band broadcast signals (e.g. ~110MHz from radio and ~540MHz for TV).

Various analysis techniques were used to distinguish the signal from noise. One of the methods was the use of the well-known Wavelets technique and most recently a windowing function techniques was introduced to focus the FFT analysis on the region of interest.

In the windowing method, two windows were defined; one pre-trigger to define the background noise and the other around trigger to provide the maximum sensitivity for the signal.

Since the signal also contains noise, a greater weighting is needed to be assigned to the frequency components that have lower noise level. After taking the rms value for each frequency over a number of repeats, the ratio of the values for each frequency in the signal window are divided by the corresponding values for the noise window.

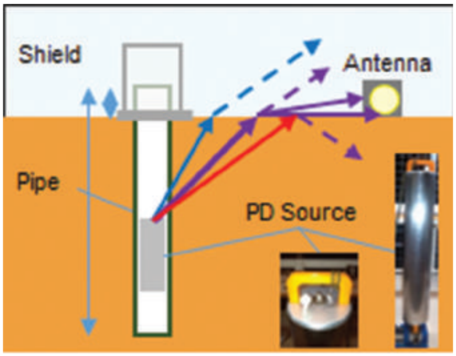

Figure 1 – Test Rig (Vertical Pipe)

Figure 2 – Test Site

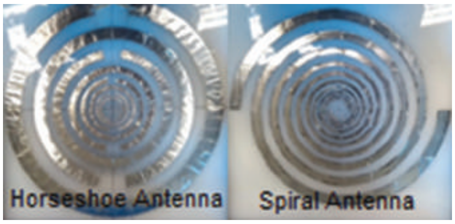

Figure 3 – Samples of Flat Antennas

Figure 3 shows two of the latest used antennas for the detection. The results obtained from using the horseshoe antenna are shown in Figure 3 are displayed in Figures 4 and 5.

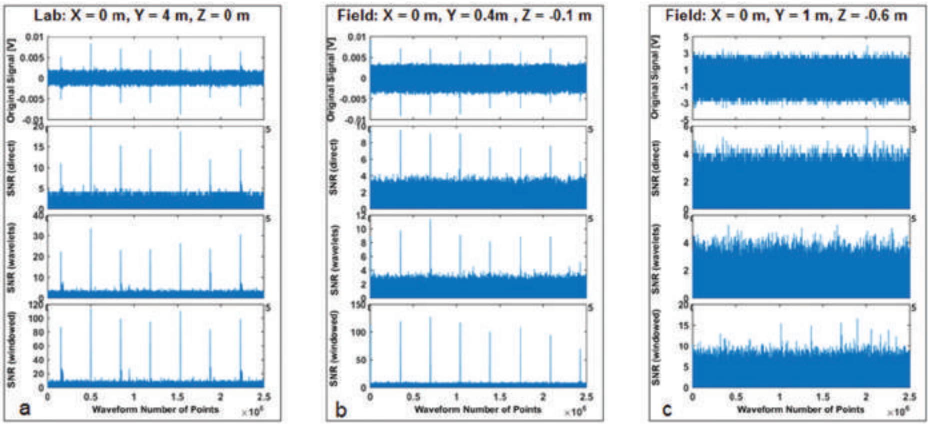

Figure 4 – Signals at different sites and positions and comparing the three SNR methods for the horse shoe antenna

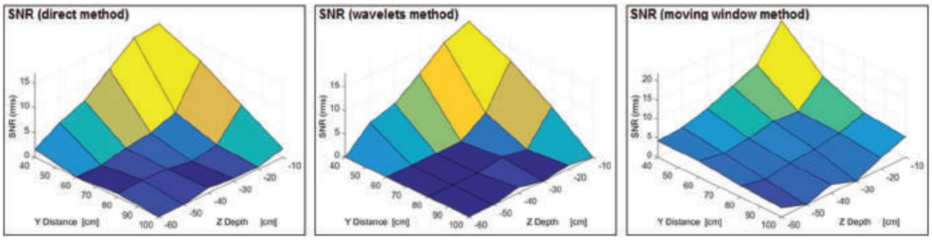

Figure 5 – 3D plots comparing the three SNR methods obtained from using the horse shoe antenna

"Partial discharge (PD) is the source of very brief electrical pulse that generate broadband electromagnetic signal. Hence, PD is considered as one of the most important quantities in assessing the condition of power assets".

"We have demonstrated that we have manged to separate the signal from noise and obtain good SNR using the windowing analysis technique".

Figure 4 shows the detected signal (top small box of a, b & c), and the final signal to noise (SNR) using three different methods. The direct SNR is shown in the second small box in (a, b & c) while the third and fourth small boxes in each of a, b & c show the SNR from using the Wavelets and windowing methods respectively.

Figure 4-a displays the measured signal in the lab with the antenna facing the PD source at ground level and 4m away. It also shows the SNR from the three methods have managed to achieve good SNR but clearly the Wavelets and windowing methods are far better.

Figure 4-b shows the measured signal in the field with the PD source buried in the soil. It is located at 0.1m below ground level and the antenna is 0.4m away from the centre of the source at ground level. This shows an increased level of noise. The SNR from the Wavelets and windowing methods are still better than the direct SNR.

Figure 4-c is showing the signal with the antenna 1m away and the source is pushed deeper into 0.6m. The measured signal in this case is heavily attenuated due to the soil's depth and barely distinguishable from the noise. Both the direct and Wavelets methods have struggled to achieve a good SNR. However, the windowing method managed obtain adequate SNR.

The values used for plotting the 3D maps, are the rms value for all frequencies in the range of interest as shown in Figure 5. The maps are drawn for the SNR versus the distance separating the antenna from the PD source centre at ground level, and various source depths. Also, Figure 6 is showing the maps for the three SNR method techniques with the windowing method showing a better gain over the surface detection range.

We have demonstrated that we have manged to separate the signal from noise and obtain good SNR using the windowing analysis technique.

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Advanced Sensing Technologies Radio Frequency Sensors

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(University of Bath)

Crack and Void Detection

This research produced a Ground Penetrating Radar (GPR) technique to investigate lateral scattering of signals from voids and cracks in the ground. Electromagnetic simulations, such as shown in Figure 1, determined that the basic frequency response from small voids rises with frequency, as opposed to the frequency response of typical cables or pipes. Further the frequency range 3 GHz to 10 GHz is of most interest. The more sensitive observation of voids was seen to be where the level of sideways scattered cross polarised signal is monitored.

To sensitise the measurement scheme to side scattered signal the antennas need to be deployed to radiate down into the ground, and capture the signal scattered sideways, almost parallel to the surface of the ground. New types of antennas were developed meet this need. Two such antenna types are illustrated in Figure 2, the pyramidal horn and the dielectric wedge antennas. These achieved the ultra-wide bandwidths needed to identify a wide range of void densities. Other antennas developed in the research included flared coaxial designs, teardrop monopoles and dipoles, and resistively loaded antennas.

Figure 3 shows a uniform paving slab placed over tarmac slabs which were manufactured with different void densities. This represents a case where weakening ground is invisible under a visually 'perfect' pavement. The new antennas are deployed over the surface of the slabs and moved along the surface obtaining a measure of the void density in the locality of the antennas.

Figure 4 shows that the frequency content of the received signals is affected by the void density of the buried tarmac slabs. The abrupt change in void density in the buried slabs is clear, and also a bright spot from a small delamination is seen.

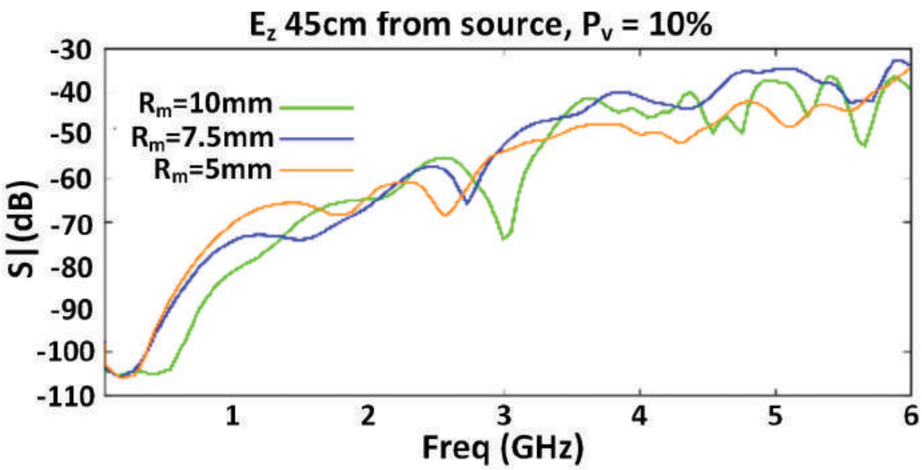

Figure 1 – Frequency Response of Signals Scattered from Voids in the Ground for Three Maximum Void Sizes

The magnitude of the frequency response gives a measure of void density, and therefore the condition of the ground.

A prototype measurement system, shown in Figure 5, was developed for the project to allow investigation of various frequency range requirements and configurations. This was based on a commercially available USRP unit with additional commercially available units to provide the greater frequency ranges needed for void monitoring.

The measurement system is scanned across an area in a manner similar to the way traditional GPRs are used. The collected data can then be processed to produce an image of what is in the ground. Research further developed a scheme to enhance the image formation, and an illustration of it observing two targets is shown in Figure 6. Over much of the image field the distinction between the target and the uniform ground is 30 to 40 dB, or a factor of 1000 to 10,000. As with many image formation schemes the registration of targets is worse near the edges At the left edge the echoing gas pipe target at a depth of 0.5m is smeared out somewhat and accompanied by a false, deeper, indication of a target.

Introducing many small voids into the ground produces a response for each void and this produces a 'fog' in the image. When the void density increases sufficiently this will obscure the target. Figure 7 illustrates a case where a high void density just obscures a target. The 'survey' here however clearly shows the condition of the ground, and indicates the very low void density in the first 0.15m of the ground.

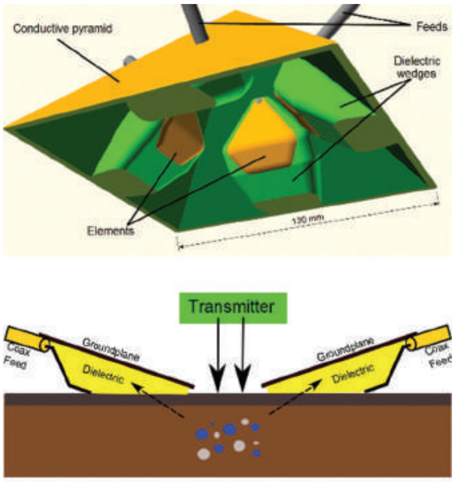

Figure 2 – Novel Antennas Sensitive to the Sideways Scattering of GPR Signals from Voids in the Ground

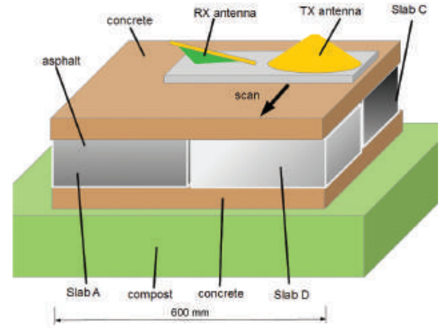

Figure 3 – Measuring Scattering from Voids in Asphalt beneath an Undamaged Concrete Slab

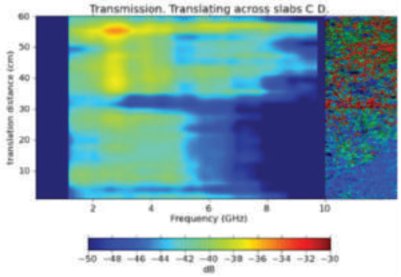

Figure 4 – Scattering from Low Void Density (Lower Half) and High Void Density (Upper Half) Asphalt

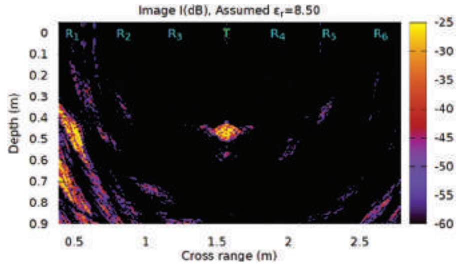

Figure 6 – Focussed GPR Image of a Gas Pipe at Cross Range 0.5m and a Metal Pipe at Cross Range 1.5m. Both Targets at Depths of 0.5m.

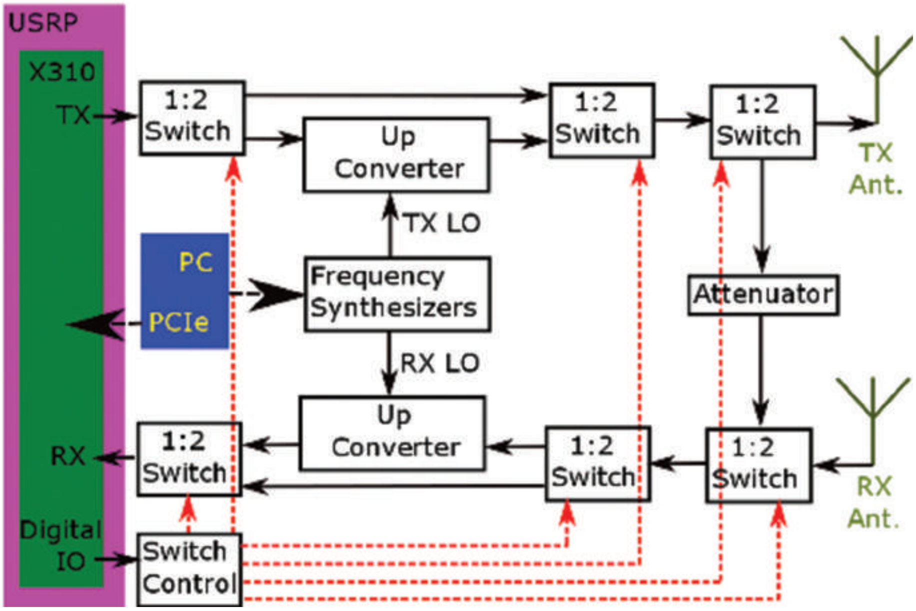

Figure 5 – Experimental System Developed to Investigate Wide Frequency Range OFDM Modulation Scheme for Void Detection

Corrosion of Iron Pipes

As iron pipes corrode over time it was known that they can become difficult to detect using GPR. This research identified that as the corrosion products diffuse into the surrounding soil a smooth variation in conductivity and permittivity is set up. This very readily absorbs GPR signals with little reflection, making the corroded pipe very hard to detect (Figure 8). GPR detection relies on distinct boundaries of conductivity and / or permeability of buried objects relative to the surrounding soil.

The attenuation as a function of frequency has been simulated for several measured and simulated corrosion profiles (Figure 9). The reduction in reflection from the pipes is often 10dB and can be 30dB for frequencies above 200 MHz. Such frequencies are commonly used by GPRs for street surveying.

Electronic Scanning along Cables and Leaky Feeders

Electronically scanning of standing wave signals has the potential to rapidly investigate the condition of a cable or scan along a leaky feeder antenna. The concept developed here is illustrated in Figure 10. By simultaneously using signal generators at both ends of the cable there is a standing wave pattern produced along the line. This has a current maxima where there is a voltage minima, and so concentrates the signal onto a series impedance in the line, as might be produced by deteriorating cable conductors. By controlling the relative time delay between the signal generators the concentration point can be moved up and down the line. Similarly the standing wave pattern can be set to give a voltage maxima and a current minima at a concentration position. This sensitises the measurement to a shunt impedance, which can be introduced by deteriorating cable insulation.

"By controlling the relative time delay between the signal generators the concentration point can be moved up and down the line. Similarly the standing wave pattern can be set to give a voltage maxima and a current minima at a concentration position".

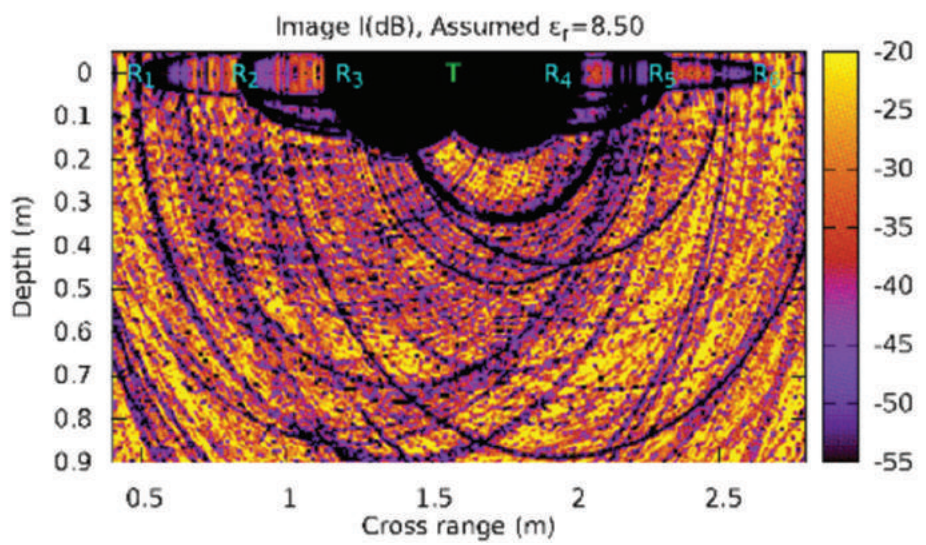

Figure 7 – Focussed GPR Image of a Gas Pipe at Cross Range 1.5m and Depth of 0.5m in Ground with 15% Void Density

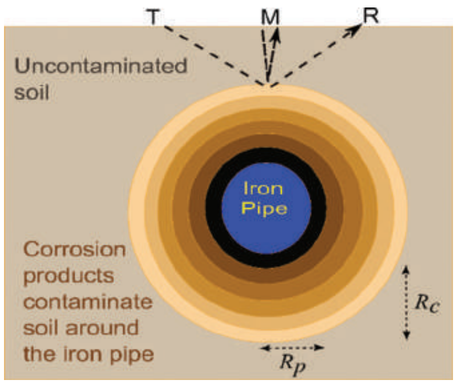

Figure 8 – Corrosion Products from an Iron Pipe Spread into Soil over Time, with a Smooth Profile

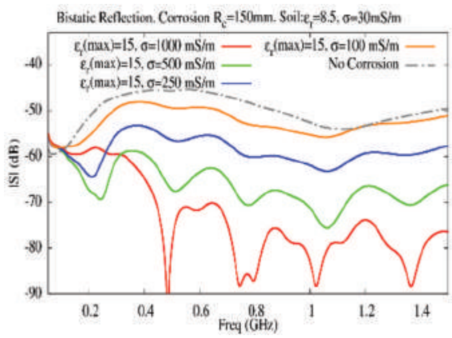

Figure 9 – Attenuation as a Function of Frequency for Several Corrosion Cases

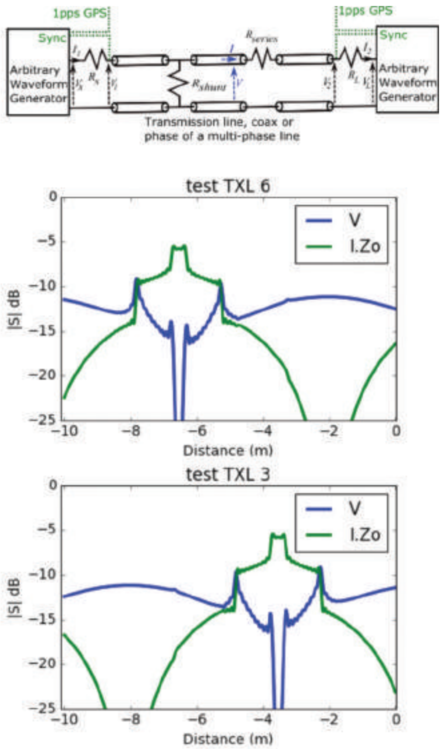

Figure 10 – System to Produce Controllable Standing Wave Pattern Along a Cable and Example Waveforms

Passive Signals of Opportunity

The airwaves are already filled with radio transmissions, from the low frequencies of submarine communications up to the several GHz of mobile phones, with broadcast radio and television in between. An example measured at a University Car Park is shown in Figure 11.

Buried metal pipes and cables also receive these signals as they penetrate through the cable sheath or pipe. As the pipe corrodes or is damaged, the penetration alters, giving a characteristic that can be monitored. The signal levels present on a cable give an indication of a change in the cable (Figure 12). More precise measures may be made by additionally broadcasting from a Test Source in the locality of a cable being investigated.

Research has shown that the frequency characteristics seen with an undamaged sheath are dominated by the conductor skin depth while a damage sheath has a capacitive frequency signature (Figure 13). This offers the potential to identify levels and type of damage or corrosion to the cable sheath or pipe.

Knowledge of the direction of the fields around the pipes and cables being investigated can assist the analysis and interpretation of the measurements. The research has also developed a three axis coil sensor to work over the wide range of frequencies of the signals of opportunity, as shown in Figure 14.

"Introducing many small voids into the ground produces a response for each void and this produces a 'fog' in the image. When the void density increases sufficiently this will obscure the target".

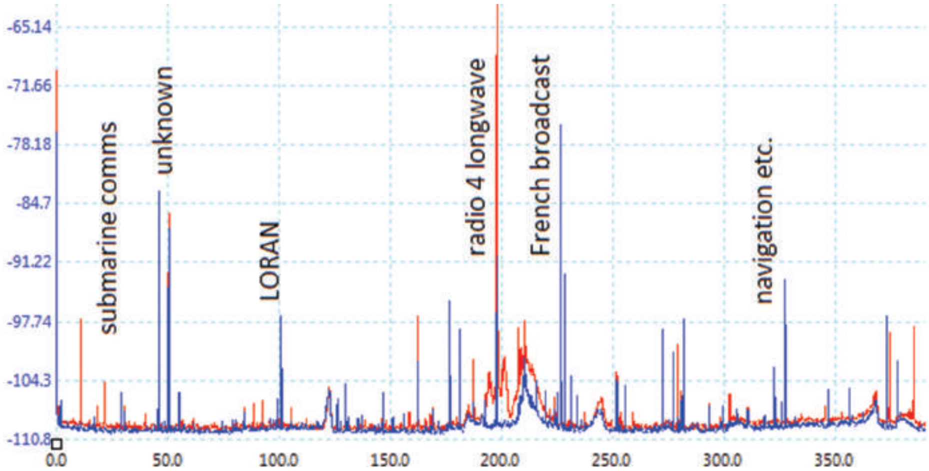

Figure 11 – Ambient Radio Signals

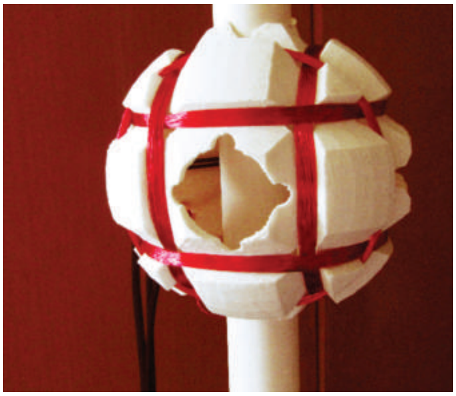
Figure 14 – Three Axis Coil Sensor for Determining Field Direction

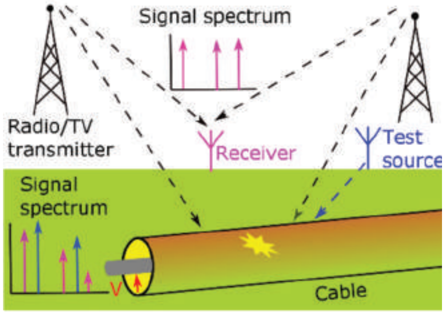

Figure 12 – Signals of Opportunity Monitored On and Near a Cable to Monitor Penetration through the Cable Sheath

"Knowledge of the direction of the fields around the pipes and cables being investigated can assist the analysis and interpretation of the measurements".

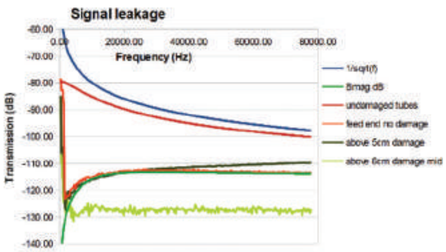

Figure 13 – Leakage Characteristics of Continuous Sheath and Damaged Sheath

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Advanced Sensing Technologies Non-Contact Electrical Resistivity

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(University of Birmingham)

The aim of this work stream was to determine the electromagnetic state (permittivity and conductivity versus spatial granularity) of the buried utility services, the transport infrastructures and the associated geotechnical foundations. This electromagnetic state provides some help in assessing the condition of the infrastructures. This was achieved using three approaches:

- By utilising non-contact electrical resistivity technique to characterise cracks and degradation in road structures.
- By determining the impact and risk factors of tree roots on subsurface structures in an urban environment.
- By detecting the secondary effects of faults in ageing utilities such as the wetting of ground due to leaks in pipes when concealed below a paved surface.

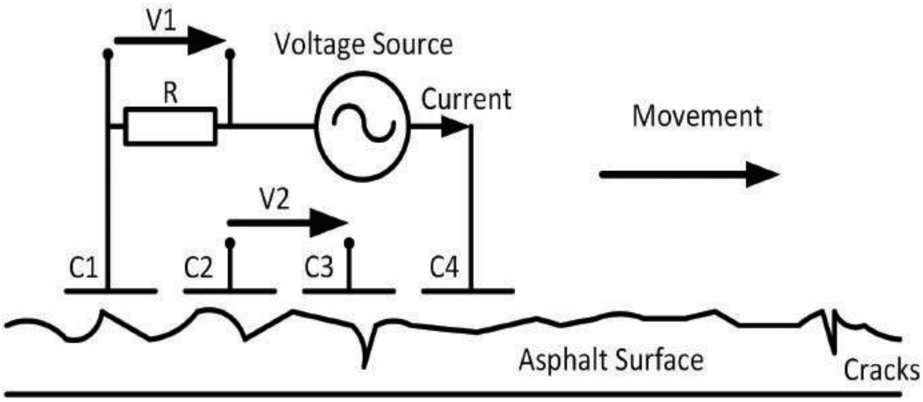

Figure 1 – Schematic on a Non-Contact Electrical Resistivity Sensor

Determination of Degradation within Road Slabs

The assessment of the condition of road slabs is frequently conducted using visual identification, supported by laser-range profiling, of surface cracks and degradation. Such methods have no capability for determining the depth of a crack, or the presence of a underlying degradation within an asphalt surface. The non-contact, electrical resistivity technique effectively induces currents within the road slab and may therefore provide lateral anomaly information about cracks at the millimetric, to centimetric, spatial scale.

The technique for measuring degradation in the top few centimetres of the asphalt surface is to inject a small sinusoidal current using two capacitively coupled plates C1 and C4, as shown in Figure 1. This current is estimated by measuring the voltage, V1, across a shunt resistor, R. The voltage, V2, appearing across two sensor plates C2 and C3 is then divided by V1 to provide an estimate of the apparent impedance of the surrounding materials. The four plates would then be moved about the area to be surveyed.

As an example of the results produced by this technique, a survey area of about 4 m^2 was selected with a range of asphalt ages and conditions, see Figure 2. The survey positions are indicated by green circles whilst 1 m grid lines are overlaid for clarity.

The apparent resistivity of the near-surface asphalt was measured with an implementation of the non-contact sensor, as shown in Figure 3.

Interestingly, this survey area yielded a wide range of apparent resistivity values that can be visually correlated with previous remedial work, asphalt of different ages and surface cracks, as shown in Figure 4. High resistivity values are assumed to be associated with good quality surfaces, whilst lower resistivity values are associated with an increased moisture content.

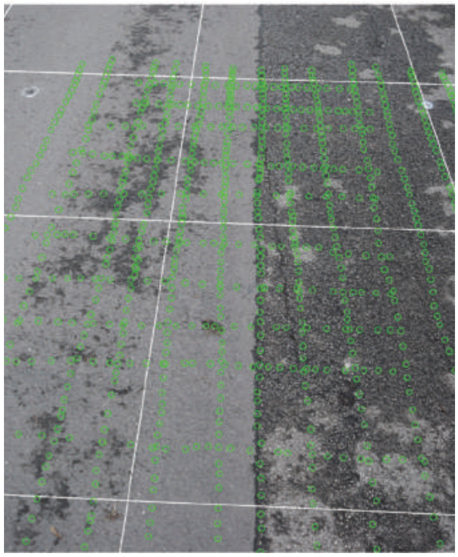

Figure 2 – Typical Asphalt Survey Area and Sampling Points

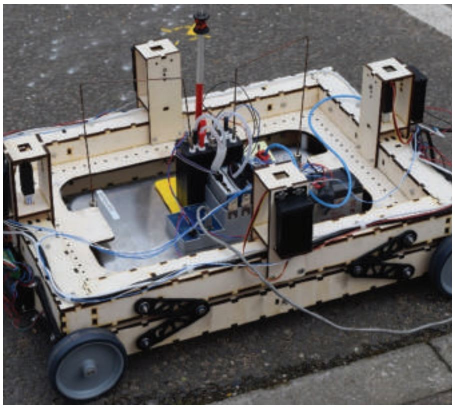

Figure 3 – Non-contact Electrical Resistivity Sensor

Figure 5 – Obtaining a 1.5 GHz GPS Survey of the Same Area

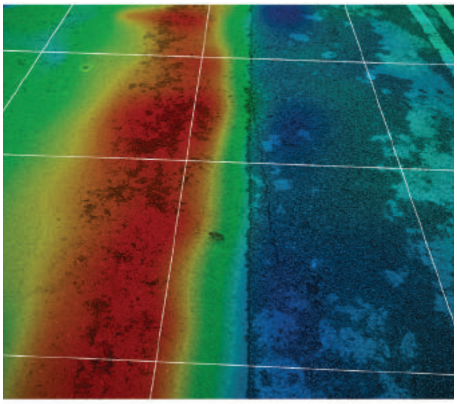

Figure 6 – GPS Survey Overlaid with Visual Image

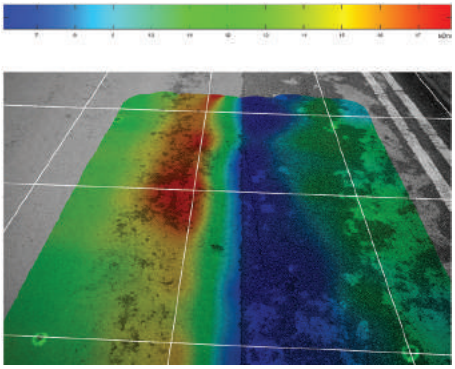

Figure 4 – Electrical Resistivity Results Overlaid with Visual Image

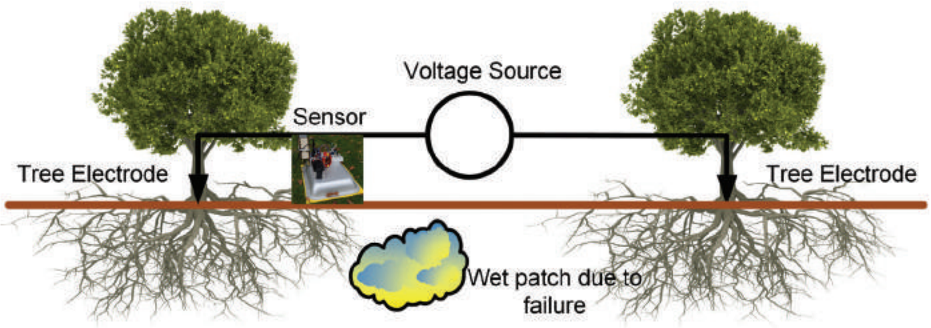

Figure 7a – Non-Contact Electrical Tree Root Survey

Unfortunately, the area cannot be investigated by excavation. To provide a comparative study a 1 GHz GPR survey was conducted using a fine-grid survey tracked to millimetric resolution using a total station, Figure 5.

Such a survey produces a vast quantity of 3D data. It is usually possible to see rapid changes in electrical properties, in particular associated with the thickness of pavement construction layers. The best correlation with the electrical impedance measurements was obtained by displaying the GPR range cell corresponding to the top 20 mm of the wearing surface, as shown in Figure 6. This did not reveal the surface cracks that were visible in both the visual and electrical impedance measurements.

Determination of Tree Root Extent in Paved Environments

Measuring the extent of tree roots in an urban environment is important for town planners, asset owners, insurance companies and building services. Currently there is very little evidential knowledge about interaction with trees until sufficient levels of damage have occurred necessitating visual intervention. The current state-of-the-art measurement techniques include GPR surveys, measurements of the total electrical capacitance of the root structure and traditional (galvanic contact) electrical resistivity surveys. These have primarily been used to estimate tree root extent over grassed areas, rather than paved areas.

The feasibility of detecting tree root extent in paved areas using non-contact techniques is being investigated. Radically, the use of the tree itself as one of the current injection techniques is being investigated by analysis, modelling and small-scale experimentation, as shown in Figure 7a, 7b. This is achieved by temporarily wrapping the trunk of the tree with aluminium cooking foil and applying a sinusoidal signal of a few volts with respect to another distant tree or electrode. The hypothesis is that some of the current flow will be due to capacitive coupling from the roots to the surrounding ground. This in-turn will introduce a small phase change in the measured signal that is influenced by the presence, or otherwise, of roots. A very high signal-to-noise ratio is required to reliably detect the fractional-degree phase changes.

A small sensor is moved around the tree. This comprises four capacitive pick-up plates for measuring electric fields coupled to high input impedance amplifiers, Figure 8. These fields tend to decay as a function of the square of range from the tree, thus obtaining the high signal-to-noise ratios required for the high-resolution phase measurements is exceptionally challenging.

An alternative is to measure the associated magnetic field using three tri-axial coils, as shown in Figure 9. This has the advantage that the magnetic field drops off with the reciprocal of range from the tree. Thus high signal-to-noise ratios are more easily achieved.

Measurements have been taken of the magnetic field associated with the current flowing from the tree, as shown in Figure 10. As expected, the flux lines circle the tree and decrease with range.

A problem to be overcome is that the magnetic approach also detects the current flowing in the wire connecting the two trees, as shown in Figure 11. Unlike the electric field case, it is very difficult to screen the sensor from stray magnetic fields. Current work is focussing on attempting to measure the position of this interconnecting wire, modelling the influence on the measured data and subtracting this from the measured data.

All initial trials have been conducted on trees during winter conditions with no sap rising from the roots. The phase change associated with root extent have not yet been rigorously confirmed. However, the use of trees as electrode-of-opportunity for other survey operation in urban areas has been proven.

“Measuring the extent of tree roots in an urban environment is important for town planners, asset owners, insurance companies and building services. Currently there is very little evidential knowledge about interaction with trees until sufficient levels of damage have occurred necessitating visual intervention”.

Figure 7b – Non-Contact Electrical Tree Root Survey

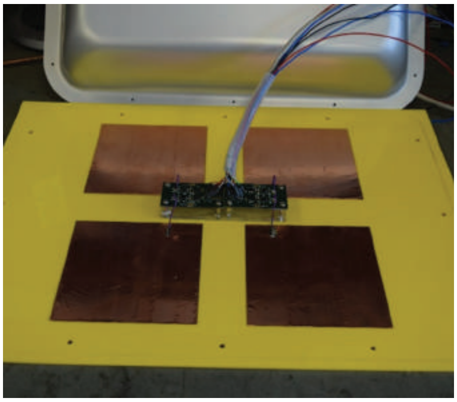

Figure 8 – Non-Contact Electrical Root Sensor

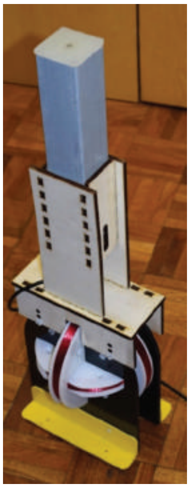

Figure 9 – Non-Contact Magnetic Root Sensor

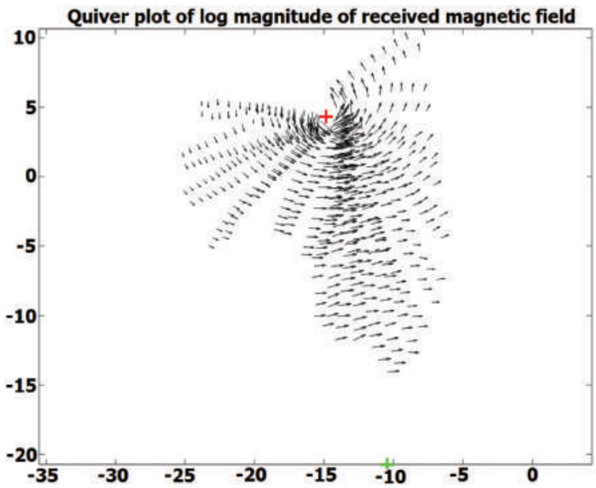

Figure 10 – Magnetic Field Associated with the Current Flowing from the Tree

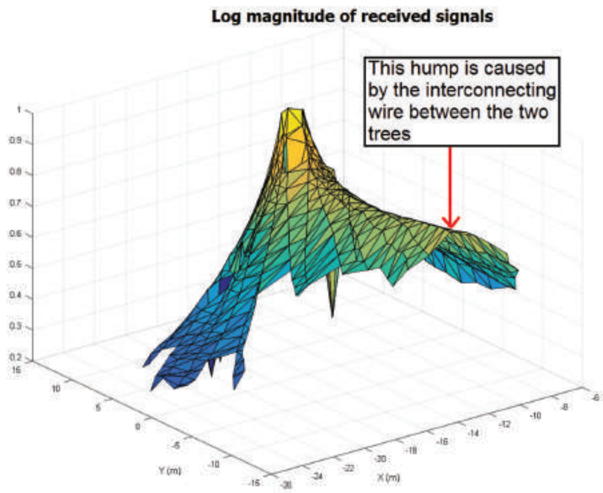

Figure 11 – The Interconnection Wire between Adjacent Trees Contaminates the Process

The Geotechnical and Road Infrastructure

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Background

The buried utility infrastructure (i.e. pipes and cables), the road infrastructure and the geotechnical assets (e.g. embankments, earth dams, levees), provide essential services to our modern society. Managing these infrastructures effectively is a challenge, particularly because of the increasing pressures of a constantly growing population and the deterioration of the existing ageing infrastructure. An appropriate asset management strategy requires a thorough understanding and knowledge of each of these infrastructures, their deterioration mechanism and their interactions. In urban areas, the ground acts as the supporting medium between buried utilities, and the roads. A change in the ground conditions can potentially lead to accelerated deterioration and even failure of the buried and road infrastructure. For this reason the ground, or geotechnical infrastructure, plays a vital role with respect to the continuing performance of the built infrastructure. The ATU research focussed on advancing our understanding of the geotechnical infrastructure through the development and novel application of soil assessment technologies, the investigation of soil deterioration mechanisms, and the study of the interaction between the ground and leaking pipes and between the ground and roads subjected to human interventions (i.e. trenching). These aspects are described in more detail in the following sections.

The Assessment of the Geotechnical Infrastructure – A Field Case Study

A leaking water pipe can lead to deterioration and/or failure of the adjacent buried infrastructure and of the overlying surface infrastructure (e.g. the roads) by fundamentally changing the conditions of the ground. In order to study the changes caused by relatively small leaking pipes to the ground properties a field test site was developed at Blagdon in collaboration with Bristol Water plc (Figure 1). Non-invasive methods, i.e. Multichannel Analysis of Surface Waves (MASW, Figure 1b) and Electrical Resistivity Tomography (ERT, Figure 1c), as well as intrusive techniques, i.e. cone penetrometer tests (PANDA CPT) and an array of buried instrumentation including temperature and Time Domain Reflectometry (TDR, Figure 1a) sensors, were used to measure the conditions of the ground subjected to pipe leakage. This research provided insights on the effect of leaking pipes on the ground and on the feasibility of using these techniques to measure the spatio-temporal variation of the ground properties. These techniques could be used alone or in combination and were demonstrated to be effective at assessing the ground conditions.

Significant effort was put into developing and improving new methods of assessment. An extensive programme of laboratory tests was conducted in order to improve the TDR technique for measuring soil gravimetric water content and dry density. Following suboptimal performance of the current method[1,2] a new improved method[3] was developed and successfully tested on a range of fine-grained soils exhibiting varying plasticity. Following soil-specific calibration performed during a standard compaction test the typical accuracy achieved was to within 2% and 5% for gravimetric water content and dry density, respectively. This method was tested using readily available and relatively inexpensive commercial TDR probes and has been used for the first time in a long-term field monitoring application at the Blagdon test site. It is proposed that the moisture-density TDR method can be used for long-term condition monitoring of geotechnical assets such as embankments, earth dams, levees etc. A number of soil parameters can be calculated from water content and density (e.g. liquidity index, degree of saturation, voids ratio, porosity) and therefore this technique has the potential to provide a more complete picture of the soil conditions compared to other methods. The method can also form part of alert systems that send warnings based on soil parameters that the geotechnical engineers are highly familiar with, for example degree of saturation (Figure 2a).

TDR is well suited for monitoring changes through time at point locations. However, to obtain spatial (in addition to temporal) information other techniques such as MASW and ERT are more suitable because they sense larger volumes of soil. The former provides details on the mechanical properties of the soil[4] (e.g. stiffness), the latter is well suited to monitor water movement within the subsurface[5]. Figure 2b shows the results obtained from MASW surveys conducted at the Blagdon test site at three points in time (i.e. pre-trench, pre-leak, post-leak). These results are presented as 2D vertical shear wave velocity sections through the centre axis of the trench. Prior to trenching, velocities within the upper 1 m ranged from 100–130 $m.s^{-1}$, whereas velocities in the backfilled trench range from around 80–100 $m.s^{-1}$. While

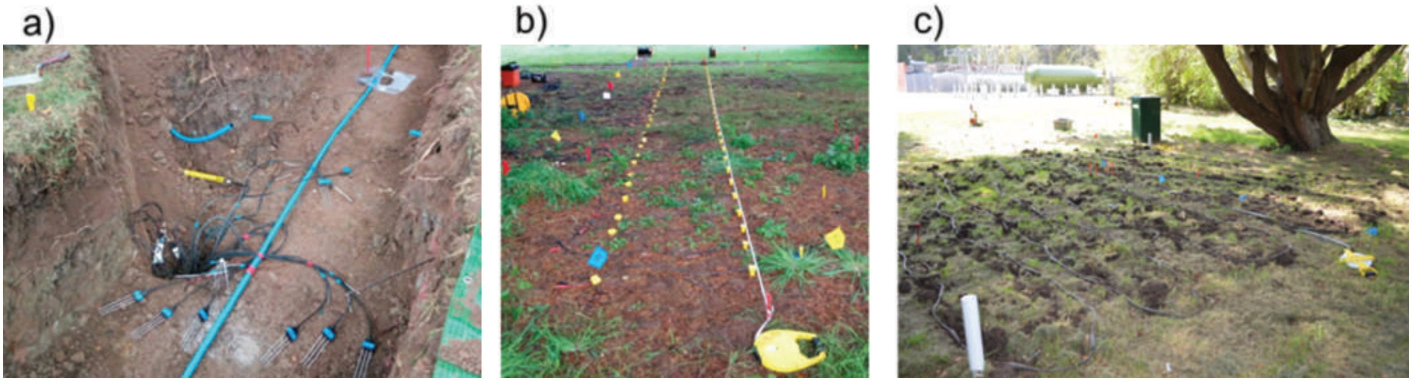


Figure 1 – Ground Assessment Techniques used at the Blagdon Test Site to Monitor Water Leaking from a Plastic Pipe: a) Buried Instrumentation (TDR), b) Array of Geophones used during MASW Surveys, and c) ERT Array of Electrodes

lower velocities where observed in the ground beneath the leak point (note the dip in the 115 m.s^{-1} contour), there doesn't appear to be any further significant lowering of the velocities in the backfilled zone in response to 2 cubic metres leaking from the pipe. It is possible that the leak water actually drained into the formation below the point of the leak.

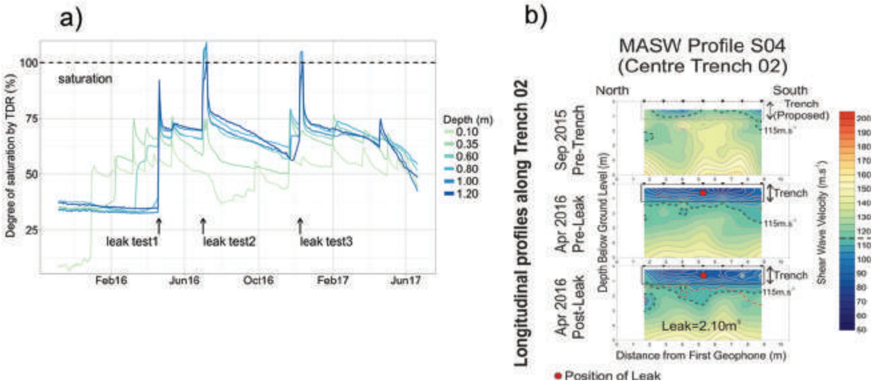


Figure 2 – Results from the Blagdon Test Site: a) Degree of Saturation Monitored by TDR at Different Depths, and b) Shear Wave Velocity from MASW Surveys Conducted at three Separate Times

In this study, the newly developed PRIME ERT monitoring system by the British Geological Survey was deployed to image the infiltration of the leak water into the formation about the pipe using time-lapse electrical resistivity difference measurements. Figure 3 shows the results of one leak experiments where 2095 L of water were introduced into the soil system. The pipe had a pressure of 1.5 bar and average flow rate of 1.7 L/min. The 10% resistivity difference iso-volumes are shown at four times ranging from immediately after, to 2 days after the initiation of the leak. These differences are presented in 3D and over the same 2D vertical sections as the MASW (and for the same leak). The apparent formation of a bulb beneath the point of the leak within the 1–2 m depth interval is consistent with the lowering of shear velocities in this same region.

The results from the Blagdon test site demonstrate the suitability of using TDR, MASW and ERT for assessing the conditions of the ground and for monitoring the evolution of water leaking pipes. These methods can be used alone or preferably in combination in order to provide more information and to increase the level of confidence in the results.

The Deterioration of the Geotechnical Infrastructure

Other complex interactions can occur that deteriorate the existing infrastructure and they are often caused by a change in hydrogeological ground conditions. The ground response can therefore be influenced by temperature (e.g. frost action[4]), the action of shrink/swell in high clay content soils[5], reduced effective strength/stiffness due to elevated pore-water pressure and the rate at which these processes act under both natural conditions and due to made-made interventions.

The term 'deterioration' has not traditionally been applied to the geotechnical infrastructure, but rather to the engineered materials that make up the buried and paved assets themselves. Therefore, as part of ATU, work has been undertaken to investigate the processes believed to reduce the performance of this supporting medium. The most common driver for the loss in performance of soils is the influence of water content change. This is particularly relevant in the context of utility engineering where not only do we routinely rely upon appropriate drainage beneath road construction but the behaviour of the ground can be rapidly altered when dealing with pipe failures.

The influence of wetting and drying cycles has been demonstrated to fundamentally modify the micro-structure of clay-rich fills by progressive aggregation and micro-crack formation (Figure 4). This has several detrimental effects such as increasing the compressibility of the material, reducing both strength and stiffness under loading and increasing the mass-permeability, leading to increased infiltration rate and extent of water, road-runoff, damaged sewerage or leaking insulation oil from electrical cables.

The near-surface zone within which our buried and road infrastructure exists is subject to both saturated and unsaturated conditions. This is as a result of commonly occupying the region between the ground water table and the surface, which is subject to complex soil-atmospheric interactions and capillary action. Therefore, the stability of the soil around pipes and cables and beneath roads is typically governed by the effective stress acting within the soil mass due to the unit weight of the soil particles and the negative pore-water pressure or 'suction'. Therefore, any change in the suction

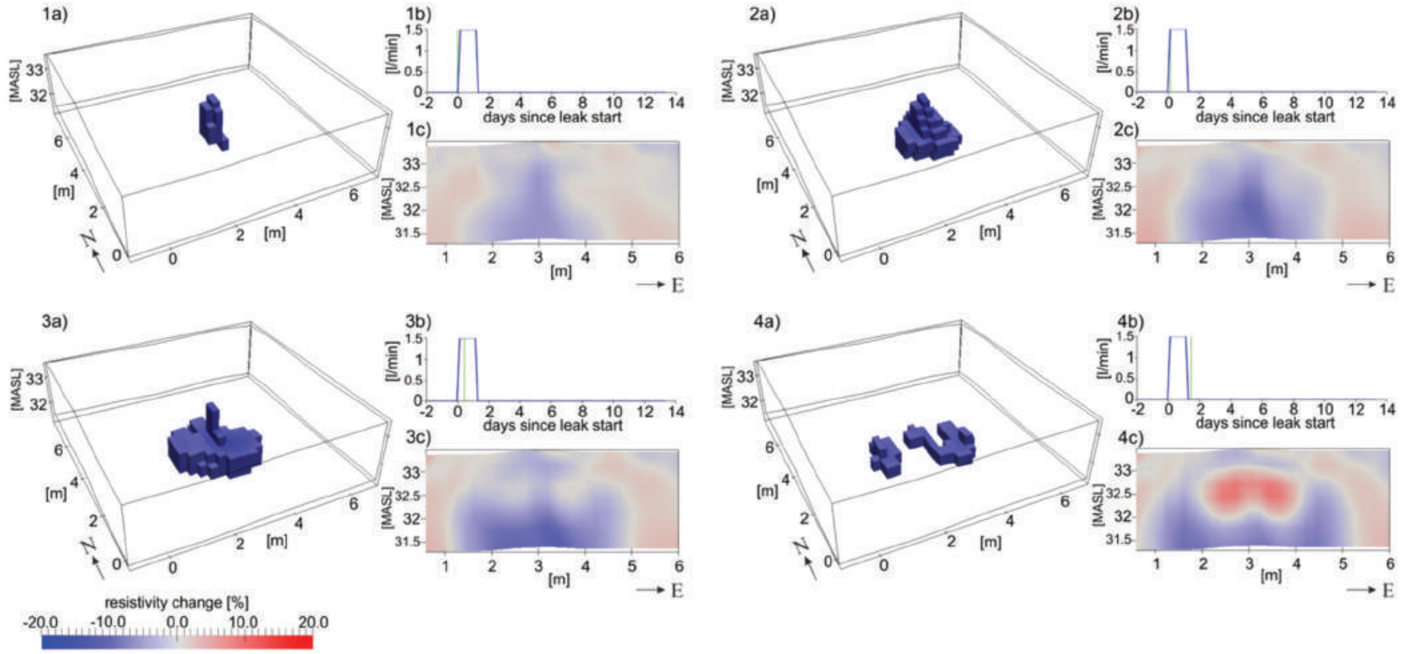


Figure 3 – Time Lapse Images Obtained with the ERT Technique during a Leak Experiment at Blagdon

"TDR is well suited for monitoring changes through time at point locations. However, to obtain spatial (in addition to temporal) information other techniques such as MASW and ERT are more suitable because they sense larger volumes of soil".

conditions within this zone can have a significant effect upon the serviceability of the support provided to urban infrastructure. As part of ATU, the potential deterioration in the suction behaviour of the ground has been studied with respect to changes in micro-structure or 'aging' of the soil fill due to environmental cycling. Field monitoring for a period of 2 years following new ground construction (fill placement and compaction) at the BIONICS research facility at Newcastle University has provided spatially and temporally complimentary water content and suction data recorded at 1.0 m depth (Figure 5a). A series of four successive drying events have been identified and the resultant Soil-Water Retention Curves (SWRC) that describe suction generation (and loss upon wetting) with changes in water content are presented in Figure 5b. A steepening trend with successive events indicates a reduction in the generated suctions for a given change in water content as well as a reduction in Air Entry Value (the suction at which air enters the pore space and desaturation initiates), further reducing the magnitude of suction generation. These properties of the SWRC are fundamentally linked to the soil fabric (pore-size distribution, shape, connectivity etc.) and demonstrate the effect of the change in compacted soils over time, specifically a reduction in the stabilising suctions that are generated as well as an increase in inferred unsaturated hydraulic conductivity. Research into the implications of geotechnical infrastructure deterioration on the wider utility environment is on-going, but the results achieved represent a crucial step in our understanding of urban infrastructure sustainability.

Assessing the ground conditions has been traditionally done using boreholes and trial pit excavations, all of which are intrusive, spatially localised and in the vast majority of cases do not account for changes occurring over time. Measuring soil properties using non-invasive shallow geophysical techniques is challenging, although Vibro-Acoustics can be used to estimate the soil stiffness and electromagnetic techniques can be used to identify wet/dry patches. In certain instances, detailed site information can be provided by using point sensors installed at important locations, for example to monitor the stability of specific infrastructures (e.g. embankments, trench walls during excavations). These include electromagnetic methods such as Time Domain Reflectometry (TDR) and Electrical Resistivity Tomography (ERT) that can be used to measure the water content of the ground. Although water content is a fundamental parameter affecting the physical behaviour of the soil, it varies over time and alone does not provide a complete picture of the conditions of the ground.

The Interaction between Geotechnical and Road Infrastructure

The roads, the buried utilities, and the ground are interdependent. An example of this interaction is a leaking water pipe buried under a paved road; the localised increase in water leaking into the ground will reduce the strength of the ground and could cause localised erosion. This could result in shear failure of the ground and loss of support to

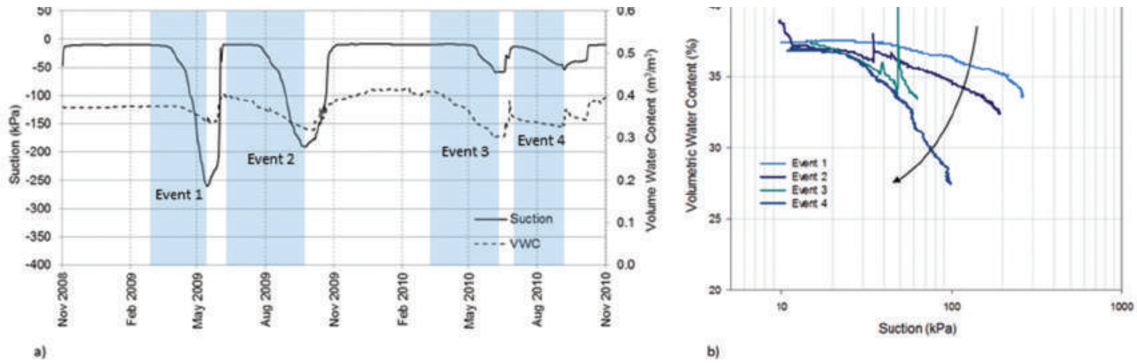


Figure 5 – Ground Hydraulic Response to Environmental Cycling Over 2 years a) Suction and Water Content Time-series Data at 1.0 m Depth Showing Drying Events b) SWRC Development with Successive Drying Events.

the overlying road structure, resulting in pothole formation[6,7,8]. The deteriorated road, which has now lost its structural, as well as its functional performance, could cause the pipe to experience increased loads and/or deformations leading to potential further damage to the leaking pipe, which in turn results in more water leaking into the ground and further damage to the road structure. This mechanism is illustrated in Figure 6.

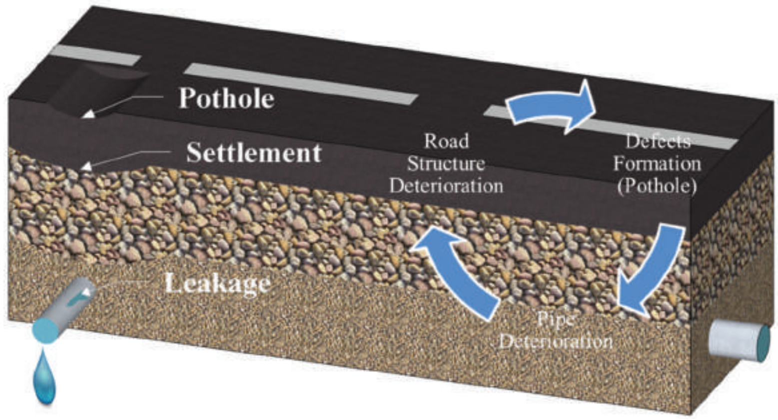


Figure 6 – Interaction between a Leaking Water Pipe and the Road Structure

A field trial was developed at the University of Birmingham campus to investigate the changes in the road and in the ground beneath caused by weather and traffic associated with two trenches constructed with opposite characteristics (i.e. trench 1 using sub-optimal materials and layer thickness, and poorly compacted; trench 2 following the best current practice with high quality materials, larger layer thickness and well compacted). Figure 7 shows the details of the test site. The methods of road and ground assessment were a combination of non-invasive and intrusive sensors. From the surface, Dynatest, Falling Weight Deflectometer and total station surveys provided information on the road settlement and micromorphology following trenching. PANDA CPT tests were also conducted soon after reinstatement. Within the ground, a number of sensors were installed including strain gauges to measure strain caused by traffic loading, strainmeters and pressure cells to monitor lateral movements within the trenched sections, and temperature and moisture TDR sensors for monitoring environmental parameters (Figure 7). A few weeks after installation the site was subjected to heavy traffic from vehicles involved in a demolition activity of a nearby building.

At the time of writing the test site was still active and only some preliminary results are presented here. Figure 8a shows the results of the PANDA CPT tests conducted soon after reinstatement. It is clear that trench 1 exhibited significantly lower resistance to cone penetration indicating reduced stiffness compared to trench 2.

Figure 8b shows the volumetric water content (VWC) measured by the TDR sensors in relation to rainfall events (vertical lines in Figure 8b. It should be noted that these are scaled values of rainfall that were added for illustrative purposes only). Trench 1 was significantly more affected by rainfall events compared to trench 2 that maintained relatively constant conditions several months after construction. These results demonstrate the importance of good construction practice in order to maintain durable road performance.

Summary

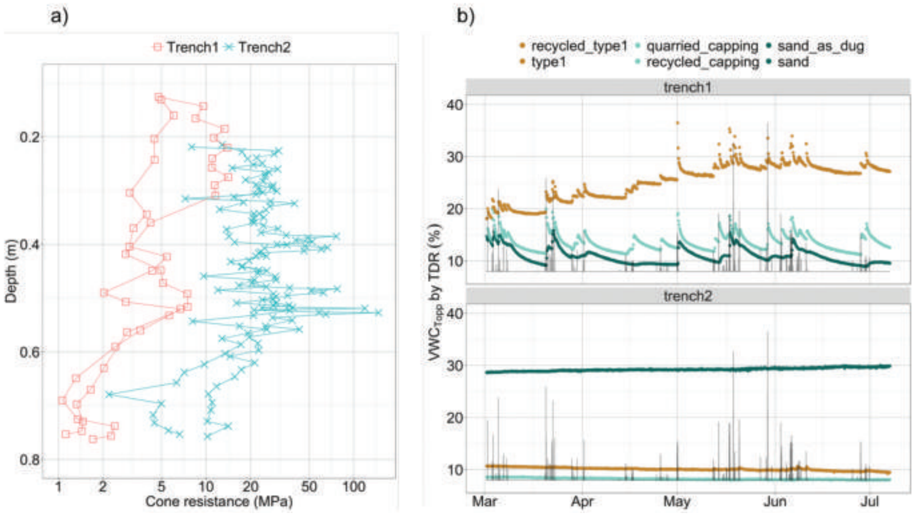
This section has demonstrated the exciting and innovative research that has been conducted to better understand our geotechnical infrastructure and its key role in the behaviour and longevity of our surface (road) infrastructure and our buried (pipe) infrastructure. The ATU research has focussed on advancing our understanding of the geotechnical infrastructure through the development and novel application of soil assessment technologies, the investigation of soil deterioration mechanisms, and the study of the interaction between the ground and leaking pipes and also between the ground and roads subjected to human interventions (i.e. trenching). All of the new knowledge gained, including the greater evidence base that this research has developed, demonstrates the importance of our geotechnical infrastructure and will be invaluable for developing future infrastructure management strategies.

"Research into the implications of geotechnical infrastructure deterioration on the wider utility environment is on-going, but the results achieved represent a crucial step in our understanding of urban infrastructure sustainability".

Trench 1 (poorly compacted)	
Material	Thickness (mm)
Sand (as dug)	300
Recycled Capping (granular)	250
Recycled type 1	150
Tarmac	100 (1 layer)
Compaction after Recycled Type 1	

Trench 2 (well compacted)	
Material	Thickness (mm)
Sand	200
Quarried Capping Layer	250
Type 1	150
Tarmac	200 in 3 layers
Compaction on all layers	

Figure 7 – Details of the Field Trial at the University of Birmingham Campus



"Assessing the ground conditions has been traditionally done using boreholes and trial pit excavations, all of which are intrusive, spatially localised and in the vast majority of cases do not account for changes occurring over time".

Figure 8 – Preliminary Results from the University of Birmingham Test Site: a) Cone Resistance with Depth Measured with PANDA CPT, and b) Volumetric Water Content Measured by TDR Probes Buried in Different Layers of the Road Structure [Note that the Vertical Lines show Scaled Rainfall Data and Not Absolute Values, and were Added for Comparison Purposes Only with the TDR Data]

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Buried Utility Infrastructure Ultrasonic Experiments for Ground Condition

J Boxall, R Collins, J Zhu, R Mills, R Dwyer-Joyce, S Anderson, T Dodd (University of Sheffield)

The UK has over £250billion invested in water infrastructure with pipe networks being by far Water Companies' greatest asset. This pipe infrastructure is an ageing and deteriorating asset base, despite escalating levels of investment such as the £22billion of private investment in water infrastructure 2010-15. Extrapolation of increasing failure rates leads to the worst case scenario of a critical break point and catastrophic 'cliff' of system failure. This can be avoided however vital to this is the development of asset mapping and condition assessment technologies.

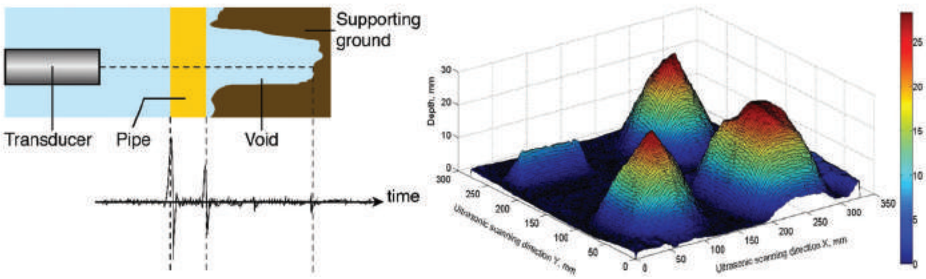

Figure 1 – Ultrasonic Scanning Process and Reconstructed 3D Image of Measured Voids through MDPE Pipe Material

This WS has developed techniques to enable in situ inspection and health monitoring for buried potable water infrastructure these techniques allow for both internal, pipe and external ground condition to assist decision making. The sensing techniques have been supported by the development of a robotic platform that will contain the sensors as payload and will have the ability, from internal inertial and external facing sensors, be able to navigate through the pipeline systems.

Voids Detection using Focussed Ultrasonics in Plastic Pipes

Plastic pipes are widely used in new installed water distribution systems in the past 40 years. The working conditions and health monitoring of them has attracted increasing attention from water authorities and researchers. The ground in which these pipes are buried is a key component of pipeline systems, providing structural support and protection from changing environmental conditions. The ground has however been largely ignored in the literature of pipeline condition assessment.

The study has, for the first time, developed the use of the focussed ultrasonic method to detect ground conditions surrounding the plastic pipes. The principle is to measure the ultrasound waves travelling through the pipe walls, and is then reflected backwards from the external media. By analysing recorded ultrasonic reflections the ground conditions (voids and water content of soil) are able to be determined.

Figure 1 demonstrates the first technique used, which measures the time of travel to the reflection point external to the pipe. This technique was developed first using simulated voids under a flat plate and then its value was demonstrated by the development of a rotating sensor head that can be placed inside and travel through pipeline systems, results demonstrated in Figure 2.

Figure 2 – Ultrasound Sensor with Rotating Mirror to Scan Ground Conditions from Inside of Pipes

Resonant ultrasound detection of pipe support

An ultrasonic methodology has been developed to detect the lack of support around metal water pipes. This sensing technique is based on the use of high intensity ultrasonic waves to excite the water pipe breathing resonance mode. When the water pipe is constrained by the presence of the soil the ultrasonic energy is dispersed in the constraining medium and the pipe does not vibrate. On the other hand, when a void is present, the pipe resonates. This resonance vibration is detected by the ultrasonic equipment and allows the precise localisation. of voids that can be fatal for the pipe integrity. The technique was successfully tested on a steel pipe and the results were validated through a comparison with the cylindrical shell resonance theory and the experimental data from a piezoelectric accelerometer.

SPIERBOT Robotic Platform Development

We have developed a small pipe inspection robot for leak detection and mapping in buried small

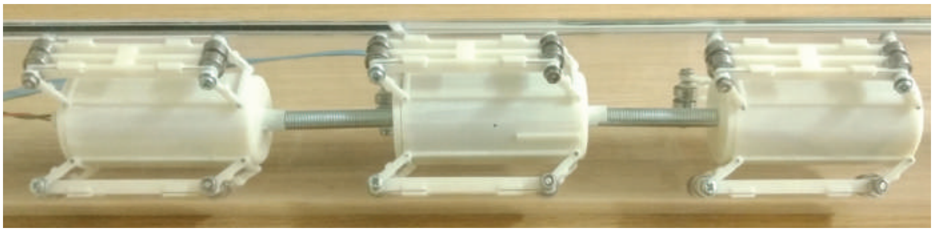

Figure 3 – Prototype of the Robotic Platform Developed to Travel through Small Scale Water Pipelines

"The study has, for the first time, developed the use of the focussed ultrasonic method to detect ground conditions surrounding the plastic pipes. The principle is to measure the ultrasound waves travelling through the pipe walls, and is then reflected backwards from the external media".

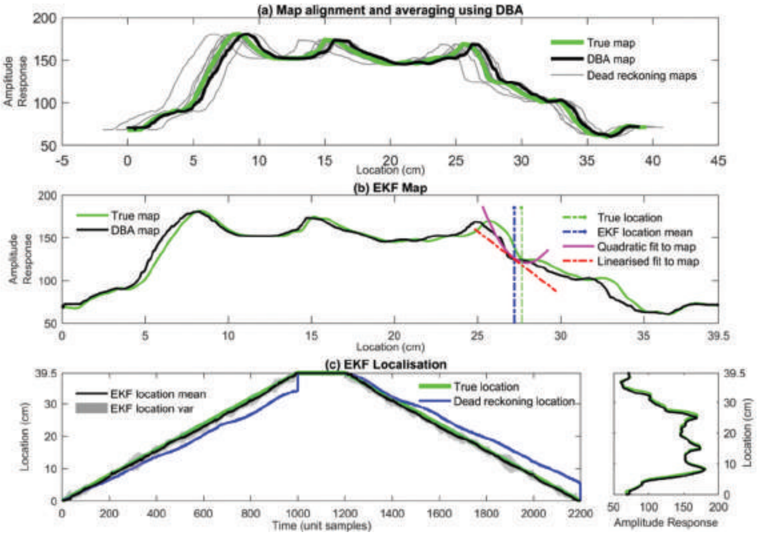

Figure 4 – Mapping and Localisation Results. (a) The use of DBA to Construct a Map Estimate from Observations with Simulated Drift. (b) and (c) Localisation using an Extended Kalman Filter (EKF). A Comparison is given to Dead Reckoning, Showing the Clear Improvement in Localisation Accuracy with EKF and PF

"By analysing recorded ultrasonic reflections the ground conditions (voids and water content of soil) are able to be determined".

plastic water pipes. Simplicity in design and versatility in nature are the principles we had in mind when designing our robot. These principles are important if we want to use this robot in the real world in the future. The robot is tethered because currently water companies will currently not let an untethered object introduced to their networks. It carries a revolving ultrasonic sensor head for full 360 degree scanning of pipes' walls to detect voids in the soil surrounding the pipe, because such voids can indicate leaks. The voids will also be used as features for simultaneous localisation of the robot and mapping of the pipe network. In parallel, we are working on a sensor head carrying a hydrophone instead of an ultrasonic sensor, for leak detection in cast iron pipes. There are also inertial measurement units that provide a complementary means of localisation. The robot has an Ethernet link to an outside processing and control unit to send out raw data from the sensors for processing. The mechanical design of the robot is such that the ultrasonic sensor stays perfectly in the center of the pipe to produce homogeneous data while revolving. For this purpose, it has passive spring loaded parallel joints and links that also help passing over obstacles such as semi closed valves, or bumps on the inner pipe wall. Our current prototype has a nominal diameter of 3" and can go from 60 to 80 mm in diameter. The robot has a modular design, with each module carrying part of the payload (electronics, sensors, motors, batteries, etc.) and different modules attached together with flexible joints. It must also be able to go around bends, which limits its size. Each module in our current prototype has a length of 70 mm.

Water distribution pipe networks are usually buried, and so are difficult to access. Robots are therefore appealing for performing inspection and detecting damage to target repairs. This work has developed a new mapping and localisation algorithm for water pipes with two key novelties: the development of a new type of map based on measured external signals from the sensors developed elsewhere in WS5, and a mapping algorithm based on spatial warping and averaging of dead reckoning signals used to calibrate the map (using dynamic time warping). Localisation is performed using terrain-based extended Kalman filtering. We have successfully demonstrated the approach showing significant improved localisation compared to dead reckoning alone. Knowing the presence of deterioration features is important, however knowing exactly where those deterioration features is vital to allow operational managers to make best use of that information.

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Integrated Inter-Asset Management of Street Works: System of Systems Approach

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HJ Reeves, D Entwisle, D Gunn (British Geological Survey)

Sustainable street works require an integrated approach as the asset systems and their interlinkages act as a holistic system. To achieve this involves complex decision making about: asset maintenance; repair and replacement planning; assessment of the condition of the ground; estimation of the condition and possible deterioration of roads and buried utility infrastructure; identification of the influence on inter-related assets; estimation of the costs associated with economic, societal and environmental impact. To facilitate the assessment and management of the underground space by different stakeholders, ATU is developing a proof-of-concept decision support system (DSS) that exploits the data, information and knowledge gathered in the project and provides intelligent support for integrated inter-asset management.

Stakeholder needs: A stakeholder consultation meeting at the start of the ATU project identified key challenges to sustainable street works, which informed the design of a decision support system:

- Urban street work decisions involve multiple, often disconnected stakeholders, such as local authorities, utility companies (e.g. water, electricity, gas, sewage, communication), transport asset owners, data providers (e.g. Met office, Environment agency, BGS), the public.
- There is no fully integrated data management or unified decision-making approach in current use across urban street work stakeholders; there is a lack of a unified authority to plan and manage the underground space.
- Decision-making requires broad knowledge of inter-asset dependencies, familiarity with the state of the art methods for asset assessment and management, and the ability to identify appropriate technologies and alternatives.
- Sustainable urban street works requires a holistic cost/benefit analysis approach, which considers the various dimensions of impact, e.g. technical, economic, social and environmental.

Through the ATU DSS, these challenges are addressed by integrating the knowledge and insights developed by the research conducted in the various ATU streams.

The DSS Architecture: An integrated approach to managing the interdependent road and underlying utility networks using contextual information and expert knowledge from road, ground and utility engineers underpins the DSS Architecture, which gives guidance on the consequences of any natural, planned, accidental or temporal change to these networks and sustainable solutions. It is an interactive system triggered by the user allowing them to place the change in context thus optimising the guidance given.

The ATU DSS is an interactive computer system that supports asset management decisions by integrating and reasoning with diverse information sources about assets and their relationships. It includes three main components.

The DSS Knowledge Model: Comprising of a suite of knowledge models defining the main underground space assets: utilities (water, electricity, gas, telecommunications, and sewage), road, and the ground. In ATU we consider the ground surrounding and supporting assets to also be an asset that enables us to reason about ground condition and composition (and actions that affect it) in the same way as for other assets. The DSS knowledge model defines: asset properties and processes; relationships between assets; various assessment and maintenance activities (including traditional methods and new sensing methods researched in ATU); deterioration models, and cost models.

Figure 1 – Typical UK Streetworks Scenario

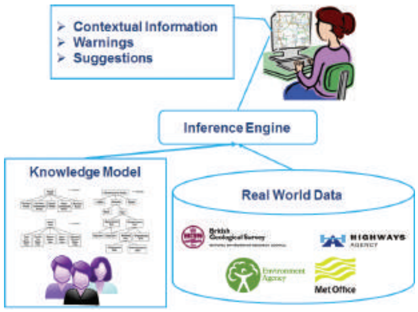

Figure 2 – The DSS Architecture

Real world data: Data related to the decision making process that provides the baseline for diagnosis and maintenance activities. This includes asset data such as historic records (e.g. asset inspection and maintenance), which is collected and maintained by the individual asset owners (e.g. local authorities or utility companies). In addition, the DSS includes data that provides important contextual information such as information on the ground conditions (British Geological Survey), environmental conditions (Environment Agency), meteorological conditions (Met Office) and traffic flow (Highways Agency, Local Authority).

The DSS Inference Engine: Links the knowledge model and the real world data, enabling an integrated systems thinking approach. It provides

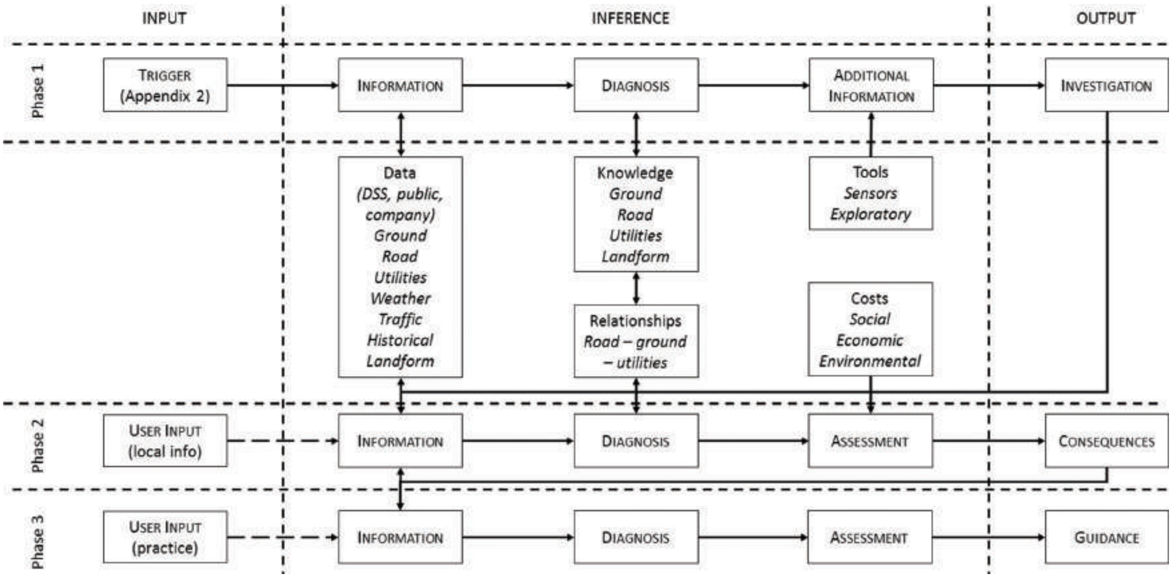

Figure 3 – ATU Decision Support System

a framework for problem analysis that makes inferences about inter-asset dependencies based on proximity and relationships to other assets (e.g. road, pipes, cables, and ground). The inference engine also identifies relevant contextual factors (e.g. meteorological conditions) that may affect asset conditions. It determines whether additional information about the asset properties and processes is needed, and suggests ways of obtaining such information (e.g. non-invasive methods such as sensing). By linking to a cost model, the inference engine suggests possible economic, social and environmental costs that may have to be taken into account when diagnostic and maintenance activities are planned.

The interactive user interface considers different triggering mechanisms that require street work decisions to be made, such as, defects (e.g. pothole, or crack in the road, or pipe leaking), environmental events (e.g. flooding, drought), planned works and routine audit. Based on the location the interface retrieves the baseline data/information, which is derived from the available asset data (historic asset owner records) and contextual data. The interface also renders the output of the inference engine in the form of prompts. These prompts point at aspects that may need further investigation as they could cause further defects or failures.

For example, a pothole reported by a member of the public has been diagnosed by local authority road expert as a category 2 road defect (minor, monitor at next inspection), as the road is in a relatively good condition, has low traffic, and is seen as having low economic impact and no impact on the road safety. When such decisions are taken, it is hard to take a global systems view, which requires additional information about the environment, knowledge about possible inter-dependencies with nearby assets, awareness of deterioration and cost of action (or inaction). Overlooking such links can lead to further defects, event to major asset failures.

A systems thinking approach would require that a decision maker answers questions like:

- What is the current condition and composition of: road surface, road foundation, adjacent pipes and cables and the adjacent ground?
- How might this condition change in the future because of: street works (excavation/reinstatement), ageing and deterioration/failure of buried assets, climate (floods, drought, and temperature), increasing population and traffic in urban areas?
- How can we carry out street works in the most sustainable manner, i.e. in an economically, socially and environmentally cost effective manner?

The ATU DSS can assist with the above questions. At the heart of the ATU DSS is the knowledge model. The core knowledge model defines the main concepts of: buried assets (e.g. pipes), ground conditions (e.g. soil/rock properties and processes), land cover (e.g. roads, topography), environment and human activities, and specifies relationships between assets. An important aspect of the ATU ontology describes sensors and observations, linked to asset properties and processes, as well as the workflow for sensing assets and underground environments. This indicates likely benefits and limitations of using sensors for sustainable asset management associated with streetworks.

The ATU knowledge model[1,2] is being developed by an interdisciplinary team involving knowledge engineers, civil engineers and utility management experts. The knowledge engineering process included needs analysis and continuous expert engagement (e.g. workshops, meetings, critical review), which enabled us to produce the domain conceptualisation, capturing the main concepts and relationships of the underground assets. Sources of knowledge are derived from the literature, related ontologies (e.g. SWEET[3] or SSN[4]), existing guidelines (e.g. National Land Use Database, classification of soil BS EN ISO 14688, Highways Agency), and authoritative datasets (e.g. British Geological Survey, UK Water Industry Research).

Each asset is described along with its main properties and processes (an example of ground properties and processes is shown below). The knowledge model specifies relationships between asset properties and processes (e.g. ground clay content influences ground compaction; ground compaction has impact on ground porosity; ground porosity affects groundwater content). It also includes inter-asset relationships that link properties and processes of different assets. For instance, ground compaction (ground process) affects road deflection (road process).

Figure 4 – Example Scenario - 'Small but Mighty' Pothole

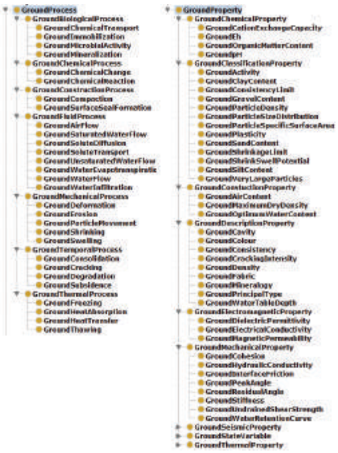

Figure 6 - Excerpt of ATU Ontology of Soil Properties and Processes

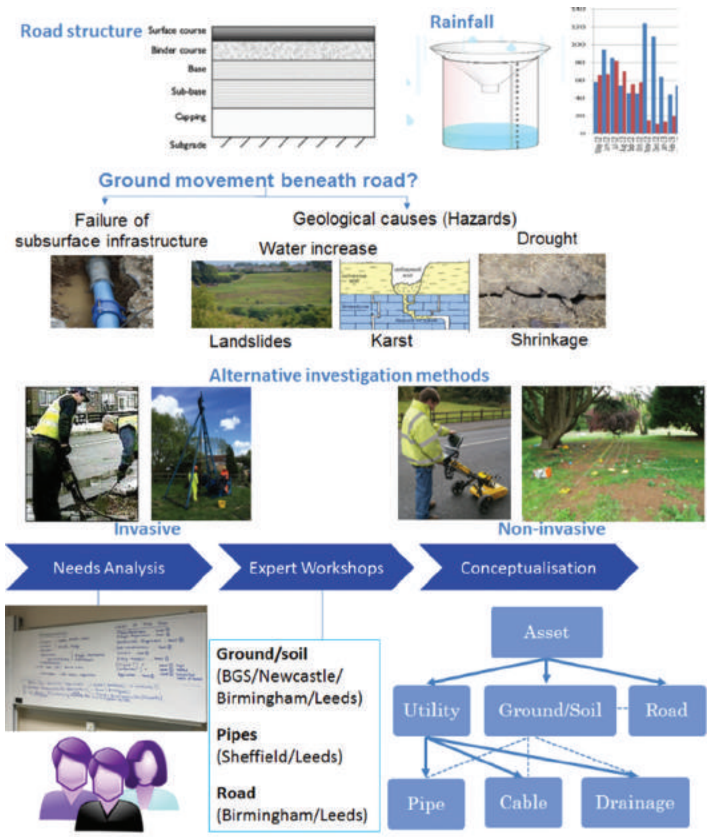

Figure 5 – Pothole Scenario Considerations and Conceptualisation of DSS Ontology

Complex decision making in domains with high impact, such as infrastructure management, is a challenging task that requires the consideration of a large number of parameters and their dependencies. This requires comprehensive sector knowledge, which only a few technical experts have and have developed over many years of experience. The aim of the ATU DSS is to capture such knowledge from multiple technical experts in a computer-processable form that augments the complex assessment of the assets and enables maintenance decisions to be made.

Capturing expert knowledge can be time consuming and prone to limitations. For example, experts may not be able to capture the true complexity of the decision making process. The process of validating knowledge models can be laborious and slow as it can be hard to identify missing or inaccurate relationships. Furthermore, as the decision making process involves a combination of factors; it is hard to identify those combinations that are strongly associated with risks. To tackle these challenges, we are developing novel approaches for linking knowledge engineering and data mining.

By adopting supervised machine learning models we can validate and extend the knowledge models derived from domain experts. The future ATU DSS work will focus on developing a systematic framework for reliable and audible intelligent decision support, which explores the synergy of human expertise (knowledge models captured from domain experts) and data (knowledge extracted from historic data).

"An important aspect of the ATU ontology describes sensors and observations, linked to asset properties and processes, as well as the workflow for sensing assets and underground environments".

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Sustainability Costing Model for Streetworks in Urban Environments

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Utility infrastructure systems are an essential part of well-functioning urban environments and are very important to the quality of life in modern urban living. Thus they have a critical role in enhancing the liveability, sustainability and resilience of cities. However, installation, operation, maintenance and upgrading of these services are very expensive and can greatly impact the local and global economy. Moreover, there are considerable issues, and associated impacts, of these streetwork operations (see Table 1). Looking forward, the global population is forecast to rise to more than 9 billion[1] with more than 70% predicted to live in cities by 2050[2]. This will increase greatly the demands on urban infrastructure systems, and has the potential to cause far greater adverse environmental and societal impacts, and yet the systems that we are putting in place today are likely to be those that support these future urban environments. We should therefore be thinking, acting and planning today to alleviate both current and future impacts. However, presently in the UK alone more than 4 million holes are excavated in roads each year[3]. In 2014-15 utility streetworks in England and Wales incurred direct costs of more than £1.5bn, while the indirect costs of using open-cut were estimated comfortably to exceed £5 billion[4]. Yet trenching remains the most widely adopted solution for utility placement by practitioners (Figure 1) even though various alternative solutions exist, such as Trenchless Technologies (TT) and Multi-Utility Tunnels (MUTs).

Issue	Impact
~ £7 billion per annum: cost of utility streetworks to the UK economy [3]	78% of which is indirect costs including social and environmental impacts [3]
Road occupation due to utility streetworks causing traffic delays	Accounted for equivalent of ~ 6.16 million days of work in the UK in 2014-2015 [4]
An estimated 1.37 million streetworks undertaken by utility companies alone [4]	This equates to 2.4 million road openings in the UK in 2014-2015 [4]

Table 1 - Issues, and Associated Impacts and Costs, of Utility Streetworks

Hence the scale of problem is huge and if we as a society are to improve significantly, a change of approach is now needed. This stems from a lack of a consistent approach to Utility infrastructure systems that currently fail to allow the broader impacts and costs to be considered both in the short and medium to long term and by doing so allows the benefits of a wider range of streetworks options to be assessed. Therefore, the main aim of this work stream was to develop a sustainability costing model and evaluation methodology for utility streetworks that will allow alternative intervention approaches to be assessed by comparing the true total (i.e. economic, social and environmental) costs and impacts. Currently, different solutions to deal with utility streetworks exist (e.g. various Trenchless Technologies and Multi-Utility Tunnels). However, decisions are commonly always made on a cost basis, focused on short term construction costs, with little consideration of longer term economic, social and environmental consequences for the choices made. The ultimate purpose of this research was to provide a basis on which to support investment decisions, alongside the comprehensive technically-informed ATU DSS outcomes, that hold well today and for the future.

WS8 has focused on capturing the specific sustainability impacts and costs of utility infrastructure streetworks projects and developing a bespoke sustainability evaluation framework to be used as an essential element within a broader value-based asset management system[5]. The main significant advances in this work are:

1. Review of existing systems and tools for sustainability assessment – more than 40 sustainability assessment tools and methods were reviewed – and selection of the most appropriate approach for streetworks.
2. Identification and development of a comprehensive set of indicators and assessment criteria for sustainability assessment of utility streetworks (see Table 2).
3. Consultation with a wide range of industry experts and stakeholders to refine and validate the indicators and assessment criteria was carried out. A questionnaire was developed. The questionnaire was distributed to a group of industry experts (Figure 2), including utility companies, local authorities, civil engineering consultants, contractors, developers and utility mapping practitioners. The questionnaire aimed to validate the developed indicator sets and to capture expert opinion on their importance and applicability (Figure 3). [The question statement for Figure 3 was: "with regard to utility streetworks projects, specify the importance of the following headline cost / impact categories, where 1 is the most important and 4 is the least important."]

Construction Indirect Economic Impact	Third party utility damage
	Compensation to businesses for loss of profit
	Compensation to customers for interruptions to services
	Loss of income to asset owners or utilities
	Compensation to local authorities for damage to their assets
Maintenance Indirect Economic Impact	Goodwill (damage to companies' reputation and brand image)
	Required training (upskilling)
	Insurance
	Loss of business to competitors
	Lost opportunity cost

Table 2 - Example Set of Indicators for Indirect Economic Costs

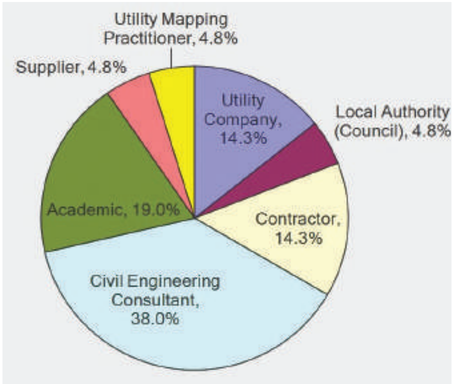

Figure 2 - Distribution (%) of Questionnaire Participants

4. In addition, more detailed interviews were conducted with selected participants from across the industry. The interviews were conducted both in the UK and in the Netherlands. The results of the questionnaire and the more detailed interviews were used to inform the Sustainability Assessment Framework for Urban Utility Streetworks (see below).
5. Development of the Streetworks Sustainability Assessment Framework (SSAF). This methodology included, but was not limited to, the adaptation and modification of an existing established Sustainability Assessment tool (Arup SPeAR®)[6] to be used for utility streetworks projects. The SSAF Methodological Development is summarised below:
   a. Conceptualising the SSAF (2 phases):
      i. Pre-Appraisal tool
      ii. Detailed sustainability-based decision-making modelling
   b. The Pre-Appraisal tool for Utility Streetworks is based on the adaptation of an existing framework and development of new sets of sustainability indicators specifically for streetworks[7]
   c. Four sets of indicators were developed based on four headline indicators (Direct Economic, Indirect Economic, Social and Environmental)
   d. Aim is to fully understand, optimise and where applicable minimise the cost / impact on all 4 categories
      Total Sustainability Cost (TSC) of streetworks is defined as:
      TSC = Direct [economic] + Indirect [economic] + Social + Environmental
6. Testing and validation of the SSAF and Sustainability Assessment Model on a number of real case studies both in the UK and the Netherlands. The case studies included:
   a. The University of Birmingham campus utility services network
   b. Pipe Subways in London
   c. Various trenching and trenchless utilities projects in different areas of the Netherlands, including:
      i. Amsterdam
      ii. Rotterdam
      iii. Utrecht
7. Integration of sustainable assessment frameworks into BIM were investigated, paving the way for BIM level 6D. The Envison[8] tool was used to integrate into BIM a methodology for sustainability assessment. The research on how to assess sustainability combining BIM and Envision has shown that 58% of the credits from Envision can be directly assessed with information already normally available on a design done using BIM model. Additionally, 24% could be assessed if extra information such as geology maps and landscaping biodiversity details were also input into to the model during the design stage. Therefore only 18% of the information needed for the Envision sustainability assessment would be needed to be collected outside the BIM model. Considering that to achieve Platinum certification on Envision only 50% of the points need to be achieved[8], the research has shown that it can be relatively straight forward to assess if a project can be certified or not with Envision using design information available on a BIM model. More importantly, regardless of the certification on this specific method or not, the research has shown that 82% of the information needed for this comprehensive sustainability assessment can be input into the BIM model, facilitating the management of the assessment process.
8. The methodology also builds on and links with parallel research being conducted in the Liveable Cities[9] and iBUILD[10]: Infrastructure

Figure 1 - An Old Problem, Still in Place: Open-Cut Trenching – Left: Laying of Sewer Pipe, Early 1900s (Courtesy of www.sewerhistory.org) - Right: Utility Streetworks using Conventional Trenching, 2016

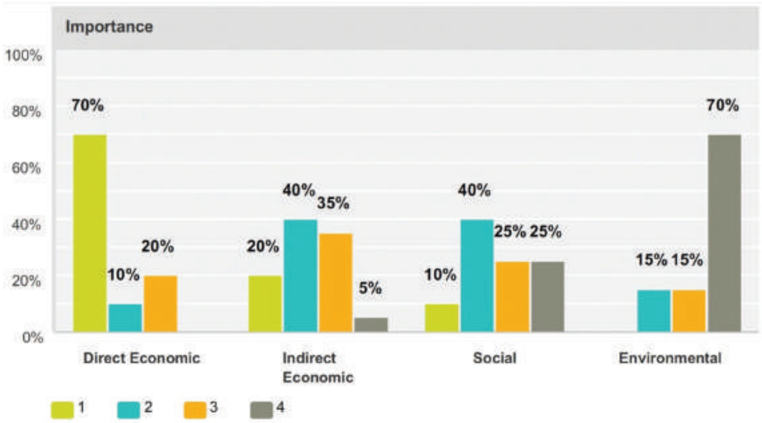

Figure 3 - Example Question in the Questionnaire (Relative Importance of Headline Indicators: 1 is the Most Important and 4 is the Least Important)

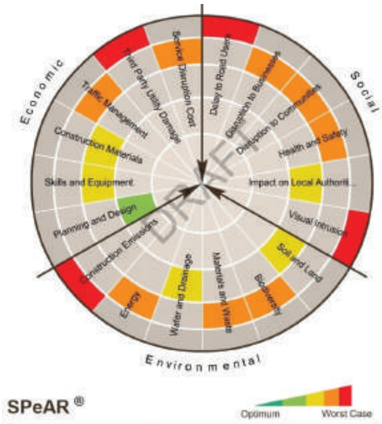

Figure 4 - Example Output of the Pre-Appraisal Sustainability Assessment of the Open-Cut Trenching Method for the Construction Stage of the Case Study

Business models, valuation and Innovation for Local Delivery research projects. The SSAF and Sustainability Assessment Model will bring a new level of intelligence to the planning, operation and maintenance activities for streetworks[11], which will in turn inform decision-makers in streetworks projects of the likely outcomes of their decisions on society and the environment, as well as in terms of direct and indirect economic costs (see Table 2).

The pre-appraisal modified sustainability tool was applied on a case study in which sustainability performance of a trenchless method was assessed against that of a conventional open-cut trenching. The assessment was carried out for both short-term and long-term stages of the project. An example of the output of the assessment presented through the modified Arup SPeAR® Pre-Appraisal software[12] is shown in Figure 4. More detailed information, results and analysis outputs are available in[7] and[13].

In summary, through the SSAF, a methodology was developed to both conceptualise the cost and impacts across short term and long term, taking into account a more holistic view of economic, social and environmental factors. This is built into the ATU DSS, so it allows informed choices and helps reduce the significant costs incurred with current utility streetworks. Thus for the first time a long term, total cost approach can be applied to any potential streetworks activity, and through this allow longer term benefits to be realised, where currently short term economic cost-based assessment precluded them.

"The pre-appraisal modified sustainability tool was applied on a case study in which sustainability performance of a trenchless method was assessed against that of a conventional open-cut trenching".

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Reshaping Utilities Business with BIM Plugging the Gap between Ambition and Action

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Across the globe, civil engineers are confronted by increasing pressures that intensify the need for innovation. These pressures manifest in different forms, such as the lack of investment in the maintenance and upgrading of existing infrastructure, which in turn results in deteriorating infrastructure that poses an existential risk to public health and safety, whilst hindering socioeconomic growth.

Furthermore, a rapidly increasing global population and urbanisation by consequence, are fuelling the basic requirement for dependable fresh water, clean air, energy provision, and safe waste disposal. All in all, governments across the world are under immense pressure to both regulate and fund these essential utilities as shown in Figure 1.

Given this context, the civil engineering industry ought to adopt technology that supports the individuals and procedural changes that are necessary to catalyse and drive innovation. Complete digitisation – the growth and continued deployment across the world of digital technologies and best practises such as Building Information Modelling (BIM) – will as a vehicle for driving innovation have a significant bearing upon operations and project delivery[2, 3, 4].

Zion Market Research[7] estimated the global BIM market valued at circa USD 3.52 billion in 2016, with a further forecast of the market estimated to increase markedly by 2022, to USD 10.36 billion – this representing a compound annual growth rate of just above 19.45% between 2017 and 2022.

Other estimates[6] further indicate that adoption and deployment of BIM best practises could result in annual global cost savings of 10-25% in the engineering and construction stages, and 8-13% in the operations stage.

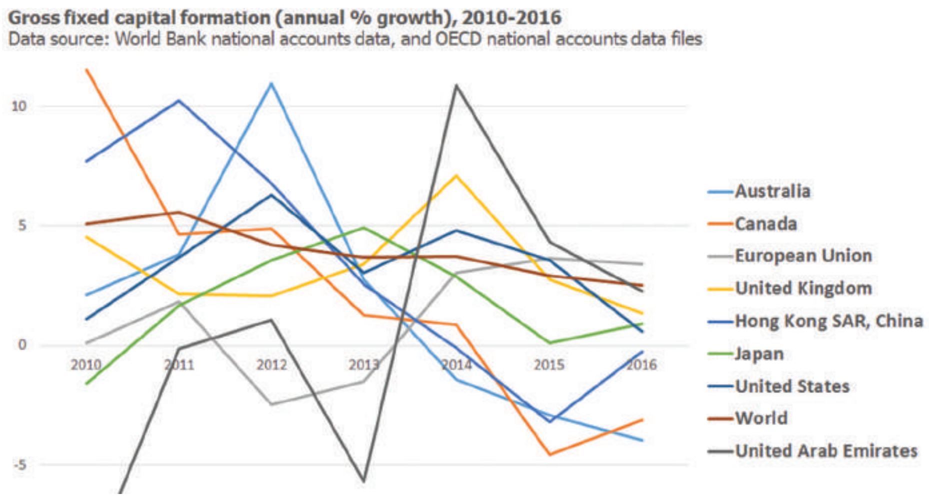

Figure 1 – Public investment is declining across the world

By region as shown in Figure 2, there exists different levels of BIM adoption with the market segmented into Europe, Latin America, North America, Asia Pacific and the Middle East & Africa. North America is currently the main contributor in the global BIM market, followed by Europe and Oceania. Several countries have yet to develop and deploy official BIM strategies and are at the inception stage, whilst a handful have publicised or plan to publicise government directives for compulsory use of BIM on public projects[5]. The need to train people, let go of old processes (e.g. using old non-BIM models), bring into line standards and adjusting regulations may hold back BIM adoption but will not stop it.

Nonetheless, the utilities industry has been sluggish to adopt elements of BIM and exploit this technology to its fullness. The potential benefits of BIM for the sector are huge as far as sustainable practise – from complex asset management and hazard minimisation to ensuring that intricate industrial build programmes are kept on track[3]. As a result, you might expect a similar level of enthusiasm for the approach – but this hasn't materialised to date[1].

Many of the larger utilities firms haven't meaningfully engaged with the technology or process, and many of the ones that have done are doing so cautiously[7]. Nonetheless, BIM has already been combined with LEED to enable better interaction between sustainability assessment and design in building construction[8], and this approach could be extended to utilities by coupling a sustainability assessment system with BIM which could maximise the efficiency and sustainability of utilities design[1].

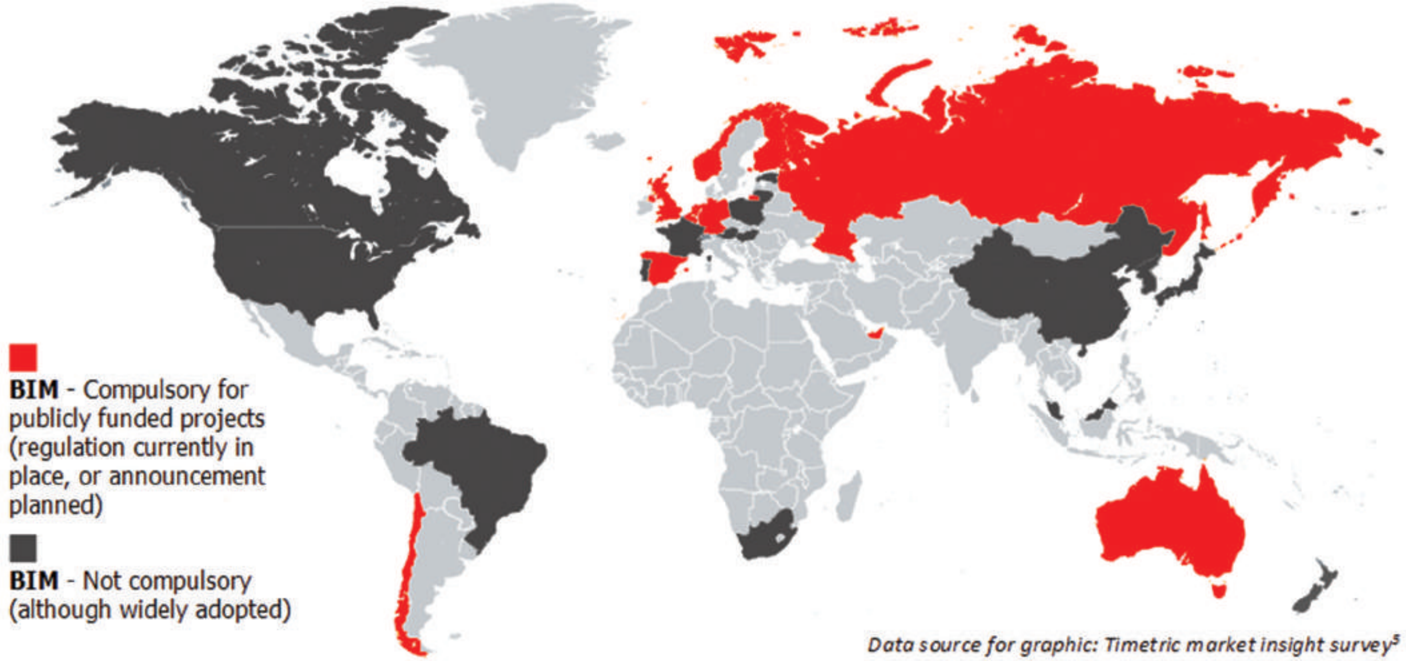

Figure 2 - BIM deployment across the world as of 2017

Consequently, the view was taken that it was high time to take the critical next step in research and establish the detailed level of impact BIM could potentially have through embedding sustainability into utilities projects. To do so, we interviewed 50 BIM stakeholders across the UK in 2017/2018, their cross-sectional breakdown shown in Figure 3, asking interviewees to quantify the potential impact of the adoption of BIM that embeds sustainability assessment in utility projects on their organisation's offerings today and five years from today, against 10 types of design and construction activities.

The results of the interviews as shown in Figure 4 demonstrate that expectations for BIM that embeds sustainable practises in the utilities sector run high. While most of the interviewees have not yet seen or realised the substantial effects from BIM, they evidently expect to in five years across several categories. Across all responses, only 13% of interviewees believe that BIM is currently having a large effect (a lot or to a great extent) on their organisation's offerings. However, 66% expect to realise these effects within just five years. Several of the highest scoring outcomes are associated mainly to utilities design activities, such as "improved constructability of final design", "improved quality/ function of final design", and "increased owners' understanding of proposed design solutions." This is logical as design consultants (architects, engineers etc.) by and large began employing BIM earlier than contractors, so these effects are more broadly experienced and as a result, well established.

Based on the findings, we expect that future research will demonstrate ever-greater benefits from the cumulative impact of BIM on utility project outcomes as a result of the digital layer it affords, which supports innovation by allowing a set of well documented and maintained application programming interfaces (APIs) for third parties to build on; permitting future incorporation of sensor information that draws upon real-time data, "what if" scenarios that inform long-term planning decisions, and a mapping component that collects location-based information on utilities. As shown in Figure 5, the BIM digital layer can be used as a mediating platform with the physical environment, underlain by ubiquitous connectivity in future cities, and makes all services that it interfaces with available to application developers via an API layer; this type of approach increases flexibility and decreases lock-in to outmoded technologies.

As stated by Ray O'Rourke KBE, Chairman and Chief Executive, Laing O'Rourke[2]:

"Rapid advances in digital engineering are revolutionising construction. But Building Information Modelling (BIM) is about more than creating models. It is about unlocking knowledge and insight, creating the platform for more efficient and sustainable solutions".

"Consequently, the view was taken that it was high time to take the critical next step in research and establish the detailed level of impact BIM could potentially have through embedding sustainability into utilities projects. To do so, we interviewed 50 BIM stakeholders across the UK in 2017/2018".

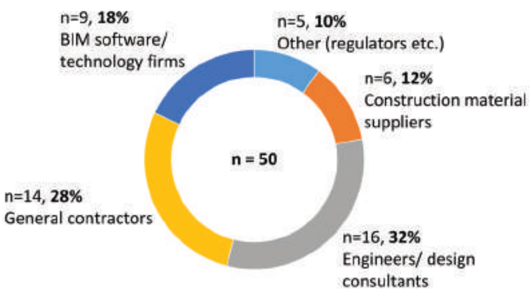

Figure 3 - The specific breakdown of interviewees by background

"Based on the findings, we expect that future research will demonstrate evergreater benefits from the cumulative impact of BIM on utility project outcomes as a result of the digital layer it affords".

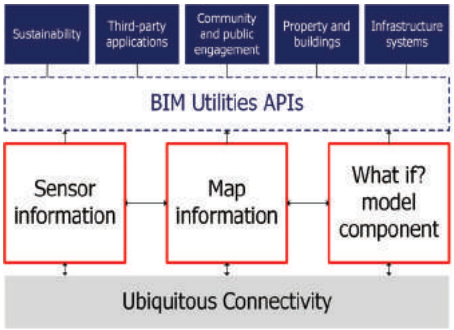

Figure 5 - BIM utilities urban innovation: the digital layers overview for future cities

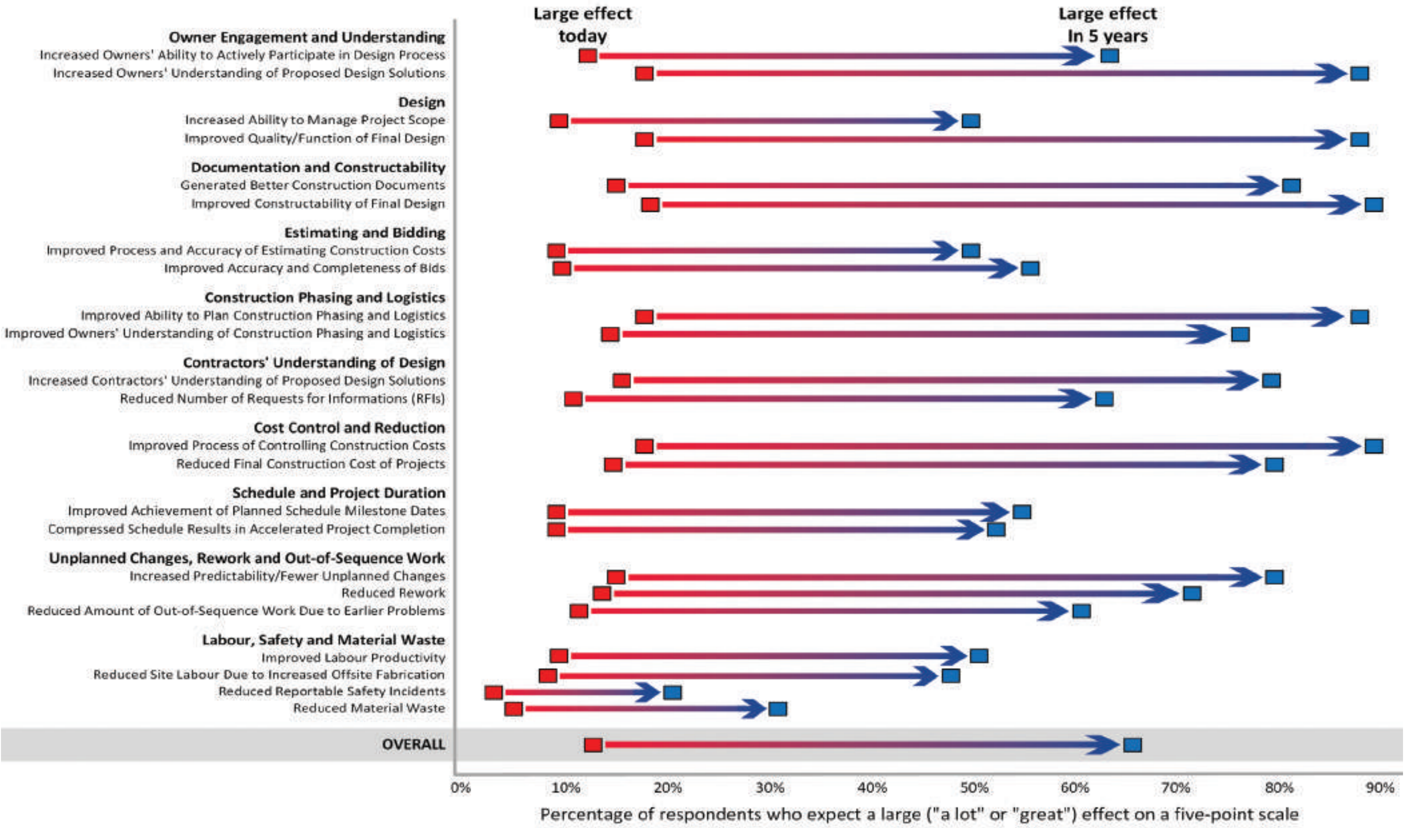

Figure 4 - Expectations for BIM adoption that embeds sustainability across the utilities sector: impact on offerings

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Advancing the ATU Roadmap
From Sensors to Global Research Impact

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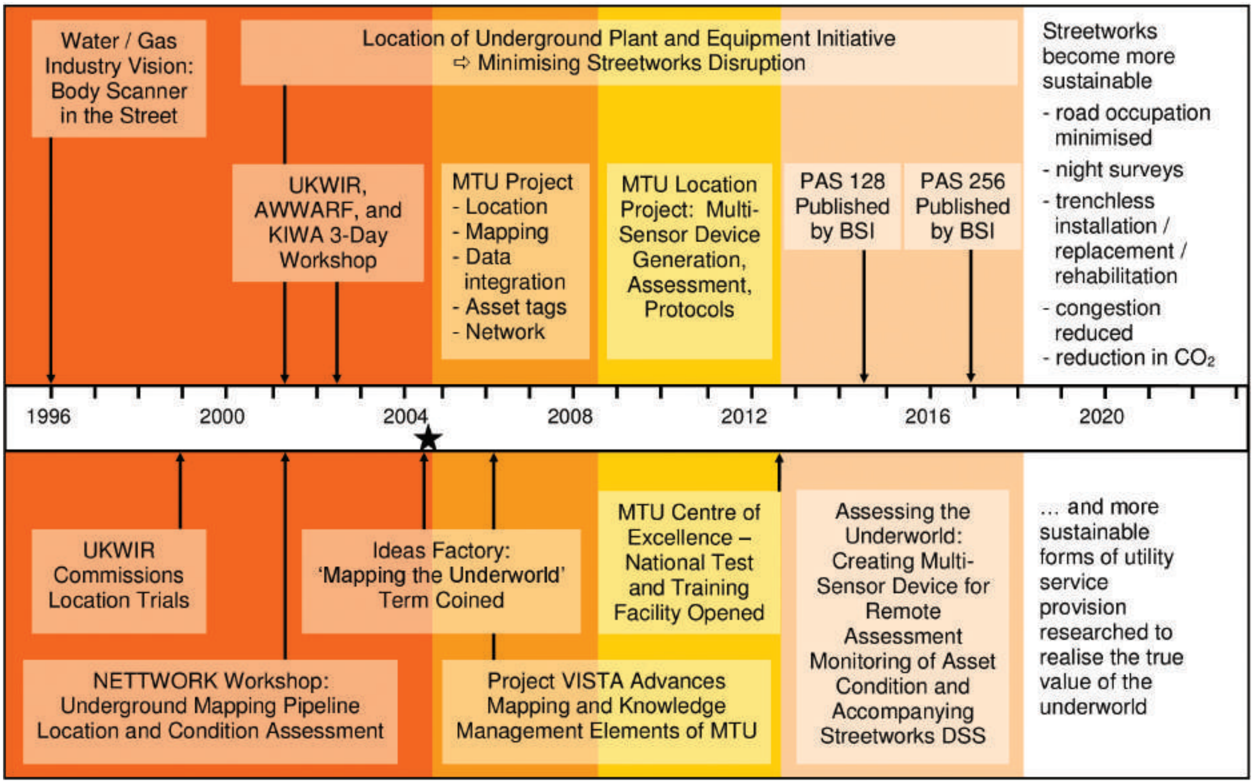

Figure 1 – Mapping and Assessing the Underworld Research Timeline: A Twenty Five Year Vision towards more Sustainable Streetworks

The history of Assessing the Underworld lies in the early attempts to transform the construction activities of the utilities industry via the adoption of trenchless technologies. One initiative that emerged was an EPSRC Engineering Programme Network in Trenchless Technology, which established a research community between academics and practitioners[1]. Termed NETTWORK, this initiative also served to set the agenda for research, both nationally[2] and internationally[3], and, with exceptionally strong backing from the industry, spawned Mapping the Underworld[1] (Figure 1). This was identified to be, and remains, one of the greatest challenges to the industry: knowing what lies below the surface, and where, before embarking on construction operations that do not involve exposing the buried infrastructure. Even as recently as 2016, the challenges with inaccurate and/or incomplete location of buried assets has been identified by the Geovation 'Dig

"One initiative that emerged was an EPSRC Engineering Programme Network in Trenchless Technology, which established a research community between academics and practitioners[1]".

Deep' initiative[5] as a key obstacle for utilising underground space safely and economically.

However it became apparent that the underlying proposition of Mapping the Underworld – combining the outputs from shallow surface geophysics with utility records and intelligence on the ground could improve asset detection, location and identification – could be built upon to deliver considerable additional value from essentially the same set of operations. A second major industrial challenge is to understand the condition of the (unseen) buried utility infrastructure, and of the overlying road structure and of the ground that supports them both, in order that the consequences of using trenchless technologies might be better predicted. Extending the MTU concept, using additional / amended geophysical techniques and additional datasets, was proposed as a means of revealing the condition of these three aspects of the 'streetworks infrastructures'[4] and was duly supported in the current Assessing the Underworld (ATU) project[1]. As is demonstrated hereafter, this research reaches beyond trenchless technologies to cover all proposed streetworks construction activities.

It should be recognised that this ambitious, a multi-disciplinary programme has, from its very inception, been a partnership between academia and practitioners. This is reflected in the award of a second network grant to run alongside the first MTU research grant[1], and the fact that subsequent MTU and ATU network activities are covered in the subsequent grants[1]. The most obvious manifestation of academia-practitioner interaction concerns the annual seminar, workshop and exhibition, which routinely attracts around 100 attendees[5]. These events provide opportunities for both dissemination and practitioner feedback to help shape the research. However, this partnership runs far deeper and is demonstrated in a range of activities for which the academic partners are able to provide an evidence base.

In line with this train of thought, there exists an underlying need to form a business case that justifies the use of more expensive sensor technologies, and use of advanced survey techniques. It is important to know the return on investment of spending more money on surveys upfront, or doing things differently and the cost savings as a result. To address this gap in knowledge a parallel study was conducted as part of iBUILD[1] to look into the true cost of utility strikes[10]. Sixteen utility strike case studies were investigated where the direct costs, indirect costs (if any), and social costs (if any) as a result of the utility strike in question were cost estimated. The study showed that the additional costs (indirect and social costs) when accounted for, can be as much as twenty nine times larger on average across all the 16 case studies, than the direct cost of repair which is more often than not the only cost consideration made by industry in the event of a utility strike incident. A change in perception and a corresponding change in the current streetworks business models is required to address this on-going streetworks challenge – these are the sort of streetworks issues that iBUILD in conjunction with ATU is addressing and has begun to influence the discussion in industry, whereby Transport for London (TfL) has already changed some of their practices when it comes to utilities streetworks, by way of a memorandum of understanding in cooperation with several asset owners, with a focus on best practice implementation of PAS128.

Nicholas Zembillas, ATU committee member and one of the top global industry experts to draft BSI PAS128 Specification for underground utility detection, location and verification explains the motivation behind the industry-changing document and its success.

As little as six years ago, the UK utility detection and mapping industry was a free for all. Both clients and practitioners had their own interpretations of an underground utility survey, ranging from a statutory record search, to a geophysical survey and accurate verification. The 'underground utility survey' was an ambiguous term that made it difficult for clients to compare scope of works and their respective quotes. They did not understand the reason there was such a large variation in scope, price, survey quality and more seriously, survey accuracy.

The frustration of both the client and utility surveying industry finally became an issue too important to ignore. Establishing a steering committee enabled the industry to create like-minded goals and objectives that would eventually become the ethos behind PAS128.

The core goals and objectives were:

- To produce a specification that would support clients procuring surveys,
- Create a level playing field for survey companies, and
- Provide detailed information on horizontal and vertical accuracies.
- Benchmark and build upon other countries subsurface utility engineering standards or specifications.

After much hard work, plenty of adjustments and fine-tuning, the PAS128 available today proudly meets these goals and objectives.

"As little as six years ago, the UK utility detection and mapping industry was a free for all. Both clients and practitioners had their own interpretations of an underground utility survey, ranging from a statutory record search, to a geophysical survey and accurate verification".

"The frustration of both the client and utility surveying industry finally became an issue too important to ignore. Establishing a steering committee enabled the industry to create likeminded goals and objectives that would eventually become the ethos behind PAS128".

Is PAS128 working?

PAS128 is readily available to purchase, and most UK project owners/agents, practitioners and other stakeholders now reference the document in tenders, quotes, marketing materials, industry forums and technical papers. Collectively these provide a better client understanding of the different quality/accuracy levels. There is also a closer collaboration between professional subsurface utility engineering, utility detection survey practitioners and their clients. When there are instances of residual risk, clients will obtain a Survey Type A (verification by nondestructive vacuum excavation) thanks to successful consultation with the professional practitioner – normally in a post survey de-brief.

Most importantly, professional practitioners are working in accordance with PAS128. Following PAS128 methodology has enabled surveyors to detect more utilities per Survey Type B criteria5.

Further investment is still required on education and training, which is something the University of Birmingham is working with the industry to finalise. The University is also instrumental in sharing the best practice of PAS128 internationally, participating on the PAS128 Steering Committee, ASCE38 committee, Transportation Research Board and other major global industry institutions & organizations (see Figure 2). Vital research[10] on the return on investment in regards to utility strikes is also thanks to the University – concluding that every pound spent on fixing a utility strike, has an associated cost of £29 for social, economic and health and safety issues.

Valuable input also comes from Assessing the Underworld, and the previous research study Mapping the Underworld, which, through presentations to industry groups have highlighted the existence of different standards across the world. As a founding member of the Utility Mapping and Detection Group (formerly Utility Mapping Association), these research projects have supported the industry to lobby BSI to develop PAS128.

Jim Anspach, ATU committee member who led the development of American Society of Civil Engineering's (ASCE) "Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data" and is President of the Utility Engineering and Surveying Institute, explains the impact ATU is having in North America.

PAS128's precursor on the North American peninsula, ASCE 38, Standard Guideline for the Collection and Depiction of Existing Subsurface Utility Data, has had a long history of MTU/ATU collaboration. ASCE 38 principles informed the original MTU project team leaders of the concepts of risk-based utility depictions based upon a series of investigative techniques. This led to joint membership on both National Academy of Science (US) and Engineering and Physical Sciences Research Council (UK) projects for researchers in both countries. In turn, MTU/ATU used their standing to assist in developing the need, and result, for a similar standard in the UK (PAS 128). PAS 128 was developed about a decade post-publication of ASCE 38 and as such, incorporated years of new technology, practice concepts, and cultural differences into its guidance.

As ASCE 38 draws close to its revision and update, MTU/ATU has representation on the review committee, including a dual designation as an ANSI standard, the importance of the collaboration of individuals and institutions in the UK and the US on solutions regarding the hidden nature of our utility and other infrastructure cannot be overlooked. The importance of the research communities on two continents coalescing around common problems is difficult to quantify, but easy to qualify. It is safe to say that ASCE's development of its Utility Engineering and Surveying Institute (UESI), language suggested for the ASCE 38 update, use of geophysical tools for infrastructure detection and characterisation beyond utilities' location, and development of ASCE's Standard for Certified Utility Record Data on Projects (Utility AS-Built Standard) have all benefited from the MTU/ATU projects. Thanks to the support of these academics, research projects and of course the industry, we mustered enough motivation to develop a tangible national specification for utility detection and mapping industry; and one that works both for the client and surveyor.

On a different note, within the UK, there is about 1.4 million kilometres of critical infrastructure with more than three quarters being underground in the form of electricity, gas, water, sewerage, drainage and communication networks; that is over one million of kilometres of utilities. Natural and anthropogenic hazards affecting utilities together with their maintenance, upgrading and replacement results in low impact high probability events which have a significant impact on communities. Accessing critical infrastructure is difficult because it is in constant use, is formed of interdependent systems and, in the case of utilities, can be highly disruptive if excavation is involved. Further, the legacy of underground critical infrastructure that exists in the UK means location and condition are difficult to assess.

"Thus, to address subsurface critical infrastructure, it is necessary to take a systems approach to value the asset, develop diagnostic tools to assess the asset and explore and develop effective action by looking at connected wholes rather than separate parts".

An EPSRC funded network, the Future infrastructure Forum, developed from EPSRC's review of structural and geotechnical engineering research6 identified ten themes (hazards, understanding material behaviour, paradigm shift in design, construction processes, building performance, smart buildings, asset management, intervention, decarbonisation and adaption) that has to be addressed. Most of these are directly relevant to underground critical infrastructure. Topics include understanding the effect of cascading failures; performance of materials in situ; assessing the value of infrastructure; identifying appropriate performance indicators that take a holistic view of the lifetime of a design; identifying failure characteristics pre-failure and the characteristics of the probability of failure; development of instrumentation to monitor reliably the behaviour of structures including load distribution, capacity and function; multi-functioning structural elements to make full use of intrinsic properties; decision making criteria; development of diagnostic tools and data acquisition techniques; predicting capacity and capability throughout life; development of early warning systems to predict failure; optimisation of planned interventions; diagnostic tools to assess impact of interventions; development of imaging techniques; introducing energy, water and carbon dioxide emissions as design criteria; and multi-functioning structures.

Thus, to address subsurface critical infrastructure, it is necessary to take a systems approach to value the asset, develop diagnostic tools to assess the asset and explore and develop effective action by looking at connected wholes rather than separate parts.

The scale of this is not only measured by the amount of subsurface critical infrastructure but also by the anticipated spend on critical infrastructure which impacts on utilities. It is estimated that there will be $57 trillion spent on international critical infrastructure in the next forty years which includes an estimated $2.8 trillion overspend due to failure to appreciate geotechnical risk. Therefore, reducing the risk and creating sustainable utilities means that systems thinking is essential to successfully deliver complex projects involving utilities where there are many stakeholders and many possible solutions as exemplified in ATU.

Parallel grants[1] have developed to complement the ATU/MTU initiative to address challenges of asset location and condition assessment. These include the development of quantum technology (QT) gravity sensors through a range of projects (GG-TOP, QT-Hub in Sensors and Metrology, SIGMA,

Affiliated Research

Active Grants:
i-BUILD - EP/K012398/1
Self-Repairing Cities - EP/N010523/1
Smart Pipes - EP/K504191/1
Liveable Cities - EP/J017698/1
UK Quantum Technology Hub for Sensors and Metrology - EP/M013294/1

Previous Grants:
NETTWORK - GR/R14064/01
MTU Network - EP/C547330/1
MTU Multi-Sensor Device - EP/C547365/1
MTU Data Integration - EP/C014707/1
MTU Asset Tagging - EP/C547373/1
MTU GPS - EP/C547381/1
VISTA - EP/C014707/1
GG-TOP - EP/I036877/1
SIGMA Gravity Sensing - EP/M508378/1

Regulatory

PAS128
PAS 256
ASCE 38

Stakeholders

Engineering Consultants (20+)
Engineering Contractors (15+)
Survey Companies (15+)
Universities (11)
Learned Societies (5+)
Funding Bodies (2)
Non Profits (3)

Stakeholder Engagement

Annual Events (5)
Conference Presentations (60+)
Journal Papers (40+)
Practitioner Workshops (9)
International Collaborations (10+)
Newsletters (7)
Industry Joint Testing (7)
Taught Engineering Students – BEng, MEng, MSc (2000+)
PhDs Graduated (10+)

ATU Impact Network

Professional Bodies and Committees

- Royal Academy of Engineering
- DfT Science Advisory Council
- European Association for Artificial Intelligence
- The Chartered Institute for IT
- Institution of Engineering and Technology (IET)
- Institution of Civil Engineering Surveyors
- Institute Of Acoustics
- Royal Institute of Navigation
- Institute of Electrical and Electronics Engineers
- UK Natural Hazards Partnership: Hazard Impact Model Working Group
- International Association of Engineering Geology & the Environment
- Engineering Group, Geological Society of London
- British Tunnelling Society
- British Geotechnical Association
- Trenchless Engineering International Research Advisory Committee
- Institution of Mechanical Engineers
- IET Transport Sector Team and Aerospace Executive Team
- IFAC Technical Committees on Robotics and Intelligent Autonomous Vehicles
- Pipeline Industries Guild Utilities Committee
- National Joint Utilities Group
- Institution of Civil Engineers (ICE)
- ICE Municipal Expert Panel
- ICE Geospatial Engineering Panel
- ICE Innovation & Research Panel
- ICE Futures Group
- ICE Learned Society Committee
- American Society of Civil Engineers (ASCE)
- US Transportation Research Board (Committee AFB70, AFS80, AFS40, AFF70, AFP60)
- Engineering College, EPSRC
- All Party Parliamentary Water Group
- ASCE Utility Standards Committee
- BSI Steering Committee for the Development of PAS128
- BSI Steering Committee for the Development of PAS256
- Utility Detection and Mapping Group
- Utility Strike Avoidance Group's Data and Reporting Working Group
- The Institution of Environmental Sciences
- Institution of Water and Environmental Management
- Sensors for Water Interest Group
- International Geosynthetics Society
- Energy and Utilities Alliance

Example of Impact

Working in Conjunction with the Tree and Design Action Group (TDAG)

Catalyses the Process to Initiate the **'Designing the Underworld'** Initiative in Conjunction with the ICE

Figure 2 – ATU Network: Global Research Impact

SIGMA+, REVEAL) to locate buried assets outside the range of traditional geophysical technologies. As gravity sensors measure a total field they do not suffer from signal attenuation through the ground in the same was as electro-magnetic signals. QT gravity sensors are more sensitive than existing microgravity sensors and are likely to detect capped mineshafts, voids, tunnels, sewers outside the range of current technologies. Initial modelling suggests that an improvement of a factor of 1.5 to 2.0 is feasible. This improvement attracted significant interest from industry and can complement the MTU/ATU technologies. In parallel, the Smart Pipes project[11, 12, 13] has developed cheap, discrete sensors, which can be attached to water pipes to detect leaks. This is currently subject of an Innovate UK (TSB) project with the aim of developing an industry prototype sensor reducing the time delay for leak detection significantly thus saving water.

A recent development has been the formation of the UK Collaboratorium for Research in Infrastructure and Cities (UKCRIC). This is a once-in-a-generation investment from the UK Government of £128m, matched by funding from industry and the collaborating institutions, to establish capital facilities at 14 universities. The investment includes the National Buried Infrastructure Facility (NBIF) at Birmingham, the National Infrastructure laboratory at Southampton, a Materials Laboratory at Leeds, and city observatories and water infrastructure research facilities at Newcastle and Sheffield. It is expected that these facilities will support a research investment of ~£200m over the next 5-10 years.

One parallel initiative that deserves special mention is *Designing the Underworld* (Figure 2). Proposed originally by members of the Municipal Expert Panel at the Institution of Civil Engineers, it comprises a group of practitioners, urban professional institutions and ATU researchers that is seeking to make the case for the introduction of alternative streetscape designs that make space for utility services, green infrastructure (including street trees) and transport infrastructures to be engineered synergistically. Inevitably incorporating multi-utility conduits as part of the design[7], it provides an overarching perspective on how the ATU research could be applied alongside new design thinking to move our streetscapes towards a more sustainable and resilient future. It equally supports the argument that we should be extending the design support in ATU's primary outcome from the shallow sub-surface to the whole of the urban subsurface[8,9], and combining it with new business models that reflect the value of the sub-surface to cities and citizens, and engineering practices that protect and enhance this value.

"This is a once-in-a-generation investment from the UK Government of £128m, matched by funding from industry and the collaborating institutions, to establish capital facilities at 14 universities".

"QT gravity sensors are more sensitive than existing microgravity sensors and are likely to detect capped mineshafts, voids, tunnels, sewers outside the range of current technologies. Initial modelling suggests that an improvement of a factor of 1.5 to 2.0 is feasible. This improvement attracted significant interest from industry and can complement the MTU/ATU technologies".

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Where do we go from here?

CDF Rogers (University of Birmingham)

Over the past 14 years, Mapping and Assessing The Underworld have created an exceptionally strong evidence base on which to found a 'business case' for radical changes to streetworks operations. In parallel the streetworks industry has pioneered new ways of working, and the two have come together in many different ways to facilitate change, both via jointly engaging in research & development and by proposing changes to codes, standards, and regulations.

While much of the evidence relates to new science and engineering – technical matters – it was always acknowledged that this is insufficient to bring about change. The business case must address all three pillars of sustainability, combining the (direct) economic case with a comprehensive understanding of the social, environmental and indirect economic consequences of streetworks operations as they manifest both now and in the future.

Given the primary purpose of buried utility pipelines and cables, and the systems of operation that enable them to provide their essential services to society, it is important to consider the supply of these services in relation to the compelling needs for sustainability, resilience and liveability.

A suite of EPSRC-funded research under the £65m Sustainable Urban Environments programme has guided this, taken forwards by programmes such as Liveable Cities[1] (or 'Transforming the Engineering of Cities to Deliver Societal and Planetary Wellbeing'), a recently-completed £6.3m programme of research that has run alongside ATU. These research programmes have helped to shape ATU's research on the wider consequences of streetworks.

Having addressed the physical science, engineering, social and environmental science aspects of streetworks, attention needed to turn to the economic case for change and the alternative business models that might be used to enable this change to happen. This piece of the jigsaw has been provided by the twin research programmes on Infrastructure Inter-dependencies and Novel Business Models: iBUILD[2] (which focussed on local and regional issues, and is most relevant to ATU) and ICIF[3] (which took a national and international perspective).

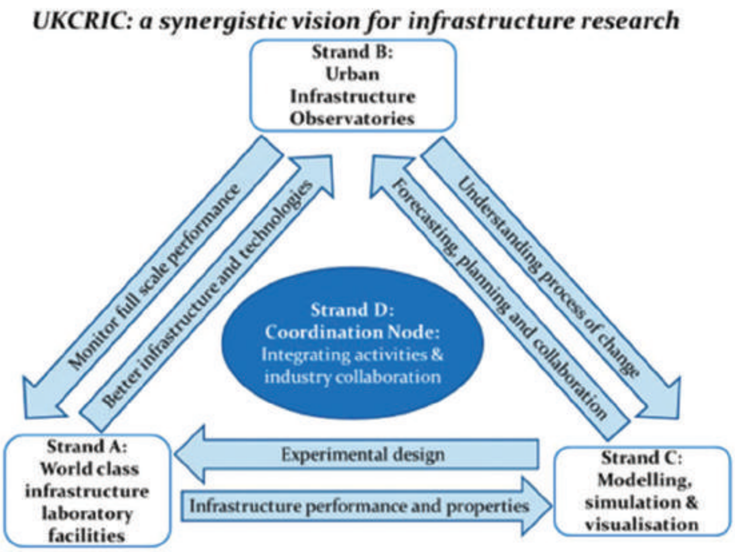

Figure 1 – The four strands of UKCRIC

That this complementary portfolio of research has matured simultaneously has proved fortunate, since each strand is mutually supportive in tackling the challenges associated with streetworks in a coherent and joined-up manner[4].

The question that now arises is: where should we go from here? One immediate, and topical, answer is robotics. If one accepts that robots are best deployed to work in places that put people potentially in the way of harm, then the use of robots for streetworks is an obvious possibility. A new EPSRC-funded £4.2m Grand Challenge programme entitled Self-Repairing Cities[5] (or 'Balancing the Impact of City Infrastructure Engineering on Natural Systems using Robots') is exploring this by looking at all of the technical, economic, social and environmental implications.

However, there is a bigger initiative that is now getting underway: UKCRIC - the UK Collaboratorium for Research on Infrastructure and Cities. UKCRIC has been established by a capital investment of £138m from the UK Government, with matching contributions (capital and running costs) from universities, users and industry, to create world-class physical laboratory, city observatory and modelling & simulation facilities. UKCRIC, initially based around 14 UK universities yet with plans for expansion, aims

Figure 2 – UKCRIC's National Buried Infrastructure Facility (NBIF)

to transform the way that research in these areas of vital importance to the UK economy and society is conducted: the clue is in the name – Collaboratorium rather than Consortium. The University of Birmingham is hosting the new National Buried Infrastructure Facility, a £27.6m development that enables research to be done at or near full-scale in a 25m x 5m, 5m pit and a suite of large and small complementary laboratories and other research facilities (Figure 2).

Although UKCRIC has organisational themes of Water (Newcastle, Sheffield and Cranfield), Materials (Imperial, Leeds and Manchester), Sensors (Cambridge), Buried Infrastructure (Birmingham), Linear Infrastructure (Southampton), Systems and Dynamic Soil-Structure Interaction (Bristol), Human Interactions (UCL) and Modelling (Oxford), an underpinning premise of UKCRIC is that themes must be considered synergistically through a transdisciplinary "system of systems" approach.

Three initial grants are underway: two link the UKCRIC Laboratories (PLEXUS) and Observatories (CORONA) via pump-priming activities, while the UKCRIC Coordination Node aims to ensure that UKCRIC's vision, promise, and value as an inclusive collaboration are fully realised. This involves shared learning and the creation of a roadmap of projects.

NBIF provides the natural home for advancing the science and engineering of streetworks and utility services, and plans to extend this thinking to the underground space beneath cities are well advanced.

*"The University of Birmingham is hosting the new National Buried Infrastructure Facility, a **£27.6m** development that enables research to be done at or near full-scale in a 25m x 5m, 5m pit and a suite of large and small complementary laboratories and other research facilities".*

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