ATU Selected Academic / Professional Journal Papers

Bilal M, Khan W, Muggleton J, Rustighi E, Jenks H, Pennock SR, Atkins PR and Cohn A (2018). Inferring the most probable maps of underground utilities using Bayesian mapping model. *Journal of Applied Geophysics* 150C pp. 52-66

Abstract; Mapping the Underworld (MTU), a major initiative in the UK, is focused on addressing social, environmental and economic consequences raised from the inability to locate buried underground utilities (such as pipes and cables) by developing a multi-sensor mobile device. The aim of MTU device is to locate different types of buried assets in real time with the use of automated data processing techniques and statutory records. The statutory records, even though typically being inaccurate and incomplete, provide useful prior information on what is buried under the ground and where. However, the integration of information from multiple sensors (raw data) with these qualitative maps and their visualization is challenging and requires the implementation of robust machine learning/data fusion approaches. An approach for automated creation of revised maps was developed as a Bayesian Mapping model in this paper by integrating the knowledge extracted from sensors raw data and available statutory records. The combination of statutory records with the hypotheses from sensors was for initial estimation of what might be found underground and roughly where. The maps were (re)constructed using automated image segmentation techniques for hypotheses extraction and Bayesian classification techniques for segment-manhole connections. The model consisting of image segmentation algorithm and various Bayesian classification techniques (segment recognition and expectation maximization (EM) algorithm) provided robust performance on various simulated as well as real sites in terms of predicting linear/non-linear segments and constructing refined 2D/3D maps.

Barry G Clarke, Derek Magee, Vania Dimitrova, A Cohn, Heshan Du, Quratul-ain Mahesar, Ali M Sadeghioon, CDF Rogers, D Gunn, D Enwisle, H Reeves, Ross Stirling, Stephanie Glendinning (2017). "A decision support system to proactively manage subsurface utilities", International Symposium for Next Generation Infrastructure, Institution of Civil Engineers, London

Abstract: Critical infrastructure assets are defined in terms of their purpose (e.g. roads, water, and energy) yet the ground, which supports these assets, can also be considered a critical asset leading to the conclusion that any assessment of critical infrastructure must consider the ground in that assessment. While the interdependency of critical infrastructures is recognised, the consequences of failing to recognise the ground as an asset can lead to failure of the infrastructure it supports. This motivates the need for a decision support system for subsurface utilities that takes into account the surrounding ground and the overlying road structure. These facilities mostly exist in an urban environment. The ground supports the road and the underlying utility which means the failure of any of these assets (road, ground, or utility) can trigger a failure in the others, the most extreme example being the collapse of roads due to erosion of the supporting ground by a leaking pipe. This paper describes the principles that underpin a novel decision support system for those engaged in street works of any kind, and how a multidisciplinary approach is being used to create a practical toolkit to reduce risk and minimise disruption to proactively manage subsurface utilities using site observations and investigations, public and private databases, expert opinions captured in a number of ontologies and an inference engine to produce guidance that takes into account risk and sustainability criteria.

Curioni G, Chapman DN, Metje N (2017). Seasonal variations measured by TDR and GPR on an anthropogenic sandy soil and the implications for utility detection. *Journal of Applied Geophysics*, 141, 34–46. https://doi.org/10.1016/j.jappgeo.2017.01.029

Curioni G, Chapman DN, Pring LJ, Royal ACD, Metje N. (accepted). Extending TDR capability for measuring soil density and water content for field condition monitoring. *Journal of Geotechnical and Geoenvironmental Engineering.*

Curioni G, Chapman DN, Metje N, Foo KY and Cross JD (2012). Construction and Calibration of a Field TDR Monitoring Station. *Near-Surface Geophysics,* **10**(3), 249-261.

Curioni G, Chapman DN, Royal ACD, Metje N, Dashwood B, Gunn DA, Inauen CM, Chambers JE, Meldrum PI, Wilkinson PB, Swift RT, Reeves HJ (2018) TDR potential for quantitative soil condition monitoring of geotechnical assets. Canadian Geo-tech. Jour. DOI *10.1061/(ASCE)GT.1943-5606.0001792*.

Dashwood BAJ, Gunn DA, Curioni G, Inauen C, Hobbs PRN, Reeves H (2018) Surface wave surveys for imaging ground property changes due to a leaking water pipe. Jour. Applied Geophysics.

Dou Q, Wei L, Magee DR and Cohn AG (2016). "Real-Time Hyperbola Recognition and Fitting in GPR Data," *in IEEE Transactions on Geoscience and Remote Sensing*, no.99, pp.1-12, 2016. doi: 10.1109/TGRS.2016.2592679.

Dou Q, Wei L, Magee D. R and Cohn A G (2016). "Real-Time Hyperbola Recognition and Fitting in GPR Data," *in IEEE Transactions on Geoscience and Remote Sensing*, no.99, pp.1-12, 2016. doi: 10.1109/TGRS.2016.2592679.

Abstract: The problem of automatically recognising and fitting hyperbolae from Ground Penetrating Radar (GPR) images is addressed, and a novel technique computationally suitable for real time on-site application is proposed. After pre-processing of the input GPR images, a novel thresholding method is applied to separate the regions of interest from background. A novel column connection clustering (C3) algorithm is then applied to separate the regions of interest from each other. Subsequently, a machine learnt model is applied to identify hyperbolic signatures from outputs of the C3 algorithm and a hyperbola is fitted to each such signature with an orthogonal distance hyperbola fitting algorithm. The novel clustering algorithm C3 is a central component of the proposed system, which enables the identification of hyperbolic signatures and hyperbola fitting. Only two features are used in the machine learning algorithm, which is easy to train using a small set of training data. An orthogonal distance hyperbola fitting algorithm for 'southopening' hyperbolae is introduced in this work, which is more robust and accurate than algebraic hyperbola fitting algorithms. The proposed method can successfully recognise and fit hyperbolic signatures with intersections with others, hyperbolic signatures with distortions and incomplete hyperbolic signatures with one leg fully or largely missed. As an additional novel contribution, formulae to compute an initial 'south-opening' hyperbola directly from a set of given points are derived, which make the system more efficient. The parameters obtained by fitting hyperbolae to hyperbolic signatures are very important features, they can be used to estimate the location, size of the related target objects, and the average propagation velocity of the electromagnetic wave in the medium. The effectiveness of the proposed system is tested on both synthetic and real GPR data.

Dou Q, Wei L, Magee, DR, Atkins, PR, Chapman DN, Curioni G, Goddard KF, Hayati F, Jenks H, Metje N, Muggleton JM, Pennock SR, Rustighi E, Swingler SG, Rogers CDF and Cohn AG (2016). 3D Buried Utility Location Using A Marching-Cross-Section Algorithm for Multi-Sensor Data Fusion. *Sensors,* 16 (11), 1827. DOI: 10.3390/s16111827.

Abstract: We address the problem of accurately locating buried utility segments by fusing data from multiple sensors using a novel Marching-Cross-Section (MCS) algorithm. Five types of sensors are used in this work: Ground Penetrating Radar (GPR), Passive Magnetic Fields (PMF), Magnetic Gradiometer (MG), Low Frequency Electromagnetic Fields (LFEM) and Vibro-Acoustics (VA). As part of the MCS algorithm, a novel formulation of the extended Kalman Filter (EKF) is proposed for marching existing utility tracks from a scan cross-section (scs) to the next one; novel rules for initializing utilities based on hypothesized detections on the first scs and for associating predicted utility tracks with hypothesized detections in the following scss are introduced. Algorithms are proposed for generating virtual scan lines based on given hypothesized detections when different sensors do not share common scan lines, or when only the coordinates of the hypothesized detections are provided without any information of the actual survey scan lines. The performance of the proposed system is

evaluated with both synthetic data and real data. The experimental results in this work demonstrate that the proposed MCS algorithm can locate multiple buried utility segments simultaneously, including both straight and curved utilities, and can separate intersecting segments. By using the probabilities of a hypothesized detection being a pipe or a cable together with its 3D coordinates, the MCS algorithm is able to discriminate a pipe and a cable close to each other. The MCS algorithm can be used for both post- and on-site processing. When it is used on site, the detected tracks on the current scs can help to determine the location and direction of the next scan line. The proposed "multi-utility multi-sensor" system has no limit to the number of buried utilities or the number of sensors, and the more sensor data used, the more buried utility segments can be detected with more accurate location and orientation.

Du H, Dimitrova V, Magee D, Stirling R, Curioni G, Reeves H, Clarke BG and Cohn AG (2016). An ontology of Soil Properties and Processes.The Semantic Web – ISWC. ISWC 2016. *Lecture Notes in Computer Science*, vol 9982. Springer, Cham. September, DOI: 10.1007/978-3-319-46547-0_4

Abstract: The Semantic Web – ISWC. ISWC 2016. *Lecture Notes in Computer Science*, vol 9982. Springer, Cham. September, DOI: 10.1007/978-3-319-46547-0_4
Abstract. Assessing the Underworld (ATU) is a large interdisciplinary UK research project, which addresses challenges in integrated inter-asset maintenance. As assets on the surface of the ground (e.g. roads or pavements) and those buried under it (e.g. pipes and cables) are supported by the ground, the properties and processes of soil affect the performance of these assets to a significant degree. In order to make integrated decisions, it is necessary to combine the knowledge and expertise in multiple areas, such as roads, soil, buried assets, sensing, etc. This requires an underpinning knowledge model, in the form of an ontology. Within this context, we present a new ontology for describing soil properties (e.g. soil strength) and processes (e.g. soil compaction), as well as how they affect each other. This ontology can be used to express how the ground affects and is affected by assets buried under the ground or on the ground surface. The ontology is written in OWL 2 and openly available from the University of Leeds data repository: http://doi.org/10.5518/54.

Dutta R, Cohn A G, Muggleton J M (2013). 3D mapping of buried underworld infrastructure using dynamic Bayesian network based multi-sensory image data fusion. *Journal of Applied Geophysics*92 8–19.

Abstract: The successful operation of buried infrastructure within urban environments is fundamental to the conservation of modern living standards. In this paper a novel multi-sensor image fusion framework has been proposed and investigated using dynamic Bayesian network for automatic detection of buried underworld infrastructure. Experimental multi-sensors images were acquired for a known buried plastic water pipe using Vibro-acoustic sensor based location methods and Ground Penetrating Radar imaging system. Computationally intelligent conventional image processing techniques were used to process three types of sensory images. Independently extracted depth and location information from different images regarding the target pipe were fused together using dynamic Bayesian network to predict the maximum probable location and depth of the pipe. The outcome from this study was very encouraging as it was able to detect the target pipe with high accuracy compared with the currently existing pipe survey map. The approach was also applied successfully to produce a best probable 3D buried asset map.

Entwistle DC, Culshaw MG, Hulbert AG, Shelley WA, Suzanne J. Gunn DG, Dobbs MR (2016). The Glasgow (Scotland) geotechnical GIS: a desk study tool. In: Eggers. 2016. Developments in Engineering Geology. Geological Society, London. Engineering Geology Special Publication, 27, 63–80, http://doi.org/10.1144/EGSP27.6

Griffiths MJ, Parry JS, Culshaw S (2016). Developments in engineering and geology. Geological Society, London. *Engineering Geology Special Publication*, 27, 63–80, http://doi.org/10.1144/EGSP27.6

Gao Y, Sui F, Muggleton JM and Yang J (2016). Simplified dispersion relationships for fluid-dominated axisymmetric wave motion in buried fluid-filled pipes. *Journal of Sound and Vibration*. Vol 375. 4 Aug, pp 386-402.

Abstract: The dispersion characteristics of axisymmetric (*n*=0) waves offer a way to gain physical insight into the low-frequency vibrational behaviour of underground pipe systems. Whilst these can be found in the literature, they are generally calculated numerically. Coupled equations of motion for the *n*=0 waves that propagate in a buried fluid-filled pipe are presented in this paper and, from this, an analytical solution is developed for the fluid-dominated (*s*=1) wavenumber. The effect of the frictional stress at the pipe–soil interface on the dispersion behaviour of the *s*=1 wave is characterised by adopting a soil loading matrix. Overall, the fluid loading has a greater effect on the propagation wavespeed compared with the soil loading: for metal pipes, the effect of soil loading is negligible; for plastic pipes, however, simply neglecting the effect of soil loading can lead to a considerable underestimation in the calculation of the wavespeed. The wave attenuation increases significantly at higher frequencies regardless of pipe material resulting from the added damping due to radiation into the soil. Theoretical predictions of the *s*=1 wavenumber are compared with experimental data measured on an MDPE water pipe. The degree of agreement between prediction and experiment makes clear that, although the wavespeed is only slightly affected by the presence of the frictional stress, the frictional stress at the pipe–soil interface needs to be appropriately taken into account for attenuation predictions.

Gao Y, Muggleton JM, Liu Y and Rustighi E (2017), an analytical model of ground surface vibration due to axisymmetric wave motion in buried fluid-filled pipes. *Journal of Sound and Vibration* 395 142-159

Abstract: The axisymmetric (*n*=0) fluid-borne (*s*=1) wave has been exploited with varying degrees of success in practical surveys for determining the location of buried pipes. Difficulties are sometimes encountered in interpreting ground surface vibration data, whilst attempting to locate the pipes, due to the occurrence of abrupt changes in the phase response over the usable frequency range. Based on a wave propagation model developed recently, this paper presents an analytical model for predicting the ground surface displacements resulting from the radiated elastic waves in the soil medium. Two representative soils have been specifically considered, where the *s*=1 wave in the pipe will leak shear waves into the soil, but may or may not leak compressional waves. In each of these cases, numerical simulations are presented to predict the ground surface displacements. The model is used to demonstrate how, when both compressional and shear waves are radiated, they can interfere such that abrupt phase changes occur at the frequencies coincident with magnitude minima in the ground surface displacements; when only shear waves are radiated, such interference does not occur. Furthermore, for sandy soil, it is found that the horizontal displacement is dominated by the radiated shear wavenumber component whereas the vertical displacement is controlled by the radiated compressional wavenumber component. Using the analytical model, theoretical predictions of ground surface displacements are compared with experimental data from a dedicated MDPE pipe rig.

Gao Y, Liu Y, Muggleton J M (2017). Axisymmetric fluid-dominated wave in fluid-filled plastic pipes: Loading effects of surrounding elastic medium. *Applied Acoustics* 116, 43–49. DOI: 10.1016/j.apacoust.2016.09.016

Abstract: Axisymmetric (*n* = 0) waves that propagate at low frequencies are of practical interest in the application of acoustic techniques for the detection of leaks in fluid-filled pipelines. A general expression for the fluid-dominated (*s* = 1) wavenumber is presented in a thin-walled fluid-filled pipe surrounded by an elastic medium. In this paper the analysis is extended to investigate the loading effects of surrounding medium on the low-frequency propagation characteristics of the *s* = 1 wave. The analytical model is subsequently applied to MDPE water pipes surrounding by three media, namely an air, water and soil. It is used to demonstrate explicitly the loading effects of surrounding medium, acting as a combination of mass, stiffness and radiation damping on the *s* = 1 wavenumber.

Good agreement is achieved between the measurements and predictions. The theory with experimental validations provides the basis for improving acoustic leak detection methods in fluid-filled pipe systems.

Gunn DA, Chambers JC, Uhlemann S, Wilkinson JB, Meldrum PI, Dijkstra T, Wragg J, Hughes PN, Hen-Jones R and Glendinning S (2014). Moisture monitoring in clay embankments, using electrical resistivity tomography. *Conbuildmat* Vol 96, Pages 82-94. DOI: 10.1016/j.2014.06.007

Hao T, Rogers CDF, Metje N, Chapman DN, Muggleton JM, Foo KY, Wang P, Pennock SR, Atkins PR, Swingler SG, Parker J, Costello SB, Burrow MPN, Anspach JH, Armitage RJ, Cohn AG, Goddard K, Lewin PL, Orlando G, Redfern MA, Royal ACD and Saul AJ (2012). Condition Assessment of the Buried Utility Service Infrastructure. *Tunnelling and Underground Space Technology* 28, 331-344.

Abstract: An extensive array of utility networks are buried underneath the ground surface and provide essential services for society's daily life in terms of water, natural gas, electricity, telecommunications, sewerage, etc. All utilities have a limited service life and it is crucial to assess their condition throughout their life cycles to avoid potential catastrophic failure due to their deterioration. This paper reviews current state-of-the-art technologies for condition assessment of underground utilities (especially water and sewage pipelines) and their advantages and technical challenges for different application areas. Recommendations on how to address these challenges are made and it is highlighted that the system of combined sensor technologies being developed by the Mapping the Underworld (MTU) project may provide a valuable addition to the street works engineer's armoury in determining the condition of the buried infrastructure. Moreover the ground in which the utility services infrastructure is buried supports the pipes and cables and prevents their permanent or transient displacement under static and dynamic loads, or lateral stress relief associated with adjacent trenching. The ability of the MTU sensing technologies to determine also the condition of the ground is thus equally relevant and is discussed.

Hen-Jones R, Hughes PN, Stirling RA, Glendinning S, Gunn D, Chambers J, Cui Y (2017) Seasonal effects on geophysical-geotechnical relationships and their implications for Electrical Resistivity Tomography monitoring of slopes' *Acta Geotechnica* . DOI: 10.1007/s11440-017-0523-7

Hojjati A, Jefferson I, Metje N and Rogers CDF (2017). Sustainability assessment for urban underground Utility infrastructure projects. *Proceedings of the Institution of Civil Engineers, Engineering Sustainability*. DOI:10.1680/jensu.16.00050

Abstract: Utility infrastructure systems, designed well, have a pivotal role to play in improving the sustainability of cities due to their critical functionality in urban environments. Equally, utility streetworks – installation, maintenance and upgrading activities – can adversely impact the local and global economies. The inaccurate location of pipes and cables lengthens streetworks operations and can exacerbate traffic congestion, notably resulting in major delays in cases of third-party utility damage, while vehicle emissions and wasted energy are other examples of the adverse impacts of congestion caused by streetworks operations. The total impact of utility infrastructure projects can be assessed only by evaluating all economic (both direct and indirect), social and environmental costs of streetworks. A dedicated tool for evaluating the sustainability impacts of utility streetworks is required. This paper provides the basis for utility streetworks sustainability assessments, and hence full costing, by critically reviewing existing sustainability assessment tools and making recommendations for developing a total sustainability costing model and indicator system.

Iodice M, Muggleton JM and Rustighi E (2016). The Detection of Vertical Cracks in Asphalt using Seismic Surface Wave Methods. *Proceedings of Recent Advances in Structural Dynamics, Journal of Physics Conference Series*, 744(1):012059, 1-14. DOI: 10.1088/1742-6596/744/1/012059

Abstract: 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. This paper presents an investigation of two surface wave methods to detect and locate

top-down cracks in asphalt layers. The aim of the study is to compare the results from the well-established Multichannel Analysis of Surface Waves (MASW) and the more recent Multiple Impact of Surface Waves (MISW) in the presence of a discontinuity and to suggest the best surface wave technique for evaluating the presence and the extension of vertical cracks in roads. The study is conducted through numerical simulations alongside experimental investigations and it considers the cases for which the cracking is internal and external to the deployment of sensors. MISW is found to enhance the visibility of the reflected waves in the frequency wavenumber (*f-k*) spectrum, helping with the detection of the discontinuity. In some cases, by looking at the *f-k* spectrum obtained with MISW it is possible to extract information regarding the location and the depth of the cracking.

Jenks CHJ (2016). Dielectric pyramid antenna for GPR applications. Antennas and Propagation (EuCAP), 2016 10th European Conference on DOI: 10.1109/EuCAP.2016.7481679

Jenks CHJ (2017). Resistively loaded 3D printed antenna for GPR applications. Antennas and Propagation (EUCAP), 2017 11th European Conference on DOI: 10.23919/EuCAP.2017.7928410

Jenks CHJ, Pennock SR (2017). The use of a Software Defined Radio as an OFDM GPR. Advanced Ground Penetrating Radar (IWAGPR), 2017 9th International Workshop on DOI: 10.1109/IWAGPR.2017.7996105

Kalkowski M Muggleton JM and Rustighi E (2016) Wave propagation in rods with an exponentially varying cross-section - modelling and experiments. *Proceedings of Recent Advances in Structural Dynamics, Journal of Physics Conference Series*, 1-12

Abstract: In this paper we analyse longitudinal wave propagation in exponentially tapered rods from both a theoretical and an experimental perspective. The tapering introduces significant changes to the behaviour of the rod. The longitudinal wave does not propagate from zero frequency, its cut-o_ frequency depending on the coefficient in the exponent. The analytical description of this phenomenon is well established, however little experimental work has been published to date. After a brief review of the classical solution of the exponential rod equation, we derive a methodology allowing the wavenumbers to be estimated from a set of equally spaced dynamic responses. Our approach is varied numerically against a element simulation and validated experimentally, both showing very good agreement. To further explain the results and provide an outlook for future work, we present a mite element model of the tapered rod embedded in an in_nite solid medium. We conclude with a discussion on the effects of the surrounding medium on the behaviour of the structure and resulting characteristic features of the wavenumber.

Kalkowski MK, Muggleton JM and Rustighi E (2018). Axisymmetric semi-analytical finite elements for modelling waves in buried/submerged fluid-filled waveguides. *Computers & Structures*, 196, 327-340

Abstract: Efficient and accurate predictions of wave propagation are a vital component of wave-based non-destructive interrogation techniques. Although a variety of models are available in the literature, most of them are suited to a particular wave type or a specific frequency regime. In this paper we present a multi-wave model for wave propagation in axisymmetric fluid-filled waveguides, either buried or submerged in a fluid, based on the semi-analytical finite elements. The cross-section is discretised with high-order spectral elements to achieve high efficiency, and the singularities resulting from adopting a Lobatto scheme at the axis of symmetry are handled appropriately. The surrounding medium is modelled with a perfectly matched layer, and a practical rule of choice of its parameters, based only on the material properties and the geometry of the waveguide, is derived. To represent the fluid and the solid-fluid coupling, an acoustic SAFE element and appropriate coupling relationships are formulated. The model is validated against both numerical results from the literature and experiments, and the comparisons show very good agreement. Finally, an implementation of the method in Python is made available with this publication

Kalkowski MK, Muggleton JM and Rustighi E (2017). An experimental approach for the determination of axial and flexural wave numbers in circular exponentially tapered bars. Journal of Sound and Vibration, Volume 390, March, Pages 67-85. https://doi.org/10.1016/j.jsv.2016.10.018

Abstract: Whilst the dynamics of tapered structures have been extensively studied numerically and analytically, very few experimental results have been presented to date. The main aim of this paper is to derive and demonstrate an experimental method enabling both axial and flexural wavenumbers in exponentially tapered bars to be estimated. Our particular interest in this type of tapering is motivated by its occurrence in naturally grown structures such as tree roots, with an outlook towards remote root mapping. Decomposing a dynamic response into a sum of contributing waves, we propose a method in which two independent wavenumbers can be calculated from five equispaced measurements. The approach was demonstrated in an experiment on a freely suspended wooden specimen supported by theoretical modelling. For axial waves we used the well-established elementary rod theory, whereas for flexural waves we build a piecewise uniform model based on the Timoshenko beam theory. The estimates calculated from the experimental data were compared with the analytical and numerical results and showed good agreement. The limitations of the method include an appropriate choice of sensor spacing, the effect of sensor misalignments and the assumption of small wavenumber variation for flexural waves.

Kalkowski M, Muggleton JM and Rustighi E (2016). Wave propagation in rods with an exponentially varying cross-section - modelling and experiments. *Journal of Physics Conference Series*, pages 1-12.

Ke M, Zhu J, Dodd TJ, Collins R, and Anderson SR (2015). Robot mapping and localisation for feature sparse water pipes using voids as landmarks. In *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* Vol. 9287 (pp. 161-166). doi:10.1007/978-3-319-22416-9_19

Makana LO, Metje N, Jefferson I and Rogers CDF (2016). *What Do Utility Strikes Really Cost?* Internal Report, University of Birmingham, School of Engineering, Birmingham, UK. Access at: http://bit.ly/2flQPGt, 84 pp.

Abstract: The UK's footways and highways house a vast network of utility and local authority infrastructure. According to Parker (UKWIR) the combined network of water, sewer, gas and electricity services extends to over 1.5 million km, which is roughly five times longer than the UK's road network. The importance of these dense utility networks to the wellbeing and continued economic health of UK society cannot be understated. The utility industry has to undertake about 1.5 million streetworks annually to repair, maintain and upgrade this vast network of buried utility infrastructure.

Consequently, these numerous holes dug as part of the streetworks annually result in substantial costs, both to the utility industry and society at large. The utility industry stomachs the direct construction costs of these streetworks, such as planning, supervision, material, and design and labour costs. Furthermore, there are indirect costs incurred by the utility providers due, for example, loss of business income. The costs which are stomached by society are the social costs sustained due to, for example, costs to other businesses, greater than before levels of air pollution as well as noise, damage to the environment and traffic delays experienced by road users. All things considered these direct, indirect and social costs are the 'true costs' linked to utility streetworks.

Construction projects will unavoidably need to continue to carry out excavations. Utility infrastructure (electricity, gas, telecommunications, water etc.) are often located below the ground surface at shallow depth. Hitting one of these services when carrying out an excavation (whatever tool is used; e.g. hand tool, mini-digger etc.) by either puncturing or damaging the sheath or protective wrap is termed a 'Utility Strike' (also known as a service strike or hit). Methods for evaluating the 'true cost' of streetworks have been proposed, but none seem to be available specific to utility strikes, moreover applied in the UK context. Elsewhere, cost-benefit analysis of one form or another have been used but these have tended to be over simplistic. Further work to develop and refine a method for evaluating true cost of streetworks, moreover utility strikes is warranted. As a result the University of Birmingham has been engaged in an on-going collaborative research initiative with several industrial

partners to address and further understand these impacts caused by streetworks, more specifically at the impact of 'utility strikes' and their quantified associated costs (direct, indirect and social).

The aim of this report is to assess the impact of utility strikes and their associated true costs by detailing 16 case studies of utility strikes and providing an objective view of all their quantified associated costs, both those paid directly by contractors (direct costs), and those borne by third parties in the contractual agreement (indirect costs), and other parties not engaged in the contractual agreement (social costs). This report details the results from the quantification of these 16 case studies, reviews literature on the subject of utility strikes and puts forward a robust methodology that can be used to estimate the true cost of utility strikes. It identifies the ways in which these costs can be minimised as well as gaps in knowledge requiring further research. Based on the findings presented in this report, it is clear that if the true costs of utility strikes are to be reliably understood and quantified throughout industry, then more work in this area will be required by industry bodies to provide joined up thinking and formulate a robust industry baseline measure for utility strike impacts beyond the status quo. This in turn will aid the development of a better understanding of what streetworks, moreover, utility strikes cost both the utility industry and society in general.

Makana LO, Metje N and Rogers CDF (2017). *Mapping and Assessing the Underworld: A Novel Approach to Utility Management in Smart and Sponge Cities.* Proceedings of the 5th International Conference on Utility Management and Safety (ICUMAS 2017): 29th-31st March 2017, Kowloon, Hong Kong.

Abstract: Owing to the rapid rise in global urbanisation and industrialisation, the need to tackle water scarcity, flooding and water quality in urban areas has increased in prominence. Addressing these challenges through inclusion of flood controls in urban planning has given rise to the concepts of Sponge Cities to deal with excess water and harvesting and reuse of rainwater to address water scarcity – this requires a reconceptualisation of urban underground space. The nexus between Smart and Sponge Cities is fundamentally underpinned by utility services, many of which are distributed using infrastructures buried beneath roads; their inaccurate location, and inaccurate mapping of underground space more generally, leads to wasteful excavations and additional costs for service providers when tackling utility management challenges that involve water permeation, water retention, water storage, water purification, water drainage, water saving and water reuse. To this end, the Mapping & Assessing the Underworld (MTU & ATU) initiative led by the University of Birmingham has engaged in fundamental multi-disciplinary research with a Smart Cities approach to utility streetworks. The focus has been on a novel, multi-sensor approach to utility detection and condition assessment of buried infrastructure, the road surface and the ground that supports them both. Alongside sensor development, a decision support system and sustainability assessment framework have been created to improve understanding of the options for and consequences of different interventions for the installation, repair and maintenance of these assets. The next stage of the research is to assess the value of the different functions that can be housed, enhanced or facilitated by the underground space. This paper will provide an overview of the MTU & ATU initiative, its key findings to date and initial ideas for realising the value of the underworld, the latter being crucial in making cities more sustainable, resilient, liveable and smart.

Makana LO, Metje N, Jefferson I, Sackey M and Rogers CDF (2018). Cost Estimation of Utility Strikes: Towards Proactive Management of Street Works. *Infrastructure Asset Management, Proceedings of the ICE* (Under Review).

Abstract: Any project involving ground excavation in urban areas is likely to be affected by utility infrastructure buried at shallow depth below the surface, which inherently poses a risk. Damage to utility services during excavation of whatever nature (impact fracture, puncturing, compromising sheathing or protective wrap) is termed a 'Utility Strike' and has potentially serious immediate or long-term consequences including: health and safety risk, service loss and disruption during repair. It inevitably incurs potentially large costs. However, the true (full) cost of a utility strike incident is rarely known. Generally, only the direct costs are used to measure the impact of utility strikes; the wider indirect and social costs are rarely quantified in monetary terms. Moreover, no established methodology exists to address this gap in knowledge, while access to fully-documented records often presents the greatest challenge.

This paper presents research that for the first time has been given access to 16 fully-detailed utility strike case studies in UK urban areas. The research has identified and assessed the impacts of these utility strikes, and provided an objective estimation of their associated (total) costs. These costs consist of those paid directly by the utility owner (direct costs), those borne by third parties in the contractual agreement (indirect costs), and those borne by other parties not engaged in the contractual agreement (social costs). Although the richness lies in the detailed case studies, the aggregated findings from all 16 utility strike case studies indicate that the total cost ratio – the ratio of indirect and social costs to the direct cost of repair – is 29:1. Thus there is a very substantial impact, which to date has been largely neglected.

Makana LO et al. (2018). Planning of sustainable subsurface use in smart future cities using agent-based modelling. *Computers, Environment and Urban Systems* - (In preparation).

Metje N and Hunt DVL (2015). Special Feature - Underground Services - *CIBSE Journal*, Exposing the Underworld, June.

Muggleton JM, Brennan MJ Rogers CDF (2014). Point Vibration Measurements for the Detection of Shallow-Buried Objects. *Tunnelling and Underground Space Technology* 39, 27–33.

Abstract: A major UK initiative, entitled 'Mapping the Underworld', is seeking to address the serious social, environmental and economic consequences arising from an inability to locate accurately and comprehensively the buried utility service infrastructure without resorting to extensive excavations. Mapping the Underworld aims to develop and prove the efficacy of a multi-sensor device for accurate remote buried utility service detection, location and, where possible, identification. One of the technologies to be incorporated in the device is low-frequency vibro-acoustics, and application of this technique for detecting buried infrastructure is currently being investigated. Here, the potential for making a number of simple point vibration measurements in order to detect shallow-buried objects, in particular plastic pipes, is explored. Point measurements can be made relatively quickly without the need for arrays of surface sensors, which can be expensive, time-consuming to deploy, and sometimes impractical in congested areas. At low frequencies, the ground behaves as a simple single-degree-of-freedom (mass–spring) system with a well-defined resonance, the frequency of which will depend on the density and elastic properties of the soil locally. This resonance will be altered by the presence of a buried object whose properties differ from the surrounding soil. It is this behavior which can be exploited in order to detect the presence of a buried object, provided it is buried at a sufficiently shallow depth. The theoretical background is described and preliminary measurements are made both on a dedicated buried pipe rig and on the ground over a domestic waste pipe. Preliminary findings suggest that, for shallow-buried pipes, a measurement of this kind could be a quick and useful adjunct to more conventional methods of buried pipe detection.

Muggleton JM and Papandreou BD (2014). A Shear Wave Ground Surface Vibration Technique for the Detection of Buried Pipes. *Journal of Applied Geophysics*, Volume 106, 164–172. DOI: 10.1016/j.jappgeo.2014.04.021

Abstract: A major UK initiative, entitled 'Mapping the Underworld' aims to develop and prove the efficacy of a multi-sensor device for accurate remote buried utility service detection, location and, where possible, identification. One of the technologies to be incorporated in the device is low-frequency vibro-acoustics; the application of this technology for detecting buried infrastructure, in particular pipes, is currently being investigated. Here, a shear wave ground vibration technique for detecting buried pipes is described. For this technique, shear waves are generated at the ground surface, and the resulting ground surface vibrations measured. Time-extended signals are employed to generate the illuminating wave. Generalized cross-correlation functions between the measured ground velocities and a reference measurement adjacent to the excitation are calculated and summed using a stacking method to generate a cross-sectional image of the ground. To mitigate the effects of other potential sources of vibration in the vicinity, the excitation signal can be used as an additional reference when calculating the cross-correlation functions. Measurements have been made at two live test sites to detect a range of buried pipes. Successful detection of the pipes was achieved, with the use of the additional reference signal proving beneficial in the noisier of the two environments.

Muggleton JM and Yan J (2013). Wavenumber prediction and measurement for buried fluid-filled pipes: inclusion of shear coupling at a lubricated pipe/soil interface
Journal of Sound and Vibration, 332(5) 1216-1230

Abstract: Acoustic methods have been widely used to detect water leaks in buried fluid-filled pipes, and these technologies also have the potential to locate buried pipes and cables. Relatively predictable for metal pipes, there is considerably more uncertainty with plastic pipes, as the wave propagation behaviour becomes highly coupled between the pipe wall, the contained fluid and surrounding medium. Based on the fully three-dimensional effect of the surrounding soil, pipe equations for n=0 axisymmetric wave motion are derived for a buried, fluid-filled pipe. The characteristics of propagation and attenuation are analysed for two n=0 waves, the s=1 wave and s=2 wave, which correspond to a predominantly fluid-borne wave and a compressional wave predominantly in the shell, respectively. At the pipe/soil interface, two extreme cases may be considered in order to investigate the effects of shear coupling: the "slip" condition representing lubricated contact; and the "no slip" condition representing compact contact. Here, the "slip" case is considered, for which, at low frequencies, analytical expressions can be derived for the two wavenumbers, corresponding to the s=1 and s=2 waves. These are both then compared with the situations in which there is no surrounding soil and in which the pipe is surrounded by fluid only, which cannot support shear. It is found that the predominant effect of shear at the pipe/soil interface is to add stiffness along with damping due to radiation. For the fluid-dominated wave, this causes the wave speed to increase and increases the wave attenuation. For the shell-dominated wave there is little effect on the wave speed but a marked increase in wave attenuation. Comparison with experimental measurements confirms the theoretical findings.

Muggleton JM and Rustighi E (2013.) Mapping the Underworld: recent developments in vibro-acoustic techniques to locate buried infrastructure. *Géotechnique*, Letters, Volume 3, pages 137-141. July-August.

Abstract: A major UK initiative entitled Mapping the Underworld (MTU) is seeking to address the serious social, environmental and economic consequences arising from an inability to locate – accurately and comprehensively – buried utility service infrastructure without resorting to extensive excavations. MTU aims to develop and prove the efficacy of a multi-sensor device for accurate remote buried utility service detection, location and, where possible, identification. One of the technologies to be incorporated in the device is low-frequency vibro-acoustics, and a number of different vibro-acoustic methods for detecting buried infrastructure have been investigated. The latest developments in the vibro-acoustic location research are presented here. Three complementary methods are described, one of which involves direct excitation of the buried asset and the other two require no such direct
access. All involve measurement of the ground surface vibration as a result of the excitation, whetherof the ground or of the buried asset directly. Together, these techniques constitute a substantial step change in the way buried infrastructure can be detected using vibro-acoustic methods.

Muggleton JM and Rustighi E (2016). A novel method for the remote condition assessment of buried pipelines using low-frequency axisymmetric waves. *Journal of Physics Conference Series, 1-9.*

Abstract: "Mapping the Underworld" is a large multi-disciplinary, multi-university research programme taking place in the UK, which aims to revolutionize the way we undertake streetworks. Within this programme, a number of vibration-based techniques for remotely detecting and locating buried pipes have been developed. Relying either on the direct excitation of a pipe as it comes up to the surface or excitation of the ground in the vicinity of a buried pipe, mapping the ground surface vibration response allows information to be gathered concerning the pipe's exact position. However, contained within this surface response is often information which could, if utilized appropriately,

provide insights into the condition of the pipe as well as its location. Furthermore, critical information regarding the condition of the ground in which a pipe is buried could, in some circumstances, be gleaned. In this paper, how this additional information might be extracted, used and eventually exploited is explored. Providing the basis for work currently being undertaken in a new programme, "Assessing the Underworld", example results are presented which demonstrate the immense potential of the proposed methods.

Muggleton JM, Kalkowski M, Gao Y and Rustighi E (2016). A theoretical study of the fundamental torsional wave in buried pipes for pipeline condition assessment and monitoring. *Journal of Sound and Vibration,* Volume 374, July, Pages 155-171. https://doi.org/10.1016/j.jsv.2016.03.035

Abstract: Waves that propagate at low frequencies in buried pipes are of considerable interest in a variety of practical scenarios, for example leak detection, remote pipe detection, and pipeline condition assessment and monitoring. Whilst there has been considerable research and commercial attention on the accurate location of pipe leakage for many years, the various causes of pipe failures and their identification, have not been well documented; moreover, there are still a number of gaps in the existing knowledge. Previous work has focused on two of the three axisymmetric wave types that can propagate: the *s*=1, fluid-dominated wave; and the *s*=2, shell-dominated wave. In this paper, the third axisymmetric wave type, the *s*=0 torsional wave, is investigated. The effects of the surrounding soil on the characteristics of wave propagation and attenuation are analysed for a compact pipe/soil interface for which there is no relative motion between the pipe wall and the surrounding soil. An analytical dispersion relationship is derived for the torsional wavenumber from which both the wave speed and wave attenuation can be obtained. How torsional waves can subsequently radiate to the ground surface is then investigated. Analytical expressions are derived for the ground surface displacement above the pipe resulting from torsional wave motion within the pipe wall. A numerical model is also included, primarily in order to validate some of the assumptions made whilst developing the analytical solutions, but also so that some comparison in the results may be made. Example results are presented for both a cast iron pipe and an MDPE pipe buried in two typical soil types.

Muggleton J M, Rustighi E and Gao Y (2016). Remote pipeline assessment and condition monitoring using low-frequency axisymmetric waves: a theoretical study of torsional wave motion. *Journal of Physics Conference Series*, 1-12.

Abstract: Waves that propagate at low frequencies in buried pipes are of considerable interest in a variety of practical scenarios, for example leak detection, remote pipe detection, and pipeline condition assessment and monitoring. Particularly useful are the *n*=0, or axisymmetric, modes in which there is no displacement (or pressure) variation over the pipe cross section. Previous work has focused on two of the three axisymmetric wave types that can propagate: the *s*=1, fluid-dominated wave; and the *s*=2, shell-dominated wave. In this paper, the third axisymmetric wave type, the *s*=0 torsional wave, is studied. Whilst there is a large body of research devoted to the study of torsional waves and their use for defect detection in pipes at ultrasonic frequencies, little is known about their behaviour and possible exploitation at lower frequencies. Here, a low-frequency analytical dispersion relationship is derived for the torsional wavenumber for a buried pipe from which both the wavespeed and wave attenuation can be obtained. How the torsional waves subsequently radiate to the ground surface is then investigated, with analytical expressions being presented for the ground surface displacement above the pipe resulting from torsional wave motion within the pipe wall. Example results are presented and, finally, how such waves might be exploited in practice is discussed

Pennock SR, Abed TM, Curioni G, Chapman DN, John UE, Jenks CHJ. (2014). Investigation of soil contamination by iron pipe corrosion and its influence on GPR detection. Presented at the Proceedings of the 15th International Conference on Ground Penetrating Radar, GPR 2014, Brussels, Belgium, pp. 381–386. doi:10.1109/ICGPR.2014.6970451

Abstract: It has been observed that the corrosion of iron pipes in soil can produce variations in ground conductivity around the pipe, and that the visibility of such pipes to GPR can be greatly reduced. This new investigation and measurement of the permittivity and conductivity of soil contaminated by iron pipe corrosion products produces more accurate knowledge of permittivity and conductivity data and their likely spatial variation with distance from the corroding pipe. The experimental data are the result of monitoring accelerated corrosion over a period of several weeks and using TDR and direct conductivity measurement schemes. FDTD simulations of GPR signals show how the corrosion induced variation in the visibility of the pipe varies with the thickness and shape of the new spatial variations permittivity and conductivity. The results indicate that in the earlier stages of pipe corrosion use of lower GPR frequencies will still detect the pipe, although at lower spatial resolution.

Pennock SR, Jenks CHJ (2014). Wideband loaded bicone antennas for GPR applications. Ground Penetrating Radar (GPR), 2014 15th International Conference on DOI: 10.1109/ICGPR.2014.6970531

Pennock SR, Jenks CHJ (2014). Road surface and pavement condition assessment by high frequency GPR diffraction. Ground Penetrating Radar (GPR), 2014 15th International Conference on DOI: 10.1109/ICGPR.2014.6970553

Pennock SR, Abdul-Latif OM, Jenks CHJ (2014) Improved GPR image focussing with repetitive normalised Superimposition techniques. Ground Penetrating Radar (GPR), 2014 15th International Conference on DOI: 10.1109/ICGPR.2014.6970516

Pennock SR, Jenks CHJ (2015). Dielectric wedge antenna for pavement void detection by scattering. Antennas and Propagation (EuCAP), 2015 9th European Conference on

Pennock SR, Jenks CHJ (2015). Antennas for pavement void detection by scattering. Advanced Ground Penetrating Radar (IWAGPR), 2015 8th International Workshop on DOI: 10.1109/IWAGPR.2015.7292629

Pennock SR, Jenks CHJ (2015). Investigation into distortion control in OFDM radar by spectral avoidance. Radar Conference (EuRAD), 2015 European DOI: 10.1109/EuRAD.2015.7346273

Abstract: Commercially available off the shelf Software Defined Radios (SDR) have many of the components required to construct an OFDM or a stepped frequency GPR. Some additional components are required in order to make phase measurements however, as described here. There are also design features of the SDR used here which could make them unsuitable, but which can be mitigated as investigated here. Published in: Advanced Ground Penetrating Radar (IWAGPR), 2017 9th International Workshop on

Pennock SR, Jenks CHJ (2017). Enhancing image formation from GPR data by a normalised geometric mean analysis. Advanced Ground Penetrating Radar (IWAGPR), 2017 9th International Workshop on DOI: 10.1109/IWAGPR.2017.7996061

Abstract: Image formation in Ground Penetrating Radar (GPR) has been used to provide data that is easier to interpret than hyperbolic traces in B-scans. A limitation of past work is a tendency to produce quite low contrast images. In this work a normalised geometric mean analysis is used that

provides a higher contrast image. Its use on simple target scenarios is initially investigated. Then the more commonly encountered and testing cases of layered ground and of significantly inhomogeneous ground resulting from a finite porosity or void density are examined in this paper. Published in: Advanced Ground Penetrating Radar (IWAGPR), 2017 9th International Workshop on

Pennock SR, Abdul-Latif OM (2017). Enhanced vector network analyzer time domain measurement using normalized superimposition. Microwave Symposium (IMS), 2017 IEEE MTT-S International DOI: 10.1109/MWSYM.2017.8058836

Abstract: The measurement of the complex scattering parameters of a device under test (DUT) in the frequency domain using a Vector Network Analyzer (VNA) is common practice. Further investigation in the time domain is often obtained where the Inverse Fourier Transformation of the measurement results is examined. Thus, the impulse and/or step responses of the DUT can be obtained, which give another form of representation of the characteristics of the DUT. One of the main problems in this scheme is the introduction of unwanted side lobes that are caused when applying FT or IFT to measured signals that are band-limited. One technique to reduce side lobes is windowing, but this has a broadening effect on the main-lobe. The Spatially Variant Apodization (SVA) and superimposition (SI) techniques have been seen to address these issues in the past, and in this paper an enhancement to the SI technique through a normalisation process is investigated. The SI technique is seen to preserve the position, amplitude and phase of the main lobe responses from a DUT in simulated and measured data, while reducing side lobes and therefore confusion in the time domain representation of the DUT. In that sense a better approximation to the ideal impulse response of the DUT can be obtained. Published in: Microwave Symposium (IMS), 2017 IEEE MTT-S International

Pennock SR, Jenks CHJ (2017). UWB shielded teardrop monopole antenna for GPR and communications. Antennas and Propagation in Wireless Communications (APWC), 2017 IEEE-APS Topical Conference on DOI: 10.1109/APWC.2017.8062303

Abstract: Ultra-wideband characteristics are often sought for radar and communications applications. This paper investigates the properties of a re-sistively loaded teardrop monopole, embedded into a cavity in such a way that the antenna face has a flat profile. Finite Difference Time Domain analysis and measurements indicate ultra-wideband performance. Investigation of coupling between closely spaced antennas shows quite good isolation, and constriction of current flow to the immediate vicinity of the antenna. The basic causes of the low level late time ringing in the antenna are seen to be related to identified mechanisms, which can then be further investigated and optimised. Published in: Antennas and Propagation in Wireless Communications (APWC), 2017 IEEE-APS Topical Conference on

Pennock SR, Jenks CHJ (2017). Imaging irregular ground with GPR data. Electromagnetics in Advanced Applications (ICEAA), 2017 International Conference on DOI: 10.1109/ICEAA.2017.8065550

Abstract: Ground Penetrating Radar data is often focussed into images of the ground to provide interpretation of buried targets that is easier to understand than traditional B-scans. This paper examines the use of a new, `high contrast', imaging technique, applied to the very realistic problem where the ground is not uniform but contains many small voids. The basic frequency dependence of the problem is outlines in terms of Rayleigh scattering. Finite Difference Time Domain simulation is seen to validate the approach and confirm basic method of identifying the signature of voids in the ground. Published in: Electromagnetics in Advanced Applications (ICEAA), 2017 International Conference on

Rogers CDF, Hao T, Costello SB, Burrow MPN, Metje N, Chapman DN, Parker J, Armitage RJ, Anspach JH, Muggleton JM, Foo KY, Wang P, Pennock SR, Atkins PR, Swingler SG, Cohn AG, Goddard K, Lewin PL, Orlando G, Redfern MA, Royal ACD and Saul AJ (2012). Condition Assessment of the Surface and Buried Infrastructure – A Proposal for Integration. *Tunnelling and Underground Space Technology* 28, 202-211.

Abstract: The surface urban transport infrastructures, which are interpreted widely herein to encompass roads, cycle ways, pedestrian areas and railway foundations, are supported by the ground and hence their structural performance is inevitably to some degree controlled by the ground. Since the utility services infrastructure that supports city living is typically buried beneath the surface transport infrastructure, street works activities to install, replace, repair or maintain the utility infrastructure using traditional techniques disrupts, and often significantly damages, the transport infrastructure and the ground on which it bears. As a consequence of this latter argument, the ground and the associated physical infrastructure, whether buried utility service infrastructure or the surface transport infrastructure, exist according to a symbiotic relationship: intervene physically in one and the other is almost inevitably affected in some way, whether immediately or in the future. The physical condition of these assets is therefore of crucial importance in determining what, and how severe, the inevitable impact on each other will be, and the close link between them (i.e. that they are both intimately linked to and to some degree controlled by the ground) must be carefully considered. This paper proposes and discusses the establishment of a universal platform in which the physical infrastructure and the ground, and their conditions, can be mapped.

Rogers CDF, Metje N, Makana LO, Atkins PR, Hayati F, Muggleton JM, Rustighi E, Al-Khoury A, Pennock SR, Jenks CHJ, Boxall JB, Collins R, Mills R, Dwyer-Joyce R, Anderson S and Dodd T (2017). Assessing the Underworld – Understanding the Context for Engineering the Next Generation Infrastructure. *Proceedings of International Symposium for Next Generation Infrastructure (ISNGI 2017)*, London, UK, 11th-13th September, 341-350.

Abstract: Next Generation Infrastructure (NGI) must integrate seamlessly with the existing infrastructure and its systems of operation. It must address the compelling needs of cities and urban systems – it must be sustainable, resilient, adaptable, smart and responsive to change (of context, addition, of use) – yet it must address the often overlooked issue of operational serviceability and maintenance. This is where this paper focuses: the nexus between new and existing infrastructure systems when attempting to deliver NGI fit for cities, and the urban systems they support, for the far future.

One core challenge is to understand the condition of the existing asset base, given that much of it is buried and thus out of sight and difficult to access. Following the philosophy of Mapping The Underworld, a new programme (Assessing The Underworld) is researching how remote sensing technologies can be deployed to reveal more than simply where the buried infrastructure is located, but what intelligence can we extract to understand its condition? Inherent in this endeavour is the appreciation that the transport and buried utility infrastructure systems are usually physically co-located and are interdependent: interfere physically in one of these systems and the other will be affected. Moreover, both are supported by the ground, and this can be conceptualised as a third, intervening, infrastructure, and all three are interdependent.

This paper describes the advances made in understanding the condition of the three infrastructures as a result of novel developments in sensing technologies as the platform for bringing a new evidence base on which to found decision-making for NGI.

Stirling RA, Hughes PN, Davie CT, Glendinning S (2014). 'Cyclic relationship between saturation and tensile strength in the near-surface zone of infrastructure embankments'. In unsaturated soils: *Research and Applications*. London: CRC Press, 1501-1505.

Abstract: The near surface properties of engineered fill have a significant impact on its engineering behaviour. A common way in which soil will change is through cracking due to the effects of desiccation, vegetation and climate. This has an impact on soil mass permeability, strength and stiffness and hence slope failure susceptibility. Knowledge of the tensile strength and degree of saturation relationship is essential to understand the development of desiccation cracking. This paper presents a study to establish the cyclic relationship between tensile strength and soil water content in

a re-moulded glacial till. Testing was conducted using a direct tensile strength test modification to standard direct shear apparatus. As with the soil-water retention, the relationship between soil water content and tensile strength shows hysteretic characteristics. Furthermore, this relationship was found to develop upon repeated drying and re-wetting cycles. This has implications for the degradation of near surface material on engineered infrastructure slopes.

Stirling RA, Hughes PN, Davie CT, Glendinning S (2015). 'Tensile behaviour of unsaturated compacted clay soils". A direct assessment method, *Applied Clay Science*, 112-113: 123-133. DOI: 10.1016/j.clay.2015.04.011.

Abstract: This paper presents a new method for testing the behaviour of soils placed under tensile load and demonstrates its suitability for testing a number of soil types under various conditions including saturation, compaction and stabilisation. Validation of the results obtained for the soils at relatively low saturation has been conducted using the established Brazilian (indirect) test for measuring the tensile strength of brittle materials. A fair comparison has been found and the results highlight the limited applicability of the Brazilian method to soils at very low water contents at which the tensile failure criterion has been assumed using this methodology. Optical characterisation of the performance of both testing methods has also been conducted using Digital Image Correlation. The consistent, accurate measurement of directly induced tensile strains using the proposed new method has been confirmed, verifying its capability to apply a direct tensile stress in the absence of shearing, a problem commonly associated with other tensile testing methods. The developed technique has then been used to investigate the water content – tensile strength relationship for compacted, unsaturated soils and offers significant advantages in the characterisation of clay soils subjected to variable climatic loading.

Stirling RA, Glendinning S, Davie CT (2015). 'Multiphase modelling of desiccation cracking in the near-surface of compacted soils' *16th European Conference on Soil Mechanics and Geotechnical Engineering*. Edinburgh, UK.

Abstract: The development of cracking as a result of desiccation is increasingly under investigation. The mechanical and hydrological behaviour of desiccated clayey soils is dramatically influenced, primarily by the preferential transmission of water. This may result in rapidly elevated pore water pressure and is widely cited as a mechanism for the strength reduction that leads to infrastructure slope failure. Continuum FD modelling has been undertaken using FLAC 2D in addition to the two-phase flow add-in enabling the unsaturated behaviour of the desiccated medium to be included. Factors affecting the incidence and scale of cracking observed in compacted clay fill have been investigated via a systematic sensitivity study. Such factors include the increase in material stiffness upon drying and parameters used in describing the soil-water retention curve. Where necessary, the influence of significant parameters has been established by means of a varied experimental program, this has given rise to the design, manufacture and testing of a laboratory test apparatus and procedure to define the tensile strength of compacted fills under varying saturation conditions. Through development of the model, desiccation, crack initiation and propagation have been simulated allowing the processes at the very near-surface to be successfully captured. The work is conducted in the context of ongoing research into the climate impacts on infrastructure slope management and contributes toward the improvement of existing slope hydrology understanding

Stirling RA, Davie CT, Glendinning S (2015). 'Multiphase modelling of desiccation cracking in the near-surface' Acta Geotechnica. Vol 9. Pages 799-816 DOI.10.1007/s11440-014-0324-1.

Stirling RA, Glendinning S, Davie CT. (2017) Modelling the deterioration of the near surface caused by drying induced cracking. *Applied Clay Science*.146,176185.doi.org/10.1016/j.clay.2017.06.003

Abstract: Assets such as roads, railways, pipelines and flood embankments are inherently vulnerable to the action of weather and in the long term, climatic change. Their exposure makes them highly susceptible to deterioration during the course of their design life and beyond. The drivers of deterioration are believed to be human (e.g. traffic, maintenance) and environmental (e.g. weather,

pollution, burrowing) but the actual deterioration *processes* are not well understood. Among the weather-driven processes, it is believed that desiccation of the near-surface and the development of cracking can significantly influence the mechanical, hydrological and thermal behaviour of geotechnical structures primarily by impacting the transmission of water between the atmosphere and soil. Enhanced infiltration during rainfall events can potentially lead to rapidly elevated pore water pressures and reduced shear strength and is widely cited as the strength reduction mechanism behind the wide spread failure of infrastructure slopes. This paper describes the development of a pseudo-discrete continuum Finite Difference model and its application to investigate the influence of soil properties (including elastic modulus, hydraulic conductivity and soil-water retention) on the desiccation process and eventual crack initiation and propagation behaviour. The generation of a desiccated crust typified by highly negative pore pressures and increasingly disintegrated texture is demonstrated. The influence of projected higher drying rates and seasonal drying-wetting cycles (that could result from climate change) on crack pattern development is investigated to gain an understanding of progressive deterioration. This points towards the potential for increased future deterioration rates of geotechnical infrastructure.

Thring LM, Boddice D, Metje N, Curioni G, Chapman DN and Pring L (2014). Factors affecting soil permittivity and proposals to obtain gravimetric water content from time domain reflectometry measurements. *Canadian Geotechnical Journal* 51, 1303–1317. DOI:10.1139/cgj-2013-0313.

Quratul-ain Mahesar, Vania G Dimitrova, Derek R Magee, Anthony G Cohn (2017), “Uncertainty Management for Rule-based Decision Support Systems”, 29th IEEE International Conference on Tools with Artificial Intelligence (ICTAI2017), Boston, USA, 2017,

Abstract: We present an uncertainty management scheme in rule-based systems for decision making in the domain of urban infrastructure. Our aim is to help end users make informed decisions. Human reasoning is prone to a certain degree of uncertainty but domain experts frequently find it difficult to quantify this precisely, and thus prefer to use qualitative (rather than quantitative) confidence levels to support their reasoning. Secondly, there is uncertainty in data when it is not currently available (missing). In order to incorporate human-like reasoning within rule-based systems we use qualitative con- fidence levels chosen by domain experts in urban infrastructure. We introduce a mechanism for the representation of confidence of input facts and inference rules, and for the computation of confidence in the inferred facts. We also present a mechanism for computing inferences in the presence of missing facts, and their effect on the confidence of inferred facts.