INTERNATIONAL SYMPOSIA FOR
NEXT GENERATION
INFRASTRUCTURE

A decision support system to proactively manage subsurface utilities

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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.

Key Words

Critical infrastructure, roads, utilities, ground, investigation, asset management

Introduction

Critical infrastructure, in the UK, is defined as those facilities, systems, sites, information, people, networks and processes, necessary for a country to function and upon which daily life depends[1]. National infrastructure includes domestic, social and economic infrastructure[2]. Economic infrastructure,

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[1] https://www.cpni.gov.uk/critical-national-infrastructure-0 accessed 25/7/2017

[2] Infrastructure and Ports Authority (2017) National Infrastructure and Construction Pipeline, UK HM Treasury, London

the lifelines on which society depends, includes transport, energy, water and communications which amounts to 1410Mm network (Fig. 1) with an investment of £300 x 10^9 in the next five years (Fig. 2). This includes £59.2 x 10^9 on utilities.

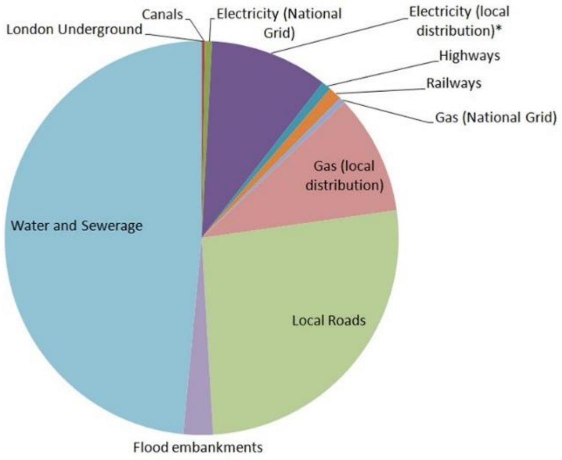

Fig. 1 An estimate of the distribution of UK national infrastructure based on a total of 1410Mm

Infrastructure systems such as water, energy, transportation and telecommunication networks perform functions critical to the health and well-being of society. Historically, they have been developed and maintained in isolation from one another. However, it is now recognised that infrastructure systems function as a 'system of systems'. A consequence of this interdependency is that they are vulnerable to failure through cascading events. Research efforts into infrastructure interdependencies have focused on risk and vulnerability, placing a primary focus on the negative aspects of system complexity[3]. Research projects funded by EPSRC include the Infrastructure Transitions Research Consortium (ITRC)[4], Infrastructure Business Models, Valuation and Innovation for Local Delivery (iBUILD)[5] and the International Centre for Infrastructure Futures (ICIF)[6], all of which are investigating infrastructure interdependencies.

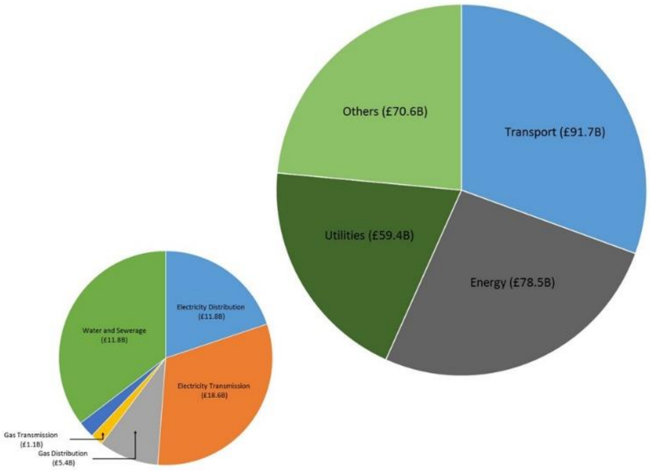

Fig. 2 The UK National Infrastructure and Construction Pipeline

The interdependency of national Infrastructure can lead to catastrophic failures. For example, rainfall in 2007 led to flooding of the water treatment works in Gloucestershire resulting in loss of water supplies to 350,000 people for up to 17 days; embankment failure and flooding on the rail network causing delays in the service and subsequent delay in the supply of fuel; repair costs of local and trunk roads were estimated at £40-60 x 10^6; and damage to electricity distribution cutting off 40,000 people in Gloucestershire for 24 hours and placing 9000 customers on rolling blackouts in Yorkshire and Humberside for several days.

These examples are highly disruptive leading to loss of service to an area yet, on a smaller scale, disruptive events can have local impact leading to a loss of service to a house, a street or a community. These small scale events, associated with utilities and the overlying road, are more common than those addressed by the Centre for the Protection of National Infrastructure and can be triggered by system failures, weather, environmental changes,

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[3] CIRIA, 2017

[4] ITRC EPSRC Grant EP/I01344X/1

[5] iBUILD EPSRC Grant EP/K012398/1

[6] ICIF EPSRC Grant EP/K012347/1

traffic, and routine and planned maintenance. From a domestic point of view, they are critical. Furthermore, the events, and hence disruption, are far more common than those relating to national infrastructure.

Characteristics of critical infrastructure

From an engineering point of view, the characteristics of critical national infrastructures include:-

1. Essential services that are critical to the health, wealth and well-being of society;
2. Design life of 120 years, but through adaption and replacement can be expected to last much longer (e.g. the UK road construction began about 2000 years ago; canals 250 years ago; and rail 200 years ago);
3. Generally capital intensive with low operational costs, though their longevity means that there will be significant periods of investment throughout their life;
4. An asset which are intended to be maintained indefinitely through replacement and refurbishment;
5. A complex network;
6. Constructions with significant volumes of low cost materials.

The characteristics of critical local infrastructures include:-

1. Providing essential services that are critical to the health, wealth and well-being of communities;
2. Being built over time, which means many of these assets are not engineered to modern standards;
3. The precise location of some of the utilities is often unknown, but it is known that the spatial distribution of utility pipes and cables beneath the streets has evolved and is chaotic;
4. Assets that are intended to be maintained indefinitely through replacement and refurbishment;
5. A complex network;
6. A limited life and, because of repeated interventions, that life has been reduced.

Topic	Total	Detail
Structural road condition (remaining life)		>15 years 53%; 5-15 years 30%; < 5 years 17%
Annual highway maintenance	£2.5 x 10^9pa	Mean £21.8 x 10^6 per authority
Annual carriageway maintenance	£1.45 x 10^9pa	Mean £12.6 x 10^6 per authority including 22% reactive
Compensation claims	£0.95 x 10^9pa	Mean £7.9 x 10^6 per authority
Potholes	1.5 x 10^9	13468 filled per authority; £46/pothole planned; £69/authority emergency
Utility openings	1.4 x 10^9	Mean 12236 per authority

Table 1 The impact of annual road maintenance in 2017[7] based on 63% of the 114 local authorities in England

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[7] Asphalt Industry Alliance (2017) Annual Local Authority Road Maintenance

At a local scale, from a user's point of view, the services that critical infrastructures provide are essential and are assumed to be fully functional. Hence, any loss of these services is highly disruptive. Indeed, this disruption, cited as a key concern by communities, is a political issue and leads to significant direct and indirect costs (Table 1). The local authority road network accounts for about 95% of the English and Welsh roads and, because of their poor condition, accounts for £53 x 10^9 in lost business[8].

Critical infrastructure is defined in terms of the service it provides and focuses on the physical asset that delivers that service. A loss of service can impact on other services; that is these services are interdependent. However, at a local scale, a failure of a utility can lead to a failure of a road yet the road does not depend on that utility. For example, a leaking water pipe can erode the surrounding ground leading to loss of support to the overlying road eventually causing collapse of the road; increased traffic and axle loads can overload a road compressing the ground, deforming an underlying utility possibly leading to failure of the utility. The road and utility assets may be considered independent since their functions are not interdependent. However, they rely on the ground for support; that is, the interdependency of these assets is through the ground. The ground can be considered to be a dormant asset that becomes active when an asset is built on or in the ground. The role of the ground is to support the asset, though the ground also transmits actions, such as load, water, or chemicals, from one asset to another. This means that the assets are indirectly interdependent.

Any structure built on or in the ground relies on the ground for support; the ground is considered a stable platform though the manner by which the ground provides that support depends on the sensitivity of the structure, the magnitude of the actions transferred and the mechanical properties of the ground. Thus, the ground has a value such that any changes to the ground can affect the structures it supports. The concept of ground as an asset, which provides support to road and utility assets, underpins a decision support system described in this paper developed for operators of road and utility assets.

The Decision Support System

A decision support system (DSS) is being developed to provide advice to an asset operator to understand the consequences of an action undertaken in response to a trigger to ensure that the action is economic, sustainable, and resilient. It was developed in consultation with industry partners and academic experts in engineering (ground, water, energy, and roads), sustainability, and computer science. The core components of the DSS, shown in Figure 3, are: the ontologies describing the triggers (natural and anthropogenic) and the ground, road and utility assets; advice (including further investigation and actions); and consequences (including impact on assets), the inference engine and the accessible databases.

There are three phases to the DSS: -

1. Phase 1 is triggered by the user responding to an external action such as routine maintenance, planned repair or replacement, environmental change, reduced performance (e.g. potholes) of service or failure of service (e.g. ground collapse). The level

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[8] Asphalt Industry Alliance (2017) Annual Local Authority Road Maintenance

of risk is inferred from an assessment of the data recognising additional information that could reduce risk and the consequences of the trigger. The output from Phase 1 is recommendations for further investigation to reduce risk.

2. Phase 2 is triggered by the user responding to the additional information from investigations and desk studies. The output from this Phase is a subjective view on the consequences of the trigger in the context of the environment in which the trigger takes place.
3. The final Phase is triggered by the user placing constraints on the diagnosis to allow for statutory requirements, policy, and practice. This leads to advice on possible sustainable, resilient solutions.

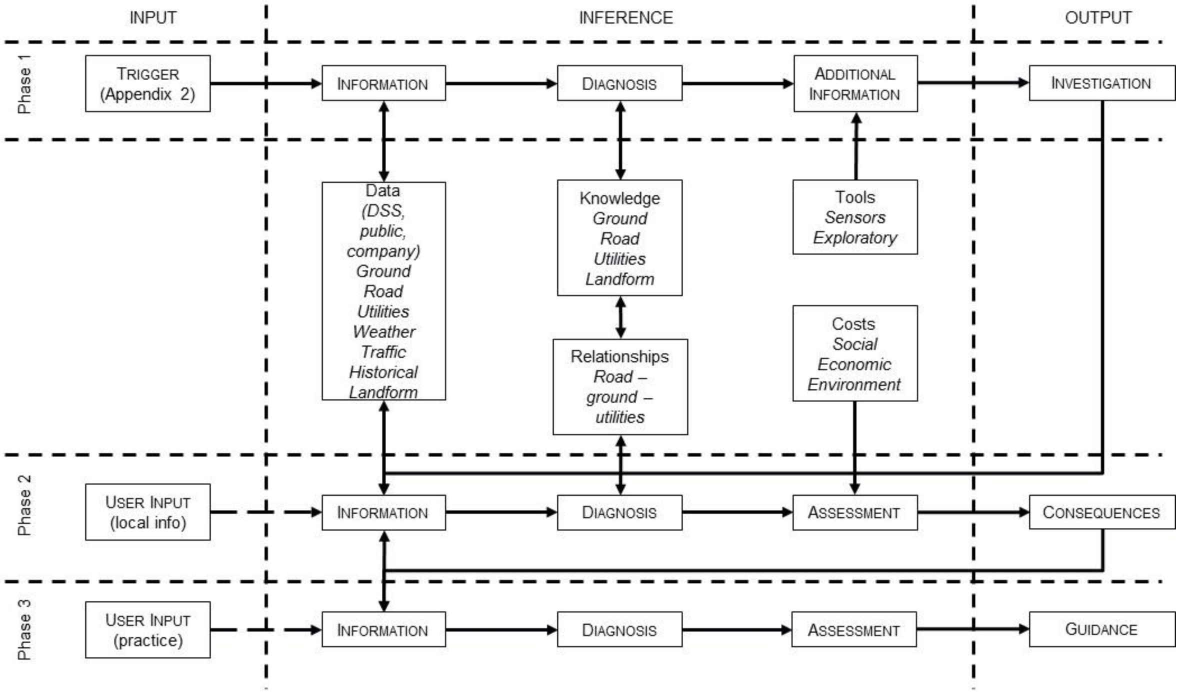


Fig. 3 The architecture of the Decision Support System

There are three stages to each Phase: -

1. The first stage, the user input, covers the trigger, local and asset owner information and statutory requirements and policy.
2. The inference stage forms the DSS core. It includes access to public information such as: data and information from the Met Office, Ordnance Survey and the British Geological Survey; asset owner and regulatory information; asset ontologies and inter asset relationships; data on investigative techniques, sustainability criteria; and possible solutions.
3. The third stage is the output stage which includes recommendations for further investigation, the impact of a trigger on all assets and guidance on solutions.

Triggers: The DSS is a knowledge-based system that is used to assess the impact of a change (Table 2) in the operational environment of the asset. These triggers can be planned (e.g. new build, routine maintenance, repair, or adaption) or unplanned (e.g. loss in pressure, road deformation, failure initiated by rainfall). They can be a consequence of an asset owner's policy and practice or public observations.

Category	Action	
Human activity	Construction works	
	Traffic flow	
Natural phenomena	Drought	
	Earthquake	
	Freezing	
	Extreme temperatures	
	Rainfall	
	Surface geohazards	Ground moving
		Surface erosion
Observations	Collapses	Ground collapse
		Mine collapse
		Sewer/tunnel collapse
	Road	Cracks
		Potholes
		Rutting
		Road fretting
		Road deformation
		Standing water
	Water pipe	Discoloured water
		Loss of pressure
		Surface water (not rainfall)
		Network capacity
		Change in chemistry
	Sewers	Surface water (not rainfall)
	Cables	Loss of power
Periodic review	Annual maintenance	
	End of life replacement	
	Update replacement	
Policy	Regulation/policy changes	
	Internal policy change	

Table 2 Triggers that are used to activate the DSS

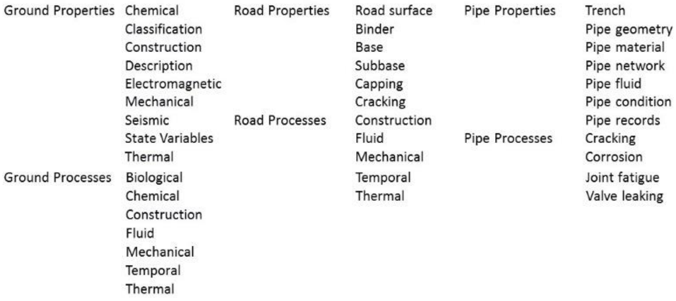
Information Sources: There is a range of information associated with a trigger (e.g. location, description of the observation, time, and date) which, if acted upon, could lead to a solution that may not be sustainable, resilient, or cost effective, and could impact on other assets exacerbating the effects; that is the level of risk may be unacceptable. A key aspect of the DSS is that it informs the asset owner of the consequences of action or inaction on their asset and the other assets. The risk can be reduced by increasing the level of knowledge developed from further information, inter and intra relationships of asset properties and processes, and further investigation.

The location can be used to describe the topography, geology, hydrogeology, and geotechnical characteristics of the site, which is the ground model. This is fundamentally important since any change to the ground could affect the assets that it supports (i.e. the road and utility pipelines and cables). In the UK, some of this information is held by the Ordnance Survey and the British Geological Survey. Further details, secondary information, may be sourced from asset owner's records, publications, and archives.

Environmental and anthropogenic factors, such as weather-related events, traffic conditions, type of road, location of utilities, can be obtained from the Met Office, Highways England, the Automobile Association, and utility companies.

Not all of this information is publicly available but many asset owners have access to the information from other asset owners. Further, the scale of an event means that this information may not be detailed enough. A key feature of the DSS is the ability to develop a database of events, results of subsequent investigations and action undertaken to deal with the event; that is, create or enhance an asset owner's data base. Further, with the agreement of other asset owners, it is possible to create a shared source of information, this being particularly important when considering inter asset relationships; that is, the DSS has the potential to be a dynamic tool that shares data across a common platform accessible by stakeholders including asset owners and operators, local and national authorities, main and specialist contractors and consultants that maintain assets.

Ontologies: There are several ontologies (computational models that define the main concepts and relationships in a domain, providing a shared vocabulary for information sharing and reuse) associated with the DSS covering the assets, the environment and anthropogenic triggers, investigative techniques, consequences, costs, and solutions. The core ontologies are those covering the three assets – road – ground – utility (Figure 4) as they set the rules for the inference engine. The triggers provide input knowledge; the others either provide interim information or output advice.



Ground Properties	Chemical	Road Properties	Road surface	Pipe Properties	Trench
	Classification		Binder		Pipe geometry
	Construction		Base		Pipe material
	Description		Subbase		Pipe network
	Electromagnetic		Capping		Pipe fluid
	Mechanical		Cracking		Pipe condition
	Seismic	Road Processes	Construction		Pipe records
	State Variables		Fluid	Pipe Processes	Cracking
	Thermal		Mechanical		Corrosion
Ground Processes	Biological		Temporal		Joint fatigue
	Chemical		Thermal		Valve leaking
	Construction				
	Fluid				
	Mechanical				
	Temporal				
	Thermal				

Fig. 4 The structure of the asset ontologies

An asset has physical, mechanical, chemical, thermal, and electrical properties. These properties can be changed by processes. Therefore, the structure of an asset ontology is based on the chain: -

………property → process → property → process ……. (1)

An example of the structure of an asset ontology is given in Figure 4[9] which describes the ground ontology structure. To satisfy Equ (1), experts developed relationships to establish the influence properties had upon processes, the impact properties had upon processes, and the effect properties had upon other properties. The ground ontology is the most complex because of the three-phase nature of the material, it is naturally spatially and temporally variable, many of the properties are related (Figure 5), and it has to provide knowledge for inter asset relationships, as well as investigative techniques and consequences.

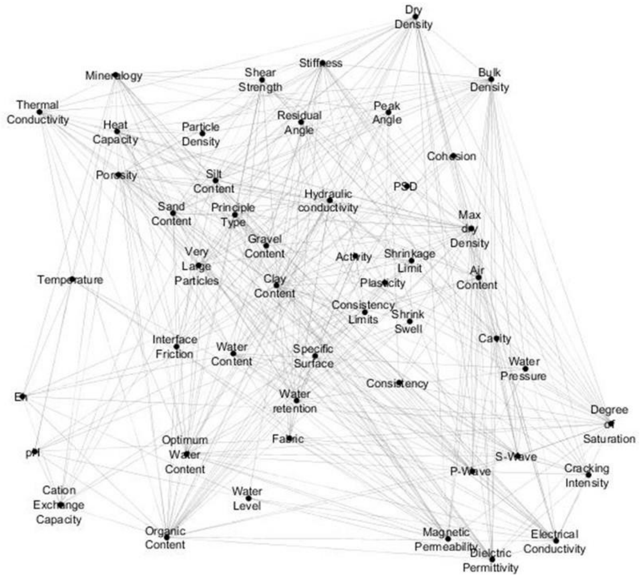


Fig.5 The complex relationships between ground properties

Inter Asset Relationships: The principle shown in Equ (1) also applies to the inter asset relationships (rules which underpin the logical reasoning in the DSS inference component), but in this case the process is transmission (Figure 6). A road will transmit a force to the ground, the force being the traffic load. It can also transmit water and chemicals if the road has been damaged. The ground is the subgrade; that is, it supports the road. Since ground is porous, any water will infiltrate (process) the ground causing a change in the water content, ground water level and pore pressure. If water is entering the ground, the ground might swell, depending on lithology, possibly causing the road surface

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[9] Du, Heshan, et al. (2016) "An ontology of soil properties and processes." International Semantic Web Conference. Springer International Publishing

to rise. A consequence of the increase in water content is that the strength and stiffness of the ground will reduce possibly leading to compression of the ground, and, therefore, settlement of the road surface. This could lead to local deformation (formation of ruts in the road surface). Cracks could develop leading to further infiltration.

Ground provides vertical and lateral support to a utility, therefore any ground movement could deform an underlying utility and, if the deformation is excessive, result in damage to that utility. For example, contaminated water could enter a water supply if a pipe is broken because of excessive deformation. A failure of a utility (e.g. leakage from a water pipe) could affect the ground. The leaking water would infiltrate the ground thus changing the properties of the ground and/or lead to erosion removing the support to the utility and overlying road.

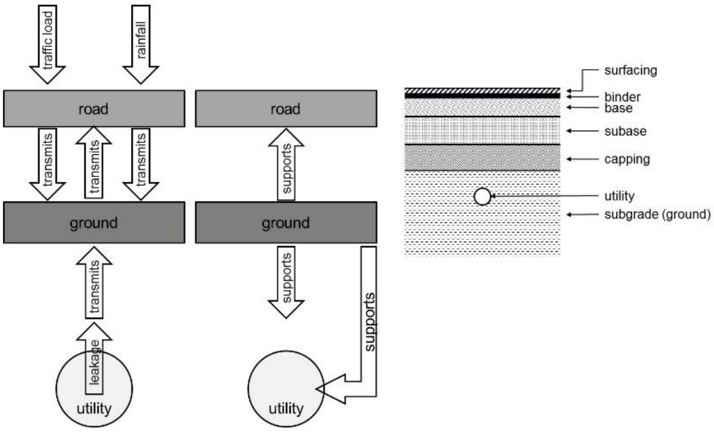

Fig. 6 The inter asset relationships to show the role of the ground in supporting the road and utility assets and transmitting actions between them

Leaking pipes and cracked roads allow water/rainfall to infiltrate the ground, changing its properties and triggering other processes which can affect road and utility assets. The fact that an action on one asset can result in damage to another asset is a feature recognised by the DSS, which ensures the full consequences of triggers can be explored, and solutions proposed.

Contaminated water, pipe corrosion and chemically-induced volume changes of the ground can be a consequence of water migration, resulting in further damage to the assets. Increase in volume of type of traffic (e.g. increase in axle loads) can deform the road surface, potentially leading to subgrade (ground) deformation which could in turn lead to deformation of the underlying utility.

Further Investigation: Further information is necessary if cost effective sustainable solutions are to be inferred from the diagnosis. This is because the public and private information is unlikely to be detailed enough and observations will, at best, be a description of the surface of the road. Therefore, further investigation is inevitable. Ideally, this will be a remote investigation using sensors that detect the asset properties. It is possible to detect with varying degree of success the geological profile, the geotechnical properties the ground water profile, the location and condition of the utilities, and the structure and condition of the road construction. The alternative is an intrusive investigation. This is highly disruptive as it involves excavation, although allows the condition of the asset to be studied in detail. Table 3 is a summary of the techniques considered which include developments from Mapping the Underworld[10].

Consequences: Experience suggests that asset operators focus on their own asset to the extent that they may not be aware of the effect of any action they take on an adjoining asset. The exception is the utility operator who will be aware, through regulations, that repairing, replacing or renewing their asset

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[10] EPSRC Grant EP/C547330/1

could affect adjacent and overlying assets, though not necessarily the detail. An advantage of the DSS is that it treats the assets as a system of systems, which means that the inference engine can realise the consequences of any trigger on any of the assets. These consequences include those that affect the asset under investigation as well as the other assets (Figure 6). The consequences are assessed using a risk matrix, which takes into account the possible severity of any damage to any of the assets. Understanding the consequences will reduce the risk but may increase the need for intervention. For example, a leaking pipe may be deemed to be a low risk by the utility operators. However, if the surrounding ground is silty sand, the leak could erode the ground leading to loss of support to both utility and the road, thereby transforming a low risk event to a high risk event.

Geophysical method		**Physical property**	**Regional studies**	**Depth to bedrock**	**Stratigraphy**	**Lithology**	**Fractured zones**	**Fault displacement**	**Buried channels**	**Natural cavities**	**Ground water**
Potential field	Gravity	Density	4	1	0	0	0	2	2	3	1
	Magnetics	Susceptibility	2	0	0	0	0	2	1	0	0
Electrical	Resistivity (sounding)	Resistivity	2	4	3	3	2	2	3	2	4
	Resistivity (tomography)	Resistivity	2	3	2	2	4	3	3	3	4
	Induced polarisation	Resistivity; capacitance	2	2	2	3	1	1	2	0	4
	Self potential	Potential difference	0	0	0	0	2	2	1	1	4
Electro magnetic	FDEM	conductivity; inductance	3	2	2	2	4	2	3	4	4
	TDEM	conductivity; inductance	4	2	2	2	3	2	3	1	3
	VLF	conductivity; inductance	2	0	0	0	1	1	1	2	3
	GPR	Dielectric permittivity; conductivity	0	2	3	1	2	3	2	2	2
Seismic	Refraction	Elastic modulus; density	4	4	3	2	3	4	4	1	2
	Surface wave profiling	Elastic modulus; density	0	3	4	3	4	3	3	2	2
	Reflection	Elastic modulus; density	4	2	2	2	1	2	1	2	2

0 – not suitable; 1 – limited use; 2 – can be used but there are limitations; 3 – excellent potential; 4 – techniques well developed and excellent approach

Table 3 The dependent properties for geophysical methods and their applications[11]

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[11] Reynolds, J. M., 2011. An Introduction to Applied and Environmental Geophysics (2nd Edition). Chichester: Wiley.

The hierarchy of consequences is: nothing will happen; there will be limited damage to the primary asset that is being triggered and no damage to the secondary assets; some damage to the primary asset and limited damage to the secondary asset; severe damage to the primary asset and some damage to a secondary asset; and severe damage to all assets. However, it is possible to have limited damage (e.g. cracked road) to the primary asset and severe damage to the secondary asset (e.g. erosion due to a leaking pipe), which could, potentially, result in severe damage to all assets.

Guidance: The DSS is not intended to provide definitive solutions to the problems caused by a trigger, but to give guidance because it is the asset operator that has ultimate responsibility for consequential action. It is important that the operator fully appreciates the consequences of any action they take. Therefore, the guidance will provide possible solutions - ranging from do nothing, repair, replace, adapt, renew to abandon the asset altogether - placing them in context within a sustainable, resilient, cost effective framework.

Conclusions

The DSS, a form of expert system, is aimed at asset operators to infer situations from observations, both anthropogenic and digital, to assess likely consequences, and give guidance on appropriate actions. It has been developed by experts in computer science and various branches of engineering after consultation with representatives from industry, national and local government, and utility companies. The DSS addresses the interdependency of the critical infrastructure of the urban environment, which is the road network and underlying utilities. These assets are linked by the ground, and, therefore, are interdependent. The ground is treated as an asset, which not only supports them but can transmit actions from one asset to another. Therefore, the DSS is designed to highlight the effect an action on one asset has upon the other assets; and the consequences of any intervention to make good an asset has upon the other assets. By using diverse sources of publicly and privately owned information, direct and indirect observations, and expert opinions, the DSS is intended to produce informed guidance to reduce risk and, thus, limit disruption thereby maintaining service to the user, and providing a sustainable solution for critical infrastructure at a local level.

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