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Soil impacts on national infrastructure in the UK

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Executive Summary

This report presents the final draft of a literature review of the soil-related impacts on national infrastructure in the United Kingdom on behalf of the UK Infrastructure Transitions Research Consortium (ITRC) project.

Much of the UK's national infrastructure is in direct contact with the soil. Soil is a diverse and dynamic bio-physical system with fluctuating volume, moisture content, temperature, chemistry and permeability. Resultantly, the effect of soil upon both above-ground and below-ground infrastructure can be considerable.

This study focuses on the effects soil exerts in terms of ground movement, corrosive attack on buried materials, mass movement and water and contaminant movement. This study excludes the roles soil plays in affecting and mitigating flooding, this being addressed elsewhere in the wider ITRC project. It considers the impacts of natural rather than engineered soil systems on infrastructure stability and resilience.

The most direct and pronounced effects of soil are exerted upon buried infrastructure such as pipes, where the ground movement and corrosion can lead to degrading effects. Soil related subsidence has the potential to chronically affect key built infrastructure having foundations in the soil column. Frost heave is identified as a contributory factor to pipe breaks in the winter, as well as consequent and related erosion leading to increased rates of sediment deposition on transport routes.

As well as the direct impacts of soil on infrastructure, soil also acts as a pathway for leachates, contaminants and pesticides, either aiding or inhibiting the route to groundwater sources. The pathways through the soil between failed septic tanks and groundwater sources are identified as important to human health particularly in rural areas.

Unlike flooding, which tends to be geographically constrained and can lead to potentially catastrophic consequences, direct soil related geo-hazards tend to be less dramatic and more geographically widespread. Road subsidence, 'potholes' and corroded or fractured leaking pipes represent some of the chronic impacts soil has upon infrastructure. Many thousands of soil-related infrastructure failures are anticipated and responded to each year nationally. Increasingly volatile climate patterns have the potential to exacerbate this situation. The soil in which pipes are buried has a key role to play in the extent to which collateral damage of neighbouring assets may also occur. A water main burst, by example, in a sandy soil can form an abrasive slurry which can quickly degrade nearby pipes or even undermine structures. Other soil issues, such as landslides have the potential to cause acute and significant disruption and cost. Because the soil underpins, surrounds and supports most UK infrastructure, this review examines the soil mechanisms at work and their interaction with the various types of infrastructure.

Glossary

CP – Cathodic Protection
CBR – California Bearing Ratio
CST – Council for Science and Technology
FCT – Freeze-thaw Cycles
ICT – Information Communications Technologies
ITRC – UK Infrastructure Transitions Research Consortium project
LandIS – Land Information System
MORECS – Meteorological Office Rainfall and Evapotranspirational Calculating System
NI – National Infrastructure
NSRI – National Soil Resources Institute
PSMD – Potential Soil Moisture Deficit
PVC – Poly-Vinyl Chloride
SMD – Soil Moisture Deficit
TRRL – Transport and Road Research Laboratory

Keywords
Soils, Infrastructure, Geohazards, ITRC

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Report cover. A segment of ductile iron water mains pipe with corrosion due to soil conditions.

This document is submitted as part of Cranfield University's involvement in the UK Infrastructure Transitions Research Consortium (ITRC) project, Work Stream Two under contract to Oxford University.

1 Introduction

National infrastructure (NI) systems such as energy, transport, water, waste and information and communication technologies (ICT) in the UK and across global, advanced economies generally face serious and unprecedented challenges. These include ageing infrastructure, overstretched public finances, growing demand and the impact of climate change and other threats and hazards. Infrastructure and associated essential services will need to adapt to climate change to provide security and resilience to the increased risks of natural hazards (HM Treasury, 2010).

National Infrastructure enables the efficient treatment, supply and transport of interrelated services, and the treatment, and disposal, of resulting waste products. Modern society is highly dependent on NI for the provision of water, energy, information and physical goods. A high-quality national infrastructure is essential for supporting economic growth and productivity, enabling competitiveness, attracting globally-mobile businesses to the UK, and for promoting social wellbeing (CST, 2009). In the UK, HM Treasury have estimated UK infrastructure investment could amount to some £200 billion in the five years following 2010. Such levels of investment are required to renew and maintain existing infrastructure as well as to meet the new challenge of setting the economy on a low-carbon trajectory (HM Treasury, 2010).

The Council for Science and Technology identified significant UK NI vulnerabilities and capacity limitations, as well as a number of NI components nearing the end of their useful life. Also highlighted was a serious fragmentation in the arrangements for infrastructure provision in the UK. Transforming NI efficiently necessitates a minimisation of the associated risks, underpinned by a long-term, cross-sectoral approach to understanding NI performance under a range of possible futures (CST, 2009).

Building resilience measures within infrastructure is important to reduce vulnerability to natural hazards. This can be achieved by improving (where necessary) protection, encouraging an ability in organisations and their infrastructure networks and systems to absorb shocks and recover, and enabling an effective local and national response to emergencies (Cabinet Office, 2011). Particular points of weakness, and especially vulnerabilities, are recognised in NI at the interconnections between systems. Such points contribute to reduced system resilience. Furthermore, there can be a lack of understanding of how widely vulnerabilities manifest (e.g. 'failure footprints') where one sector of the NI is dependent upon another and the consequent effects of failure 'cascade' through the system (CST, 2009).

In its National Security Strategy and Strategic Defence and Security Review (HM Government, 2010), the Government set out the need to improve the security and resilience of the infrastructure most critical to keeping the country running. Risks to the UK's national security interests posed by natural hazards were identified alongside other threats such as international terrorism, cyber-attacks and major accidents.

A large proportion of national infrastructure is buried in, or rests upon the dynamic soil system, which impacts on the stability and longevity of this infrastructure. The impact that soil-related hazards exert on national infrastructure can be significant. The primary effects of soil on national infrastructure are those of stability, ground movement and subsidence, corrosivity, erosion and landslides and issues of drainage and wetness. A changing climate will affect the severity of these effects. Many soil-related hazards are caused by or exacerbated by extreme weather conditions. Central estimates of climatic change predictions for the UK, by the 2080s, indicate increased summer and winter mean temperatures, with wetter winters and drier summers (Murphy et al., 2009).

Parts of the UK Infrastructure Transitions Research Consortium (ITRC) are considering the effect of extreme climatic events on infrastructure failure due hazards such as flooding, extreme heat and wind. Within a risk framework, the outcome of acute flooding hazards can be assessed from the likelihood and consequence of the hazard using probabilistic modelling (Sene et al., 2009; Lamb et al., 2010). This takes into account uncertainty in the hazard prediction and the effect on a range of probable inundation outcomes. Due to the chronic nature of many soil-related hazards the frequency and response is difficult to quantify and sparse data leads to greater uncertainties in threshold responses. However, the vulnerability of NI to soil-related hazards can be achieved through identifying the spatial distribution of key mechanisms, such as the occurrence of swelling clays and climate conditions (Jones et al., 1995; Leigh et al., 2010; Harrison et al., 2012).

This paper identifies the key mechanisms by which soil and soil conditions specifically impact on UK national infrastructure, considering the sectors of energy, transport, water, waste and ICT. It considers the major responses of soil geohazard mechanisms; ground movement, corrosion, mass movement and soil water and contaminant movement and the resulting consequences for infrastructure. It will also identify where particular hazards can be assessed within a risk framework and make recommendations for gap analysis.

2 Ground movement

Soil-related ground movement is recognised as a potential hazard to national infrastructure (Cabinet Office, 2011). The mechanisms of soil-related ground movement include clay shrinkage and swelling, sand-washout, frost heave, compression of soft soils, peat shrinkage, and solifluction, slope instability and landslip. Stages recognised in reinstated and made soils include immediate settlement, consolidation and creep (Robson, 1991). Each of the contributing mechanisms outlined below relates to specific static, as well as dynamic, soil properties. There are a range of process mechanisms that cause differential ground movement, resulting in similar chronic outcomes to infrastructure. Commonly, these have limited consequence but can occasionally cause catastrophic effects. Deeper ground threats also exist related to cave-ins and ‘void migration’ of historic mines (Robson, 1991) and collapse of solution pits (dolines). Ground movements due to mass failure tend to result in more catastrophic impacts on the soil functions required to support infrastructure.

2.1 Clay related shrink-swell

The volumetric change caused by shrinkage and swelling of silicate clays is related to their mineralogy as well as the seasonal changes in soil moisture content. Clays are comprised of arrangements of silicate (tetrahedral) and aluminium, magnesium and iron (octahedral) sheets contained in crystal units or layers, each being only some 0.1 to 1.0μm in size (Brink et al., 1982). There are two main clay groups: 1:1 layer-lattice silicate clays, having one tetrahedral and one octahedral sheet, and 2:1 layer-lattice silicate clays, having one tetrahedral layer sandwiched between two octahedral sheets (Brady and Weil, 2002).
The 1:1 silicate clays include kaolinite, halloysite, nacrite and dickite but these clays are not prone to shrink and swell to any great extent as local moisture content changes. Some 2:1 silicate clays such as illite (mica) and chlorite do not expand and contract, changing little in volume when wetting and drying. However, other 2:1 silicate clays, including smectites and vermiculites, are capable of significant expansion and contraction when wetting and drying. Smectitic clays, by example, have an extremely large internal surface area of 550-650m^2/g

(Brink et al., 1982), onto which water can bond, causing expansion when water molecules enter the inter-layer spaces. Conversely, as the smectitic clay minerals dry out, water is lost from the layer-lattice structure and consequent shrinkage occurs. The National House Building Council (NHBC) identify (NHBC, 1985) how clay soils affected by seasonal desiccation can cause movement to a depth of 1.0m in soils having a large potential to shrink and swell.

Soils that have high content of swelling clays therefore have the capacity to shrink and swell in response to changes in the soil water content (Reeve and Hall, 1978). Engineering tests such as the 'Co-efficient for Linear Expansion' (COLE) are used to determine relative changes in the volume and linear dimensions of clods in expansive soils subjected to changes in moisture (Hazelton and Murphy, 2007). The water content in the soils of NW Europe follows a general seasonal trend from excess rainfall in winter and excess evapotranspiration (the sum of evaporation and transpiration from the land to the atmosphere) in summer. The balance of rainfall, and evapotranspiration has been the subject of intensive research by Penman (1948; 1962), Monteith (1965) and Smith (1967) for planning irrigation scheduling in the UK. The principles and processes evaluated (Smith, 1976) also explain the structural changes that take place in soils under changing moisture content.

Soils lose moisture during the spring and summer months as evapotranspiration progressively exceeds rainfall, reducing the amount of water held in the soil. This state is called a soil moisture deficit (SMD), during which time plant roots must extract water directly from the surface and subsoil layers (horizons) to sustain growth. In lowland England for example, a moisture deficit usually develops in April or May, reaching a maximum in July, August or September and thereafter declines during autumn but in some dry eastern districts can persist into January (Jones and Thomasson, 1985). Under such conditions, soil progressively dries out to a depth of 1m or deeper allowing cracks to form in the soil (Figure 6) that are wider and deeper in soils with swelling clays than in soils with non-swelling clays. In coarse textured soils, cracks do not form on drying but small reductions in volume can occur because coarse pores (>60μm diameter) lose their water and become filled with air and are thus more compressible under load. In clayey soils experiencing a large soil moisture deficit, the cracks can be both wide at the surface and extend down to depths greater than 1m.

Under extremely dry conditions, wedge-like structures develop between the cracks (Brady and Weil, 2002), into which some surface soil can eventually fall. During the following wet season, rainwater will enter the cracks, by-passing the upper horizons and wet the soil near the bottom of the cracks first. Subsequently the whole soil profile wets up allowing clays to expand and the cracks to close. As the smectitic clays expand, this entraps the displaced surface soil within the vertical cracks. The increased soil volume causes first lateral, then upward soil movement after the cracks have closed. If the heave continues the soil mass can shear due to the strain creating 'slickensides' (Figure 3). Differential swelling and shrinking can also lead to lateral movement of structures (Figure 1). Robson (1991) further identifies how clay bricks used in construction of buildings can themselves be subject to moisture expansion of 0.02 to 0.06%.

Vegetation can significantly affect soil moisture conditions, as it can extract large amounts of water from the soil. Most SMD modelling is based the meteorological balance of rainfall and evapotranspiration related to a 'short grass sward' (Penman, 1962; Smith, 1967). The more recent operational datasets such as MORECS (Thompson et al., 1981; Gardner, 1983) adopt the same approach with corrections applied for various agricultural crops to provide cropadjusted soil moisture deficits (Jones and Thomasson, 1985). However, larger plants, such as trees and shrubs, are capable of transpiring more water than short green grass because of deeper rooting and larger leaf area indices. This in turn can exhibit considerable drying effects on the soil (White, 1975). Biddle (1998a; 1998b; 1998c) identifies the impact of a range of tree species and other large shrubs and vegetation across a range of soil types on underground structures, noting how in cases of subsidence due to shrinkable clay soils, at least 80% of cases can be linked to trees.

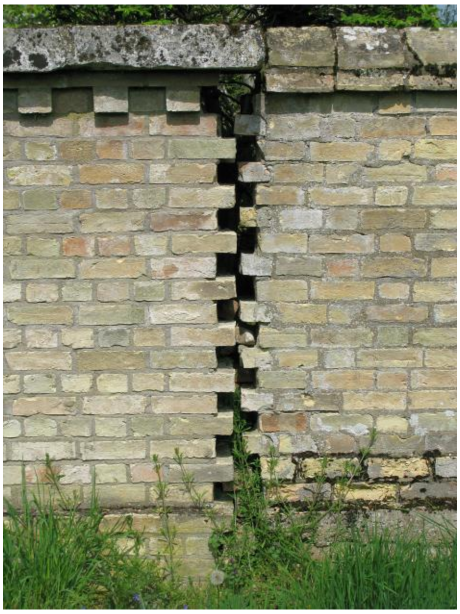

Figure 1 - The effects of severe clay-related movement on brickwork.(Wimpole, Cambs. *S. Hallett*)

Figure 2 - Exposed vertic (swelling clay) soils exhibiting surface cracking. (*S. Hallett*)

Figure 3 - Slickensides, or clay shear plates. (*S. Hallett*)

Figure 4 - Characteristic mottling in seasonally-waterlogged gley soils. (Northamptonshire. *S. Hallett*)

Figure 5 - House underpinning necessitated by soil-related subsidence. (*S. Hallett*)

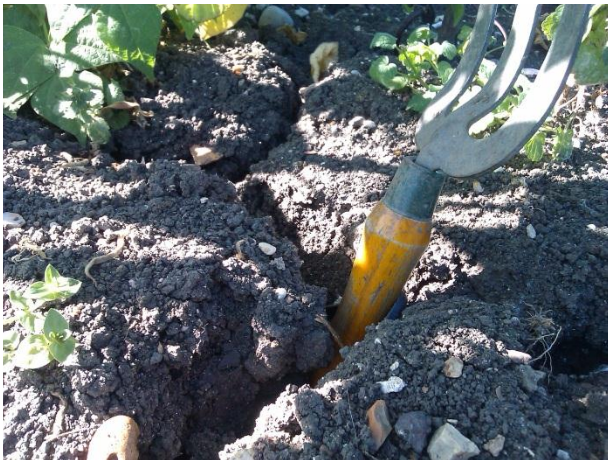

Figure 6 - Soil cracking in shrinkable soil in Cheddington, UK. (*I. Truckell*)

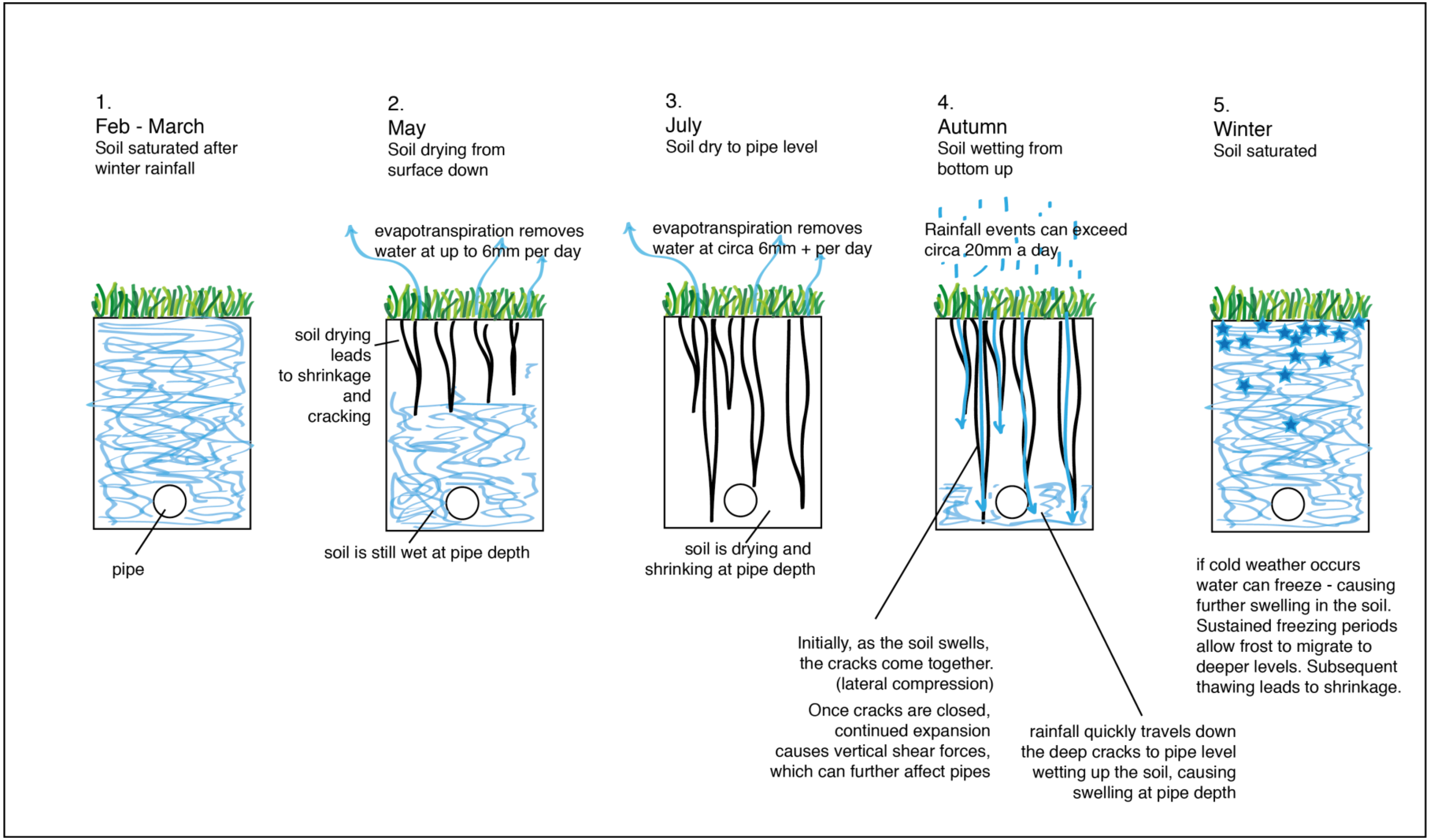

Figure 7 - The seasonal processes effecting soil movement and pipe failure.

2.2 Frost Heave

Moisture fluxes in soil, combined with freezing conditions can cause soil heave in fine grained soils such as silts, loams and clays (Bronfenbrener and Bronfenbrener, 2010). On freezing, ice expands by some 9% of the volume of water, yet Taber (1929) showed how it is the growth of successively layered ice lenses within soil pores that causes volumetric change, rather than solely an immediate expansion of a water-filled pore alone. Where water permeates through loosely-consolidated soil and freezes, then such 'ice lens' expansion can lead to significant consequent damage to buried assets (Friedl et al., 2012). A secondary effect of cold temperatures is an increased brittleness of cast iron pipes as the soil body moves around them.

Bronfenbrener and Bronfenbrener (2010) state that under freezing conditions, in fine grained soils, cryostatic suction causes an increase in upward water permeation, allowing ice lens growth and secondary frost heave. They describe three general conditions required for frost heave to occur; (1) frost susceptible soils (those soils being fine grained enough to allow capillary flows to feed the growing ice lenses) (2) the availability of ground waters, and (3) thermal conditions that will cause freezing front propagation to take effect slowly enough to allow concurrent water transport. If the soil freezes too quickly – the water will freeze in situ and no frost lenses are formed, even in frost susceptible soils.

Selvadurai and Konuk (1999a) state that, in cold regions, the heave effects of frost action in soils is an important consideration on many civil engineering components, including buried pipelines, foundations, highway pavements and retaining walls. They describe accurate three-dimensional modelling of frost action on buried pipelines as being complex and computationally intensive, as it needs to involve a variety of themo-mechanical models, including: (1) the coupled process of heat conduction and soil-moisture transport within the frozen and unfrozen soils; (2) the mechanical behaviour of the frozen and unfrozen soils; (3) moving boundary problems associated with the development of a freezing front, and; (4) the nucleation and growth of anisotropic ice lenses.

2.2.1 Soil heat flux

Soil is generally a poor conductor of heat and thus soil temperatures at depth tend to respond slowly to changes in surface air temperature (Hall, 1945). Soil heat flux or thermal diffusivity is a function of the soil thermal conductivity (k) and specific heat capacity(c) (Baver, 1956), thus:

$$\alpha = k/c$$

Where:
k is the thermal conductivity - rate of change of the temperature gradient and the change in temperature over a given period of time
c is the specific heat capacity - the heat required to raise a unit volume of soil by 1°C

The important factors affecting the thermal conductivity are soil composition, moisture and porosity. In a seminal experiment, Von Schwarz (1879) showed the thermal conductivity of different soils followed the order of sand (quartz) > loam > clay > peat, with water content increasing conductivity. Later investigations (Smith and Byers, 1938) confirm these findings, but also highlight the significance of soil porosity on soil thermal conductivity (being the degree of packing, or bulk density, of the soil particles). The rate of increase in thermal conductivity and density is approximately the same at any moisture content for a given soil.

The magnitude of temperature variations decreases with depth with temperature effects on soil being more pronounced in the topsoil region. Smith (1932) showed that at about 3.5m depth, annual soil temperature variation remained fairly constant. Above this depth, seasonally-driven absorbtion, conduction, diffusion and convection lead to increased subsoil temperatures, whilst conversely diffusion, conduction, vaporization and radiation lead to decreased subsoil temperatures. The rates of temperature flux are governed by the characteristics of the solid, liquid and gaseous phases of the soil mass. In Smith's experiments, heat was shown to continue to move upwards even after November from depth through the soil column; after March the direction of heat transfer was reversed downwards. Surface conditions can affect this flux; snow layers act as an efficient insulator of soil against rapid and extensive temperature changes, unless air temperatures sink very low for prolonged periods (Baver, 1956).

In a large scale experiment (Selvadurai et al., 1999b) showed sandy soils to be more temperature conductive than silt, with frost penetrating to 1.8 m after 367 days in the sandy soil and to 1.3 m in the silty soil. However, the heave associated with the silty soil (20 cm) was much greater than that for the sandy soil (3 cm) after a year of freezing conditions. In the UK, where cold temperatures do not usually last for more than a month on average, frost-induced soil heave will more greatly affect infrastructure that interacts with the near surface - where the frost front develops, than at installations founded at a greater depth.

2.3 Sand Washout

In sandy soils there is a significant danger posed by excess water moving through the subsoil, resulting in 'running sand' conditions (Brink et al., 1982; Walsby, 2007) where a cavity can develop under a structure, for example a leaking pipe, resulting in collapse of the pipe structure due to 'bridging'.

2.4 Soil Bearing Strength, Compressibility and Shrinkability

The bearing strength of the soil, the capacity to support an applied load without distortion or compaction, is a key parameter in consideration of the interaction with infrastructure. In this context, compaction can be defined as the 'The densification and distortion of soil by which total and air-filled porosity are reduced, causing a deterioration or loss of one or more soil functions' (Huber et al., 2008 p. 107 -123). If the soil is not strong enough to support an applied load, which might be the weight of a fixed asset (e.g. a building, road, or buried pipe), then the soil material beneath the asset will be compressed leading to subsequent settlement, deformation or ultimate failure of the asset. At any given time, the soil's bearing strength depends on its moisture content as well as its texture and structure. When the moisture content is high, pressure from the applied load will easily shear the soil and distort its structure.

Jones(1975) measured the bearing strengths of a range of mineral soils using a cone penetrometer and the results show how much soil bearing strength reduces with increasing moisture content. The impact of load on the mechanical stability and on the physical properties of soils has been further researched in depth by (Horn and Fleige, 2003); Horn et al. (2005) define a classification of pre-compression stress, as a measure of compactability, the higher the pre-compression stress then the lower the vulnerability of the soil to compaction.

Table 1 Classification of pre-compression stress † (After Horn et al., 2005)

Class	Pressure
Very low	< 30 kPa
Low	30 – 60 kPa
Medium	60 – 90 kPa
High	90–120 kPa
Very high	120–150 kPa

† at suction of 6KPa

Van den Akker (2004) has reported on a soil compaction model to calculate soil stresses and subsoil carrying capacity and Hall et al. (1977) describe in detail the measurement of water retention properties and bulk density of soils. Earl (1997) demonstrated that soil moisture deficit (SMD) offers a useful parameter for strength prediction, except in swelling clay soils, which is of particular importance to the agricultural sector as trafficking the soil when it is too wet can lead to severe soil compaction and increased runoff of water and sediment (Rounsevell and Jones, 1993).

However, the extrapolation of soil strength measurements, and likely pre-compression stresses, into the wider landscape is difficult because of the spatial variability of soils, and their variable moisture contents over relatively short distances (often < 500m). Nevertheless, Jones et al. (2003) provide a preliminary analysis of the vulnerability of subsoils to compaction based on the interaction of soil texture and density, from soil survey, with SMD.

However, the bearing strength of peat soils is generally insufficient to support most types of infrastructure, even when the peat is dry. This is mainly because the bulk density of peat is very low, ranging from 0.1 g ml^{-1} for fibrous peat to about 0.4 g ml^{-1} for amorphous peat (Hammond and Brennan, 2002 p.86-98) and thus the porosity is very large. As a result, peat soils are easily compressed when subjected to relatively small pressures – low pre-compression stresses (< 30 kPa) and, because their water holding capacity is very large (Hall et al., 1977), there is considerable shrinkage when peat material dries under suctions of 200 kPa. Similarly, alluvial and lacustrine deposits have low bearing strength (< 60 kPa) and are easily compressed, leading to subsidence under loading.

2.5 Ground movement impacts on infrastructure

2.5.1 Impacts on built structures

The effect of shrinking and swelling of clay soils on structures with shallow foundations can lead to considerable subsidence issues (Jones et al., 1995; Hallett et al., 1994; Reeve and Hall, 1978) (Figure 5), and remediation costs (Corti et al., 2011). These effects apply broadly to all types of national infrastructure having shallow foundations of between 1.5 to 2m depth within the soil layer. Therefore, infrastructural buildings such as pumping stations, sewage treatment works, recycling facilities, substations, telephone exchanges etc. are all susceptible to soil related subsidence. The presence of expansive and shrinking clay soils requires special construction techniques (Godfrey, 1978) due to the impact this can exert on built and buried structures (Jahangir et al., 2012; Li, 2008; Kitchen, 1994).

Leaking drains and gutters, in conjunction with sandy, or loose textured soils can also contribute towards subsidence damage. Approximately one in five subsidence claims are a direct result of drains leaking into sandy soil material causing subsurface soil erosion beneath a building's foundations (Direct Line, 2012).

2.5.2 Impacts on utilities

The wetting up of shrinkable clay soils can lead to considerable, and rapid volumetric expansion which can fracture pipes carrying water, waste water, oil, natural gas, or other substances, such as CO_2 for carbon capture and storage (Koornneef et al., 2009). Cast iron pipes are particularly susceptible to failure. Makar (2000) describes the process of cast iron pipe failure as a combination of factors – external loading (affected by soil movement), internal pressure, manufacturing flaws, and corrosion. The result will be failure in typically, one of four ways:

1. Bell splitting – a longitudinal split beginning at the bell;
2. Through-hole corrosion pit;
3. Circumferential cracking – where a pipe splits in a circle across its axis;
4. Longitudinal cracking – split along axis (often starting with a thinning of the wall by corrosion.)

The effect of (often seasonal) differential ground movement on buried pipes can range from inconvenient (e.g. water / sewerage pipes bursting in a heavy clay soil, which is relatively impermeable) to catastrophic (gas pipes bursting in a sandy, permeable soil). Studies have shown between 23% and 33% of sewer-to-manhole connections can be faulty (Davies et al., 2001). Differential settlement around sewer connections to manholes may account for some these faults. Davies et al. (2001) also note that clay rich soils have been shown to be associated with higher defect rates in rigid sewers than in chalk and sandy soils, and that sewer pipe segment lengths having higher length-to-diameter ratios were also shown to be more susceptible to fracture. As pipe length increases, so too does the likelihood that the pipe will span a significant change in soil texture, which can lead to differential movement. Ground movement leading to buried asset failure can also be anthropogenic, with point loading, for example bus stops and junctions, on soils with lower bearing capacities, leading to a higher rate of fractures. Likewise, sewers can sink into soil below trench as a result of the weight of the backfill (Davies et al., 2001) and uneven settlement can lead to joint fractures.

When water mains fracture, it is not uncommon for other proximal services, such as gas or sewers to fail (Davies et al., 2001), as the action of a pressured mix of water and coarse sand or rock fragments can be very abrasive. Majid et al. (2010) describe a case where failure of a water pipe in a sandy subsoil formed a highly abrasive soil-water slurry in close proximity to two 6 month old gas pipes. The erosion removed the protective coatings of the gas pipes, leading to rapid thinning and failure of the gas pipe by the rapid corrosion with simultaneous removal of the oxidised material. Also, pressured water can effectively cause cavities to form in the soil. If these cavities form under pipes, "bridging" can occur. Such poorly supported pipes are more susceptible to failure under loading conditions. A secondary effect of shrinkable clay soils is the increased risk of groundwater contamination by effluent (by fast, preferential flow), with materials passing to shallow aquifers when clay soils dry, shrink and crack (Oostindie and Bronswijk, 1995). Also, as pipelines transmitting natural gas are often routed through built up areas there are significant secondary risks to human life, should these pipes fail (Jo and Ahn, 2005).

Many buried high voltage (> 33 kV) electrical cables are carried in pressurised oil filled tubes, as this is an efficient form of power transfer. Due to the high pressures in some of these tubes (> 14 bar) a fracture of such cables can lead to thousands of litres of oil leaking from these cables in a few hours (Goodwin and Test, 2011). This oil may also impact on the stability of other buried infrastructure. In addition, ambient soil temperature can affect the current carrying capacity of underground power cables (Gouda et al., 2011; De Lieto Vollaro et al., 2011).

Like many buried pipes, sewers are affected by ground movement and surface pressure. Sewers have been shown to exhibit a steadily decreasing defect rate to a depth of 5.5 m below which the defect rate began increasing with depth (Davies et al., 2001). Shallower sewers are more likely to be affected by changing moisture conditions – and related soil volume, and more susceptible to the effects of traffic. This movement can affect not only inflexible pipe materials such as cast and ductile iron (Clayton et al., 2010) but the soil movement also affects more contemporary materials such as polyethylene or PVC pipes (Gallage et al., 2012).

Studies report frost-related damage to sanitary engineering plants and water-pipe networks (Bittner and Heine, 1998; Hotloś, 2009; Royal et al., 2011). Instatement procedures and condition assessment are suggested as being crucial measures in protecting infrastructure in areas exposed to sustained cold temperatures.

Experimental research has identified causes of pipe leakage to be the net result of a range of factors, including leakage flow, water pressure, freeze/thaw events, and pressure surges as well as poor installation and maintenance (Noack and Ulanicki, 2007) and such impacts present a real threat to infrastructure serviceability. Further to this, there is also a direct effect of soil temperature, moisture and texture on the effectiveness of ground source heat pumps and earth to air heat exchange systems.

2.5.3 Impacts on transport infrastructure

Soil can have a direct impact on the stability and longevity of roads. In general, we would expect the effect of soil to be more pronounced on minor roads (and especially on unsurfaced farm tracks, foot paths and cycle routes with thin surface construction) than on motorways and A-roads, as the engineering which is involved in the major roads is more robust (TRRL, 1984). The Transport and Road Research Laboratory (TRRL) identify geotechnical measures needed to ensure stability of transport infrastructure against adverse ground conditions (TRRL, 1973). Work is on-going to minimise the effect of ground movement of loose, fine textured soils on minor roads by the use of geofibres and synthetic fluids (Hazirbaba and Gullu, 2010).

Similarly, one would not expect significant impact of soils to be observed on railway lines or tramways, both of which are highly engineered and have a wide spread of load. For these reasons, railways are capable of traversing even problematic fenland with relatively minor consequences. However, if good building practices are not followed, heavy trains can cause motion that is destructive to the track, and its embankment-subsoil system (With and Bodare, 2009). Soils with a high bearing strength (typically assessed by the California Bearing Ratio or CBR) will be more suitable to support roads than more compressible soils, which may require soil modification or improvement to support the road surface (Hazirbaba and Gullu, 2010). The CBR value of natural soil can often be improved by compaction (Jarvis et al., 1979). Current road design allows for some movement in the supporting soil, as roads are designed with some flexibility. When subsidence or ground movement does occur, the current practice is to fill in the holes.

In his seminal work on frost heaving Taber (1929) states that uniform frost heaving "can cause limited damage to pavements or structures, but unequal heaving may be very destructive. Local differences in soil texture, and in the amount of available water are the major causes of differential heaving. Differences in the amount of soil cover are important, and difference in load is a minor factor." Subsidence under a road can lead to cracking of the impermeable road surface. With water ingress, pothole formation can occur at an increased rate.

The stability of 'natural' and engineered road embankment is affected soil movement and shrinkage (Anderson et al., 1982; Bertrand and Papanicolaou, 2009; Baylot et al., 2012). Soils which suffer from volumetric change or frost heave may be less stable and suffer soil creep or contribute to deposition of sediment on the road surface. Farms tracks, which have minimal engineering, and are often constructed on soil which is excellent for crops, but not particularly well suited to repeated trafficking, are especially susceptible to soil movement, compaction and erosion. In the context of dirt roads or farm tracks, wheel rutting is more likely to occur in compressible soils. Long-term effects of traffic on dirt roads can be seen in the sunken lanes of southern England as described by Barton (1987). Use of modern geotextiles placed 50 mm below the surface of the road can significantly help spread the load of farm traffic and enhance the stability of the track.

The design of embankments for road or rail should consider the texture, and horizon structure of the soil. If improperly designed, clay soil embankments can fail in a circular manner known as slip circles (Konkol, 2010). These can be triggered by construction of heavy infrastructure, or heavy machinery at the top of the embankment.

2.5.4 Impacts on solid waste infrastructure

The siting of waste disposal sites need to be designed to cope with movement (Chen et al., 2008). Thus soil and underlying geology plays a key role in the placement of waste sites. Impermeable clay soils are ideal as they can seal in leachates which may leak through the site liner. Waste sites are rarely placed by preference on sandy soils as these would allow rapid transmission of leachate and spillage to underground water resources.

2.5.5 Impacts on ICT infrastructure

Soil creep and solifluction have the potential to move structures such as telephone poles and disrupt communications. The impact of soil movement on ICT infrastructure is less dramatic than on water or gas pipes as the impacts are less severe. Signal degradation may occur if fibre optic cables are deformed beyond certain thresholds. However this effect does also potentially permit the development of novel techniques for assessing soil related strain on infrastructure through the use of fibre-optic sensors placed proximal to underground objects, whose consequent strain movements can then be charted (Wan and Leung, 2007).

3 Soil Corrosivity

Soil conditions can be strongly corrosive to buried assets, particularly those constructed from ferrous iron due the electrochemical conditions at the soil-metal interface. There are number of factors causing corrosivity in soils and often the local situation is a complex interaction of pipe-specific properties and the surrounding soil environment. In general, the contributing factors to soil corrosivity are the concentration of soluble salts such as sulphate (SO_4^{2-}) or chloride (Cl^-), pH, soil resistivity, water content, temperature and soil redox (E_h) potential (Cole and Marney, 2012; Kleiner et al., 2012; Md. Noor et al., 2012; Jiang et al., 2011; Jarvis et al., 1997). Corrosion of iron in the absence of air is strongly influenced by sulphate reducing bacteria (SRB) (Venzlaff et al., ; Angell and Urbanic, 2000). Interpreted soil maps, classified according to the soils likely corrosivity, can be used to help predict the risk of corrosion to buried ferrous iron assets (Jarvis et al., 1997; Jarvis and Hedges, 1994).

Soil environments containing high concentrations of sulphides (principally iron sulphides) result from soil formation in sulphate-rich marine or estuarine deposits under waterlogged, anaerobic conditions. If these soils are drained and oxygen is introduced to the system the iron sulphides oxidise to sulphuric acid. This results in extremely acidic soils being classified as acid sulphate soils (Dent and Pons, 1995). Acid sulphate soils are not widespread in the UK, but can potentially be very corrosive in areas that have been formerly drained.

Corrosion can also occur in the absence of oxygen, under anaerobic waterlogged conditions. These conditions are only found in soils where there is persistent waterlogging at depth due to a high groundwater tables. Anaerobic corrosion is commonly facilitated by SRB, which produce hydrogen sulphide (H_2S) as a result of sulphate reduction in the absence of oxygen. At low pH H_2S can be corrosive to ferrous metals.

Chloride in soils is primarily in the form of salts. The provenances of the salts are 1) inherited from saline deposits in which the soils are formed 2) produced in situ through intense evaporation under arid climates or 3) from atmospheric deposition of Cl^- from seaspray. Thus, in the UK soils with high salinity potentially only occur close to the coast. Locally significant chloride concentrations can occur in soils subject to wash-off from surfaces that have been treated by de-icing agents.

Indicators of the corrosivity of soils are measurements of soil resistivity (the reciprocal of conductivity) and soil redox potential. Redox potential is an indicator of aerobic (positive E_h) or anaerobic soil conditions (negative E_h), which can characterise the soil environment with respect to the stability of ferrous compounds. Soil resistivity is a function of soil moisture content, temperature and the concentration of soluble salts. Low soil resistivity values typically indicate a corrosive environment Table 2).

Table 2 Soil resistivity values and corrosivity effects (ASTM, 2012)

Soil resistivity (Ω cm)	Corrosion classification
Up to 1000	Very severely corrosive
1001-2000	severely corrosive
2001-5000	Moderately corrosive
5001-10,000	Mildly corrosive
> 10,000	Very mildly corrosive

The electrochemical properties of the soil, which are the soil resistivity of the soil volume, the relative permeability of the soil layer adjacent to buried ferrous objects and the chemical properties which could be considered as the pH of the soil film layer around the object (e.g. buried pipe) as affected strongly by changes in soil moisture content, corrosion rates changing with variations in soil humidity (Ahmed, 2011). Knowledge of localised soil conditions can therefore play an important role in determining routes for pipe laying, as well as the design of Cathodic Protection (CP) schemes for buried infrastructure.

3.1 Soil Corrosivity impacts on Infrastructure

3.1.1 Impacts on utilities

Both cast iron and ductile iron pipes can be particularly susceptible to soil-related corrosion (Gummow, 1984; Ismail and El-Shamy, 2009b), although certain practices such as cathodic protection can be useful in mitigating such conditions. Mild steel is also susceptible to corrosive attack (Ismail and El-Shamy, 2009a). This is important because as well as the cost of reinstatement and repair, water supplies can also become contaminated as a result of corrosion to metallic pipes – an additional cost to a water utility (Hussain et al., 2010). Predictions can be undertaken to identify the levels of spatial vulnerability to such corrosion based upon localized soils and climatic information (Corcoran et al., 1977; Smith, 1968). Pipe corrosion leads to characteristic pitting of the pipe and ultimately localized failure (Figure 9).

Figure 8 - Characteristic pitting in water mains pipe due to soil-water corrosion. (*S. Hallett*)

Buried natural gas pipelines are also subject to the types of corrosive attack outlined for water pipes. Corrosion pits are the most common cause of failure on ductile iron pipes (Makar, 2000). Soil-water regimes in the soil body adjacent to the pipe installation trench have been observed to lead to the proliferation of SRB – a principle cause of pipe destruction (Karpachevskii et al., 2011). Leakage from gas mains, where soil factors are involved, can also lead to fatal consequences (Ogle et al., 2011). Leakage of water pipes in sandy soils has also been reported as affecting adversely adjacent gas lines due to the formation of acidic sand/water slurries (Majid and Mohsin, 2012). Corrosion of the base of a tank at Esso Petroleum in Fawley, Hampshire in July 1999 led to the release of 400 m^3 of crude oil (UKHSE, 2000).

Large seasonal fluxes in soil water content represent causal factors in pipe damage and affect engineering parameters (Richards, 1968). Where a fluctuating water table is present the changing reducing-oxidising state of the soil can be particularly aggressive on buried metal assets (Corcoran et al., 1977; Kleiner et al., 2012). The more contrasting the soil water regime is in the surrounding soil mass, the greater the amount of pipe damage is likely to be caused from factors such as soil water corrosivity (Karpachevskii et al., 2011).

Such approaches can be extended to permit water companies and other utilities to choose the tools required to plan for mains replacement with less vulnerable materials (Jarvis and Hedges, 1994). Predictions of the causes of corrosion from analysis of corrosion pits (Figure 8) compared with surrounding soil conditions have been undertaken (Kleiner et al., 2012) and multi-sensor locational devices used to map pipe condition with surrounding environmental conditions (Royal et al., 2011).

Concrete can be susceptible to corrosive attack particularly when there are high levels of sulphates in the soil (Dehwah et al., 2002) and when the soils are wet (Jarvis et al., 1979). Because concrete is alkaline, alkaline soils are not aggressive to concrete. In clay soils that are aggressive to concrete, a larger amount of cement is used in the cement mix is typically used to mitigate the corrosive effects of the soil.

3.1.2 Impacts on other infrastructure

While corrosion is a key issue in transport infrastructure, this is rarely linked to the soil, and has had stronger association with salt application in icy conditions. However, corrosion can occur to pipes, petrol and LPG tanks at fuelling stations (Melchers and Feutrill, 2001) with potentially serious consequences. Typically telecommunication cables are wrapped in corrosion resistant materials, so unless these are breached, soil-related corrosion is not a significant issue.

Soil resistivity also impacts on grounding systems at sub-stations in the energy network (Busby et al., 2012). For effective earthing soil should offer low resistance, these conditions are often met by moist soils. However, as soils dry out this increases resistivity and decreases the earthing potential, potentially exposing persons to electrical shock or resulting in significant network disruption (Laver and Griffiths, 2001). Excessively drained soils (e.g. sands) with high hydraulic conductivity (see section 5.1) that develop significant seasonal moisture deficits are particularly susceptible. Thus any changes in soil water regime as a consequence of climate change will make these soils particularly vulnerable to resistivity fluctuations.

4 Erosion and Landslides

4.1 Erosion

Soil erosion is a natural process that has been largely responsible for shaping the physical landscape we see around us today through subsequent distribution of the weathered materials produced by geomorphic processes. Erosion has been defined as "The wearing away of the land surface by physical forces such as rainfall, flowing water, wind, ice, temperature change, gravity or other natural or anthropogenic agents that abrade, detach and remove soil or geological material from one point on the earth's surface to be deposited elsewhere” (Soil Science Society of America, 2001). When the term ‘soil erosion’ is used in the context of being a threat to landscape and infrastructure, it refers to ‘accelerated soil erosion’, i.e. ‘Soil erosion, as a result of anthropogenic activity, exceeds the rate of natural soil formation’ (Verheijen et al., 2009). Poorly managed soils may have a lower infiltration rate, resulting in increased susceptibility to overland sheet flow (Gatto, 1995) that causes significant erosion issues as well as local flooding.

Erosion has many forms and causes (Huber et al., 2008) all of which can ultimately impact on infrastructure. Water erosion causes the most damage in the UK, but wind erosion is a significant problem in some areas, such as Eastern England.
The following erosion mechanisms operate:

- Water: Flow of excess surface water via rills (Gobin et al., 2004; Kirkby et al., 2008), gullies (Imeson and Kwaad, 1980) following heavy rainfall and/or snowmelt; an associated mechanism is slumping of banks of rivers and lakes;
- Translocation: Disturbance of soil material as a result of land levelling (including subsidence following reinstatement) and trafficking during construction and maintenance work;
- Wind: Air movements that are strong enough to displace particles from bare soil (Fullen, 1985);
- Coastal: Wave action along coastlines;
- Landslides: see section 4.2;
- Dissolution by underground water flows of carbonate-rich soil and geological materials.

Water erosion involves detachment of material essentially by two processes, displacement by impact from above and flow traction. Transportation of eroded soil particles occurs mainly by overland water flow, and to a lesser extent by saltation through the air in the case of wind erosion. Erosion of river and lake banks, and coastal erosion, result from saturation with water such that soil and sediment become liquid. Sloughing is an effect where the high soil pore water pressure in the soils near locks on canals leads to significant erosion of banks. To minimise sloughing, and the associated sediment deposition, sheet piling is typically installed around locks. The economic consequences of soil loss and subsequent deposition by these processes are significant (Boardman et al., 2009; Auzet et al., 1993; Boardman et al., 1996; Woo et al., 1997; Evans, 2010; Kirkbride and Reeves, 1993; Poesen et al., 2003).

Deposition of eroded material in reservoirs is also a serious problem that has been studied in detail at a several reservoirs in northern Italy by Van Rompaey et al. (2005) and research showed that the Abbeystead Reservoir in Lancashire has been reduced to 6% of its original capacity over a period of 140 years (Rowan et al., 1995). Furthermore, the removal of suspended sediment at water treatment works is costly, time consuming and requires careful management (Plappally and Lienhard V, 2012; Wang and Hu, 2009).

Freezing and thawing events can have a marked effect on bank stability (Gatto, 1995). Gardiner (1983) notes that over a 14-month period, more than 90% of the total erosion on the River Lagan in Northern Ireland occurred during the winter due to the action of needle ice formation and soil heaving and the creation of a highly erodible soil surface. Needle ice can raise surface soil many cm above the ground (Gatto, 1995).

Alternate winter freezing and thawing cause a granulating, or disintegrating, action on soil clods. This process is usually more effective (pronounced) than drying and wetting processes and leads to 'aggregated' soil structures in spring (Baver, 1956). Certain soil conditions seem to be essential for realising the maximum effects of freezing. Thus, where soils dry during the winter there is little subsequent soil disintegration; where soils are wet and thawing is accompanied by rain, any aggregated materials can become dispersed. Vegetation acts as a slope stabiliser, and thermal insulator – mitigating the effects of unstable slopes and freeze-thaw erosional cycles (Gatto, 1995). It also acts as a windbreak, reducing the effectiveness of wind as an erosive agent. As discussed in section 2.3, subsurface erosion can take place in loose textured soils. This can lead to unsupportive bridging of pipes and subsidence of built structures. Without support, pipes are more likely to fracture.

4.2 Landslides

A landslide is the movement of a mass of rock, debris, artificial fill or earth down a slope, under the force of gravity (Cruden and Varnes, 1996). This 'en masse' movement (or slope failure) may be induced by physical processes such as excess rainfall, snow melt or seismic activity, or it may be a consequence of human interference with slope morphology (e.g. constructing over-steepened slopes), which affects slope stability. Landslides will occur when the inherent resistance of the slope is exceeded by the forces acting on the slope. This is expressed as the 'Factor of Safety' (F) of a slope, which is defined as the ratio of the available shear strength of the soil to that required to maintain the slope stability, i.e.:

$$F = \frac{\text{Resistance of the soil mass to shear along a potential slip plane}}{\text{Shear force acting on that plane}}$$

There are many different types of landslide (Jarvis et al., 1979), making classifications complex and sometimes contradictory. However, there is a general consensus that mass movements can be classified according to their mode of failure and the different types of failure are summarised by Cruden and Varnes (1996) as follows:

i) slides - rotational or translational mass displacements with limited internal deformation, and relatively uniform velocity profiles;
ii) flows – associated with relatively high moisture contents, and with non-uniform velocity profiles, reflecting frictional effects between the base of the flow and the in-situ ground;
iii) falls – slope displacement that are principally vertical in nature;
iv) topples – slope displacements with both lateral and vertical components;
v) lateral spreads – slope displacements that are primarily horizontal;
vi) ground or frost-heave – associated with expansion/contraction of individual constituents of the slope material, which destabilises the slope e.g. freeze/thaw exfoliation (Carson and Kirkby, 1972).

Robson (1991) identifies how granular soils are generally stable unless subjected to vibration, or acted upon by water (common vibration causes being traffic and pile driving). In these cases the soil can pack down and settle.

Figure 9 illustrates how the failure of slopes can be directly related to the type of soil/rock, its strength, the water conditions in the slope and its geometry. These modes of failure can be subdivided further, depending on whether the material is propagated mainly as individual particles, e.g. rockfall, rock avalanche, or as a reworked mass, e.g. mudslides, earthflows, and debris flows. Other classifications are based on the velocity of failure, e.g. very rapid, rapid, moderate, slow, very slow (Varnes, 1978). The latter approach is useful as it expresses indirectly the level of risk, as the velocity at which the displaced material moves at the onset of the event determines the amount of damage caused. This includes early warning systems and organisation of evacuation away from the failing slope.

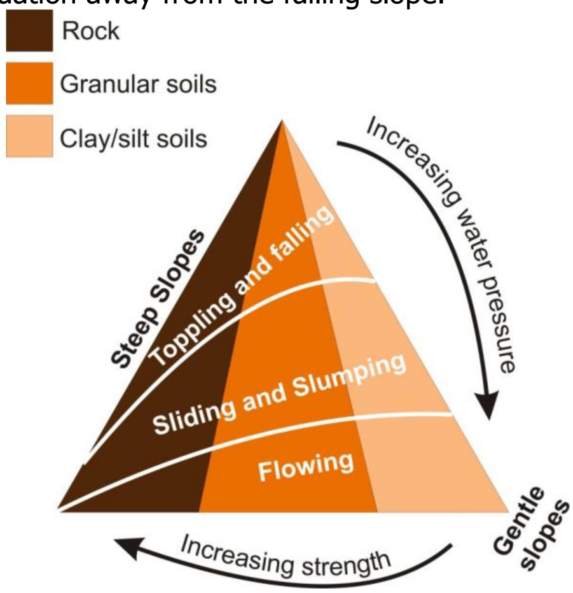

Figure 9 Failure of slopes (after Carson and Kirkby, 1972)

A simpler classification could be based on whether the landslides are a consequence of natural or anthropogenic factors. For instance, the South Wales coalfield has one of the highest rates of landslides in the UK (Bentley and Siddle, 1996) on a per area basis. In terms of environmental protection, it could be argued that natural factors can rarely (or should not) be controlled, whereas anthropogenic factors can be prevented altogether. In reality, individual landslide events usually result from a complex, unique combination of natural and human factors acting simultaneously.

In terms of protecting soil, consideration must be given to three critical areas in the landscape where the soil resource is under threat: (1) site of the slope failure where topsoil and or substrate have been removed; (2) failed mass itself (assuming it remains relatively intact), and; (3) temporary or permanent destination of the failed mass. As this is true for all types of mass movement (slides, flows, falls, topples, lateral spreads and ground/frost heave), further discussion will combine all types of slope failure under the generic term ‘landslides’.

Often the economic losses from landslides are difficult to determine as they usually occur as a consequence of other natural hazards such as seismic activity or flooding. It has been estimated that in terms of costs to society, landslides can cost up to €1.2 billion per event on an annual basis (Europa, 2006).

It is increasingly clear that landslide hazard assessment forms an important part of land use planning, especially in hilly, mountainous and coastal environments, which are most prone to landslide activity. In densely populated/industrialised areas, landslide hazards may be exacerbated by soil sealing (and compaction), thereby further increasing the socio-economic impacts of landslides.

Major mudslides and soil movements linked to seismic activity (Li et al., 2004; Hwang et al., 1998; Koseki et al., 1998; Huat et al., 2012) are not common in the UK. Mass soil creep, e.g. as a result of 'solifluction' does occur, and erosion (and subsequent sediment deposition) is common. Solifluction occurs over a period of time when a mass of soil moves under gravity downslope, with conditions often hastened by climatic conditions, freeze-thaw events and soil wetting (Matsuoka, 2001).

4.3 Erosion and Landslide impacts on infrastructure

4.3.1 Impacts on utilities

Landslides have the potential to effect large structures such as energy pylons. Should a pylon be damaged or destroyed, the effect of a break in the electrical distribution network would be considerable. The collateral damage of a water main bursting in erodible, abrasive sandy soils had been discussed in section 2.5.2. Similar processes can occur near the surface or near streams where extreme rainfall or flood events can wash away large volumes of erodible soil leaving pipes exposed. As pipelines are often designed as composite structures in conjunction with the ground this unsupported state can lead to pipe cracking and failure. Extensive erosion from arable fields or building sites can overwhelm water and sewage treatment works. Costs also increase as more sediment needs to be removed from water prior to supply (Plappally and Lienhard V, 2012).

4.3.2 Impacts on transport infrastructure

Landslides over tracks can disrupt services. A landslide on the 17th October 2012 prevented trains from travelling between Barrow and Carlisle, adding 60 minutes to passengers' journeys for two days (North West Evening Mail, 18 October 2012). Another landslide between Hebden Bridge and Blackburn was cleared within one day (Hebden Bridge Times, 23 October 2012). Slower moving landslides (with rates of movement less than 160 mm per annum) with only minor displacements as low as 100 mm may be sufficient to severely damage bridges, yet the same damage would be unlikely in urban communities (Mansour et al., 2011).

Barton (1987) describes the planning problems associated with sunken lanes or hollow ways of Southern England which arise from historic down cutting of wheeled traffic from a previously un-surfaced road (Figure 11). As sunken lanes represent an attractive and historic element of the landscape reengineering of such lanes to current standards may not be appropriate. As an indication of the erosive effects of tyres on roads, crossroads typically require deeper foundations (TRRL, 1984) so that wheel rutting is less problematic.

In addition to direct effects on infrastructure, frost induced soil heave and freeze-thaw cycles can make a soil considerably more erodible (Gatto, 1995), as the action of the frost separates the soil particles and loosens the soil surface. Upon thawing these loosened grains may be more easily removed by water. This can cause significant slippage and slumping on banks (Gatto, 1995) and lead to deposition of soil on roads, railways etc. When road cuttings are made, the cutting can expose more erodible material than might be found at the surface, which may result in an increase in the amount of material deposited on the road. Roadside gully pots are a common and integral part of many surface water drainage networks, which seek to retain heavier particular matter and associated pollutants to break the road to river pathway (Butler and Memon, 1999). Excessive erosion can overwhelm these pots (which are typically c.90L) reducing their effectiveness. Unmaintained pots full of sediment were the cause of at least three floods on the M1 Motorway between Junctions 11 and 12 in 2007 (Navid, 2011). Soil deposition on minor roads (Figure 10) is of less consequence than that on motorways and railway tracks, but can still disrupt traffic.

Figure 10 – Sign warning of soil deposition on a rural road in Suffolk (Photo: T. Farewell)

Figure 11 - Road at lower level to surrounding field due to hundreds of years of rural traffic in Suffolk (Photo: T. Farewell)

5 Water and contaminant movement

5.1 Soil Water regime

The importance of the soil water regime has been recognised since the classical beginnings of pedology. In Western Europe, the importance of climatic influences, a seasonal surplus of water and its effect on soils, is everywhere apparent (Robson and Thomasson, 1977). Therefore, soil water regime can be defined as the cyclical seasonal variation of wet, moist or dry soil states. The main property affecting the soil's natural water regime, and its response to artificial drainage measures, is its permeability (Ragg et al., 1984).

Permeability is a function of soil texture, structure and density. These properties control the pore size distribution throughout the soil, where pores embrace spaces between particles or aggregates irrespective of their shape, size or continuity. In a saturated soil, all sizes of pores are full of water, with the exception of entrapped air, but as the soil drains, the water-table falls, suction increases and larger pores release water (Thomasson, 1975). The drainable pore space, which represents the pore space that can be drained under the force of gravity, is the volume of macropores (> 60µm). Micropores (< 60µm) hold water with increasing suction as pore size reduces to 0.2µm and water held in these pores can only be extracted by external forces, other than gravity, exerted for example by plant roots. The pores smaller than 0.2µm remain water filled under suctions >1500kPa (Thomasson, 1975; Hodgson, 1997).

Permeability is measured as the hydraulic conductivity, which is the transmission of water according to Darcy's Law:

$$q = Kai$$

Where: q is the volume rate of flow
K is a constant of proportionality
a is the cross-sectional area
i is the hydraulic head difference

Soil moisture regime classes, now termed Wetness Classes, have been defined by Hodgson (1997 p 106-7) as the duration (in days) of wet states of soil. Dense clayey soils, and fine loamy or fine silty soils with a hydraulic conductivity of < 10cm d^{-1} are classified as slowly permeable, and are effectively impermeable. Sandy, well-structured loamy and clayey soils, and peaty soils are permeable with a hydraulic conductivity > 60cm d^{-1}. Such soils are either naturally well drained or respond well to artificial drainage measures (see Figure 12). The term moderately permeable is restricted to soils which have variable hydraulic conductivity and cannot be placed with confidence into either the slowly permeable or permeable categories (Thomasson, 1975). The Hydrology of Soil Type (HOST) classification (Boorman et al., 1995) relates to this coarse categorisation by introducing parent material.

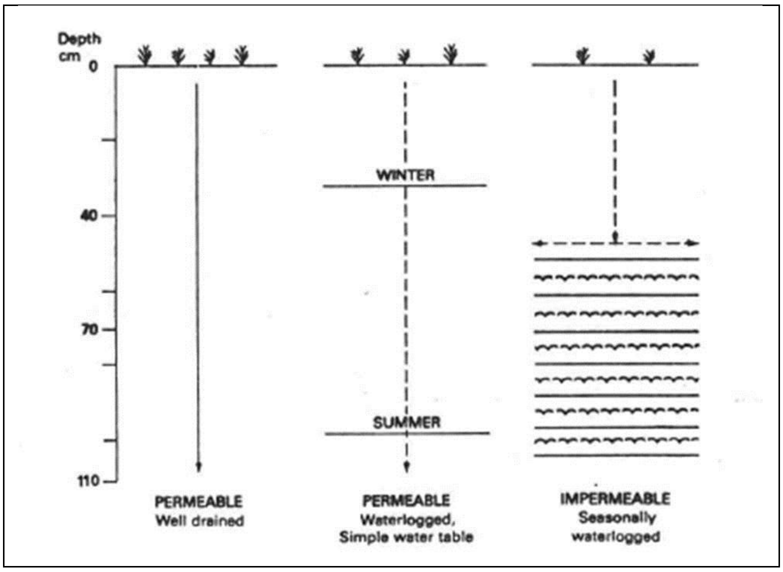

Figure 12 - Types of soil water regime. (After Jones, 1985)

A characteristic of soils that are subject to fluctuating water table levels is 'mottling' (Figure 4). This is where ferrous iron in the soil is oxidized to a characteristic brown or ochre colour, contrasting with the 'anaerobic' grey and olive coloured clay (Fitzpatrick, 1974). Waterlogging of such soils leads to the reduction, mobilization and removal and re-deposition of any iron compounds present. Such soils have grey layers and distinctive orange mottles where poorly and better aerated parts of a soil layer show the differential effects of gleying (Reeve, 1989). Additionally, changing pore pressure in these soils can produce upward thrust which can impact upon infrastructure.

5.2 Pesticide and contaminant movement – runoff and leaching

Soil can adsorb pesticides and contaminants, allowing degradation of these chemicals before they reach rivers, aquifers, or treatment works. Soils have varying capabilities to retain leaching contaminants. In a comparison between a beach sand soil (with a narrow particle size distribution) and an organic soil (with a range of particle sizes) Diaz et al (2010) found that E-coli bacteria were more effectively retained by the organic soil. They also found that breakthrough curves differed when E-coli was compared with P. *putida* and L. *innocua*, with more of the P. *putina* being retained in the soil. Hydraulic conductivity can be increased in clay soils which have undergone freeze-thaw cycles (Othman and Benson, 1993). Where soils overlie aquifers, particular attention needs to be paid to the ability of the soil to adsorb agrochemicals. Many of the UK water companies use a catchment management system (e.g. CatchIS) (Kannan et al., 2007; Brown and Hollis, 1996; Breach et al., 1994) to minimise treatment and monitoring costs at their works.

The pathways between soil and potable water sources is also a critical factor in sludge-to-land acceptance models as soil is identified amongst the main sludge outlets (Andrés et al., 2011). The waste products from sewage works, if properly treated, can have offer water companies a cost effective method of disposing of the waste. Issues remain regarding the leaching of contaminants particularly heavy metals, from sludge to land applications and the effects on human health as well as in-soil invertebrates and microbial communities (Pourcher et al., 2007; Burton et al., 2003; Andrews et al., 1997a; Andrews et al., 1997b; Barry et al., 1995). Composted green and food waste as well as paper mill (G. Piearce and Boone, 1998) waste can be applied to a wider range of soils, minimising the need for this waste to go to landfill, as well as acting as a soil conditioner.

5.3 Soil water regime impacts on infrastructure

5.3.1 Impacts on utilities

Noack and Ulanicki (2007) investigated the leakage characteristics of pipes buried in different soils. They found sandy soils exhibited a leakage of water all around the pipe, which is similar to leakage to air, whereas less permeable soils, such as heavy clays, lost significantly less water, with a low flow rate. Davies et al. (2001) note that infiltration of groundwater and sediment through fractured sewers can occur when the water table is at the same height, or higher than the sewer. This can lead to the formation of voids surrounding a sewer. As sewers should be supported on all sides to maintain their structural stability, failure is more likely to occur when voids form.

In areas where mains water and sewerage are not available, the location of septic tanks and boreholes is critical (Butler and Payne, 1995). In conjunction with ground movement fracturing pipes and septic tanks, a secondary effect of shrinkable clay soils is the increased risk of contamination (by fast, preferential flow) to shallow aquifers when clay soils dry, shrink and crack (Oostindie and Bronswijk, 1995).

It has been shown that as a result of migration of soil moisture, it is possible for drier zones to form around underground power cables under loading conditions (Gouda et al., 2011) and this can have an effect on the ampacity (current carrying capacity) of the cable (De Lieto Vollaro et al., 2011). Ground source heat pumps are increasingly being used in the UK as primary sources of heating (Boait et al., 2011). As ground source heat pumps rely on circulation of moisture through the soil, the moisture content and texture are possible controls on the effectiveness and longevity of these systems (Mattsson et al., 2008; Self et al., 2013).

Trenchless technology or directional drilling for asset installation is a growing area of research and practice (Chapman et al., 2007), the volume of sharp stones in the soil can be problematic for uPVC pipes, as this can lead to scoring down the length of a pipe, weakening it. Also the ease of installation as well as the effectiveness of earthing rods is controlled to a large extent of the soil (Colominas et al., 2001). In heavy clay soils installation is likely to be more problematic than in a softer soil. When a clay soil is dry, it transfers forces acted upon it through the soil and onto any structures that may underlie it. This can be problematic when digging trenches to replace or repair one utility, as the use of heavy pneumatic drills may fracture proximal pipes or fibre optic cables.

6 Conclusions

A large proportion of the UK's utility, transport, energy and built infrastructure is in direct contact with the soil. Soil is a diverse and dynamic system, with fluctuating volume, moisture content, temperature and permeability. The soil's effect upon infrastructure is often seasonal, with many of the physical and chemical processes being linked to patterns of moisture levels - wetting and drying, and freezing and thawing. Failures of particular assets can be considerably problematic. The most direct effects of the soil are upon buried infrastructure such as pipes, where ground movement and corrosion can degrade the buried assets. Frost heave is a contributory factor to pipe breaks in the winter, as well as being a contributory cause of increased rates of sediment deposition on transport routes. As well as the direct impacts of soil on infrastructure, soil also acts as a pathway for contaminants and pesticides to surface or groundwater sources, thus for example in rural areas, failed septic tanks linked by permeable soils to groundwater sources are identified as a potential risk to human health. Table 3 summarises the key mechanisms causing soil-related geohazards and primary consequences for infrastructure.

Table 3 Summary of key mechanisms, responses and consequences of soil related geohazards

Mechanism	Response	Consequence
Shrink-swell Frost heave Sand washout Bearing strength Compressibility	Ground movement	Subsidence Pipe failure Instability on minor roads Instability in clay-rich embankments
Salt concentration Soil redox potential waterlogging pH	Corrosion	Pipe failure Failure of concrete structures
Erosion Landslides	Mass movement	Electricity network disruption (e.g. pylon damage) Interruption of transport infrastructure
Soil water regime Leaching and runoff	Water and contaminant movement	Contamination of pipe network Increased clean-up costs at WTW Groundwater contamination

Finally, Figure 13a illustrates different scenarios of infrastructure responses to soil-related hazards. Unlike the acute and locally devastating effects of flooding, the soil effects upon national infrastructure are more widespread and chronic. Many soil related infrastructure failures, such as structural subsidence and pipe corrosion are to be expected each year (Figure 13b), but the majority of the consequences can typically be managed with existing response systems. For instance, differential soil movement fractures thousands of pipes each year, yet water companies have many rapid response teams to fix or replace failed assets with improved materials. What is more problematic is where a failure impacts on other infrastructure networks causing cascading failures across infrastructure systems. For example, landslide movement which leads to overhead power line failure that can lead to disruption in the electricity supply to pumping stations and water treatment works, arresting the delivery of these services.

As climate is a driver of many of the seasonal changes in soil conditions, more extreme climatic patterns have the potential to exacerbate the risks caused by soil to infrastructure. Colder winters will lead to more soil-frost heave, which has been shown to lead to more pipe fracture in water and gas networks. Similarly, hotter and drier summers will remove more water from the soil. Fluctuations of the moisture content in swelling clay soils at pipe or foundation depth will lead to greater differential movement of the infrastructure (Figure 7). Under a changing climate, the frequency and severity of specific soil-related hazards to infrastructure is likely to increase. The resilience of national infrastructures to soil-related hazards is thus a function of how mechanisms in the soil system respond to environmental perturbations and how the impacts can be continually assessed and managed into the future.

This review of mechanisms and responses to soil related hazards will be developed into a subsequent National Framework Methodology. The framework will then be used to undertake a critical assessment of soil-related geohazards in the context of future climate and infrastructure vulnerability.

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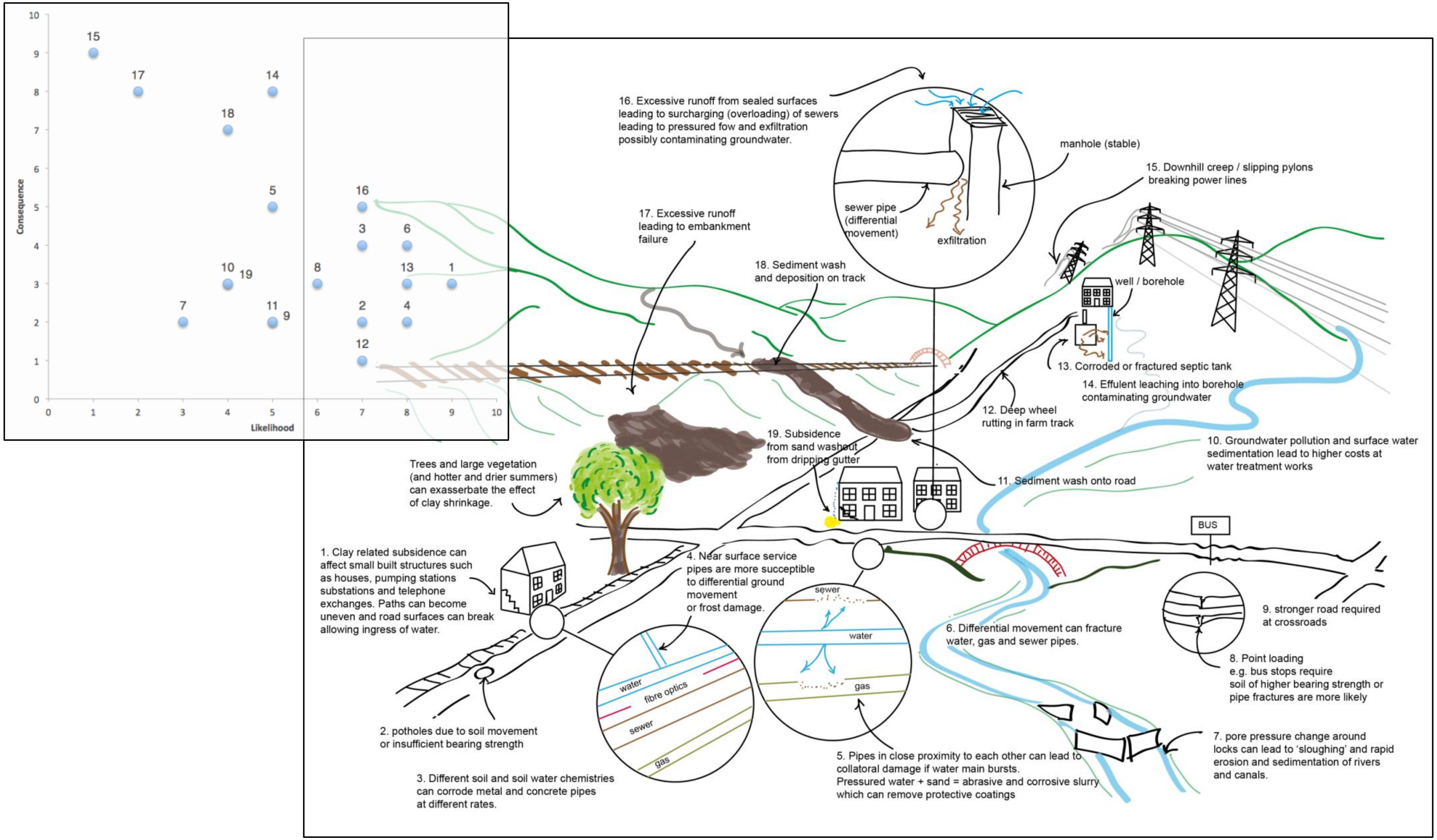

Figure 13 – a) Scenarios of soil-infrastructure interactions and b) their proposed likelihood and consequences.

8 References

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