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Soil impacts on UK infrastructure: current and future climate

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This paper undertakes a critical review of the literature concerning mechanisms and impacts of soil-related geohazards to UK infrastructure. The country is predicted to have drier, hotter summers and wetter, warmer winters that in turn will increase the magnitude and frequency of many soil-related geohazards – predominantly due to changes in soil moisture. Probabilistic assessment will be required given the inherent uncertainty in assessing chronic soil hazards. The aim of this paper is to recommend a national framework methodology to aid the management of future risks posed by soil geohazards to UK infrastructure. The framework will help to prioritise ground investigations in high-risk areas, help to design suitable mitigation measures and encapsulate expert knowledge to interpret risk.

1. Introduction

The UK's critical infrastructure forms the backbone of economic, social and physical wellbeing (Defra, 2013). Infrastructure provision in the UK is threatened by climate change and extreme climatic events (Defra, 2011; Hall *et al.*, 2006, 2013), and is comparable with other immediate threats including international terrorism, cyber attacks and major accidents (HM Government, 2010). The UK's Department for Environment, Food and Rural Affairs' (Defra, 2013) vision for infrastructure is to create 'an infrastructure network that is resilient to today's natural hazards and prepared for the future changing climate'.

The majority of the UK's physical infrastructure assets have foundations within the soil (i.e. not resting on bedrock), predominantly within a depth of 1·5 m below ground level (Busby *et al.*, 2012) (Figure 1). However, the impact of climatic change on soil-related geohazard processes and consequently on infrastructure networks is far from understood. Climate and infrastructure resilience is the basis of many UK national infrastructure assessment reports (Cabinet Office, 2011; CST, 2009; HM Treasury, 2013; Royal Academy of Engineers, 2011). Hall *et al.* (2006) argue that infrastructure systems (often extensive and linear) are not 'static artefacts constructed in a stable environment', but are instead at the mercy of diverse ground conditions and hazards.

This review concerns the natural soils within this upper 1–1·5 m of the ground surface, rather than anthropic engineered soil systems (*technosols*); albeit that the same mechanisms can exist in the latter. Natural soils are inherently varying and complex and, in the UK, comprise some 700+ soil types (Keay *et al.*, 2009).

Infrastructure operators, designers, engineers and policy makers need to be aware of the impacts that soil geohazards and climate change may have on UK infrastructure networks. In some instances, the UK construction industry and the bodies maintaining infrastructure assets demonstrate a lack of awareness concerning potential climate change issues. Often this is due to their reliance on standards that are devoid of climate adaptation methods (Vivian *et al.*, 2005).

Section 2 of this paper reviews the principal soil geohazards that impact on UK infrastructure, specifically the utilities (i.e. water, wastewater, energy) and transport sectors. Discussion of infrastructure resilience to geohazards is considered, and how it is often a combination of soil factors that can lead to asset

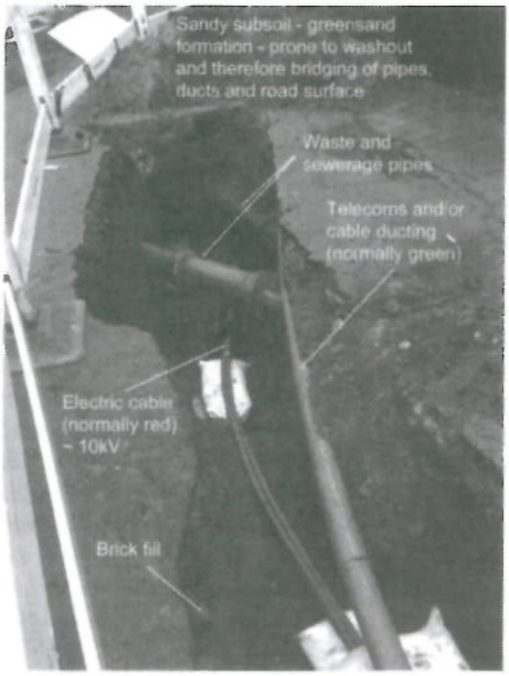

Figure 1. Complexity of underground assets, Ampthill, Bedfordshire

failure. Section 3 describes the impact of projected climate change on soil processes and how this may affect the magnitude and frequency of soil-related geohazards, also considering the inherent uncertainty in probabilistic geohazard modelling. Finally, Section 4 discusses the need for a national framework methodology, allowing knowledge sharing and mitigation of soil-related geohazards for future projected climatic scenarios.

2. Soil geohazards

The UK is not subject to large-impact geohazards, such as high magnitude earthquakes and volcanoes. Landslides represent the highest magnitude geohazard typically impacting the UK's infrastructure. The most prevalent soil-related impacts on UK infrastructure include ground movement, corrosivity and mass movement (Table 1). This section aims to give a brief interpretation of each geohazard mechanism and the impacts of the geohazards on UK infrastructure.

2.1 Ground movement

Soil-related ground movement is recognised as a potential hazard to national infrastructure (Cabinet Office, 2011). Table 1 identifies the processes resulting in soil-related ground movements in the UK, including clay shrinkage and swelling, sand washout, soft (compressible) soil movement and peat shrinkage (Farewell *et al.*, 2012; Hallett *et al.*, 1994).

2.1.1 Clay-related shrink–swell

The volumetric shrinkage of susceptible silicate clays is considered to present the most prevalent and damaging soil-related geohazard to infrastructure, commercial buildings and domestic dwellings (Culshaw and Harrison, 2010). The amount of shrinkage is controlled by clay mineralogy and seasonal moisture flux (Reeve and Hall, 1978). Shrink–swell susceptible clay minerals (i.e. smectite and vermiculite) have high surface areas, with a 2:1 layer lattice onto which water bonds (Brink *et al.*, 1982). Increased water content results in significant interlayer expansion (swell) and with water loss, subsequent contraction (shrinkage). However, not all 2:1 clays are susceptible to shrink–swell, that is, illite (mica) and chlorite (Brady and Weil, 2002). During spring and summer months, when evapotranspiration progressively exceeds rainfall, soil moisture deficits (SMDs) develop as soils dry out from the surface downwards. Typically, UK SMDs affect the top 1·0–1·5 m of soil, but in particularly dry years or during drought

Mechanism	Response	Consequence
Shrink–swell	Ground movement	Subsidence
Sand washout		Pipe failure
Bearing strength		Instability on minor roads
Compressibility		Instability in clay-rich embankments
Salt concentration	Corrosion	Pipe failure
Soil redox potential		Failure of concrete structures
Waterlogging		
pH		
Erosion	Mass movement	Electricity network disruption (e.g. pylon damage)
Landslides		Interruption of transport infrastructure

Table 1. Summary of key mechanisms, responses and consequences of soil-related geohazards to UK infrastructure (after Farewell *et al.*, 2012; Hallett *et al.*, 1994)

conditions this can reach greater depths (Clarke and Smethurst, 2010; Corti *et al.*, 2009; Hawkins, 2013).

SMDs can be exacerbated by the presence of large vegetation, particularly high water demand trees (Biddle, 1998; Sanders and Phillipson, 2003). Cracks in clay soils allow roots to penetrate deeper, consequently resulting in deeper soil drying and further shrinkage (Clarke and Smethurst, 2010). Surface soil and debris falling into wedge-shaped shrinkage cracks may lead to subsequent heave and lateral pressure on re-swelling of clays in wetter winter months, potentially resulting in further damage to infrastructure assets (Brady and Weil, 2002; Forster *et al.*, 2006) (Figure 2).

2.1.2 Soft and compressible soils

If the soil is not strong enough to support the applied load from infrastructure (e.g. buildings, roads or buried pipes) or the presence of overburden (e.g. embankments), then compression can lead to settlement, deformation and ultimate failure of the infrastructure (Kechavarzi *et al.*, 2010; MacKellar and Stott, 2011). Compressible soils include alluvium (fluvial, marine and lacustrine), organic clays and peats. Organic soils (i.e. peats) are known for their poor bearing capacity due to large pore structure and high water content, which can be up to ten times the solid soil weight (Hall *et al.*, 1977; Page, 1998). Alluvial clays often have a firm crust that is not representative of the clay beneath, often causing settlement under loading (BRE, 1993).

2.2 Ground movement impact on infrastructure

Shrink–swell susceptible clays are the most damaging form of ground movement, estimated to cost the UK between £300 million and £400 million per year (Forster *et al.*, 2006). Approximately 80% of domestic subsidence claims are as a result of susceptible clays (Page, 1998). The south-east of England is at highest risk due to the combination of shrinkable clays in areas with commonly high SMDs.

2.2.1 Built structures

Most damage from ground movement occurs on light, brittle structures, such as one to two storey buildings (Jones and Jefferson, 2012). Here, swelling soils have the potential to exert high (~200 kN/m^3) pressures on foundations (Johnson, 1982). Infrastructure assets, particularly those with strip foundations at shallow depths, are at risk of soil-related subsidence. Such structures include pumping stations, sewage treatment works, recycling facilities, distribution network substations and telephone exchanges.

2.2.2 Utilities

The wetting of shrinkable clay soils can lead to considerable and rapid volumetric expansion, which can fracture pipes carrying water, wastewater, oil, natural gas or other substances, such as carbon dioxide for carbon capture and storage (Koornneef *et al.*, 2009). There are numerous mechanisms by which buried utilities fail and, of these, fractures are the most contributory to water leakage (Clayton *et al.*, 2010).

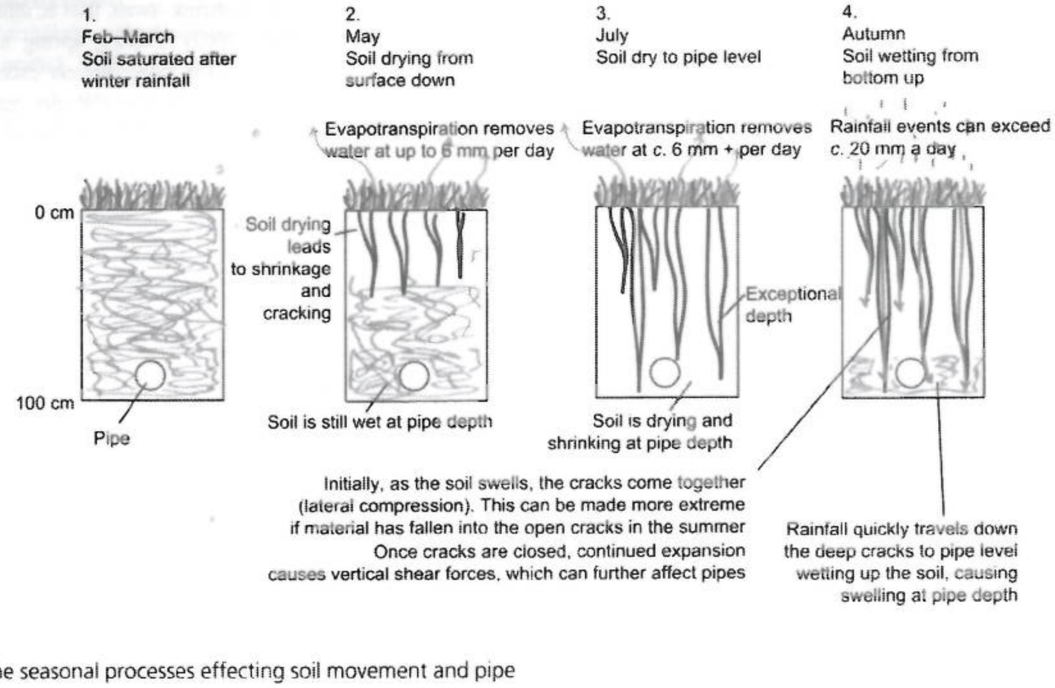

Figure 2. The seasonal processes effecting soil movement and pipe failure

The failure of drains and water mains can lead to the egress of water, which when sustained or at high pressure can result in ground movements affecting other proximal buried services. Often pipes are located extremely close to one another (~10–50 cm), especially in congested urban areas (R.G.O. Burton. Investigation of soils in Thames Water excavations in North London (January and March, 2001), unpublished report). Hawkins (2013) argued that utilities entering structures are likely to suffer differential settlement as a result of the building's influence on local soil moisture regimes. Failure of utilities could then result in further/additional damage to structures (e.g. escaping water wetting cohesive soils and reducing bearing strength, or forming cavities).

In coarse-grained soils (i.e. sand/gravel), escaping water originating from a fractured pipe can form a highly abrasive soil–water slurry. In one example, a high-pressure water pipe failed in close proximity to two 6-month old (polyvinyl chloride (PVC)) gas pipes. The resultant abrasive soil–water slurry led to a rapid thinning of the PVC gas pipes, causing their eventual rupture (Majid *et al.*, 2010). Failure of gas/oil pipes, especially those routed through urban areas, can have significant secondary risks to human life (Jo and Ahn, 2005).

The UK's water industry regulator Ofwat reported the UK sewer network to be significantly cracked or deformed, resulting in higher vulnerability to future ground movement (Ofwat, 2004). Studies argue that between 23% and 33% of sewer to manhole connections are faulty (Davies *et al.*, 2001). Maintenance activities (e.g. drain jetting) can also lead to infrastructure failure with subsoils being washed out, damaging other nearby services – for example, water mains (BBC, 2013a).

Overhead electricity and telecommunication transmission lines can also be susceptible to ground-related movement, especially wooden, singular pylons (Figure 3).

Figure 3. A section of the A1011, Bates Drove, Norfolk, showing leaning telecommunications pylon (left) and undulating road surface due to soil shrinkage

2.2.3 Transport

Highways are particularly vulnerable to ground movement, due to their light construction and potential to become brittle after road-material oxidation (Wu, 2009). Major highways in the UK (motorways and 'A' classified roads) are well engineered and designed to cope with potential geohazards (Chaddock and Roberts, 2006; TRRL, 1984). However, minor roads representing 98% of the UK's highway network (Defra, 2013) are more susceptible to soil hazards. Soil subsidence and surface water run-off present the main geotechnical risks, both likely to be exacerbated by projected climatic change (Adept, 2009).

Following droughts in 2003, a significant deterioration in road quality was identified by several East Anglian council authorities. The East Anglian region has a high proportion of shrink–swell susceptible clay and low bearing capacity peat soils. Many of the roads on these soils have been subject to differential settlement, resulting in severe cracking and undulating morphologies, necessitating speed restrictions or road closures, and totalling millions of pounds in maintenance costs (Adept, 2009). Figure 4 presents the mechanisms leading to road failure as a result of shrink–swell susceptible clay soils.

Railway embankments and cuttings are at risk from cyclical swelling of clay soils, resulting in undulating tracks and landslip initiation. Where railways rest on soft and compressible soils, for example peat bogs, track deformation can lead to a necessary reduction in train speeds (Hendry *et al.*, 2010). The Stainforth landslide in 2013, caused by colliery waste spoil surcharging compressible (saturated) alluvial deposits, followed a significant period of extreme rainfall and caused the closure of a main railway line for 5 months with consequent revenue losses to the rail operator (BGS, 2013; Network Rail, 2013).

2.3 Erosion

Soil erosion is 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' (Huber *et al.*, 2008). Sandy soil is particularly susceptible to erosional processes or washout, with excess water resulting in running-sand conditions (Brink *et al.*, 1982; Walsby, 2007). Erosion represents a significant soil threat in both upland and lowland areas in the UK (Brazier, 2004), with water being the main driver. However, it is generally anthropogenic activity that results in accelerated soil erosion (Alvarez-Mozos *et al.*, 2013; Verheijen *et al.*, 2009).

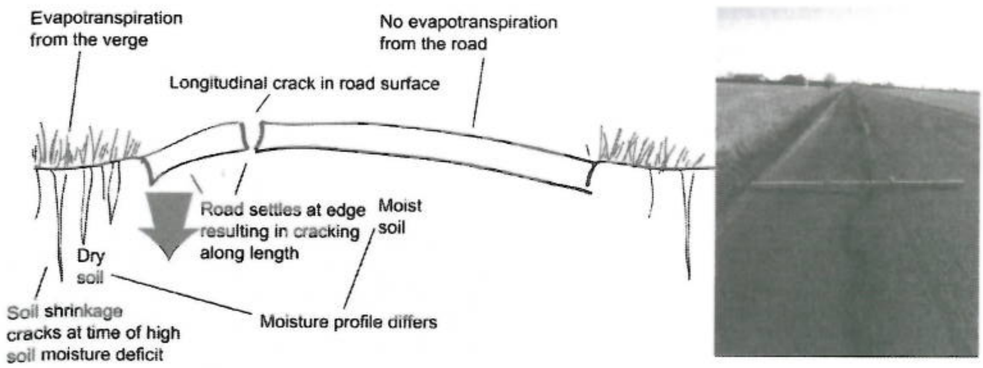

Figure 4. Soil processes leading to longitudinal road cracking and with photo example from Fodderdyke, Lincolnshire (photograph: Lincolnshire County Council, reproduced with permission)

2.3.1 Impact of erosion on infrastructure

Rivers are a cause of rapid erosion, particularly on meandering sections where saturation of the riverbank can lead to soil structural failure. This can cause considerable damage and may lead to failure of infrastructure in close proximity (i.e. electricity pylons and roads).

Deposition of eroded material in reservoirs can reduce the volume of water that can be stored (Palmieri *et al.*, 2001). Rowan *et al.* (1995) have shown that Abbeystead Reservoir in Lancashire has been reduced to 6% of its original capacity as a result of soil sedimentation over a period of 140 years. Similarly, Foster and Walling (1994) documented sedimentation rates varying between 1·7 and 4 cm/year in a Devon reservoir.

The movement of fine material (i.e. clay/silt) can impact significantly on perforated drainage systems. This, together with silting up of drainage pots, can result in increased surface water flooding, causing particular concern near major highways (Highways Agency, 2008). Wind-induced erosion in the East Anglian fenlands, also termed 'fen blow', has led to major traffic disruptions, consequent to poor visibility and soil deposition on highways (BBC, 2013b).

2.4 Landslides

Landslides or mass movements are collective terms for a mass of rock, debris, artificial fill or earth passing down a slope under the force of gravity (Cruden and Varnes, 1996). Landslide classifications are further detailed in Cooper (2007) and Cruden and Varnes (1996).

Soil-related landslips represent a significant proportion (53%) of landslips in the UK, compared to those originating in underlying geology (37%) (Mansour *et al.*, 2011), often being the result of landslide reactivation (Dixon and Bromhead, 2002; Forster and Culshaw, 2004). However, recent debris flows on the A83 'Rest and Be Thankful' pass are largely associated with soil-derived deposits and heavy rainfall events (Pennington and Harrison, 2013). Such conditions highlight the potential for activation of previously undeveloped landslides. Similarly, a survey of 570 km of motorway embankments, often composed of constructed fill, documented that 81% of failures occurred between 0·5 and 1·5 m below ground level with only 5% of failure surfaces occurring at depth greater than 1·6 m below ground level (Table 2) (Perry, 1989).

First-time slope failures are a result of formed pre-failure mechanisms, such as a continuous rupture/shear surface, their full development defining the failure point (Fell *et al.*, 2007). Pore-water pressure is an important factor in slope stability (Abramson *et al.*, 2002), increasing pressures resulting in a decrease of a soil's shear strength, causing shear surfaces to move relative to one another.

A low SMD has been regarded a likely triggering factor for landslides on infrastructure embankments (Dixon, 2008). This is supported by peaks in railway earthwork failures in winter

Depth of failure surface: m	Percentage of total slip length
0·2–0·4	14
0·5–0·9	35
1·0–1·5	46
1·6–2·0	4
2·1–2·5	1

Table 2. Percentage of slips with different depths of failure for 570 km of motorway embankment (after Perry, 1989). © TRL (Transport Research Laboratory)

when moisture contents are high; by contrast peaks are seen in late summer following desiccation caused by high temperatures (RSSB, 2011). Moore *et al.* (2010) have described landslide behaviour prediction as a 'poorly developed and applied' science. However, accurate forecasting has clear benefits to managing risk to infrastructure assets.

2.4.1 Impacts of landslides on infrastructure

2.4.1.1 UTILITIES

Buried utilities are particularly susceptible to damage in landslide-prone soils, as they are designed as composite structures in conjunction with the ground. A landslide in St Dogmaels, Pembrokeshire, in February 1994 caused disruption to an 11 kV electricity and mains water supply (Gibson *et al.*, 2012). Above-ground structures such as energy pylons, substations and pumping stations can also be affected by landslides and mass movement of soil.

2.4.1.2 TRANSPORT

Landslides have had a significant impact on the transport sector in the UK, particularly in 2012 (BGS, 2014). Approximately 1·2% of the main transport networks (motorways, 'A' roads and railways) are situated in high-risk landslide areas, with a further 6% at moderate risk (Dixon, 2008). A series of superficial debris flows in 2004 significantly impacted on the Scottish highways network, resulting in key roads being closed for a substantial period (Winter *et al.*, 2005).

On average, 50 embankment failures occur on the UK rail network per year (Loveridge *et al.*, 2010), often leading to major disruptions (Bromhead, 2013). For example, an embankment landslide on 17 October 2012 prevented trains from travelling between Barrow and Carlisle, adding 60 min to passenger's journeys for 2 days (*North West Evening Mail*, 2012).

2.5 Soil corrosivity

Corrosion affects almost all metals, as they react with their environment (Bradford, 2001). The predominant deterioration mechanism on the exterior of cast and ductile iron, representing much of the UK's water infrastructure, is electrochemical corrosion at the soil–metal interface, resulting in corrosion pits (Rajani and Kleiner, 2001) that enlarge to the point of failure.

Contributing factors to soil corrosivity include the concentration of soluble salts in the surrounding soil (sulfates and chlorides); pH; soil resistivity; temperature; and soil redox potential (Jiang *et al.*, 2011; Kleiner *et al.*, 2012; Md Noor *et al.*, 2012). However, moisture content is the most consistent factor regulating soil resistivity (Cole and Marney, 2012; Laver and Griffiths, 2001). Soil resistivity is indicative of the ability of a soil environment to carry corrosion currents, being regarded as the most common indicator of soil corrosivity (Bradford, 2001). The prevalence of moisture and mineral salts in soils means they act as good electrolytes (Payne, 1999), essential in the redox reactions that occur during the corrosion process.

In anaerobic (oxygen-depleted) soil environments, it is generally assumed that microbial activity is the main influence on corrosion. Microbial activity of sulfate-reducing bacteria produces hydrogen sulfide, during the reduction of soil sulfates (Pankhania, 1988). Knowledge of localised soil conditions therefore plays an important and cost-effective role in determining routes and materials for pipe laying, as well as in the design of cathodic protection schemes for buried infrastructure.

2.5.1 Impacts of soil corrosivity on infrastructure

The cost of all corrosion in the UK is estimated as 2·5–3·5% of the gross domestic product (Frances, 2006). In particular, soil-related corrosion in the UK impacts on buried (metallic) pipelines serving the water, wastewater and gas sectors (Cole and Marney, 2012).

2.5.1.1 IMPACTS OF SOIL CORROSIVITY ON TRANSPORT

Soil nailing, undertaken on highway and rail embankments to prevent movement, uses closely spaced steel nails (Yean-Chin and Chee-Meng, 2004). However, the nails are often unalloyed or low-alloyed steel (Nurnburger, 2012), making them prone to subsequent attack from aggressive soils (Prashant and Mukherjee, 2010). Concrete encapsulation has been applied to prevent this, but inherent cracking in concrete can leave exposed metal surfaces vulnerable to attack (Phear *et al.*, 2005). By contrast, the majority of metallic corrosion that occurs on transport networks derives from de-icing salts and is not a soil-related issue.

2.5.1.2 IMPACTS OF SOIL CORROSIVITY ON UTILITIES

Hembara and Andreikiv (2012) state that soil corrosion is a major factor in decreasing the reliability of buried pipelines. The particularly aggressive nature of the London Clay formation means cast-iron pipes are particularly susceptible to corrosion processes (Schmidt *et al.*, 2006).

The impact of soil excavation can also alter the corrosion potential. Soil disturbance allows oxygen, through formed pore spaces, to reach exposed metal surfaces, as well as introducing foreign materials and organisms, both altering the soil chemistry (i.e. pH) (Bradford, 2001; R.G.O. Burton, Investigation of soils in Thames Water excavations in North London (January and March, 2001), unpublished report).

Angular soil particles can score or pierce the passive protective layer of metallic pipes, having a profound effect on corrosion rates and leaving pipes exposed to potentially aggressive soils (Sjogren *et al.*, 2011). Corrosion-resistant PVC pipes are also subject to the abrasive action of angular particles, leading to

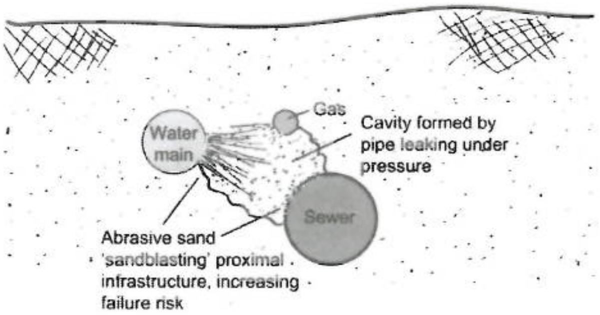

Figure 5. Forming of soil abrasive 'slurry' on pipe failure in coarse-grained soils

possible failure of the service (Figure 5), especially when using trenchless installation methods in abrasive soil types.

A gas explosion resulting from cast-iron pipe corrosion in Bridge Street, Shrewsbury, in 2010 highlighted the consequence of asset failure. This particular event culminated in the destruction of six commercial town centre properties, along with telecommunications and traffic light cabling (BBC, 2010; HSE, 2010). The sandy-gravel soil at this location was recorded as being moderately to very corrosive and, due to its loose texture, allowed gas to migrate from the severed pipe into the buildings, which were subsequently destroyed in the explosion.

Stray currents, originating from mass transit systems and overhead electricity pylons and substations, can result in severe corrosion of underground assets (Flounders and Danilyak, 1995; Wang *et al.*, 2013). Zhu *et al.* (2011) have suggested that soils with a higher resistivity can counteract the issue of stray currents by limiting the soils' current carrying capacity. Drying soils leads to a corresponding decrease in soil resistivity, decreasing the soils' earthing potential, affecting substation earthing systems (Busby *et al.*, 2012; Laver and Griffiths, 2001).

Oxidation of drained peats and pyritic soils (acid sulfate soils) can lead to the formation of ochre. This can lower pH values to less than 3·5, causing corrosion of metallic structures (e.g. drain culverts) (Stuyt *et al.*, 2005).

Often telecommunications and electricity cables are wrapped in corrosion-resistant materials and placed in plastic ducting, so preventing their direct contact with potentially corrosive soils.

2.6 Interconnectivity of soil geohazards

Soil geohazards often do not occur in isolation. However, they often act as a sequence of processes, which can culminate in infrastructure asset failure.

Cohesive soil shrinkage cracks, sometimes propagating to depths of 1·0 m or more, can have the effect of allowing oxygen to reach exposed metal surfaces, increasing corrosion rates (Brady and Weil, 2002). In this instance the combination of shrink–swell soil and metallic corrosion can lead to premature pipe failure.

Shrinkage cracks present a significant factor in slope stability, causing progressive failure during repeated shrink–swell cycles, but also allowing rainfall to reach shear surfaces easily (Figure 6). The latter causes a sharp increase in pore-water pressure at the shear surface, which during intense rainfalls can result in slope failure (Dixon, 2008; Hughes *et al.*, 2009) (Figure 6). Cracks can also act as preferential pathways for soil contaminants, originating from a pipe breakage or other external sources, which, in areas of highly permeable soils or in shallow aquifers, can cause significant environmental issues (Oostindie and Bronswijk, 1995).

2.7 Infrastructure resilience to geohazards

Infrastructure resilience to extreme weather impacts is defined as the ability to prevent, withstand, recover from and learn from the impacts of the hazard(s) (Hallett, 2013). The resilience of national infrastructures to soil-related geohazards is thus a function of how mechanisms in the soil system respond to environmental perturbations and how such impacts can be continually assessed and managed into the future.

Much of the UK's infrastructure, especially water, wastewater and railway networks, are of Victorian origin (e.g. a third of Thames Water's mains are in excess of 150 years old (Greater London Authority, 2003)) and are less well engineered when compared to modern day installations. To upgrade its ageing infrastructure, Network Rail recently announced a planned investment of £37·5 billion, the largest investment since the inception of the railways (Milner, 2013). During 2007/2008

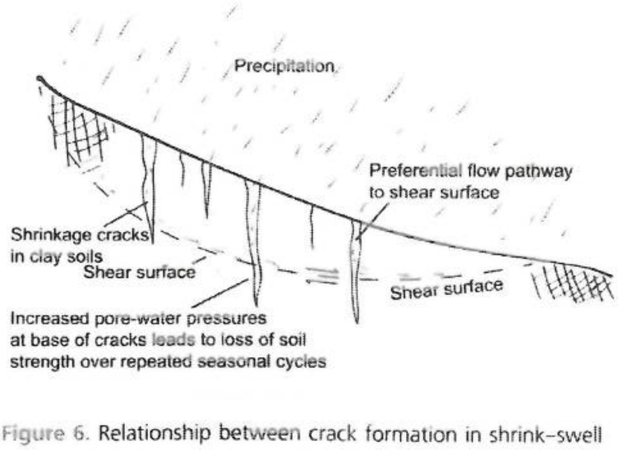

Figure 6. Relationship between crack formation in shrink–swell susceptible clay soils and land instability

Network Rail spent approximately £80 million on earthwork maintenance alone, with a large proportion spent on preventive measures (RAIB, 2008).

Like humans, infrastructure assets become increasingly susceptible to external impacts as they age. However, unlike humans who wind down in old age, infrastructure assets are often subjected to greater increases of required performance and extended service in their later life and indeed well beyond their design life, often due to increasing population demand (D'Agata, 2003).

Investigating and/or replacing existing ageing infrastructure can result in negative impacts, leading to repeated failure in other parts of the network and to adjacent assets. For example, dry clay soils transfer the forces acting on them to structures buried within them. This is specially so when mechanical excavators and pneumatic drills are used, resulting in damage to proximal services.

Responsibility for infrastructure resilience lies with owners and operators. The infrastructure regulators (i.e. Ofwat, Ofgem and Ofcom) play an important role in ensuring asset replacement occurs at a sufficient rate without pushing considerable expense towards consumers (Cabinet Office, 2011). However, varying levels of resilience are found acceptable across different industries. The severe consequences of gas pipe failure, for example, has resulted in the HSE (2001) enforcing statutory replacement of cast-iron gas pipes with corrosion-resistant PVC. Often the condition of the gas pipes replaced are significantly better than many water mains currently deemed fit for service.

The government regards infrastructure as a key basis for economic growth in the UK, and is seeking to make relatively short-term investments to result in maximum financial gain (HM Treasury, 2013). It is therefore imperative to understand the risks posed by soil geohazards when replacing and upgrading infrastructure assets.

3. Impact of climate change on soil processes

The climate is a driver of the seasonal changes in soil conditions, which consequently exert effects on infrastructure, as identified in Section 2. Soil strength is fundamentally determined by its water content (Bihne and Lessing, 1988), with wetter soils generally being weaker (Dexter, 1988). Therefore, understanding future impacts of climate change requires a sound knowledge of soil geohazard processes in their current environmental setting (Forster and Culshaw, 2004).

UK Climate Projections (UKCP09) indicates the increased probability of hotter, drier summers; milder wetter winters; more extreme rainfall events; and increased ultraviolet radiation in summer (Jenkins *et al.*, 2009). Projected climate change and extreme weather conditions are therefore likely to cause significant but varying impacts on soil geohazards in the UK.

Hotter, drier summers will remove more soil water, up to 20–40% in the south-east of England (Sanders and Phillipson, 2003). Wetter winters will lead to significant fluctuations in soil moisture over the future annual cycle. These conditions are likely to result in potentially damaging differential movement at pipe/foundation depth.

Higher soil moisture contents can increase corrosion rates (Ahmed, 2011; Norin and Vinka, 2003) with a seasonally fluctuating groundwater level changing the reducing-oxidising state of the soil, increasing the soil's aggressiveness to metallic, buried infrastructure (Kleiner *et al.*, 2012).

Cracked, shrinking clays are likely to contribute to an increased probability of progressive slope failure. When coupled with high-intensity rainfall events, leading to rapid increases in pore-water pressure at potential shear surfaces, they cause inevitable slope failure (Hughes *et al.*, 2009).

Erosional processes will increase with projected climate change (Jones *et al.*, 2009), especially in non-cohesive soils. These soils are more likely to initiate overland water flow during extreme rainfall events, ultimately preventing re-wetting of soils and so promoting erosion and localised flooding of proximal infrastructure.

Infrastructure assets can themselves have a profound impact on soil moisture regimes. Sealed surfaces and structures prevent moisture from readily entering the underlying soil. In times of drought this can lead to further soil moisture deficits and shrinkage, leading to damaging differential settlement (Hawkins, 2013; Pritchard *et al.*, 2014).

Regional climate modelling will allow future predicted changes in SMDs to be calculated, which can then aid probabilistic soil-related geohazard modelling. Currently, only limited research has been undertaken in modelling soil geohazards for future scenarios (Blenkinsop *et al.*, 2010; Clarke and Smethurst, 2010; Harrison *et al.*, 2012; Loveridge *et al.*, 2010), the main focus often being on evaluating existing historic datasets (i.e. Crilly, 2001).

3.1 Climate modelling uncertainties

Flooding is an acute hazard, its likelihood and consequence(s) are assessed using probabilistic modelling (Sene *et al.*, 2009). However, the chronic nature of soil-related geohazards makes their frequency and response difficult to quantify. Furthermore, sparse data lead to greater uncertainty in threshold responses. Nevertheless, work is ongoing to establish the relationships between soil geohazards and related infrastructure failure (Free *et al.*, 2006; Hall *et al.*, 2006).

The inherent uncertainty in probabilistic climate modelling means infrastructure risk analysis is generally qualitative in nature. However, UKCP09 probabilistic projections allow a number of scenarios (i.e. high, medium and low emissions) to be evaluated. UKCP09 differs from its predecessor UK Climate Impacts Programme 02 (UKCIP02), which gave a single estimate of change; instead UKCP09 allows the user to incorporate probabilities of differing amounts of change (Jenkins *et al.*, 2009).

The quantification of uncertainty is paramount in the utilisation of geohazard models in infrastructure risk management (Royse, 2011). Sanders and Phillipson (2003) agreed, but suggested that uncertain predictions will prevent regulators from making significant adaptations. Certain efforts have been made to model physical changes in soil-biological systems to aid probabilistic modelling methods – for example, the 'Bionics' embankment experiment (Hughes *et al.*, 2009).

4. Towards a sustainable framework

The increased threat to UK infrastructure from soil-related geohazards in the past decade has resulted in this issue becoming embedded in the wider concept of sustainable development (White *et al.*, 2001), especially within spatial planning approaches (Wilson and Piper, 2010). Soil geohazards are well understood in the UK but they still catch many by surprise, and, with land pressures increasing, developers and infrastructure owners are looking to land that previously was considered unsuitable due to hazardous ground conditions. This will inevitably increase the vulnerability of infrastructure(s) in future years if not appropriately designed.

Brook and Marker (2008) state that awareness of geohazards is greatest in areas subject to high frequency events, where understandably experiences in dealing with these issues are more established. However, climatic change could mean areas previously unaffected could in future become more prone to geohazards. Similarly, geohazard mechanisms may change; that is, landslides lying previously dormant could be reactivated by climatic perturbations (Pennington and Harrison, 2013).

Therefore, there is a need for both infrastructure operators and earth scientists to share knowledge of how to mitigate the potential impacts that may arise from increasing vulnerabilities to soil-related geohazards. Current asset inspection regimes have an apparent inability to detect deterioration not yet visible (ICE, 2013). This is particularly so with soil-related hazards, including landslides and shrink–swell clays that represent chronic processes that manifest over (many) seasons, in contrast to acute flood events. Geohazard impacts are poorly recorded, for example the Highways Agency does not routinely record the impact of landslides, making it difficult for engineers to understand the causes of failure (Gibson *et al.*, 2012). Similarly, local authorities (e.g. highways) and many other infrastructure operators make decisions in the absence of earth-science expertise.

The need for a framework methodology, with the aim of providing practitioners' best practice approaches for avoiding future risks posed by soil-related geohazards, is apparent. Flooding, due to its high economic impact and public visibility has spawned a number of reviews (Pitt, 2008; Stern, 2006) considering how society can more efficiently manage this geohazard. However, currently little information in the civil engineering sector exists on how to manage soil-related geohazards, particularly considering an interconnected system-of-systems approach of UK infrastructure.

It is suggested that a case study approach is required to assess both expert and practitioner knowledge on a range of soil geohazards across different sectors (i.e. water, transport, energy, etc.) and over a range of geographical areas in the UK. An understanding of the current impact of soil geohazards and how they have been dealt with will then enable an analysis of how future climatic predictions and soil geohazard modelling can be incorporated into sustainable designs and maintenance regimes. A multidisciplinary approach to infrastructure planning and design is argued as a necessity (Hall *et al.*, 2013).

5. Conclusion

UK infrastructure faces a range of soil-related geohazards, many of which are likely to be exacerbated by climatic change (Figure 7). This is a result of the climate regulation of soil moisture content, fundamental to the occurrence of many soil geohazards.

Significant future geohazards are likely to comprise cyclical shrink-swelling of clays due to large seasonal differences in SMD; shallow landslides as a result of repeated shrink–swell cycles and high-intensity rainfall events; and higher erosion rates (non-cohesive soils) due to overall drier soils and intense rainfall events.

However, research to date has principally focused on assessing current/historic geohazard distribution and its impact on UK infrastructure. Although this is essential in understanding the fundamental processes, to ensure a sustainable future for the UK's infrastructure, a probabilistic approach to soil geohazard infrastructure interactions is now required.

Projections from the UKCP09 climate model suggest the UK is not likely to face any unseen soil-related geohazard threats.

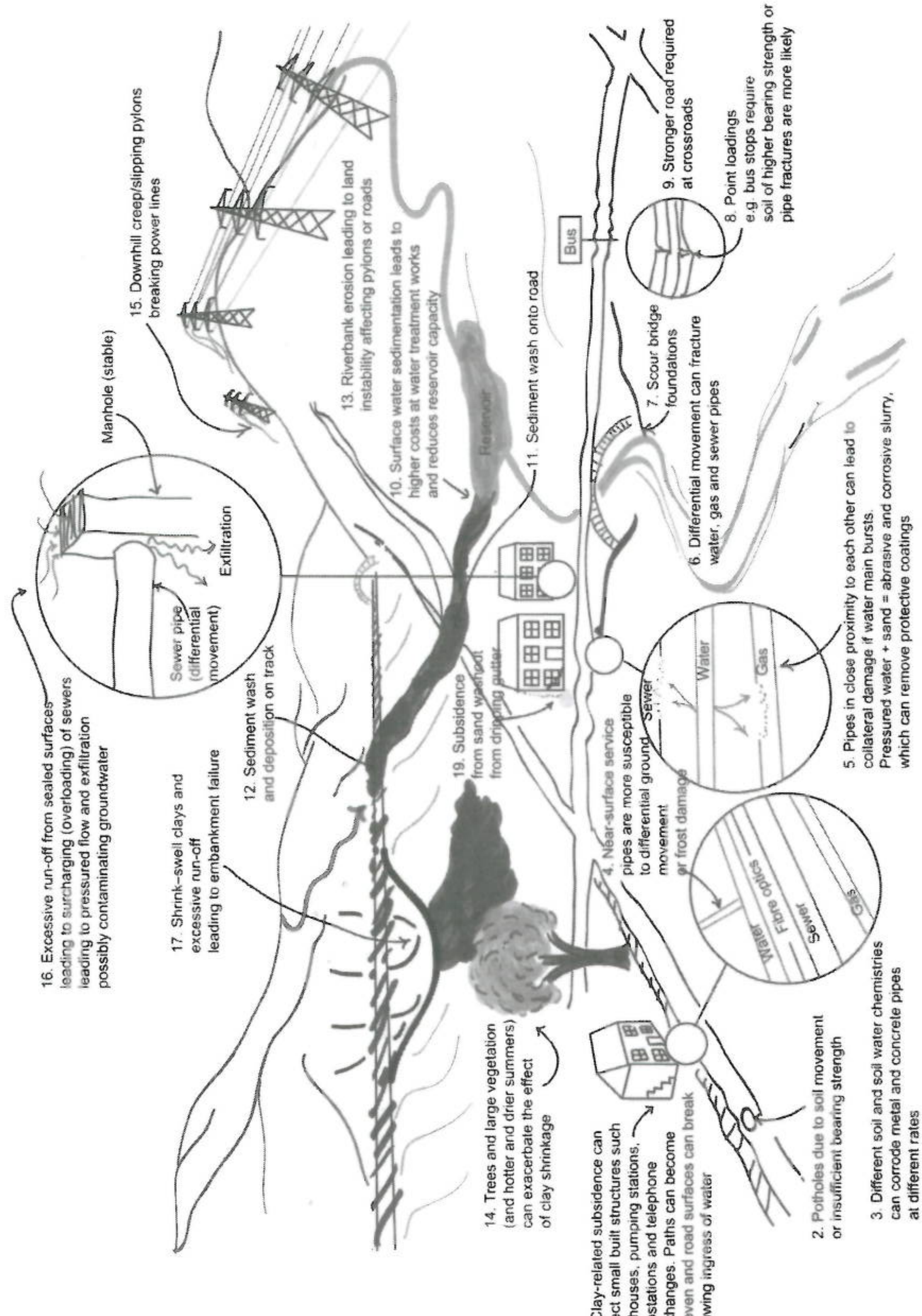

Figure 7. Scenarios of soil–infrastructure interactions

However, the magnitude and frequency of existing soil-related geohazard events are likely to increase and previously unaffected areas could be susceptible to an increased vulnerability.

The sharing of best practice for the management of soil-related geohazards among civil engineers is required through a suitable framework methodology. Ideally, this will incorporate existing collections of geohazard assessments, climatic projections, and infrastructure network asset locations and condition assessments. Together, these have the potential for highly visible benefits, enabling the infrastructure sector to prioritise ground investigations, design sustainable assets, and to encapsulate expert knowledge to interpret risk.

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Soil impacts on UK infrastructure: current and future climate

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