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Soil movement in the UK – Impacts on critical infrastructure

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Executive Summary

Almost all of the systems/structures related to critical infrastructure (CI) of the United Kingdom (UK) are in contact with the soil substrate. Therefore how the ground reacts to them both naturally and as a result of their [CI] impact being placed upon them needs to be understood.

The main causes of ground movement and associated soil types within the UK have been identified as follows;

- Clay – Shrink/Swell
- Sand – Erosion
- Peat – Shrinkage
- Silt – Frost heave
- Alluvial soils – Compressibility
- Sulfate Bearing soils – Ground heave

This review aims to describe the following soil processes and understand their interaction with critical infrastructure systems within the UK in light of a changing UK climate. Climate change is highlighted as being the main driver of a changing risk to infrastructure systems if future climate predictions are proven correct.

This will be occur through the influence of changes to soil moisture that has the possibility to result in prolific ground movement issues, the south east of England is likely to witness the greatest increase in ground movement. Almost all of the soil [ground movement] processes discussed are somewhat or wholly dependent upon the soil moisture regime, fundamentally soil strength is determined by its water content, water suction and their change upon loading generally being weaker on wetting.

Shrink swell clays pose the highest cost and subsequent risk to infrastructure systems within the UK, which could exceed the economic costs of flooding in the future if climate predictions are accurate.

The use of soil surveys in an engineering application has been briefly discussed, with the limitations of using only superficial and geology maps when planning critical infrastructure risks to ground movement. With the majority of critical infrastructure systems such as highways, gas, water and sewerage systems being placed within the top two metres of soil, the use of soil survey information can be critical.

The relationship between climate change and shrink/swell processes is still not fully understood in regards to future climatic change and currently no UK national data exists on such a matter. This highlights a need for further research on an issue that will prove socially, economically and environmentally problematic to critical infrastructure future provision within the UK.

Glossary

ADEPT – Association of Directors of Environment, Economy, Planning and Transport
BRE – Building Research Establishment
BGS – British Geological Survey
Defra – Department of environment, food and rural affairs
HSE – Health and Safety Executive
ICT - Information Communications Technologies
ITRC – UK Infrastructure Transitions Research Consortium
LandIS – Land Information System
Leacs – Leakage assessment due to corrosivity and shrinkage
MORECS – Meteorological Office Rainfall and Evaporation Calculation System
NHBC – National House Building Council
NPD – Natural Perils Directory
NSRI – National Soil Resources Institute
UK – United Kingdom
UKCP – United Kingdom Climate Projections

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Report cover, shows a section of road at Holme Fen, Cambridgeshire that has undergone significant rutting due to peat shrinkage. (O. Pritchard)

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Key Findings;

- Soil movement in the UK has a financial impact of between £300-500 million per annum.
- There is currently no national estimation of shrink swell effects in light of future climate change.
- It is predominantly the South East of the UK that is under threat from climate change and shrink/swell processes.
- Generally only lesser-engineered infrastructure systems are at risk of soil related ground movement.
- Structures can have a significant effect on the soil moisture regime.
- Climate change is likely to exacerbate soil related ground movement rather than introduce new issues.

'The soil varies from place to place, and many of its properties vary in time too. This is what makes the soil so fascinating'
(Heuvelink and Webster, 2001).

1. Introduction

Almost all of the systems/structures related to critical infrastructure (CI) of the United Kingdom (UK) are in contact with the soil substrate. Therefore how the ground reacts to them both naturally and as a result of their [CI] impact being placed upon them needs to be understood. The Cabinet Office (2011) highlight the lack of knowledge and understanding of the effects of climatic change and natural hazards upon infrastructure provision and maintenance within the UK. Defra (2011) state that although infrastructure is becoming more prepared for large scale natural hazards (i.e. flooding) it is less prepared for 'incremental' change (i.e. subsidence), therefore the deeper understanding between these processes and critical infrastructure assets would be desirable (Royal Academy of Engineers, 2011).

Hallett *et al*. (1994) identify the following soil materials and effects that are the main cause of ground movement within the UK;

- Clay – Shrink/Swell
- Sand – Erosion
- Peat – Shrinkage
- Silt – Frost heave
- Alluvial soils – Compressibility
- Sulfate Bearing soils – Ground heave

Although not being considered within this review, ground related movement related to past coal and metalliferous mining activities also occurs within the UK (Brook and Marker, 2008).

"The UK is a country with limited direct experience of natural disasters" (Gibson *et al*. 2013), and does not suffer from large scale catastrophic geohazards. However the geohazards that do occur, some of which are indicated above by Hallett *et al.* (1994) can and have resulted in costly damages (Walsby, 2007). Swelling and shrinkage of clay soils arguably results in the highest losses of any know ground/soil condition within the UK (Culshaw and Harrison, 2010), during 2002 it was estimated that subsidence related ground movement resulted in costs of £300-500 million.

Almost all of the infrastructure within the UK is emplaced within or upon the soil, often with little or no ground investigation, that can lead to future failure through progressive ground movement. Even those infrastructures that undergo intensive ground investigation, can, in time become more susceptible as a result of climatic change, which causes a change in soil processes.

It must be remembered that infrastructure systems are not 'static artefacts constructed in a stable environment' (Hall *et al*. 2006), but are instead subject to a changing, potentially damaging, environment. It is therefore a necessity to further understand ground movement issues within the UK in context of a changing climate and the threat it possibly poses to infrastructure provision within the UK.

1.1 Ground movement and legality in the UK

The UK Government formulated the Planning Policy Guidance 14 (PPG 14), regarding the development on unstable land (Department for Transport, Local Government and the Regions, 2002), to identify the responsibility of the developer to consider land instability issues during the design and construction phase.

Building regulations also advise on control to prevent the impact of ground stability (Anon, 2004), whereby 'the building shall be constructed so that ground movement caused by':

> 'Swelling, shrinkage or freezing of the subsoil';
> 'Landslip or subsidence (other than subsidence arising from shrinkage), in so far as the risk can reasonably foreseen, will not impair the stability of any part of the building'.

It is generally only subsidence, i.e. that caused by the 'downward movement of a site' that insurance policies will cover. The insurance industry has incorporated subsidence into their policies since 1971 (Webb, 1999), with the average subsidence insurance claim in the UK being £9k (Pugh, 2002). It is often thought that subsidence within the UK, in a domestic light, is underrated due to people's general ignorance to subsidence cracks if not impeding on their day-to-day life (Page, 1998; Crilly, 2001).

The impact of a structure (i.e. building) that results in consolidation and settlement of a soil is however not covered, and generally is included within the design of the foundations (Financial Ombudsman Service, 2013). It should also be regarded that landslips and slope stability issues are incorporated within PPG14, however these issues will not be discussed within this review and have been considered in a previous document (Pritchard *et al*. 2013a).

Brook and Marker (2008) stress that knowledge of ground instability [subsidence] appears to be 'deteriorating' in the planning process, inevitably leading to the possibility of structures not being designed to withstand ground movement, especially with regards to a changing climate.

Planning Policy Statements (PPS) have been 'prepared by HM Government to explain statutory provisions and provide guidance to local authorities on planning policy' (Planning Portal, 2013). They acknowledge natural hazards, encompassing subsidence, however guidance is not included within the document on how to design for subsidence issues and reference is made to the earlier PPG14. Brook and Marker (2008) stress that planning authorities and developers may consider PPG14 outdated and instead refer solely to the more modern PPS's, leading to greater subsidence risk/exposure to structures.

With regards to critical infrastructure in the UK, failure of an asset due to ground movement may result in liability or indeed corporate manslaughter in the most unfortunate event (ADEPT, Undated).

2. Soil 'ground movement' processes

2.1 Soil moisture

All soil processes related to ground movement, that are to be discussed, are somewhat or wholly dependent upon the soil moisture regime, therefore it is important to firstly explain this importance. Fundamentally, soil strength is determined by its 'water content, water suction and their change upon loading' (Bohne and Lessing, 1988), soils being generally weaker on wetting (Dexter, 1988).

Water content in soils is very complex and is altered significantly by climatic and environmental conditions (Seneviratne *et al*. 2010), soil properties (i.e. texture, depth to bedrock and rock fragment content) have a dominant control over soil moisture storage and transport (Famiglietti *et al.* 2008). Zhu and Lin (2011) showed that steep sloping sites (>8% slope) have a dominating effect on soil moisture availability over soil properties, whereas this was reversed for low relief areas.

Smith and Smith (1988) describe the following 'conceptual' sectors of the 'Aeration Zone', that is water held in the soil above the groundwater level (Figure 1), of which predominantly concerns UK soils, due to soil moisture complexity average depths of these within the UK are not known;

- Capillary Fringe – Where owing to capillary action, water is drawn from the saturated groundwater zone into the voids of the overlying soil, being held in a state of suction (negative pressure). Finer soils have greater capillary rise, i.e. silt -2.5m and clay soils >2.5m.

- Intermediate Belt – As a result of percolating rainwater a certain amount is held by the soil through processes such as; surface tension, capillarity, adsorption, chemical action. This water is often beyond the reach of plants.

- Soil belt – The zone affected by evapotranspiration

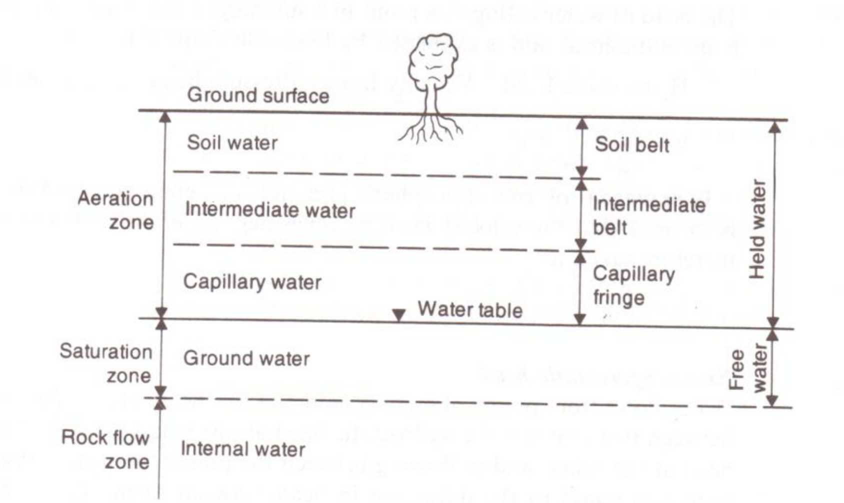


Figure 1: Types of subsurface water (From: Smith and Smith, 1988)

The water table is sometimes also referred to as the '*phreatic'* surface, this is the level at which the pore water pressure is atmospheric, below this depth the soil is assumed fully saturated, although air filled voids can still exist (Craig, 2004).

Soils generally lose moisture throughout the spring and summer, as a result of evapotranspiration exceeding precipitation; this results in the formation of a soil moisture deficit (SMD). SMD is defined as the amount of water required to bring a soil profile to field capacity (Figure 3) (Earl, 1997). Field capacity being 'the soil-water content after the force of gravity has drained or removed all the water' (Evans *et al*. 1996) which usually occurs after 1-3 days after rainfall (Bridges, 1997). In a typical year within the UK this deficit becomes apparent in early spring (February/March) (Clayton *et al*. 2010) reaching a peak at the end of the summer/early autumn months, however this can prevail through to the next year (i.e. January) if climatic conditions allow (Hough *et al*. 1995; Farewell *et al*. 2012).

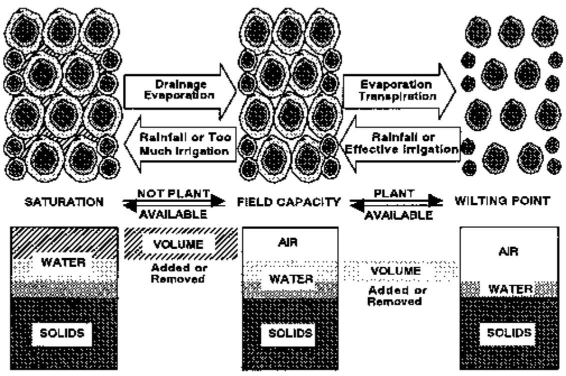


Figure 2: Soil-water relationship identifying concept of saturation, field capacity and wilting point (From: Evans et al. 1996)

The UK Meteorological Office established the MORECS (Meterological Office Rainfall and Evaporation Calculation System) in 1978 (Thompson *et al.* 1981), this system uses 'daily synoptic weather data to provide estimates of weekly and monthly evaporation and soil moisture deficit, in the form of averages over 40 x 40km grid squares' (Hough and Jones, 1997). Hough and Jones (1997) updated the system (Version 2.0) to incorporate land use change, specifically the introduction of oil seed rape as an arable crop, which made it more relative to typical crops of the 1990's.

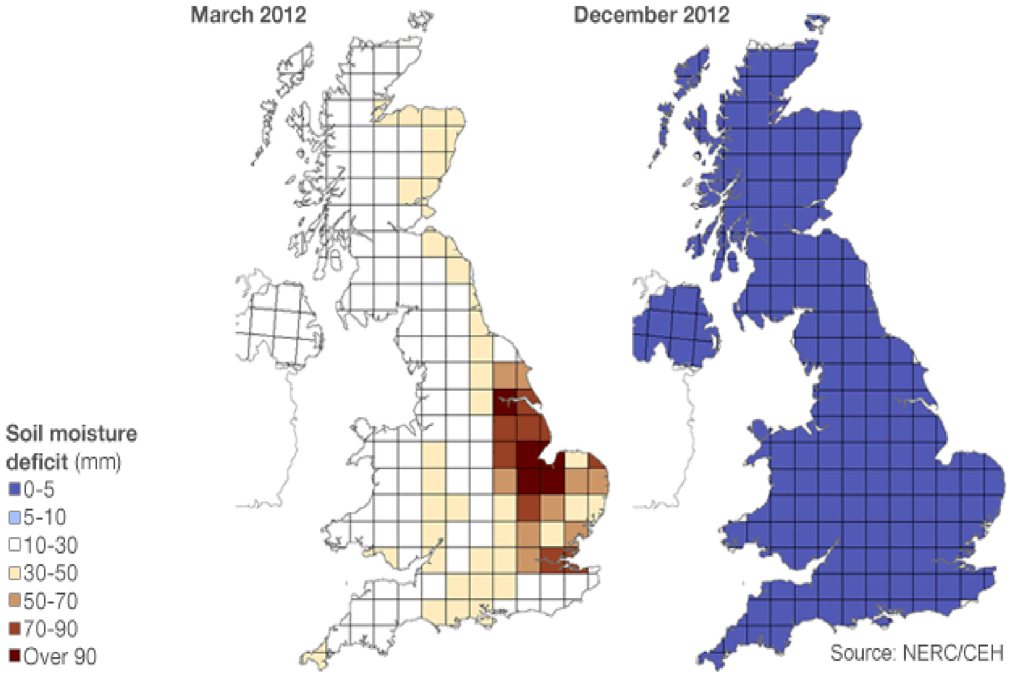


Figure 3: Soil Moisture Deficit (SMD) for the UK (2012) (From: http://www.bbc.co.uk/news/science-environment-20898729)

2.1.1 Soil Permeability

As identified by Farewell *et al.* (2012), the soil water regime is greatly controlled by the permeability of the soil mass. All soils are, to an extent, 'permeable' (Craig, 2004) and allow the movement of water through interconnected pores. However, it is the rate of this movement that differs between soil types, with coarser (sand/gravel) soils generally being more permeable than that of fine (clay/silt) soils(Figure 4).

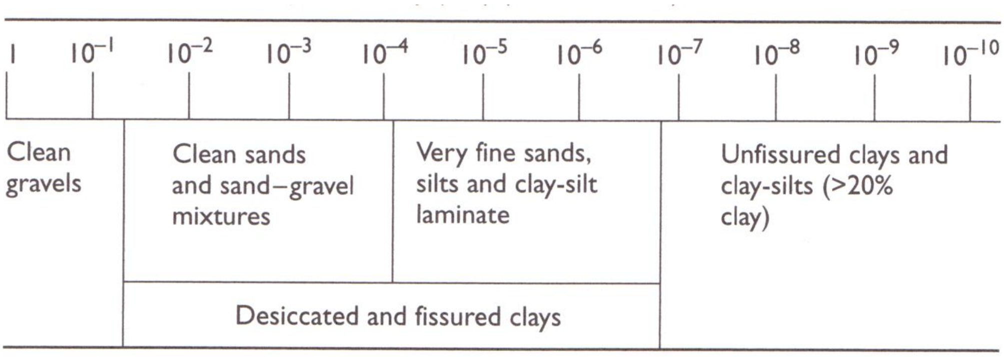


Figure 4: Coefficient of permeability (m/s) (BS8004:1986 in Craig, 2004)

The permeability of a soil is governed by its particle size and shape as well as soil structure and density (Craig, 2004; Farewell *et al*. 2012). The definition of soil structure being 'the spatial arrangement or clustering of primary soil particles into secondary units called aggregates or peds' (Alaoui *et al*. 2011).

Darcy's Law, also known as the coefficient of permeability (k), is as follows;

$Q = Kai$

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

2.1.2 Soil moisture and climate change

The importance of soil moisture has been intensively reviewed by Seneviratne *et al*. (2010) who explain the significance of soil moisture regimes and their feedback on the global climate regime. Ferranti and Viterbo (2006) have suggested that the drought conditions witnessed by Western Europe during 2003 were exacerbated by reduced soil moisture. The lower moisture contents ultimately reduced humidity (Pan Chun *et al.* 2013) and inhibiting convection, therefore rainfall, a statement supported by Brabson *et al*. (2005) who found that higher temperatures are strongly coupled to low soil moisture content.

The specific impact that water has upon certain soil processes will be considered in the chapters throughout this review.

2.1.3 Water repellent soils

Water repellent soils are common throughout the world. It was previously only thought that sandy soils could be 'hydrophobic' as a result of their small surface areas, however it has since been proven that this can be the case for clay soils also (McGhie and Posner, 1980 In: Jarvis *et al*. 2008). Water repellent soils defined as those which do not allow the spontaneous entry of a drop of water (Letey *et al*. 2000).

There are several established tests to deduce the water repellency of a soil, including the Water Drop Penetration Time (WDPT) test and the molarity of ethanol droplet test (de Longe *et al*. 1999; Carrillo *et al*. 1999; Jarvis *et al*. 2008), however details of these tests will not be explored within this review.

Soil fungi, volatile organic substances (Carrillo *et al*. 1999) and waxes produced by plants (de Longe *et al*. 1999) increase water repellency. Carillo *et al*. (1999) explain that 'fairy rings' commonly found within turf soils are a result of Mycelia which have a 'wax-like repellent surface'. The reorientation of these organic molecules on the solid inorganic surfaces result in a non-zero contact angle between the soil and water which ultimately gives them their hydrophobic qualities.

Water repellency has the effect of increasing erosion by promoting overland flow and in dry periods, causing the preferential flow of water through the soil to the deeper underlying soils and groundwater, which could result in groundwater contamination (de Longe *et al*. 1999; Bauters *et al.* 2000).

2.1.4 Sealed surfaces and soil moisture regime

Soil seal is defined as 'a thin layer which limits infiltration through the (wet) soil' (Duley, 1939 in Scalenghe and Marsan, 2009). The total global area of sealed soils is thought to be in the region of 500,000km^2, equivalent to an area the size of France (Elvidge *et al.* 2007), with 9% of the European land area currently sealed by impermeable cover (Scalenghe and Maran, 2009). Scalenghe and Marsan (2009) have conducted a thorough review of soil sealing within Europe.

The soil moisture deficit, fundamental to shrink/swell cycles is controlled by precipitation, temperature and evapotranspiration, the latter being stifled by the presence of sealed surfaces. This is a result of precipitation not being able to penetrate or infiltration being significantly reduced through the generally impermeable sealed surface, therefore the soil is dependent upon lateral moisture movement in the surrounding soils.

Road and paving construction reduces the ability for moisture to enter or leave the ground (Harrison *et al.,* 2012), dependent on the permeability of the seal (Figure 5). Burton (2001) hypothesized that soils under sealed surfaces (such as the north London roads he studied) would have stable soil moisture levels. However, where mature trees were present, he found soil moisture decreased by up to 8% in the summer months in both fine (clay, silt) and coarse (sand, gravel) soils (Burton 2002). Where trees were absent, there was no significant alteration to the soil moisture profile.

Ground temperatures are significantly affected by sealed surfaces, Takebayashi and Moriyama (2007) state that daytime surface temperatures decrease with differing surface coverings respectively; cement surface, surface with gray paint, bare soil surface, green surface and surface with white paint. Surface temperatures being primarily dependent on their relative albedo, for example a tarmacadam road has a low albedo effect.

Concrete	Clay Soil	Asphalt	Block Paving	Road Surface	Sandy Soil
					
Low	>--------------------- Increasing Permeability ----------------------->				High

Figure 5: Surface type and relative permeability (From: British Geological Survey, 2013)

Conway (2007) identifies that even 2% impervious cover can affect the pH and salinity of soils, both having impacted upon road embankments in Australia (Biggs and Mahony, 2004). Sealed surfaces have the negative effect of providing non-point source pollution to catchments as a result of urban/infrastructure development, however they can also suppress contaminant flow through soil to groundwaters, this is especially the case on petrol forecourts (Clark, 1998).

With increasing urbanisation and development likely to occur in future years, the impact of soil sealing is not a problem that is going to dwindle. Permeable paving (Figure 6) allows higher rates of groundwater recharge, a method that is being used in new developments, which could have the positive effect of not overloading drainage systems which could result in flash flooding, and preventing differential movement as a result of shrink-swell processes. However it does allow contamination resulting from the output of automobiles including hydrocarbons and polycyclic aromatic hydrocarbons (PAH's) to more readily enter the soil and therefore groundwaters.

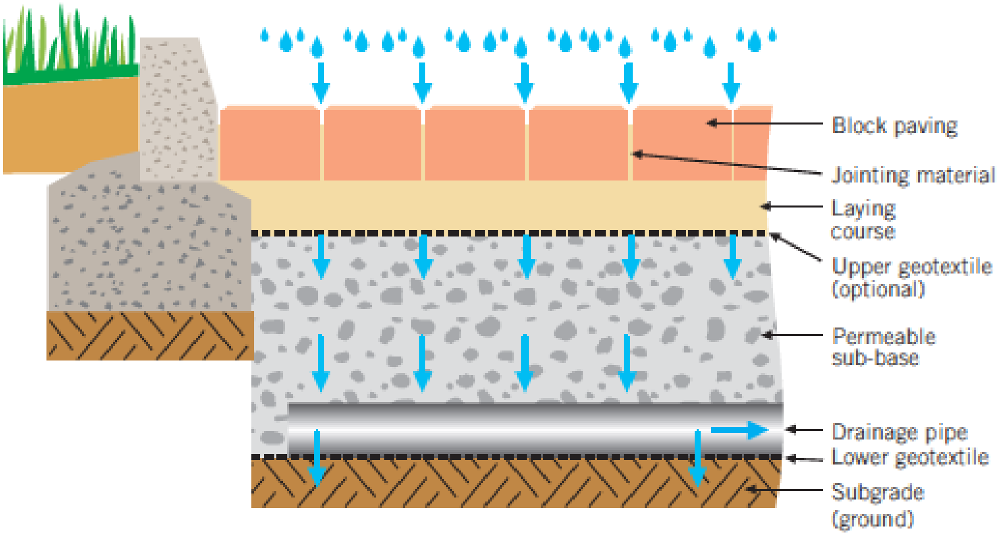


Figure 6: Permeable pavement design method (From: InterPave, 2008)

2.2 Vegetation and subsidence

Vegetation, in particular trees can have a direct and indirect action upon infrastructure assets. Indirectly they induce shrinking of clay soils as a result of their additional uptake of water, often regarded as being the most damaging effect (Forster and Culshaw, 2004), Driscoll and Skinner (2007) have suggested that 70% of domestic subsidence claims are as a result of vegetation induced clay shrinkage. Trees are considered in the calculation of SMD (orchard, deciduous and coniferous), although intra species variability is not considered, deciduous trees having varying temporal 'bud bursts' which influences their water uptake (Biddle, 1998). Trees and their impact on subsidence have raised many issues, both in an engineering and legal capacity.

Directly, the impact of tree roots can cause damage to infrastructure assets, for example a pipe could be exerted to additional pressures by the close proximity of the root system (BRE, 1999; Cameron, 2001).

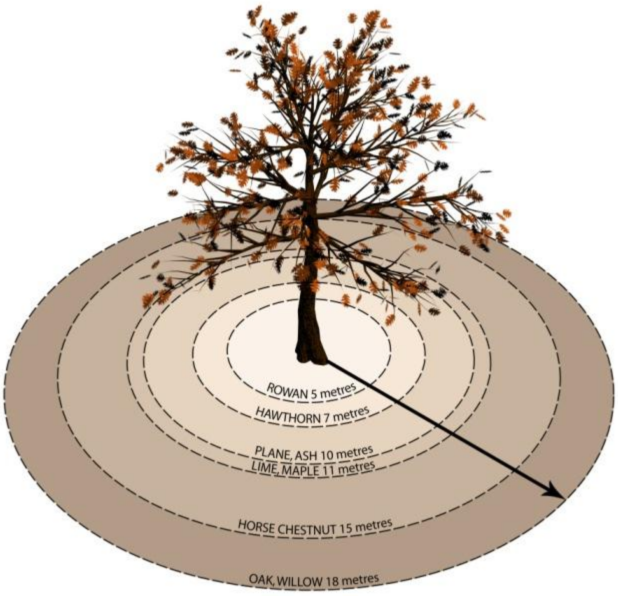


Figure 7: Zone of influence of some common UK trees (From: Jones *et al*. 2012)

The number of claims relating to tree roots has increased throughout the years (Association of British Insurers);

- 1994 – 27,660 claims at an overall cost of £125 million
- 1997 – 53,000 claims at an overall cost of £472 million
- 2003 – 54,100 claims at an overall cost of £390 million

Within London there have been identified approximately 400,000 street trees and 6 million trees of other types (Lawson, 2004). The careful management of trees, incorporating proactive cyclical pruning, helps reduce moisture content uptake, therefore reducing shrink-swell processes (LTOA, 2007). London Borough's that have not undertaken pruning have had to remove twice as many trees as those that have carried out pruning, however removing trees can have the affect of allowing underlying clay soil to rehydrate, resulting in heave and further foundation damage.

The impact of a mature willow and an oak tree to the surrounding soil moisture was considered in North London (Plante and MacQueen, 2011), and showed that moisture loss and subsequent ground movement increased with distance from the tree. Drying was also greatest at a depth of 2-2.5m, Burton (2002) previously showed that a mature oak tree withdrew little water from the top 1.6m of ground. Dessication is generally not thought to occur below 3-3.5m bgl (below ground level) due to the relative inability of tree roots to 'proliferate' under anaerobic conditions, whereas Crow (2005) suggests that tree roots often don't penetrate deeper than 2m, with 80-90% within the top 60cm of the soil profile.

A typical strip foundation (low rise building) exerts an additional load upon the soil, approximately between 20-60 kN/m^2, whereas the load implied through desiccation as a result of moisture uptake by trees can be between 300-1400 kN/m^2 (BRE, 1993). This can be especially problematic where routes encroach upon foundations, as seen in Figure 9.

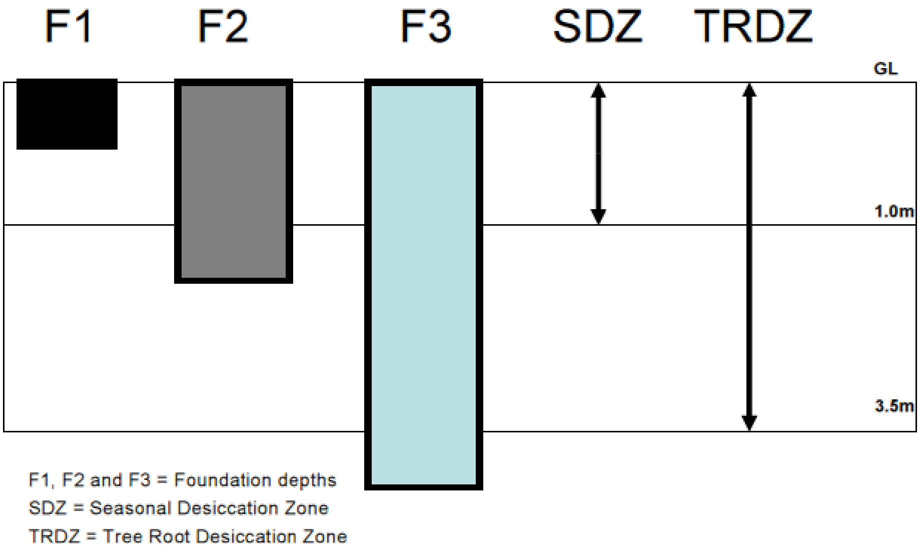


Figure 8: Foundation depths and dessication zones (From: Howorth and O'Sullivan, undated)

The presence of vegetation does not, however, always have a negative effect on the engineering properties of soils, often the overall strength of a soil is increased by the presence of vegetation (roots). Roots of 1-12mm diameter preventing lateral movement of soil particles, therefore reducing vertical cracks propagation.

Depletion of soil water also enables a reduced pore water pressure, subsequently increasing soil suction and bringing soil particles closer together. If soil is not permitted to rehydrate to a point where it could result in swelling (if prone) then the soil mass will be more resistant to deformation as a result of load implied on it (Coppin and Richards, 1990).

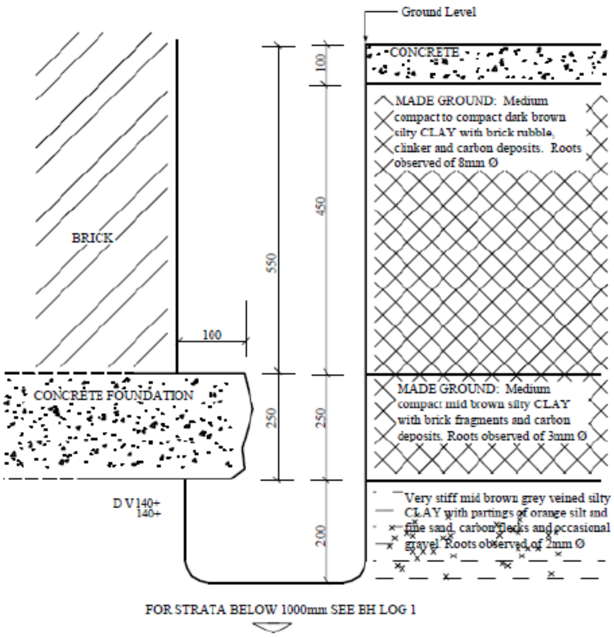


Figure 9: Example cross sectional drawing of foundation ground investigation - note roots present in 'natural clay' at base of strata (From: Parvin and Maclarens, 2012)

2.3 Groundwater impacts on subsidence

Groundwater has a significant effect on clay minerals, due to their high specific surface areas and the polar nature of water molecules (Gillott, 1986). Whereas with granular soils the removal of the finer material (clay/silt) can result in reorganization of the soil particles inducing settlement, especially when under load or being loaded.

Lowering of the water table can either be naturally or human induced, the former meaning little can often be done in terms of remediation. The human action of withdrawing (pumping) groundwater results in a 'vacuum' effect, whereby the finer particles from the soil mass are removed increasing susceptibility to consolidation (Chen *et al.* 2012).

Water table management is a prominent issue for subsidence rates in both a UK and global context. Zanello *et al*. (2011) showed groundwater levels directly controlled subsidence rates in Venice, subsidence halving if the current water table level of 0.5 m bgl was highered to 0.2m bgl. Often lowering of the water table is used to over-consolidate the ground, resulting in reduced pore water pressures and a greater effective stress (Charles and Watts, 2002) that increases bearing capacity.

The natural and/or human lowering of water courses can also have a profound effect on structures, as this often keeps the underlying soil moistened during wetter periods, which if next to infrastructure systems (i.e. highway, rail, buried pipeline) could result in ground movement (Page, 1998). Rising groundwater levels in the prevalent drift and fill that covers much of the city of Birmingham could, under saturated conditions result in reduced bearing capacities of up to 50% compared to that if they were 'dry' (Knipe *et al.* 1993).

Groundwater overexploitation can cause significant impacts on ground subsidence, for example in Indonesia ground levels have fallen some 160cm in the space of six years (Abidin *et al*, 2001) and significant differential settlement has occurred in Murcia, Spain as a result of over extraction of groundwaters. However in the UK, strict regulations on groundwater extraction, which carries a volume-based charge (Cassar, 2010), have been put in place by the Environment Agency as documented in their groundwater protection report (Environment Agency, 2012).

Groundwater recharge is primarily driven by precipitation, and controlled to some extent by the permeability of the soil (Kim and Jackson, 2011).

2.4 Shrinkage and Swelling of soils

Scientific interest in shrink/swell processes in soil was established by Tempany (1917) and Haines (1923), Clay related subsidence (shrink-swell) affecting predominantly the top two metres of ground, that which is most influenced by changes in soil moisture (Harrison *et al*. 2012), however Hawkins (2013) has shown that this could extend to depths of 2.5m.

Approximately 50-60% of housing stock of the English lowlands is built upon clay soil prone to subsidence (Lawson, 2004), covering 20% of postcode sectors (Plante and MacQueen, 2011). Subsidence is generally a process that develops over a significant length of time, i.e.

across seasons, being especially prevalent during drought conditions (Corti *et al*. 2009), therefore unlike mass movement (landslides) and flooding it can be more of a 'chronic' issue.

Corti *et al*. (2009) have suggested that in recent years the impact of soil subsidence in France has been equivalent, financially, to flooding. Within the United States, the financial cost of swelling soils has exceeded other natural disasters (i.e. tornadoes, earthquakes and hurricanes) (Sudjianto *et al.* 2011).

2.4.1 The distribution of expansive soils

The south east of England is particularly prone to shrink-swell processes, this is due to the geological clay formations that are present including; Woolwich and Reading beds, London, Gault, Weald, Kimmeridge, Oxford and Lias Clays and the more geologically recent glacial till (Samuels, 1967). The London Clay formation arguably poses the greatest risk to foundations within the UK (Crilly, 2001).

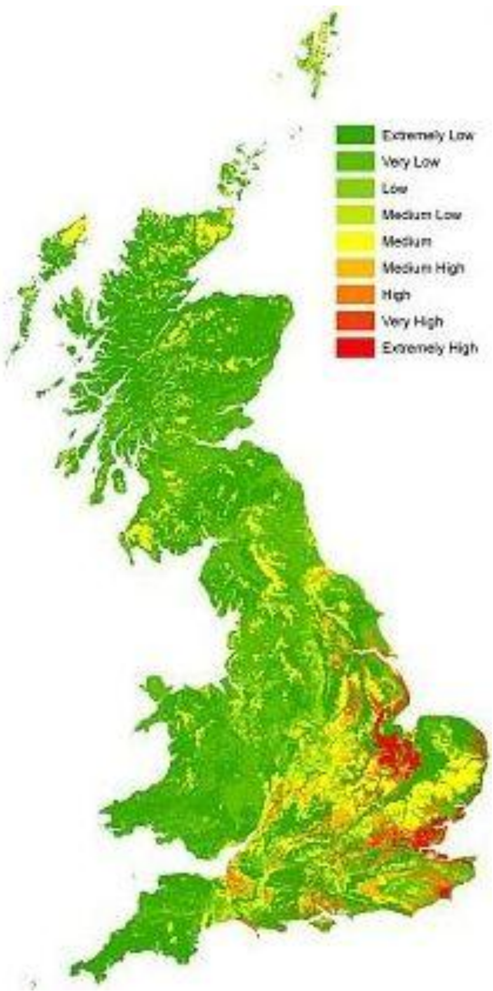


Figure 10: The susceptibility of UK soils to clay related subsidence (NSRI, Cranfield University)

2.4.2 Clay Mineralogy influence on shrink/swell cycles

The clay mineralogy of a soil refers to the type of clay mineral, each of which has a differing grain size, surface area and physico-chemical characteristics (Moore, 1991). Clay minerals in both engineering and in soil science are particles that are less than 0.002mm in size (Mitchell and Soga, 2005).

Clay minerals are derived from (Carroll, 1970): 1) alteration of minerals as rocks in situ as a result of chemical leaching; and 2) altered original minerals removed by erosion and redeposited. There are also a number of clay sized non-clay minerals that are present within clay soils including quartz, feldspar, dolomite, calcite, iron oxides and zeolites.

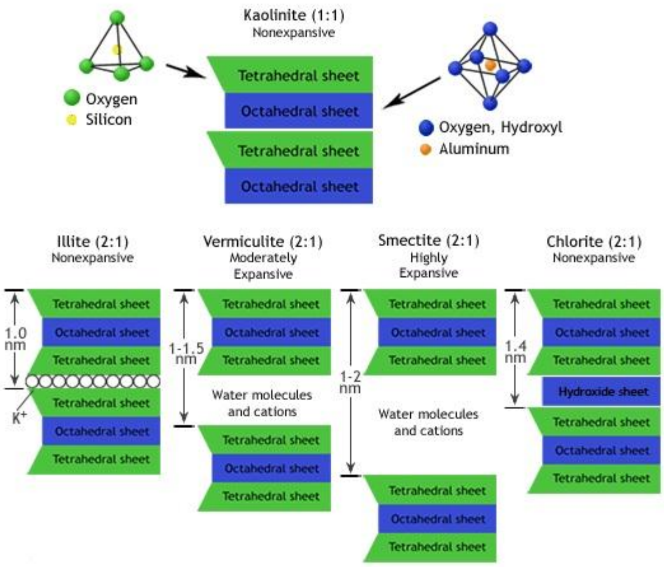


Figure 11: The structure of clay minerals (From: The Cooperative Soil Survey, http://www.soilsurvey.org/tutorial/page8.asp)

It is generally accepted that higher clay mineral content results in higher swelling/shrinkage capacity, Schaffer *et al*. (2008) have also shown that organic carbon is a strong dependent of the shrinkage capacity of a soil.

Clay mineralogy often has a limited role in the geotechnical characterization of soils, due to the expense and time requirements of analysis (Chittoori and Puppala. 2011). Higher clay mineral content and high water contents can limit swelling capacity, due to lower 'micropore' volumes that allow clay mineral expansion (Boivin *et al.* 2004).

Cation exchange capapcity (CEC), the ability of a soil to hold and exchange cations and anions that are able to neutralize negatively charged ions in the clay material (Chittoori and Puppala, 2011;Bridges, 1997). CEC directly affects the thickness of water held between the double layers, smectites and vermiculites have a high exchange capacity, which gives them their highly expanding properties.

The type of cation adsorbed is of importance, monovalent cations (i.e. sodium (Na^{+})) allow greater adsorption of water compared to divalent cations (i.e. Calcium Ca^{2+}) (Biddle, 1998),

the latter explaining why lime treatments are often used to remediate swelling soils, to be discussed later in the review.
The chemical dispersion of clay minerals can infill the pore space immediately below the soil surface, effectively sealing the surface, this reduces permeability and thus the moisture content of clay soils (Stern *et al.* 1991).

2.4.3 Clay surface area

Clays have a high surface area, especially the smectite group that incorporates montmorillonite, often associated with shrink-swell soils (Greene-Kelly, 1974). Approximately one gram of this expansive soil will have a 'specific surface area' of 800m^2 (Godfrey, 1978), the high surface area allowing more water to adhere to the clay surface.
Often however, the presence of pores within the soil mass allows excess water to be stored reducing the swelling potential.

Clay minerals and their surface areas (After: Moore, 1991);

Kaolinite and Chlorite – 5-100 m^{2}g^{-1}
Mica and Illite – 100-200 m^{2}g^{-1}
Vermiculite – 300-500 m^{2}g^{-1}
Montmorillonite – 800 m^{2}g^{-1}

Smectites and vermiculites allow water to be absorbed between the unit layers due to weak interlayer forces (Lippmann, 1976) and the polar nature of water molecules (Gillott, 1986) which is then held in place by hydrogen bonding (Figure 11).

2.4.4 Impact of repeated shrink swell processes

Depending on the local climate, clay soils have the potential to undergo repeated shrink-swell processes, this alternate and repeated process can have a significant effect on soil structure. Repeated cycles can reduce the expansive nature of the soil, as a result of the 'soil fabric becoming disorientated', occuring approximately after the fifth cycle of wetting and drying (Basma *et al*. 1996). Basma *et al*. (1996) also showed that partial drying hampered the swelling potential, whereas fully drying the soil caused an increase in the swelling potential. Yazdandoust and Yasrobi (2010) similarly showed that after four cycles the shrink/swell equilibrium was established and after the first intial cycle the swelling potential decreases, scanning electron microscope (SEM) analysis showed the rearrangement of clay particles after each wet/dry cycle.

2.4.5 Phases of soil shrinkage

Soil shrinkage is defined as 'the specific volume change of soil relative to its water content' (Boivin *et al.* 2006), four phases of shrinkage have been identified (McGarry and Malafant, 1987) as follows;

1. Normal shrinkage – Normal over major part of moisture range reached in the field for soils that shrink and swell.
2. Structural shrinkage – Only occurs over a small part of the range.

3. Residual shrinkage – Only in very dry conditions
4. Zero shrinkage – Soil particles have reached their densest configuration, volumes cannot decrease any further (Bronswijk, 1991).

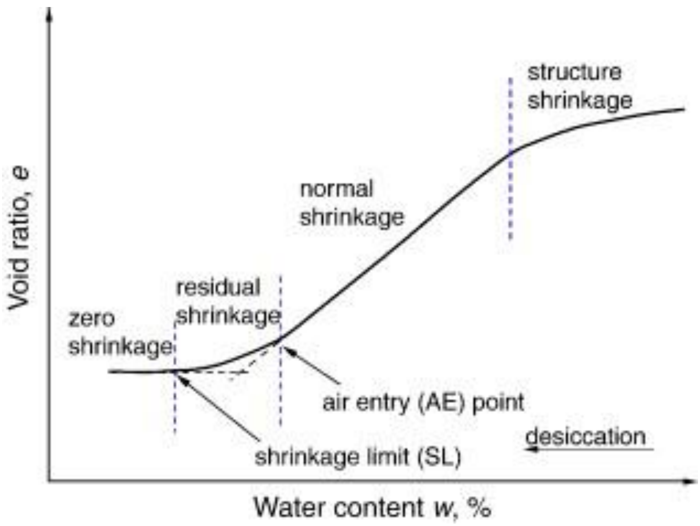


Figure 12: Phases of soil shrinkage as a factor of void ratio and water content (From: McGarry and Malafant, 1987)

The latter [zero shrinkage] would be an extremely rare occurrence, as all the voids from the soil would have to be removed. Jaillard and Cabidoche (1984) suggest that there is great lateral variability with regards to the water content and volume change within a soil mass at the field scale, the cracking of clay soils adding to the complexity. Several studies have sought to further understand the changes at field scale as summarised by Cabidoche and Voltz (1995) with some studies suggesting isotropic change (Aitchison and Holmes, 1953) whereas others have suggested one-dimensional change (Berndt and Coughlan, 1976).

Figure 13: Soil shrinkage in Denchworth soil association, Lincolnshire (Photo: O. Pritchard)

2.4.6 Importance of shrinkage cracks in clay soils

The 'shape, magnitude and pattern of shrinkage cracks' are something that spatially vary throughout the year in many UK soils (Bronswijk, 1988). Cracks within soils represent the boundaries of the aggregates or peds that are formed within the soil mass (Dexter, 1988), and are the result of horizontal shrinkage, with subsidence being the effect of the vertical component (Peng *et al.* 2006). Farewell *et al*. (2012) have already highlighted the issue of surface soil falling into cracks and causing lateral and upward soil movement.

Figure 14: Columnar structure below dessication cracks in a trench excavation in the Oxford Clay, Melksham (From: Hawkins, 2013)

Hawkins (2013) highlights a structural issue of shrinkage cracks in soils, particularly in relation to the construction of trenches. The columnar structure (Figure 14) that is produced in clay soils upon drying is prone to toppling when trenched, and even on rewetting can still be an issue.

However trench stability issues can generally easily be overcome by the use of sufficient shoring methods when constructing trenches (Figure 15) be it for buried utility trenches, foundation trenches or associated earthworks for construction purposes.

The formation of cracks allows for rapid transport of contaminants through the soil profile, allowing contamination of underlying groundwater acquifers (Oostindie and Bronswijk, 1995), a result of increasing permeability (Figure 4).

Shrinkage cracks can have an influence on pore water pressures, which in homogenous clay embankments can lead to the presence of a 'perched' water table (Anderson et al. 1982). Anderson et al. (1982) suggest that a perched water table could lead to softening of the clay, and if near to shear/fissure surfaces could result in embankment failure, especially during high rainfall.

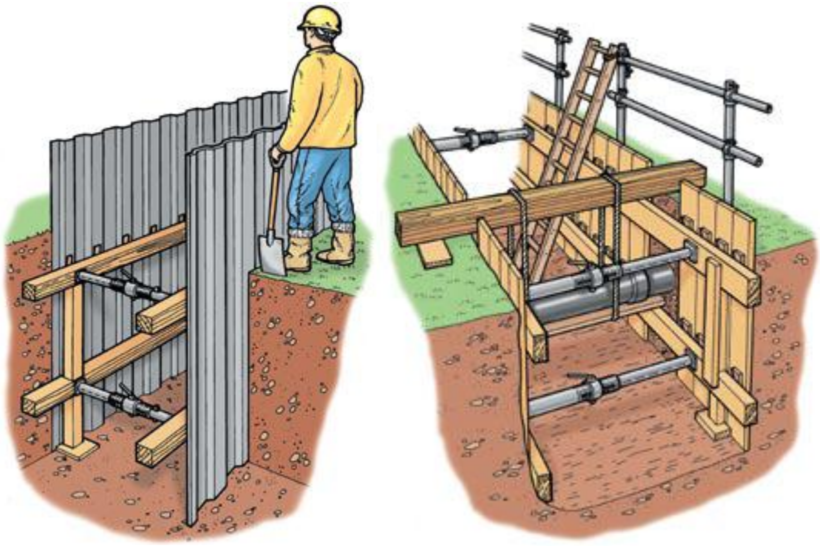


Figure 15: Good practice for digging excavations (HSE, 2012)

2.4.7 Horizontal cracks in soils

Horizontal cracks are a secondary result of vertical crack formation, Chertkov (2013) states that these cracks are not significant with regards to shrinkage factor, however they are of great importance to the soils hydraulic conductivity, the rate at which water flows through the soil (Hazelton and Murphy, 2007).

Bouma and De Laat (1981) suggest how horizontal cracks could hamper upward flow of water throughout the soil profile in particularly dry conditions where surface moisture is scarce.

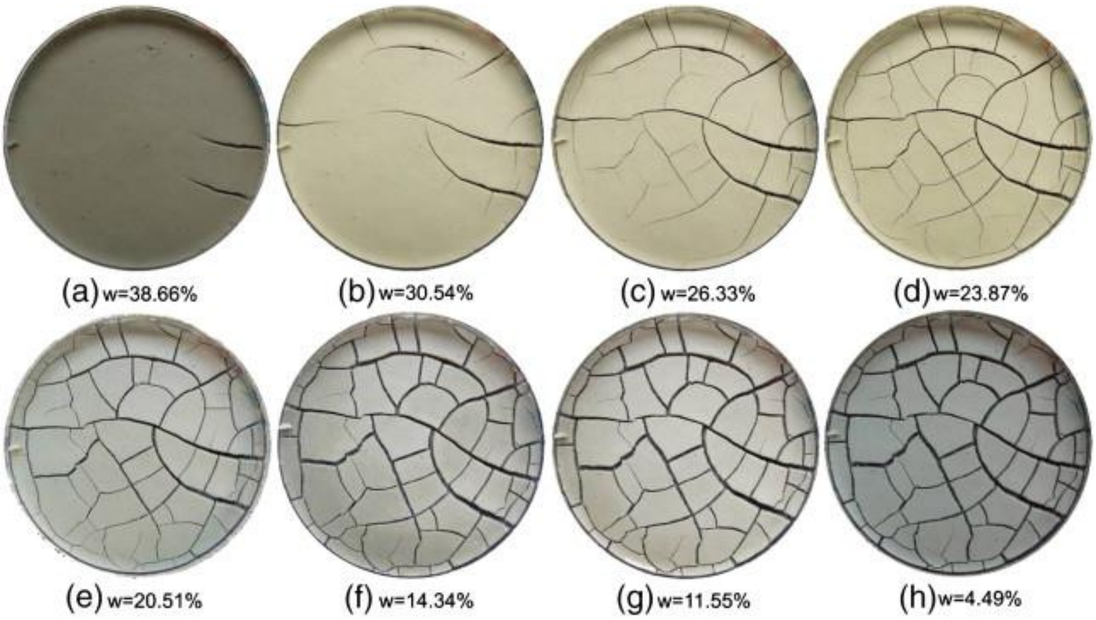


Figure 16: Soil crack formation under differing water contents (From: Tang et al.)

2.4.8 Calcium Carbonate

The formation of diffuse double layers on clay surfaces is shown to be the main driving force behind the swelling of clay soils. Calcium carbonate inhibits the swelling of clay particles by suppressing the formation of these double layers, calcium ions increasing the solubility of the clay (Rimmer and Greenland, 1976). This was demonstrated in the gleyed calcareous soils of the Evesham and Wicken series, when compared to the non calcareous equivalents (Avery and Bullock, 1977).

Calcium carbonate can also act as an inorganic cement which prohibits the clays from being able to swell, and in extreme cases can completely encrust individual clay particles. Often ground is treated with lime based products in order to reduce swelling processes (Anderson *et al*. 1982).

2.5 Testing methods for shrink/swell soils

There are a number of testing methods for establishing the shrink/swell potential of clays. A measure of the relative change in the volume of clods subject to moisture change (Hazelton and Murphy, 2007) is the coefficient of linear extensibility (COLE) (Soil Survey Staff, 1975).

Suspected swelling soils are often tested within the UK using routine measurements such as Atterberg limits (the liquid limit (LL), plasticity index (PI) and shrinkage limit (volumetric and linear) (Dakshanamurthy and Raman, 1973). Clayden and Hollis (1984) express the close relationship between COLE and the linear shrinkage measurement (British Standards Institution, 1975), the latter being more readily undertaken in the UK. The COLE measurement is shown to have a close correlation to CEC, which subsequently shows a good correlation with liquid limit (Figure 17) (Avery and Bullock, 1977).

Plasticity index represents the water content at which the soil behaves as a plastic material (i.e. unrecoverable deformation that does not result in cracking or crumbling) where shrinkage is directly proportional to the amount of water removed from the soil. Plasticity is gained from the abundance of clay minerals and/or organic material (Craig, 2004), however the role of clay mineraology (Sridharan and Prakash, 2000) is often not considered during ground investigations, which as previously discussed are rarely tested due to time and cost restraints.

Prior to plasticity index testing the coarser fraction (>425µm) is removed during sieving for particle size distribution calculations. The resultant plasticity index is therefore suggestive of the 'pure' clay fraction rather than the in-situ material (BRE, 1993), which in glacial tills often have a sandy/gravelly component. Glacial tills show extreme variability in their plasticity indices, as shown by Denness (1974), where within 1m^2 of soil, liquid limits varied between 50 and >35% and plastic limits between 22 and >16%. Trenter (1999) states that caution should be taken in using plasticity indices of glacial tills to interpret strength and compressibility.

Plasticity measurements are correlated with other swelling parameters of which have been summarized extensively by Yilmaz (2006). Biddle (1998) suggests that plasticity index is of limited value in predicting actual shrinkage behaviour, allowing only for a qualitative estimation in the ‘normal’ phase of shrinkage.

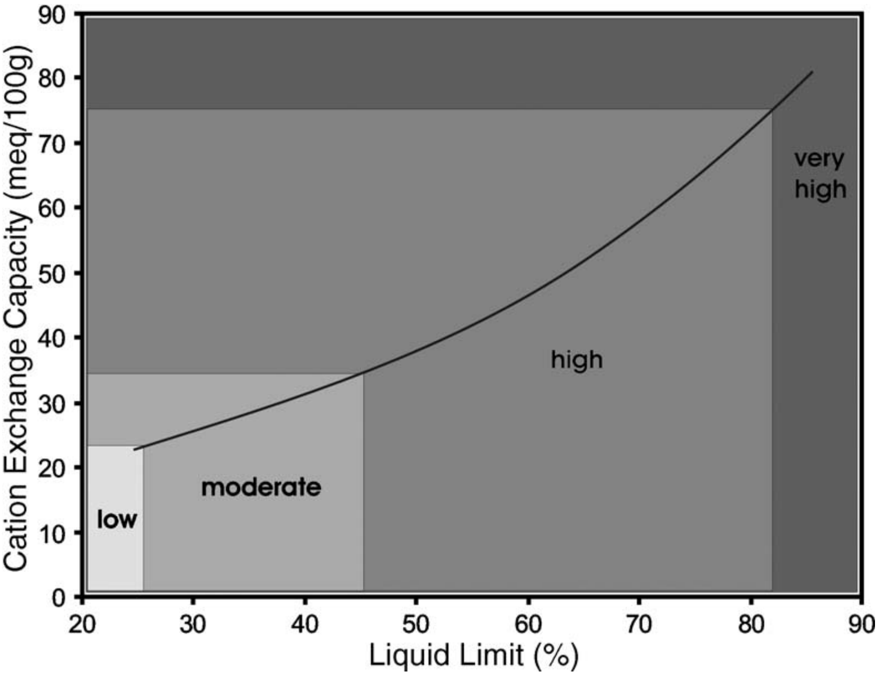


Figure 17: Proposed swelling potential chart for the soils based on cation exchange capacity and liquid limit (From: Yilmaz et al. 2006)

However Izdebska-Mucha and Wojcik (2013) and Sudjianto *et al.* (2011) have shown that volumetric shrinkage of clay soils show a good correlation with plasticity index as well as initial moisture content, shrinkage range and clay content. Crilly (2001) has shown that plasticity index is closely related to shrink-swell damage, with virtually no cases of foundation damage recorded with plasticity indices of less than 10%.

2.6 Use of remote sensing in assessing shrink/swell susceptibility

It is established that specific minerals have differing optical properties, the use of reflectance spectrometry in laboratory conditions has demonstrated this (Hunt and Salisbury, 1970), identifying the specific clay minerals allows a determination of swelling potential.

The use of remote sensing techniques to establish clay mineralogy of near surface soils and their subsequent engineering properties (Yitagesu et al. 2009) has been established, however heavy vegetation cover and poor reflectance could hamper satellite visibility (Chabrillat *et al*. 2002).

Other studies have used remote sensing to directly measure the subsidence rate of the ground surface, for example Boyle *et al.* (2007) have shown differential ground movement across the London Boroughs. Cigna *et al.* (2012a) have shown how remote sensing, specifically InSAR (Synthetic Aperture Radar Interfereometry) can be used on a nationwide scale for the UK, to assess for natural/human-induced subsidence, ground collapse and shrink swell clays, often to a millimetric accuracy. te Brake *et al.* (2013) have also shown how frost heave can be deduced from InSAR technology at an agricultural field scale.

Overall the use of remote sensing within the UK and worldwide is shown to be of great use with regards to expansive clay research and categorisation, especially for large infrastructure networks that span large geographically distant areas, which cannot ultimately avoid geohazards. Remote sensing also allows for better designed ground investigations prior to the construction phase.

2.7 Shrink Swell impacts on critical infrastructure

2.7.1 Structures

Most damage that results from shrink swell processes are apparent on light brittle structures such as 1-2 storey buildings (Gourley *et al*. 1993) with most research aimed at the domestic property market (Driscoll and Skinner, 2007; Institute of Structural Engineers, 2000).

Swelling soils can exert a pressure of up to 200 kN/m on [light] structures (Johnson, 1982), which are brittle by nature of their construction, often placed upon strip footings. Recommendations are generally made for void spaces to be present between the soil surface and floors of properties to allow for such expansion (NHBC, 2010), as often the maximum heave is in the centre of the structure, where moisture levels are highest (Brink *et al.* 1982).

Farewell *et al.* (2012) identify the following infrastructural buildings being at risk of shrink swell processes, including; 'pumping stations, sewage treatment works, recycling facilities, substations and telephone exchanges'.

Johnson (1982) highlights the varied nature of foundation failure as a result of shrink-swell clays, considering 8 domestic sites on the London Clay in Fareham Only one site had undertaken an extensive ground investigation of the highly susceptible (shrink/swell) London Clay soil, which had previously plagued rail projects and the construction of the M27 in the locale.

Many studies have considered the impact of shrink/swell processes on structures, but few have sought to investigate the impact of structures on shrink/swell soils, however consideration was attempted as early as 1948 (Cooling and Ward, 1948).

Hawkins (2013) has since examined the effect of structures on shrink/swell processes, predominantly structures affect the amount of sunlight that reaches the ground around them (Figure 18). Hawkins (2013) also states differential movement caused by shrink-swell clays can exert large stresses where buried utilities enter buildings. This is likely to result in failure of the utility with cast iron pipes being most susceptible, however plastic pipes can eventually weaken and fail due to this process.

Where clay soils shrink laterally away from the exterior wall of a building it can be problematic, as its allows a preferential pathway for water to enter the deeper substrate, which can lead the walls and foundations to buckle outwards (Page, 1998).

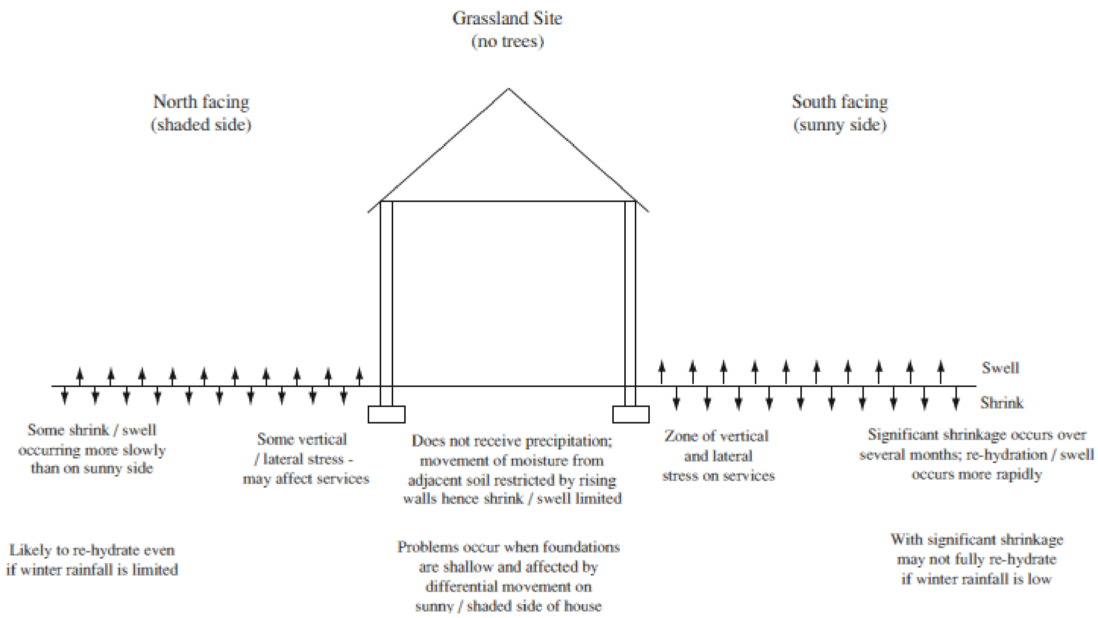


Figure 18: Influence of a structure on shrink/swell processes (From: Hawkins, 2013)

2.7.2 Underground utilities

The UK water supply network is characterised as an 'ageing, predominantly cast iron, infrastructure' (Atkinson *et al*. 2002), consequently the Office of Water Services (2004) identified that leakage of the UK's water network was equivalent to 360 litres per hour per kilometer of main.

There are numerous mechanisms in which pipes fail, fractures being the most contributory to leakage (Clayton *et al*. 2010), Clayton *et al.* (2010) state circumferential failure as a result of the bending or tensile of a pipe section being representative of a typical failure model. A significant amount of the UK sewer network is cracked or deformed by 5% or more, which leaves it vulnerable to any additional ground movements that it may face (Ofwat, 2004).

Corrosion of pipes has been considered in a separate report (Pritchard *et al*. 2013b), however it is of importance when considering pipe failure as a result of ground movement. Cast iron water pipes that have corrosion pits extending to 11mm can result in a reduced strength of <50 MPa (Clayton *et al.* 2010), therefore desiccation of soil caused by tree roots exerting pressures of between 20-30 MPa can be a potential threat to partly corroded pipes. Atkinson *et al.* (2002) showed that even pit development of 2-4mm is responsible for a change in failure mechanism.

Drying clay soils tend to harden, leading to more problematic excavation, which when investigating/replacing underground infrastructure can result in further damage, especially if using mechanical excavation techniques. However in recent years this has been compensated by using hydro/air vacuum excavation (Figure 19), which eases the stresses imposed by excavation on underground infrastructure. Disturbance of the soil profile could also lead to premature failure through settlement and consolidation (Sosa and Alvarez-Ramirez, 2009).

Failure of drains and water mains and subsequent escape of water (often at high pressure) can result in ground movement affecting other proximal buried services, which can be as little as 10-50cm from the affected service (Burton, 2001).

Leaking water in clay soil can result in swelling of up to 10% of the original volume (Nelson and Miller, 1992) resulting in significant movement that could damage utilities (especially partly corroded pipes) (Jones and Jefferson, 2012). Page and Murray (1996) identified leaking sewers as being a major contributor in structural defects in domestic properties, the typical 'glazedware' material and shallow burial depth (<450mm) make them extremely prone to shrink/swell effects.

Oliff *et al*. (2001) regard the settlement of soil as both inducing failure in older (cast iron) pipelines but also the most common cause of failure in modern (plastic) pipelines. This is especially prevalent where backfill has not been compacted suitably, which results in a higher vertical diametral strain (VDS) on the plastic pipe/duct (Hounsome and Fairfield, 2001). VDS is shown to increase with temperature, newly laid bituminous tarmac could heat the underlying soil to temperatures of ~90^{o}C, however in the study by Zohrabi *et al.* (1998) the pipe was protected by the insulating properties of the sand backfill.

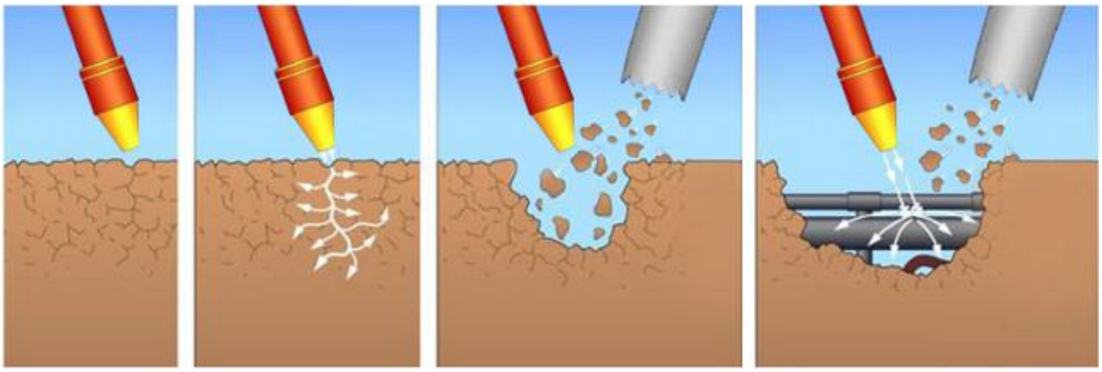


Figure 19: Process of air/hydro vacuum excavation in soils to expose buried infrastructure (From: www.suction-excavator.com)

A sandy backfill can however result in the formation of a man made aquifer, which in a clay soil could create a preferential pathway for groundwater flow or liquid derived from a burst pipe. The resultant erosion that could occur could lead to the settlement of pipe(s) could lead to fracture and further failure.

2.7.3 Pylons

Single wooden post pylons used to carry overhead electricity and telecommunications lines can be particularly vulnerable to soil movement (Figure 21) as they do not have sufficient ground investigation before their installation, and appropriate foundations.

High voltage power lines, carrying voltages in excess of 132kV are generally better intrinsically designed (Figure 20) having either piled or large concrete pad foundations, often adequate ground investigation is conducted, the same applies for larger scale substations (>132kV).

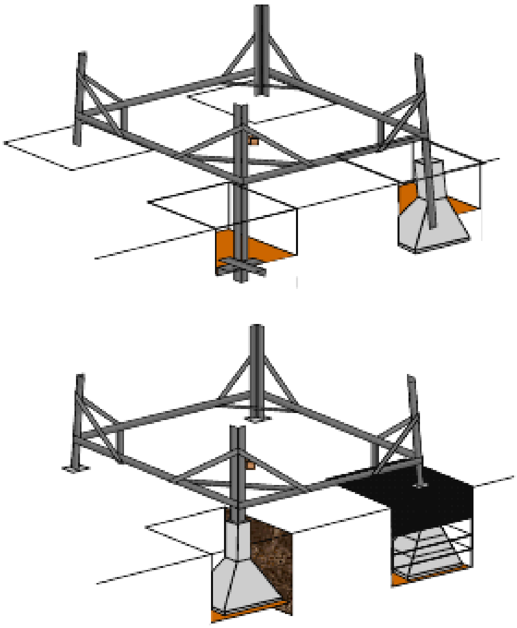


Figure 20: Foundation techniques for high voltage electricity transmission pylons (From: National Grid)

Figure 21: Telecommunications pylon leaning as a result of subsidence, A1011, Bates Drove, Norfolk (Photo: O. Pritchard)

2.7.4 Piled foundations

Crilly and Driscoll (2000) have investigated the effects of shrink/swell clay soils (London Clay) and their impact on lightly loaded piles. They found that on drying the shrinkage of the soil in the top two metres of ground had little effect on the pile as the soil shrank away from it, however when swelling occurred an uplift force was placed upon the pile, it was only the result of lower shear forces (between 4-6m) that prevented further uplift of the pile shaft.

As piles are normally aimed for deeper applications, the near surface soils generally don't have a considerable effect on piles.

2.7.5 Highways

Similar to light structures, highways are susceptible to shrink swell clays, due to their relatively light construction. Generally major UK highways (A roads and motorways) are well designed and better engineered to cope with potential geohazards (Chaddock and Roberts, 2006). Minor highways (B-Unclassified roads) represent the largest majority of the UK network and have greater interaction with underlying soils, as engineering fill material is not often used within their construction (Brink *et al*. 1982), with often a thin covering of tarmacadam (Figure 22).

Authority	Reported Drought Damage (£000)
Lincolnshire	7,397
Essex	5,614
East Sussex	5,568
Kent	4,167
Cambridgeshire	3,522
Hampshire	3,030
Peterborough	2,400
West Sussex	2,221
Isle of Wight	1,500
Wiltshire	1,302
Buckinghmshire	1,200
Surrey	1,000
Suffolk	750
Norfolk	650
Bedfordshire	300
Total	**40,621**

Table 1: Drought damage to roads in 2003 (From: Willway *et al*. 2008)

These evolved roads are deemed to be the most vulnerable and fragile systems posing the highest financial risk to local authorities, particularly in regard to soil movement (Willway *et al.* 2008). Table 1 shows the relative costs of drought damage for highways across the UK during 2003, showing the large impact that soil can have upon highway asset maintenance.

Astbury (1958) has suggested that roads in the fenlands of East Anglia were among the first roads to be built in England, during the Bronze Age. The next section is going to discuss the impact of ground movement on roads in East Anglia.

2.8 Peat shrinkage and Fenland roads, East Anglia

Fenlands of the UK cover an area of 439,000 Ha (Carey *et al*. 2008), the fenlands of East Anglia in particular are an important agricultural resource (Dawson *et al*. 2010), the draft European Soil Framework Directive (2006) regard the decline of soil organic matter as one of their top priorities.

In these predominantly agricultural communities there is reliance upon the highway network to transport goods to market and bring in vital supplies. There is also a need for providing maintenance access to other critical infrastructure systems such as substations, pumping stations etc.

Several East Anglian highways authorities (Lincolnshire, Suffolk, Norfolk and Cambridgeshire) have stressed that soil subsidence has caused heavy damage to their highway network, most reportedly in times of drought. This culminated in a bid to government for additional road funding that was unsuccessful (Mike Coates, *Pers. Comm*.), local media reported "'Drought' cracking up roads in Peterborough: multi million pound bid for cash for repairs" (Peterborough Telegraph, 2011). Norfolk county council have highlighted that approximately 4,000km of their road network are on subsidence prone soils (Robert Noakes, *Pers. Comm*.).

Peat wastage as a result of drainage measures since the 17th century have had a great impact on critical infrastructures (i.e. roads) due to the overburden pressure posed by the infrastructure asset. An applied load 'strongly influences the relationship between the shrinkage geometry factor and moisture value' resulting in a greater magnitude of subsidence (Oleszczuk *et al*. 2003). Peng *et al.* (2007) also suggest that organic soils show higher shrinkage and less swelling than those of inorganic soils.

Unclassified roads in the fenlands are deemed evolved, whereby they have not been subject to modern engineering development and instead have 'evolved' from older roads likely dating back to Roman occupation and possibly beyond.

It has been shown that in certain countries, lightweight fill has been utilized in order to construct embankments for such things as highways and railways using 'polystyrene blocks, sawdust, brushwood, and peat bales' (Riad *et al*. 2004; Shorten, 2004; Waltham, 2002).

Figure 22: Thickness of tarmacadam on an unclassified road, Nr Grantham, Lincolnshire (Photo: O. Pritchard)

Figure 23: Severe rutting on an unclassified road, Holme Fen, Cambridgeshire (Photo: O. Pritchard)

3. Consolidation

Consolidation theory was first described by Terzaghi (1925) and is generally well understood by geotechnical engineers today, the theory is based upon a load being applied to the underlying ground. It has to be noted that consolidation can only occur on cohesive (silt/clay) soils as the process is deemed compression on non-cohesive (sand/gravel) soils. Incidentally the process of 'compression' is almost instantaneous when a load is applied to non-cohesive ground (Das, 1994).

Clay soils, especially that of glacial origin can be naturally consolidated, often referred to as 'overconsolidated' clays whereby they have in the past had loads applied to them (i.e. glaciers/deposited material), loads which they have subsequently lost. This loss of load results in swelling (rebound) of the clays that can take place over significant lengths of geological time, an example of this would be the effect of the glacier load at the end of the last ice age (Craig, 2004). Other forms of load could be the construction of buildings, embankments, or a piece of infrastructure (i.e. road, rail lines).

The amount and rate of consolidation of a soil body is determined by: 1) Fabric and structure and 2) time and rate of loading. When the load is applied the water within the soil is forced out, without air entering the pore system of the soil, effectively the bulk volume of the soil decreases.

The result of the applied load and subsequent consolidation results in downward movement of the ground surface, it is sometimes practice on some sites to now pre-apply a load to the area of development which 'pre-consolidates' the ground (Figure 24). Schaffer *et al.* (2008) showed that compaction of the ground will lead the soil structure to become 'rigid' as pore space is reduced and individual grains become interlocked.

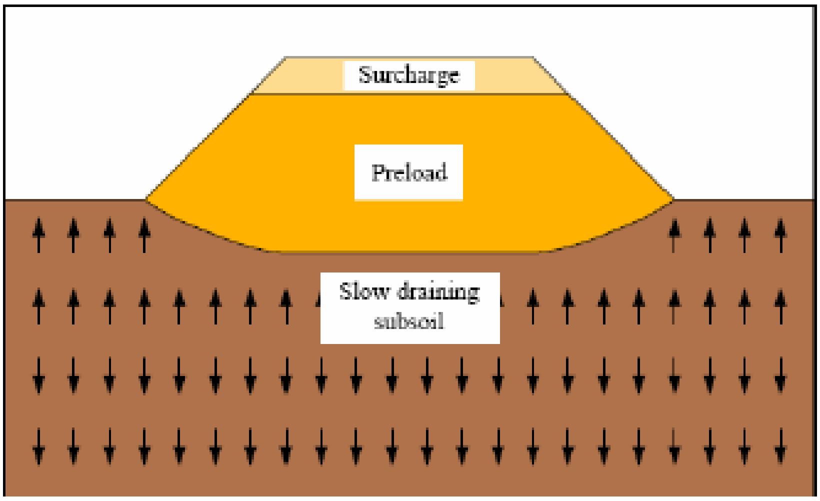


Figure 24: Preloading of subsoil (From: Stapelfeldt, 2006)

3.1 Settlement

Although consolidation is encompassed within 'settlement', rather than the expulsion of water, the mechanism is more reliant upon the 'change in shape of the soil elements' (Fang and Daniels, 2006).

It is differential settlement (Figure 25) that is harmful to structures and infrastructure (i.e. highways) as their brittle construction causes tension cracks to form that could result in eventual failure of the system/structure. Page and Murray (1996) identified a property in Nottingham that had suffered severe differential movement as a result of fines being washed out of the fill material placed under the domestic property as a result of a sewer pipe breakage. The differential shrink/swell around a structure (Figure 18) could result in the differential movement, often especially near the corners of a structure.

The most famous example of differential settlement is the leaning tower of Pisa, Italy, where soft alluvial clays have caused the tower to lean significantly, as a result of deformation of the clays imposed by the 14,500-ton structure (Burland *et al*. 1998).

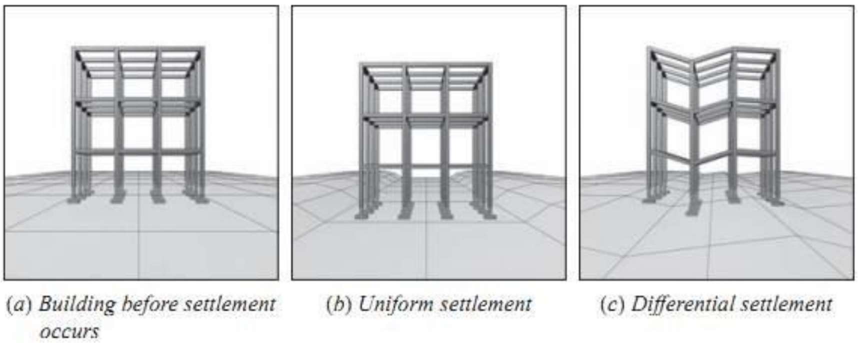


Figure 25: Types of settlement of building foundations (From: http://theconstructor.org)

4. Erosion

Erosion of soils, within UK studies often relate to the soil loss associated with agriculture (Boardman, 1983), a significant problem in both UK upland and lowland areas (Brazier, 2004).

Erosion can take place in a variety of ways, due to water, wind, mass movement, dissolution of carbonate rich material, translocation and mechanical processes (Farewell et al. 2012; Toy et al. 2002). Water is the main driver in the UK for erosion of soils, with the latter 'mechanical' process incorporating mass movement of soil material and the tillage of agricultural fields. All erosional processes involve two distinct mechanisms, firstly 'detachment' of soil particles from the rest of the soil mass, leading to secondary 'transportation' by one of the previously identified mechanisms to their place of deposition (Garvin *et al*. 1979).

In the UK it is more often agricultural practices that lead to increased mobility of soil particles, as a result of tillage (van Oost *et al*. 2006), however construction projects that disturb the soil substrate can have a similar effect. Considerable quantities of soil can be transported through erosional processes, Boardman (1983) suggests that up to 181 tonnes per hectare was lost (fine loamy soil) in a 9 month period from Albourne, West Sussex, however this was due to agricultural processes.

Erosion on highway embankments have been extensively studied, in particular embankments that have recently been constructed or devegetated are at most risk of erosional processes. Rapid erosion and deposition of soil across roads and railway tracks can cause significant delays and associated costs. Cerdà (2007) showed that erosion rates are higher in winter during wetter soil conditions, as cracks (within clay soils) are not present which subdue overland flow.

Farewell *et al.* (2012) have identified that sandy soils are prone to erosion, especially near leaking drains and gutters.

The Clay Research Group (2012) have recently highlighted that 25% of valid subsidence claims are as a result of escaping water (i.e. leaking drains/water mains) in non-cohesive soils, supported by statistics from Direct Line (2012) and supports the findings of Page and Murray (1996) who state that ~30% structural defects can be attested to leaking sewerage and storm water systems alone.

Wind induced erosion occurs where soil particles are transported through the process of saltation with much finer particles being transported through suspension (Toy *et al*. 2002). Wind erosion is abundant across much of East Anglia, the phenomenon locally known as 'fen blow' (Figure 27) has resulted in major disruptions to traffic as a result of poor visibility (BBC, April 2013). With little or no vegetation, the reduction of shear velocity of the wind (i.e. drag on air flow) cannot occur, leading to higher wind speeds and more erosive power (Morgan, 1995).

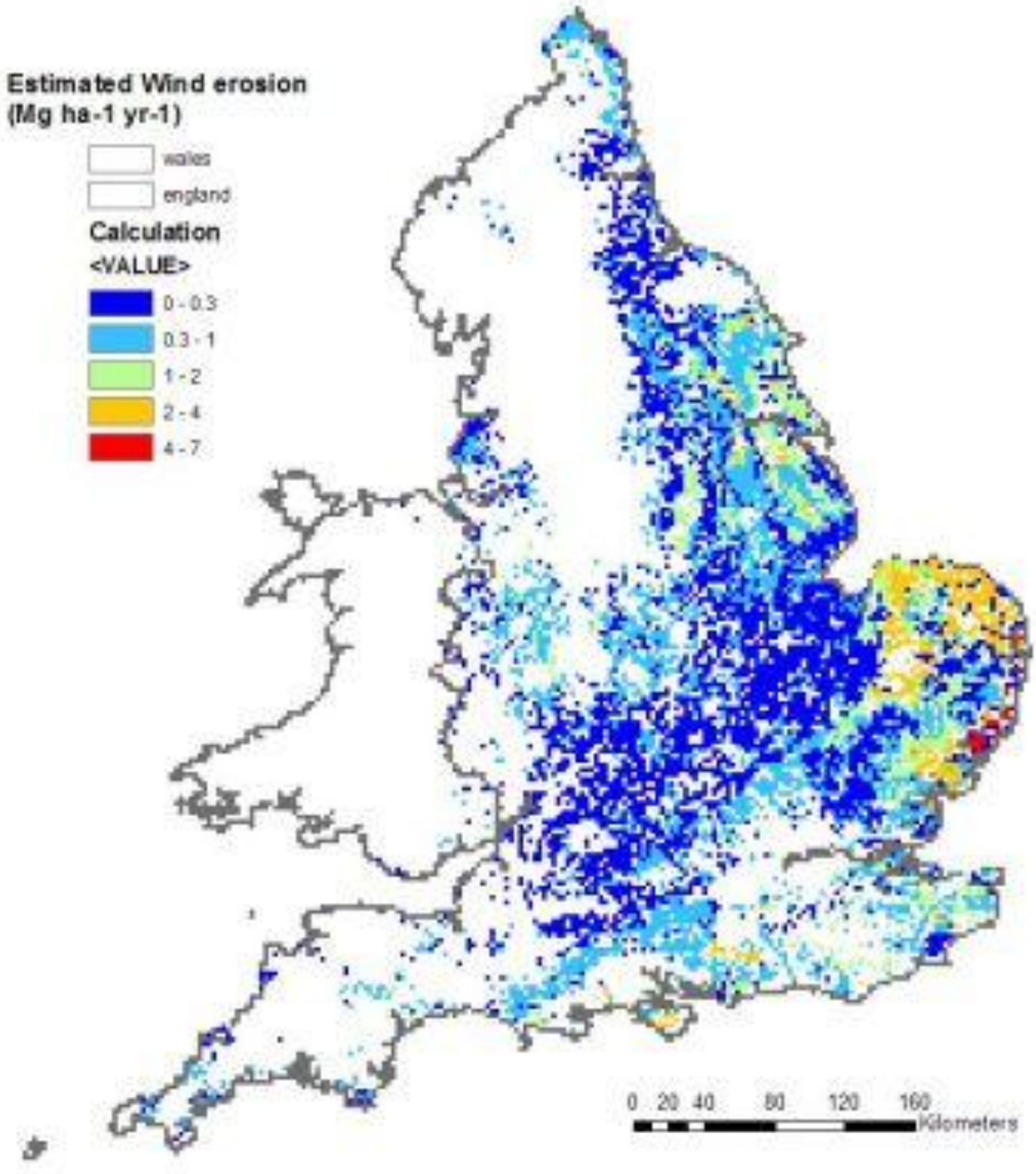


Figure 26: Estimated wind erosion rates for UK soils (NSRI, Cranfield University)

Figure 27: 'Fen Blow' across Hod Fen Drove, Yaxley, Cambridgeshire (M.Trolove, geograph.co.uk)

Combatting erosion on road embankments has employed a number of techniques (Barton, 1987), these techniques could also be used for erosional processes that affect other critical infrastructures, and are as follows;

- Erection of a crash barrier at slope toe to prevent further erosion by traffic
- Cut off drain in field parallel to slope crest to intercept potential run-off.
- Hydroseeding bare soil areas
- Placement of 'geo-grids', pegged to the slope that allow for vegetation growth to help further stabilize the soil mass.
- Soil nailing
- Regrading slope and providing on slope drainage
- Revetting, gabions etc.

Sandy soils do not have the same advantage as clay soils, as they are unable to form a 'protective crust' (Figure 28) that stops their initial erosion. Sandy soils are therefore prone to rapid erosion, especially during a pipe burst, which often results in longitudinal failure of the pipe (Balkaya *et al.* 2012). This has been counteracted in certain geotechnical operations via the injection of gel into the sandy substrate, which provides cohesion and prevents sand washout (Shroff and Shah, 1980).

Erosion and subsequent exposure of piles as a result of burst water mains or a flash flood can lead leave them susceptible to damage, especially in sandy soils as shown in Figure 30.

Figure 28: Formation of a surface crust in a sandy loam soil (From: NSRI, 2013)

Rivers can act as a rapid source of erosion, especially on meandering bank sections, where saturation of the soil results in the soil mass becoming 'liquid' leading to collapse (Farewell *et al*. 2012). In areas with little or no engineering protection measures, certain critical infrastructures may be at risk, for example, electricity pylons (Figure 29).

Deposition and sedimentation are a subsidiary impact of erosion at a local and considerable distance from the source site, this can be a particular issue with regards to dam/reservoir volume(s), that Palmieri *et al*. (2001) suggest is a currently prominent issue. Rowan *et al*. (2005) have shown that Abbeystead Reservoir in Lancashire has fallen to 6% of its capacity over the 140 years that it has been in existence (Farewell *et al*. 2012).

Figure 29: National Grid pylon route near eroding riverbank (centre-left) being investigated for erosion protection measures, UK (Photo: O. Pritchard)

A small scale study on a reservoir in Devon showed an average sedimentation rate of 1.7 cm yr^{-1}, with some more extreme events providing 3-4cm of deposition (Foster and Walling, 1994). The movement of fine material (e.g. clay/silt) can also be problematic for drainage systems, the fine grains causing blockage of perforated drains (Navid, 2011).

Figure 30: Washout of sandy gravels revealing bridge foundations (From: ADEPT, Undated)

4.1 Soil piping

The study of soil piping within the UK is little understood, especially regarding their distribution. It was until recently believed that sediment transport was only achieved as a means of mass wasting, and/or overland flow systems, established by Horton (1945) who proposed the conception of Hortonian Overland Flow (Bryan and Jones, 1997).

Jones (2004) suggests that approximately 30% of UK soils are susceptible to piping, especially in peat and podzolic soils. The significance of piping is that they can result in the rapid erosion of subsurface soils, forming pipes of up to 1 metre diameter (Waltham, 2002) that can subsequently collapse; they also can result in alteration of groundwater regimes resulting in slope stability issues (Garcia-Ruiz *et al.* 1997).

The use of ground penetrating radar can generally identify soil pipes, however if less than 10cm in diameter they are often undetectable (Holden *et al*. 2002).

5. Ground heave

5.1 Frost Heave

The freezing of water leads to an expansion of approximately 9% its original volume. The alternate freezing and thawing of soils, can have the affect of rearranging the structure, leading to greater aggregation of particles and some degree of soil mass consolidation (Kozlowski and Nartowska, 2013). Soils most susceptible are silts, loams and clays that have a fine texture (Bronfenbrener and Bronfenbrener, 2010).

Frost action in soils within the UK is generally limited to depths between 0.5-1.0m bgl (Craig, 2004), the depth at which most buried infrastructure and foundations are emplaced, the effect of frost heave on block walls and wooden post is considered in Figure 31.

However freezing ground can have the positive effect of slowing down microbial activity in soils, which in wasting organic soils could result in slower rates of subsidence (Drotz *et al.* 2009).

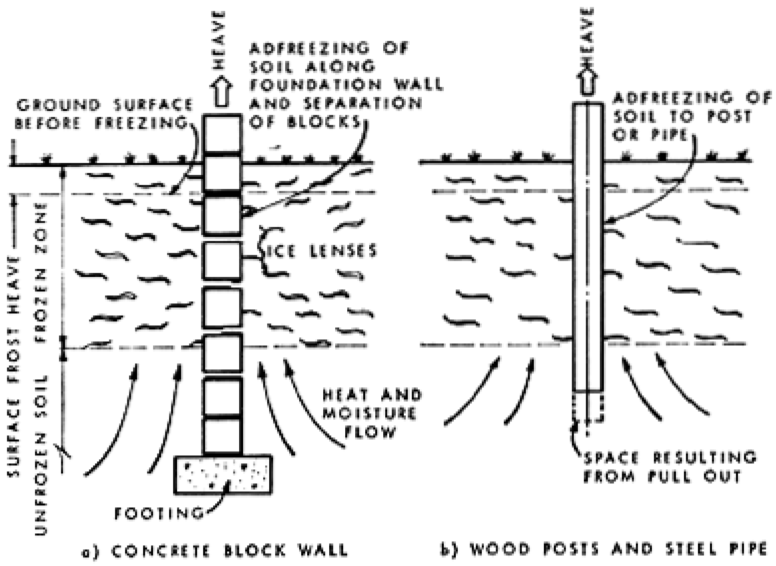


Figure 31: Behaviour of concrete block walls and wooden posts in frost heave susceptible soils (From: Penner and Burn, 1970)

The predictions of the UKCP09 climate models suggest that frost heave is not likely to be a significant factor in future years (Willway *et al*. 2008). Farewell *et al.* (2012) suggest that frost action that does occur will generally only affect shallower placed infrastructure systems.

5.2 Expansive soils and sulfate

Practitioners have sought to alter the physicochemical properties of clay materials (Petry and Little, 2002), however it was previously considered that 'sulfate induced heave' was a result of shrink-swell processes in underlying natural clay soils (Puppala *et al*. 2005), whereas it is often a result of the addition of calcium based stabiliser treatments (Lime/Cement) (Dermatas, 1995;Kota *et al*. 1996).

Infrastructure networks (ie roads, rail, pipelines) covering large geographical distances often encounter shrink-swell prone soils. It is common for these soils to undergo various ground improvement techniques to influence their 'engineering characteristics' (Cai *et al*. 2006). Lime and cement are added to improve the strength of soils and prevent 'soil heaving' (Puppala *et al.* 2003), the process results in ion exchange and cementitious reactions, allowing soils to gain strength by decreasing plasticity index and swell/shrinkage strain potentials of expansive soils (Hausman, 1990). This occurs most commonly in the construction of roadways and structural fills (ie embankments) (Mitchell and Dermatas, 1992).

Sulfate heave does not generally cause problems in high plasticity clays, therefore plasticity index can be considered a value of susceptibility.

Rollings and Rollings (1996) identify two types of sulfate attack on stabilised (lime/cement) soils;

- Type I: Conventional sulfate attack – Where chemical products (ie calcium, sulfate and alumina) are provided by the Portland cement/lime being used.
- Type II: Clay based sulfate attack – Where Portland cement/lime provides calcium and the clay minerals provide the alumina to react with the sulfates.

It is type II sulfate attack that we are concerned with in this review, Snedker and Temporal (1990) suggest that the following conditions are necessary for sulfate attack to occur, including high pH, sufficient clay mineral content giving an adequate supply of alumina, silica and carbonates, presence of sulfates, correct temperature conditions and availability of sufficient water.

There has to be sufficient clay mineral content to initiate sulfate heave (Hunter, 1988). Hunter (1988) showed even with very high sulfate levels (20,500 parts per million) only minor swelling occurred due to the clay sized fraction (<0.002mm) being less than 10%, whereas a soil with a sulfate content (10,000 parts per million) but a clay sized fraction of between 10-55% exhibited a higher swelling content.

Void (pore) size is also important regarding the magnitude of swelling, Puppala *et al*. (2005) showed sandy soils with larger void spaces suffered less heave than that of a clayey soil with much smaller void spaces. Larger void spaces allow the resultant formation of ettringite to fill the space before rearrangement of the soil particles occurs, thus limiting swelling potential.

The formation of microscopic needle like ettringite, whose volume is over 200% that of its natural constituents (Rollings *et al*. 1999), is expansive only when formed by a chemical reaction between sulfate ions in solution and chemically active alumina.

5.2.1 Case study: A10 Wadesmill Bypass

A road project on the A10 in Wadesmill, Hertfordshire during 2002/2003 involved the application of a lime stabilised capping layer. The underlying soil consisted of [glacial] boulder clay made up of Jurrassic mudrock that is known to contain large quantities of pyrite, which oxidises when exposed to sulfides and sulfates, a process that engineers were aware of.

During the initial site investigation, low sulfate levels were recorded (1.2% SO_4), whereas post stabilisation tests revealed values of 4.1-4.3% (Ground Engineering, 2004). However the work was undertaken during a period of drought and the lime treated boulder clay exposed was subject to desiccation, upon rewetting this allowed the previously unreacted lime to form ettringite and thaumasite that expanded considerably. However the road surface had already been lain by this time, therefore resulting in significant damage to the road surface, with heaving of up to 80mm (Ground Engineering, 2004) as shown in Figure 32 & Figure 33.

Figure 32:Edge of 'blacktop' having heaved by up to 70mm relative to side concrete gully, A10, Hertfordshire (Photo: Ian Longworth, *Pers. Comm*.)

The highways agency encountered a similar problem during the M40 construction in the 1990's, where the lime stabilised layer expanded by up to 60% its original volume (Hawkins, 2013). As a consequence the HA prepared the guidance document HA74/00, this illustrated how to ensure heaving of lime stabilised layers did not occur, however it did not suggest how to account for this in drought conditions, of which were encountered during the construction of the A10 (NCE, 2004; Hawkins, 2013).

At the A10 site, up to 35% of the new unused bypass had to be replaced at a significantly large cost of up to £10m (Longworth, *Pers. Comm*.), during the construction of the M40, removal of the sections that contained large amounts of sulfates and sulfides was undertaken, once again at a large cost.

Figure 33: Transverse humps in the newly layed surface layer as a result of sulfate heave, A10, Hertfordshire (Photo: Ian Longworth, *Pers. Comm*.)

6. Soft and compressible soils

Compressible soils comprise alluvium (fluvial and marine), lacustrine and organic clays and peats. Alluvium is generally a soft to firm material, the crust of which often desiccates giving it a firmer pseudo- strength compared to that of the underlying material (Barron *et al*. 2002), its makeup can also vary widely across a river valley where it is deposited, ranging in texture from clay to boulders (Waltham, 2002).

Bearing pressures on sandy alluvium often range between 100-600 kPa, whereas that of clayey alluvium is generally much lower (0-200 kPa), Farewell *et al.* (2012) suggest that the latter is generally <60 kPa. Earl (1997) has shown a good correlation between cone penetration resistance and soil moisture deficit, which in his study he used to work out the trafficability of agricultural soils

The Drax power station in Yorkshire is placed upon 12,000 piles to rock head due to the presence of soft alluvial clays (Waltham, 2002). Infilled river channels caused by migrating river courses can result in potential geotechnical issues during construction of linear infrastructure, often resulting in differential settlement if not adequately designed, as seen in relation to a domestic dwelling in Figure 34 below.

.

Figure 34: House sinking in infilled river channel, Millers Way, Warboys, Cambridgeshire (Photo: Richard Humphrey (geograph.org.uk))

6.1 Collapsible deposits: Loess soils in the UK

Loess soils are aeolian (wind) blown deposits that in the UK are generally derived from glacial 'grinding' and as a result of periglacial activity at the end of the last ice age (Smalley and Derbyshire, 1990), also known as 'brickearths' within the UK, due to their use in brickmaking. Loess soils are dominated by silt sized quartz and feldspar minerals and occur as 'sporadic accumulations in the southeast of England', however they rarely achieve thicknesses greater than four metres (Derbyshire and Mellors, 1988).

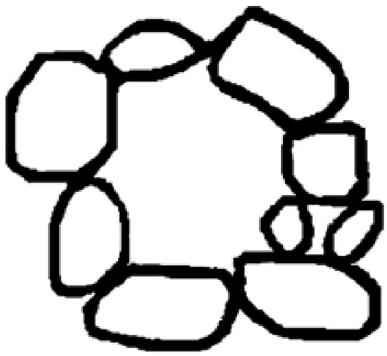


Figure 35: 'Trellis pore' sketch showing generalised layout of silt particles in loess deposits (Yuan and Wang, 2009)

The collapsible nature of loess soil is born from their being wind blown, that results in the formation of an open structure (Rogers *et al.* 1994). Figure 35 above shows the 'trellis pore' analogy suggested by Lin (1960), the concept being that silt sized particles within loess deposits arrange themselves in a manner where the resultant pore spaces are larger than the individual mineral grains of the soil mass (Yuan and Wang, 2009). The individual silt grains are bonded by variable amounts of clay sized particles with carbonates that have a cementation effect of binding the silt particles (Kruse *et al*. 2007).

Loess soils have a high bearing capacity at natural moisture content but become collapsible when soaked. When loess is wetted, a process called 'hydroconsolidation' occurs whereby the mineral grains are realigned. This realignment causes the relatively large open pores within the soil structure to close, leading to the settlement we see at the land surface. The applied combination of soaking with subsequent loading (i.e. structures) of loess soils can lead to increased acceleration of the collapse of the soil mass (Assallay *et al.* 1997; Dijkstra *et al*. 1995).

The use of loess soils within critical infrastructures has in the past had disastrous consequences, the most significant being the construction of the Teton Dam, Idaho. The core of the dam was constructed from aeolian deposits that when subjected to wetting as the dam was filled caused collapse of the soil structure, inevitably it led to dam failure (Smalley and Dijkstra, 1991). Smalley and Dijkstra (1991) advised that if loess type material were to be in future used for such construction then its plasticity index would need to be raised, essentially this is the amount of clay particles that are within the deposit.

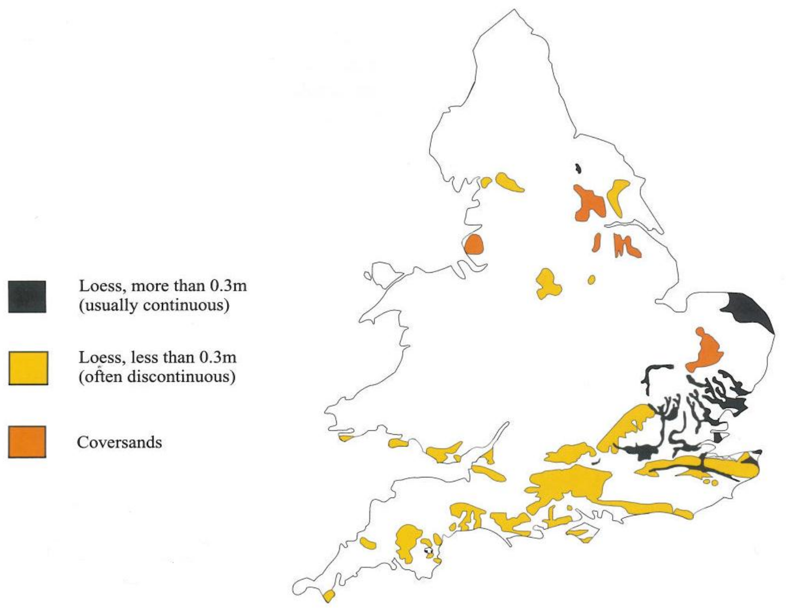


Figure 36: Distribution of wind blown deposits in England (Adapted from Goudie and Brunsden, 1994 In: Jones, 2007)

Even though loess soils are not particularly prevalent within the UK, their location within the south of England (Figure 36) could 'economically' be high risk. The placing of certain critical infrastructures in areas underlain by loess soils may not be a problem for the majority of buried services as they do not generally impose a large load on the soil mass (unless highly engineered, (i.e. high pressure gas pipelines) but for other services that do such as road, rail, airports etc. the load imposed would certainly be an issue. Even after wetting of loess soils and their collapse, it has been shown that the soil can be turned into 'soft, very deformable ground, able to manifest settlements of centimeters or tens of centimeters…unbearable for the structures' (Bally, 1988).

6.2 Organic soils: subsidence prone?

Organic soils (histosols) contain a 'significant proportion of dispersed vegetable matter' (Craig, 2004), and are associated with high groundwater levels.

The high water content, up to ten times its own weight in water (Hall et al. 1977; Page, 1998), can result in considerable shrinkage on drying, and consolidation where soil water is forced out of the pore space upon loading (Price and Schlotzhauer, 1999). Drainage of organic soils for agricultural purposes is common, it is this practice that often culminates in ground movement (Hutchinson, 1980; Stephens *et al*. 1984).

However even when dry their bearing strengths are low, due to low bulk densities (0.1-0.4 g ml^{-1}) (Farewell *et al.* 2012; Hammond and Brennan, 2002). The presence of overburden, whether in the form of other natural material (i.e. alluvial/marine deposits) or man made structures (i.e.roads/railways) will ultimately lead to greater subsidence of organic soils (Kechavarzi *et al*. 2010).

Stephens *et al*. (1984) identify two types of subsidence that are related to organic soils;

- Densification (Loss of buoyancy, shrinkage and compaction)
- Actual loss of mass (biological oxidation, erosion, mining, burning)

Permeability of underlying strata is a key issue of water retention and subsequent subsidence rates on organic soils in the Fenlands of the UK (Dawson *et al.* 2010), with more impermeable underlying strata such as the 'Fen Clay' yielding lower subsidence rates (1.50 cm yr^{-1}) compared to those of higher permeability (1.89 cm yr^{-1}).

The oxidation of peat can have secondary effects to infrastructure systems, such as the formation of ochre which contains sulfate reducing bacteria that can corrode metallic structures (i.e. culverted drainage). Rojstaczer and Deverel (1995) have shown that subsidence is accelerated if crop residue is burned.

Gebhardt *et al*. (2010) highlight the presence of 'subsidence morphologies' within highly organic soils (i.e. peat), which leads to differential settlement of soils which is of harm to local, especially linear infrastructure.

6.3 Soft soils and high velocity trains

Ground vibration caused by the passing of surface trains has recently gathered interest (Sheng *et al.* 2003), with it likely that trains may exceed the propagation velocities of waves in soft soils. Timoshenko (1927) first hypothesised that a rail and sleeper system 'elastically' supported on ballast should have a critical speed as to which excessive dynamic amplification of vertical motion could be expected.

When railway tracks cross regions of 'soft soils', inevitable due to their linear nature and varying geology, it often proves too expensive to remove elements of 'soft' substrate that can be significant thicknesses, therefore the assessment of vibrations induced by passing trains and their impact on soft soils is therefore of great importance (Costa *et al.* 2010).

If a train's speed exceeds the Rayleigh wave velocity of the supporting soil, a resultant 'ground vibration boom' occurs (Krylov *et al.* 2000), Krylov *et al.* (2004) state that trains break the 'sound barrier' of the subsurface soils. Rayleigh waves are a type of surface acoustic wave that travels along solids (soils) (Viktorov, 1967) or a free surface (ie earth-air interface)(Xia *et al.* 1999).

Yang *et al.* (2009) showed that dynamic effects of Rayleigh waves became apparent when train speeds were greater than 10% of the Rayleigh wave speed of the subgrade material (soils), at 50% the shear stresses acting upon the subgrade will be underestimated by 30% in static analysis and with train speeds greater than the wave velocity the dynamic effects increase dramatically. Train acceleration and braking amplify the effects of increased shear stresses and horizontal displacements in the soil.

It is assumed that the ballast/subgrade of rail-tracks can withstand a velocity of up to 1800 km/h (Esveld, 1989), far beyond the speeds of current trains (Madshus and Kaynia, 2000). The Rayleigh wave velocities within soils (type dependent) are known to range from 150-800 km/h (kilometres per hour) (Vostroukhov and Metrikine, 2003; Krylov, 1994), although Woldringh and New (1999) suggest that this could be as low as 104 km/h in some soft soils in the Netherlands. Therefore a matter of concern, considering the cruise velocities of the French TGV, German ICE and the Swedish X-2000 are in the region of 200-300 km/h with ever the need for increasing speeds (Vostroukhov and Metrikine, 2003).

The majority of railway infrastructure in the UK was constructed during the 19th century when high speed trains were inconceivable, therefore the routing of the lines through zones of soft soils were not sufficiently engineered to withstand these new record speeds.

De Nie (1948) successfully engineered a section of track to withstand the deflection forces of a train's velocity by placing the rails on a concrete slab that reduced the deflections from 8-15mm to 1.5mm respectively.

Examples of UK rail infrastructure affected by soft soils include Stilton Fen, Cambridgeshire and Thandestron Bog, Norfolk, both sites underlain by soft/compressible peat and organic clays. At Stilton Fen, track displacements are caused by passing trains (180 km/h), and the embankment at Thandestron bog is often subject to slope failure and large settlements.

A study undertaken by Hendry *et al.* (2010) at Brackagh Bog, Northern Ireland, showed the large displacement that occurs on tracks passing over a peat bog (Figure 37), additionally the drivers here report a reduction in power and therefore increased journey times as the tracks deform over the peat.

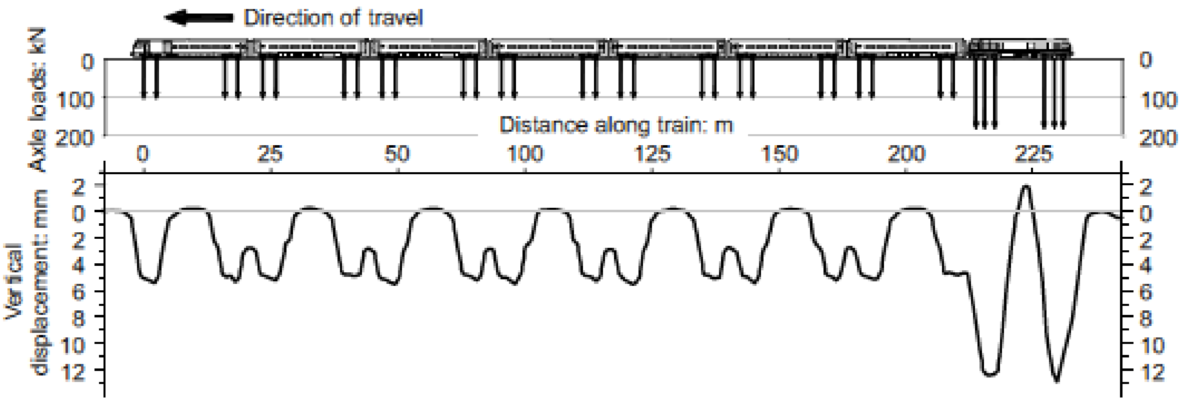


Figure 37: Comparison of applied axle loads from train with dynamic displacement data taken at Brackagh, Northern Ireland (From: Hendry *et al.* 2010)

6.4 Made Ground

The term fill or made ground is used to describe a deposit that was not formed by geological processes and is anthropogenic in formation (Ciria, 2002).

Made ground can be the result of many years of human interaction with the soil, where new layers are constantly formed, or waste from mining and smelting activities, particularly prevalent within the UK (Jones, 2007). Often it is the necessity to remove fill material and replace with material of a known engineering standard, as such was the case of the London Docklands regeneration, where centuries of development had led to settlement prone ground (Young and Rutty, 1991). This is often undertaken during roadbuilding where a more compact 'subgrade' is placed below the road surface to ensure trafficability (Brink *et al*. 1982).

Human activity has also resulted in ground contamination (Bridges, 1997), most notably from past industrial sites, and how contaminants migrate is dependent upon soil type and groundwater conditions.

Contamination of ground can lead to the solution of soil minerals, altering particle contact and increasing compressibility of the soil mass, oils can also act as a lubricant, especially in sandy soils, which could lead to slope stability issues (Dundulis and Ignatavieius, 1999). However this is a topic of its own and will not be considered in this review, one should refer to the relevant guidance on this topic if further interested (Environment Agency, 2000).

7. Impact of climate change on ground movement within the UK

Hall *et al.* (2006) state 'climate change will be a driver of changing risk to infrastructure systems over the 21st Century'. Toll (2011) has stressed that buildings and infrastructure are under threat from soil related ground movement as a result of climatic change, however the scale of climatic change and their spatial impacts are relatively little understood, at least in the UK.

Harrison *et al*. (2012) explain that the current British Geological Survey's GeoSure geohazard dataset have been developed without incorporating the longer term changes in climate, specifically temperature and precipitation which are vital in controlling the soil moisture deficit, similarly this has not been undertaken within NSRI's NPD soil hazard modelling either. Harrison *et al.* (2012) in their study sought to further understand the effects of climate on shrink swell processes in south-east England, however no such study has considered the national scale changes of projected climate change on shrink-swell processes.

The UKCP09 probabilistic climate model shows mean daily maximum temperatures are set to rise between 1-9.5^{o}C, with higher temperatures being predicted for Southern England (Jenkins *et al.* 2009). Wetter winters are estimated, with summer rainfall estimated to decrease by -12% in Southern England. These estimated values inevitably show that the soil moisture deficit is likely to exhibit both ends of the scale throughout a summer/winter cycle allowing more prolific shrink/swell processes.

Long term trends in drought have not established for the UK, and we therefore do not fully understand the implications for the future (Pan Chun *et al*. 2013). However the implication of soil moisture on near surface weather can have a significant effect (Seneviratne *et al*. 2010), which subsequently will have consequences for the soil processes imposing on critical infrastructure.

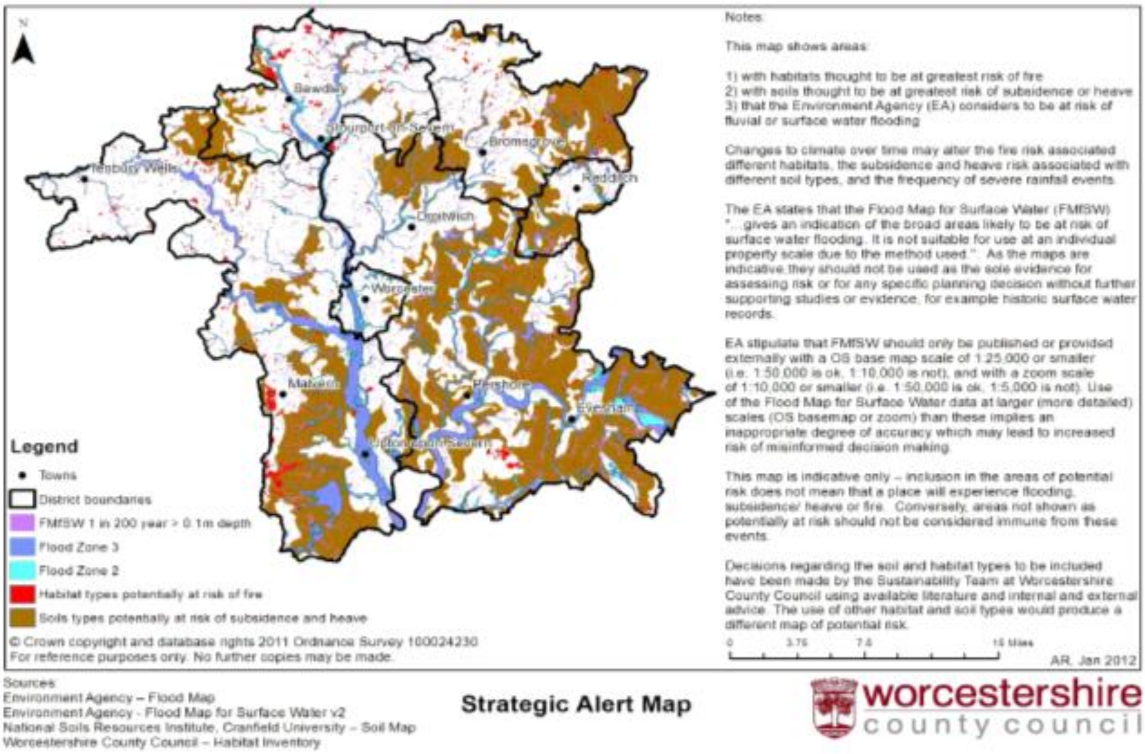


Figure 38: Worcestershire strategic alert map showing individual layers for flooding, soil types and fire risk (From: Sustainability West Midlands, 2012)

Climate resilient infrastructure is one of the key objectives of HM Government (Cabinet Office, 2011). Projects have thus far undertaken hazard assessments to understand if climate will impact on current and future infrastructure systems, recently Sustainability

West Midlands (2012) used a composite of climate, land use and soils datasets to create a series of ‘risk profiles’ for infrastructure(s). Figure 38 shows the entire county and its composite risk from flooding, fire and soils (brown) that are prone to subsidence and heave, incidentally the soils data is derived from NSRI.

7.1 Increased development

The need for more housing, especially in the south east may result in development on ‘green-field’ sites that are prone to subsidence (Brook and Marker, 2008), with this inevitable development will come new infrastructure services to meet with the demands of the new customers in the area, therefore these systems may also be at risk.

The spreading of existing conurbations and the stretched availability for land often means that construction is undertaken on particularly unsuitable ground (Jarvis and Mackney, 1979).

The need for an already stretched water resources in the south east (Evans *et al*. 2003) could also exacerbate the issue of ground movement in this area.

8. Trenchless technology

Trenchless technology was first used commercially during the post world war two reconstruction of Japan in the 1960’s (Downey, 2006). Increasingly within the UK the use of trenchless technology to install underground infrastructure services is being adopted, this is due to the lower cost and less disruption that comes with having to expose a significant trench (perhaps in a highway). 2006) When crossing major highways, railways and rivers, this has the great benefit of not disrupting the other infrastructure services and lowers overall engineering cost (Kramer *et al*. 1992).

The HSE (HSE Construction Sheet No. 8 Rev. 1:1997) have identified a number of issues relating to open trenches as part of street works, of which could be mitigated by using trenchless methods including;

- Collapse of trench sides
- Materials falling onto people working in the excavation
- People and vehicles falling into excavation
- Undermining nearby structures
- Contact with (other) underground services
- People struck by plant

Many studies have examined the impact of service trenches on pavement life, which Lee and Lauter (1999) believe to give a reduction in service life of 32.4%. Pollock (2009) also suggests that trenching not only disturbs the immediate soil but also that which is 0.6-0.9m in proximity of the trench.

Considering the secondary and social impacts of trenching being often greater than the cost of the engineering work (Downey, 2006), one can see the benefits of using the more expensive (engineering wise) trenchless technology. However, trenchless methods do not allow for particular soil hazards (soft/compressible soils, voids, shrink/swell clays) to be remediated during pipe laying, something which generally during open trench installation would be dealt with prior to laying the buried service. Therefore can we possibly expect failures of underground services as a result of this in future scenarios?

9. The use of geotextiles in the UK

Geotextiles are predominantly constructed of polymer materials (Jewell, 1996), however they can sometimes be constructed of natural materials, but this is not a practice generally adopted within the UK.

As well as supporting the ground, they can also be used to stop the migration of potentially contaminated materials, this has been undertaken on a proposed electricity site in London where contaminated material was removed and a geotextile placed to ensure further contamination from other possible sources does not reach the chalk aquifer below (K. Williams, *Pers. Comm*.).

10. Current UK 'ground movement' mapping projects

There are relatively few ground movement mapping projects that have been undertaken within the UK, this is probably a result of the relatively large datasets, expert knowledge and associated time that are needed for their preparation. Identified below are two such models, comprising the British Geological Survey (BGS) and the National Soil Resources Institute, Cranfield University, who for a license fee have certain geohazard datasets pertinent to ground movement issues within the UK. Below is also detailed some recent work on the PanGeo project, which considers city scales of geohazard data, which in the UK is being led by the BGS.

10.1 PanGeo

The EU FP7 PanGeo project commenced in 2011 (http://www.pangeoproject.eu) aims to provide free access to a range of geohazard information for a number of cities within Europe. In England this currently includes London and Stoke on Trent. It combines geological, landuse and other geospatial layers, using remote sensing data to derive actual ground movement in order to create a series of geohazard maps for future planning and risk management strategies (Cigna *et al*. 2012b). It is envisaged that this project will be further expanded to other cities within the UK and the rest of Europe over time.

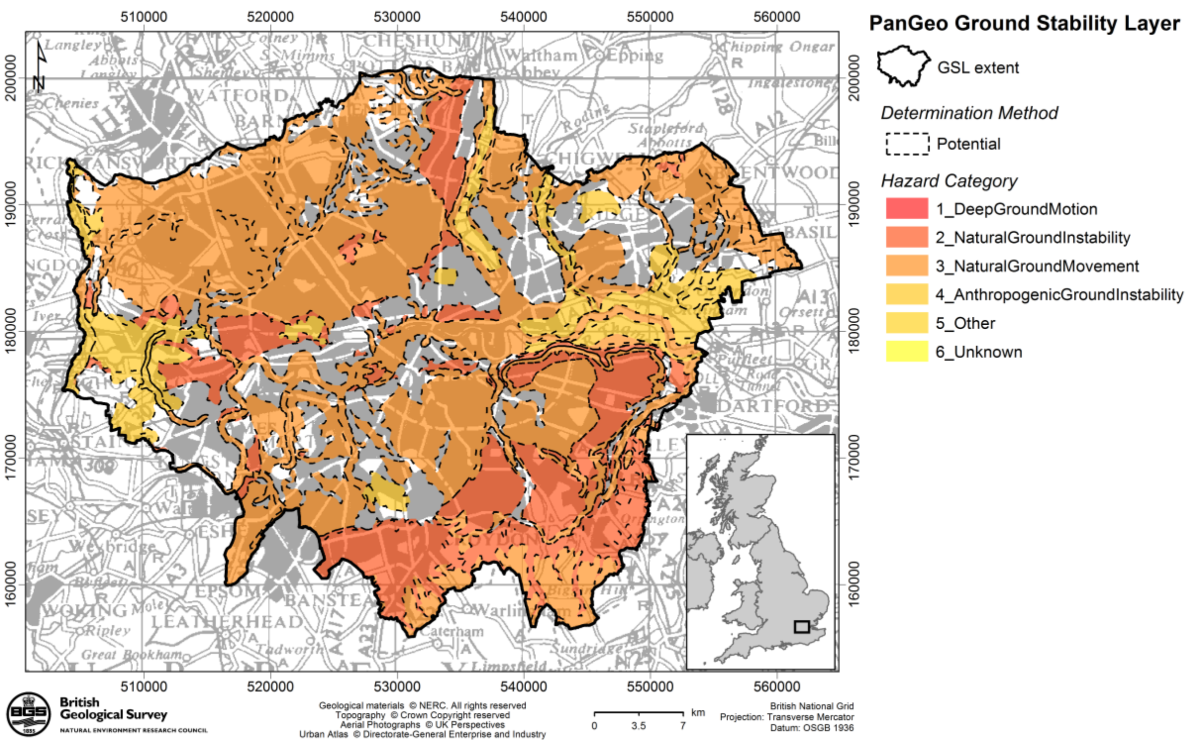


Figure 39: Potential geohazards mapped in the PanGeo GSL of Greater London classified by PanGeo hazard category (From: Cigna *et al.* 2012b)

10.2 British Geological Survey's Geosure

The BGS have developed a dataset called Geosure which seeks to increase the public understanding of hazardous ground conditions within the UK. The dataset shows; Shrink swell, Landslides, Soluble rocks (dissolution), compressible ground, collapsible deposits and running sand (Booth *et al.* 2010).

However, there shrink swell maps appear to be predominantly based on bedrock and superficial deposits (engineering soils), and therefore shrink/swell susceptibility is often based on deeper deposits and not the overlying soils which are often present. The BGS have recently (Harrison *et al*. 2012) sought to establish the relationship between climate change using the UKCIP02 and UKCP09 models for South East England. This research was established primarily because Geosure was not developed to consider the impact of future climatic change on subsidence issues.

10.3 NSRI and Natural Perils Directory

The National Soil Resources Institute (NSRI), Cranfield University hold the national soil data for England and Wales, within a computerised 'Land Information System' (LandIS). LandIS is the largest database of its kind in Europe and recognised by UK Government as the definitive source of national soils information (Keay *et al.*, 2009).

NSRI's Natural Perils Directory (NPD) geohazards thematic dataset derived from the LandIS system comprises a detailed and comprehensive assessment of the environmental vulnerabilities to building structures and infrastructure posed by soil-related subsidence, flood extent and wind exposure (Hallett *et al*., 1994; Jones *et al*. 1995).

The dataset is expressed in GIS format on a vector polygon basis across England, Wales and Scotland. This unique data provided exclusively by NSRI represents the most detailed available information for any kind of soil-related vulnerability assessment in the environmental sector. The subsidence peril includes a range of soil-related models that not only includes the standard model which combines potential soil moisture deficit (PSMD) with shrink-swell data incorporating expert knowledge of soil behaviour to derive 9 classes. However as well as this the model that is a view of the 'average' conditions there are several extreme conditions that are given, i.e. 1 in 3, 1 in 15, 1 in 45 and 1 in 150 year respectively, however this does not represent future climatic change projections.

Because of the natural fine-scale local variation of soils, multiple soil series are present within the delineated polygons of the NPD data. Therefore the NPD features the inclusion of the 'subdominant' soil types in the assessment of the geohazard(s). Each of the soil series that are included within the national soil map have been considered for the individual geohazards and the distribution of the risk classes, within each geohazard classification, have been calculated on the basis of this area.

11. Use of soil surveys in Engineering

Primarily the use of soil surveys around the world have been aimed at increasing agricultural productivity, however more recently their use in engineering has been discussed, represented by many articles and books (e.g. Simonson, 1974, Brink *et al*. 1982, Hartnup and Jarvis, 1979), however there appears to have been a lapse in more modern approaches to soil survey and engineering, i.e. post 1990.

Jarvis and Mackney (1979) regard to the following soil data as being of interest to engineers;

- Strength
- Consistence
- Ease of compaction
- Consolidation
- Shrinkage
- Susceptibility to frost heave
- Permeability
- Corrosiveness

For major infrastructure projects, the knowledge of near surface soils (<2m bgl) are often not required as often either bedrock geology or 'engineering' soils are encountered. However during these works, embankments are often constructed using recycled soils (Allemeier, 1974), therefore their structural and textural properties need to be known to ensure appropriate design. Allemeier (1974) express that mention of a soil series brings to mind the underlying 'geology, topography, texture, and drainage characteristics' of that particular soil type.

Farewell (2010) identifies that superficial geological maps often fail to include strata, for example; 'peat…less than 1 metre thick, colluvium is only shown locally and loess appears to be missing from parts of East Anglia'. Therefore infrastructure that is likely to be emplaced upon/within these layers (i.e. minor roads) may be ill designed as a result and further states the importance of soil maps in an engineering capacity.

Doris *et al*. (2008) have used artificial neural networks (ANN) in the prediction of actual vertical surface movement using only rainfall and temperature data. This shows the usefulness that this technique could have if expanded using combined soil survey data, climatic projections such as the UKCP09 dataset could also help give estimated values for actual soil movement which could prove helpful to the design of infrastructure systems for the future.

12. Conclusion

Ground movement in the UK is a widespread and regrettably unavoidable phenomenon, however its impacts appear more severe in the south east of the country, where development and infrastructure is predominantly focused. Nearly all of UK critical infrastructure is placed on or situated in the soil; therefore ground movement impacts can have a significant social, economical and physical effect on infrastructure provision both at present and in future years.

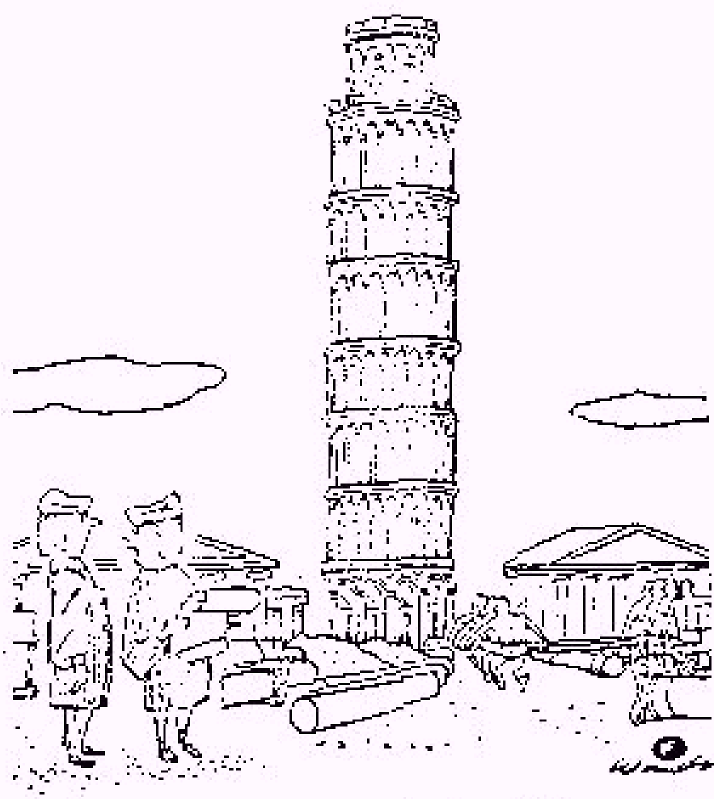
Soil conditions are driven by their moisture contents that are dependent on climate; therefore climate change has the potential to exacerbate the risk of soil related geohazards (Farewell *et al*. 2012). Harrison *et al*. (2012) have shown that the projected climate models (UKCIP02 and UKCP09) suggest a 'raised' and 'significantly raised' susceptibility to shrink swell processes in south-east England for both 2020 and 2080 scenarios. The lack of a UK wide assessment relating to climate change and ground movement has been considered indicating that further research is therefore needed in this area, to further understand the consequences of climatic change.

It is only really since the 1970's when the insurance industry began to provide cover on ground movement issues that the full scale of the problem was recognised, to date it is insurance related data that has enabled the UK to quantify the impacts of subsidence and ground movement. It is apparent that within the UK focus has been on past analysis of domestic properties, as the insurance industry has a key stake in ensuring that the impact of ground movement is minimized, currently claims amount to ~£300 million per year (Forster and Culshaw, 2004).

Shrink-swell processes are by far the most damaging process to critical infrastructure in the UK, often resulting in differential movement of the soil. The highways, water, gas and to a lesser extent telecoms and electricity are at risk of failure if future climate projections are correct.

The use of soil survey within engineering has proven useful in recent years, with much critical infrastructure resting upon or emplaced within the top 1.5m of the soil surface, that most prone to ground movement issues.

Glossop (1968) in Brink *et al.* (1982) highlights the need for further investigation into soil processes; 'If you do not know what you are looking for in a site investigation, you are not likely to find much of value. What you look for should be suggested by the natural environment, and by the nature of the problem to be solved'.



"I skimped a little on the foundation, but no one will ever know it!"

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