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Soil corrosivity in the UK – impacts on critical infrastructure

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Soil Corrosivity in the UK – Impacts on Critical Infrastructure

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Executive Summary

Corrosion is the degradation of a metal as a result of a reaction with its environment, affecting almost all metals. The cost of corrosion for most developed European countries is assumed to be approximately 4-5% of the gross national product, suggesting it is an important and real hazard to critical infrastructure.

The predominant form of soil corrosion is electrochemical, resulting in the formation of corrosion pits. Soil environments have generally good electrolytic properties which are essential for the redox (oxidation-reduction) reactions that take place during corrosion, whereby metallic substrates are converted into oxides, hydroxides and aqueous salts within a cathode-anode system.

The complexity and heterogeneous dynamics of soil environments means that soil influenced corrosion is a complicated and not entirely understood phenomenon. A number of soil properties that are thought to contribute to soil corrosivity have been critically reviewed within this report.

The impacts of soil corrosion on critical infrastructure in the UK have been considered. It appears that within the literature most corrosion studies have been instigated, as a need by the gas and water sectors, and a lesser extent to the highways sector. The electricity and telecommunications sectors appear to be little affected by subsurface corrosional processes as cable design has often mitigated this risk and there is little published knowledge stating the contrary. Electricity pylons have been subject to corrosional processes, however the use of cathodic protection has often greatly reduced this risk over recent decades.

As well as having a ‘direct’ impact on infrastructure networks, corrosion can also result in the contamination of soils and groundwater as a result of leakages and bursts. This not only affects potable water supplies but can also have a significant effect on agricultural land quality for (many) future years. Fire and explosion caused by rupturing fuel lines and leaking gas mains has the potential to cause great harm, especially within an urban environment.

Corrosion alone can result in the failure of buried infrastructure assets, however it is more often due to a series of supporting event(s) that leads to the inevitable asset failure; i.e. 1) shrink/swell clays, 2) loss of support (soil erosion), 3) use of mechanical machinery in cohesive material used to investigate failure, 4) influence of tree roots.

The development of the soil survey mapping and the risk potential formulation of soil corrosivity throughout the last ~50 years have allowed an evaluative method to identify areas that pose a risk to underground metallic infrastructure assets. However further information would be advantageous in supporting the models in place (i.e. sulfates).

Ultimately the prevention of corrosion is deemed to be all but impossible. Soil conditions are inherently heterogeneous and certain soil properties change as a consequence of a changing climate and significant anthropogenic inputs that over time seek to inhibit this prevention. However we can aim to control corrosional processes, whether in the choice of material that we use for our sub-services, as established within the telecoms and electricity sectors, or as a result of cathodic protection.

Glossary

BRE – Building Research Establishment
CST – Council for Science and Technology
Defra – Department of environment, food and rural affairs
GIS – Geographical Information Systems
GNP – Gross National Product
HSE – Health and Safety Executive
ICT - Information Communications Technologies
IMRP- Iron Mains Replacement Program
ITRC – UK Infrastructure Transitions Research Consortium
LandIS – Land Information System
Leacs – Leakage assessment due to corrosivity and shrinkage
MIC – Microbially Induced Corrosion
NSRI – National Soil Resources Institute
SRB – Sulfate Reducing Bacteria
UK – United Kingdom

Keywords
Soils, Corrosivity, Corrosion, Infrastructure, Geohazards, ITRC

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Report cover, shows a section of the Barton Stacey to Lockerley pipeline, near Kents Oak, Hampshire, UK. (Rosemary Oakeshott, 2008, Geograph)

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Key Findings

- Soils within the UK are heterogeneous and therefore extremely complex in relation to corrosion studies.
- Soil parameters contributing to soil corrosivity do not occur in isolation and are often interrelated.
- It is often a combination of soil processes with human activities that culminates in infrastructure failure.
- The impacts of soil corrosion on buried infrastructure can be economically, environmentally and socially high.
- The water, gas and highways sectors appear the most susceptible to soil corrosional processes within the UK.
- The establishment of the soil survey and subsequent soil mapping has assisted in the asset management and economical replacing of buried critical infrastructure within the UK in many instances.
- The corrosive action of soil cannot be eliminated but can be managed.

1. Introduction

Corrosion, the degradation of a metal by a reaction with its environment, affects almost all metals (Bradford, 2001).

1.1 Economic cost of corrosion

Within the UK the cost of corrosion has been estimated to be approximately 4-5% of the Gross National Product (GNP) (Uhlig, 1985), an increase when compared with the earlier figure from 1971 of 3.5% of the GNP (DTI, 1971). In the USA estimated corrosion costs were reported of $276 billion in 1998 (Yang, 2008). The large costs and impacts generated by trunk mains failure highlight clearly the need to understand the probability of such failures, the soil-related mechanisms and the associated consequences.

1.2 Consequences of infrastructure failure as a result of corrosion

The failure of trunk mains (greater than 300mm in diameter) can pose problems related to disruption, repair costs, reinstatement and compensation claims (Cooper *et al*. 2000). Within the water supply sector, distribution networks often also account for up to 80% of the total expenditure (Kleiner and Rajani, 2001). For pipes carrying fuels and other potentially hazardous liquids a leak can result in ecological disasters due to contamination of both soil mass and associated groundwater from which ecosystem services arise, or potable water supplies are extracted.

1.3 Monitoring buried assets

Ideally, inspection of buried assets on a regular basis would ensure corrosion is not likely to incur failure of service. However this is impractical due to both the expense and time that it would take to uncover pipes, often which are placed beneath or adjacent to highways (Metcalf, 1991). In most developed countries, the average life of cast or ductile iron pipes is considered in the region of 50-75 years (Rajani *et al*. 1996).

1.4 Factors resulting in infrastructure failure

Pipe breakages are often a result of several factors:

Construction: Pipe structural properties, pipe material type, pipe-soil interaction and quality of installation and reinstatement;

- *Content:* Internal loads due to operational pressure and external loads due to soil overburden pressure, traffic loads, frost loads and third party interference;
- *Environment:* Material deterioration due to largely the external and internal chemical, biochemical and electrochemical environment.

D'agata (2003) adds to this by suggesting that: differing materials; different times of installation by many different contractors, in different ground conditions, and; servicing differing needs, all contribute to pipe failure. He further comments that predicting the life of a buried pipe is not dissimilar to predicting the life of a human, whereby our heritage, living conditions and lifestyle are key factors in ensuring longevity.

The buried soil environment is a 'bewilderingly complex environment, structures placed therein affecting one another in very complicated ways' (Parker, 1962) (Figure 1). Hembara and Andreikiv (2011) regarded soil corrosion as 'one of the most important factors decreasing the reliability of pipelines'.

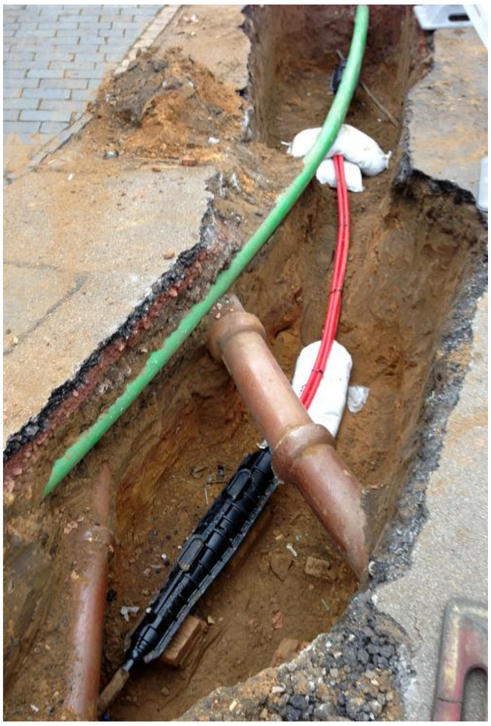

Figure 1: The complexity of buried assets (S.Hallett)

2. Soil corrosivity

2.0.1 Definition of soil(s) and interaction with buried infrastructure

Soil scientists define soils as the unconsolidated layer on the earth's surface that contains living matter capable of supporting plants. Within the UK, soils typically have an approximate depth of some 1.5 m (Busby *et al*. 2012). Therefore with most underground services being at depths between 40 and 100 cm, near-surface soil interaction with buried infrastructure assets is of great importance. High voltage electricity (>132kV) and large diameter gas and water mains are generally founded deeper than 100cm below ground level for both security, engineering and design practicality (HSE, 2000).

Soils encompass an extensive range of surficial geologic deposits including unconsolidated sediments, saprolite (decomposed rock) and bedrock (Wysocki et al. 2005). Saheb *et al.* 2010 suggest that very few studies (within archaeological soils) on corrosion consider the environment that the metal is placed within, but rather the corrosion products that are formed upon the metal substrate. Similar to archaeological studies, Moore and Hallmark (1987) have suggested that pipeline engineers often assumed the failure of underground pipelines must generally be as a result of manufacturing issues rather than considering the impact of the soil mass that they are buried within.

2.0.2 Soil corrosivity mechanisms

Soil corrosivity, when compared to that of the atmosphere or seawater corrosivity is often more difficult to categorise with regards to both pipe specific parameters and surrounding soil properties (Ferreira, 2006). This is due to the soil's extremely localized complexity and heterogeneity. The complexity of soil was recognized as early as 1942 in a study by Hudson *et al*. (1942). The key soil factors affecting corrosivity are presented in Figure 2.

The predominant deterioration mechanism on the exterior of cast and ductile pipes is electro-chemical corrosion with damage occurring in the form of corrosion pits (Rajani and Kleiner, 2001). Atmospheric corrosion is only important within the context of soils so far as it aids the formation of a protective oxide coating prior to the metals burial within the soil environment (Adams, 1994). Pitting corrosion occurs as a result of different areas of the 'metal surface being at different potentials, these potential differences arise due to contact of different metals, inclusions or impurities, intermetallic compounds, strains or any variance from a uniform composition or structure' (Mughabghab and Sullivan, 1989).

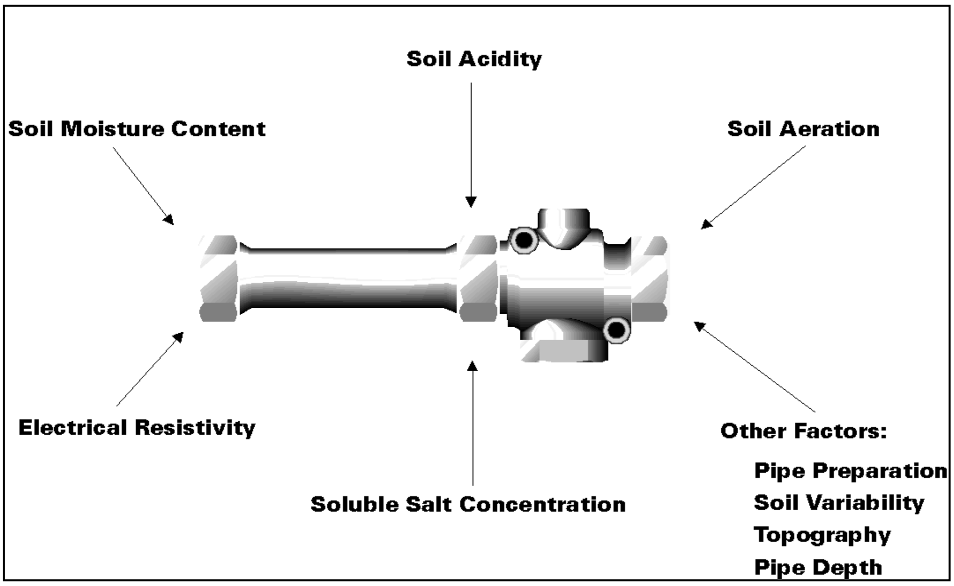

Figure 2: Soil corrosivity factors (NSRI, 2013)

For corrosion to occur a system must be present that allows for at least one species to change its electron valence number. This includes the presence of an anode and a cathode and subsequent paths for electrical electron conduction and electrolytic ionic conduction

(Figure 3). There are two expressed methods in which metals in electrolytes corrode, namely galvanic corrosion and electrolytic corrosion. The latter is often a result of stray currents, which are often sourced from overhead or buried power lines and electric powered railway systems (Bertolini *et al*. 2007; Wang *et al*. 2013; Flounders and Danilyak, 1995; Ibrahim, 1999). Therefore electrolytic corrosion is not directly soil-related, however soil resistivity properties of the soil would affect how these currents are transmitted through the soil medium, an issue discussed later.

Within this review we are therefore principally interested in galvanic corrosion, which is the result of two dissimilar metals placed within an electrolyte. This is considered the primary source of external deterioration (O'Day, 1989). Soils, due to their prevalence of moisture and mineral salts, are generally assumed to be 'good' electrolytes (Payne, 1999). Electrons are firstly lost from an anodic partial reaction (oxidation) and gained in the cathodic partial reaction (reduction) (Trethaway and Chamberlain, 1995). Each of these reactions (oxidation and reduction) is considered a 'half-cell' reaction and at least two are needed within each corrosion system (Pittsfield and Hickary, 1972). This comprises the theory of a redox reaction, where the metallic substrate is transformed into oxides, hydroxides and aqueous salts. However stress corrosion cracking does not always conform to this theory as it can involve no metal loss (Contreras *et al*. 2012).

Ibrahim (1999) describes the process of corrosion in the form of a copper ground rod and some part of a steel piping system that become electrically connected, both being buried in a soil. As established, the electrolytic nature of the soil allows the copper to act as an anode and the steel as a cathode. This completes the electrolytic circuit with a current flowing through the soil from the steel to the copper. Corrosion then takes place when the iron discharges current to the soil, resulting in an electrochemical equivalent amount of metal being removed, forming a corrosion pit on the steel surface. Local differences in soil properties or moisture content can lead to fluxes in these galvanic currents and subsequent corrosion within the same metal structure.

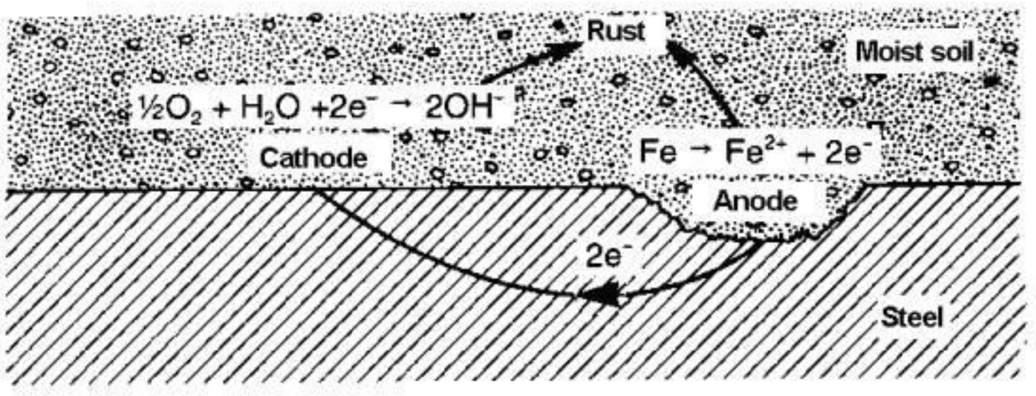

Figure 3: Representation of electro-chemical reaction in one corrosion cell (From: Camitz, 1998)

2.0.3 Service trench backfill influence on corrosion activity

The variation in soil chemical and physical properties, even over a single site, can change how an object corrodes compared to another identical object. When underground pipes are first installed a backfill is made up of available (often disturbed) soil from nearby, often this soil will contain transported material and building waste, either from the nearby surface or, if it is brought into the site from elsewhere, it is what geotechnical engineers describe as 'made ground' (Waltham, 2002) (Figure 4).

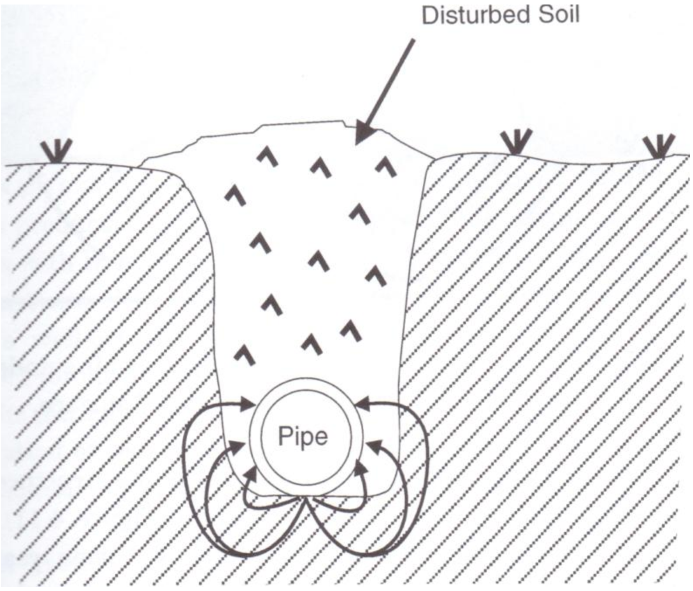

Figure 4: Corrosion cell set up on a pipe in disturbed soil vs. undisturbed soil. Arrows show direction of positive current flow (From: Bradford, 2001)

Norin and Vinka (2003) identified that the presence of ‘made ground’ can greatly influence the localised corrosion rates on buried metals compared to that of the ‘natural’ soils. Their study was in an urban location, however another study concerning the construction of regional ‘rural’ pipelines in Russia highlighted the problem of soil mixing during trench backfill (Karpachevskii *et al.* 2011). Palmer and Bunyan (1999) when examining North London soils discovered a strong contamination of lime within trench backfill, which raised the pH of the surrounding undisturbed London Clay soils.

Karpachevskii *et al*. (2011) suggest that often the upper horizons (lighter texture) are removed to the bottom of the trench and the lower (heavier textured) material is brought to the top, which together along with compaction of the backfill allows the formation of gley horizons near to the buried pipe as a result of soil waterlogging. However pipe depths ranged between 0.8 to 3.0m, with the shallower pipes being more subject to gley conditions after trench backfill. Karpachevskii *et al*. (2011) conclude that the greater difference between soil properties in the disturbed (trench) and background (natural/undisturbed soils) will often result in a greater probability of corrosion of buried pipelines.

Excavations can also increase soil aeration compared to that of the surrounding natural soils, allowing oxygen to be more accessible to the buried metal increasing corrosion rates due to the availability of oxygen in the cathodic reaction (Phear *et al*. 2005; Ismail and El-Shamy, 2009). The large cathode (undisturbed soil) and small anode (backfill/pipe) (Figure 3) results in corrosion being rapid, especially if the soil conditions are already particularly aggressive (Bradford, 2001).

2.1 Soluble salts

2.1.1 Sources of soluble salts

Many aggressive anions are present within the soil environment, including sulfates and chloride ions. Farewell *et al*. (2012) identify a number of sources of soluble salts, including 1) inherited from saline deposits in which soils are formed, 2) produced in situ through intense evaporation under arid climates (unlikely in present UK climate), 3) from atmospheric deposition of Cl^- from sea spray, 4) De-icing agents used on anthropogenic surfaces (less extensive). Sulfates are most common in clay soils and acidic waters, resulting from the breakdown of pyrites within rocks and clay materials. (BSI, 1999).

2.1.2 Soluble salts and the corrosion process

The process of corrosion pitting is induced by aggressive anions, such as Cl (chlorides) and SO_4 (sulfates) (Alamilla *et al*. 2009). Chloride ions in particular can introduce pitting corrosion of the protective layer (passive film) decreasing the overall protection of the buried metal asset (Li *et al*. 2007; Bertolini *et al*. 2004). Chloride is argued to be the leading cause of corrosion of steel reinforcement in concrete structures (Moreno *et al.* 2004).

The primary cause of corrosion of buried stainless steels has been the result of high levels of sulfides within soils (Sjogren *et al*. 2011). Iron sulfides are capable of decreasing corrosivity by forming a ‘biofilm’ that protects the underlying unreacted metal, this is effectively the process that is undertaken in the production of stainless steel (Hamilton, 2010). However due to the inherently unstable nature of iron sulfide films, ruptures often occur leading to the formation of very localised active corrosion cells on the metal surface (Hamilton, 2010), that leads to quick failure of the infrastructure asset. The mechanism for this process is iron sulfide acting as a cathode and the exposed steel surface as an anode.

The oxidation of Pyrite (FeS_2) undergoes biological and chemical reactions and is subsequently very complex (Wallace and Wallace, 1992). Ultimately pyritic oxidation leads to the formation of sulphuric acid, which is not only inherently a problem with relation to the corrosion of metallic materials but also a significant environmental pollution risk to surface and ground waters (Evangelou and Zhang, 1995). The use of pyritic containing alluvium (sand and gravel) (Figure 5) within backfill on a road project in the UK led to the formation of sulphuric acid that (soon) after construction directly attacked the galvanized steel used for the drainage culvert (Reid *et al*. 2005). Within this alluvial deposit the pyritic crystals were framboidal in shape. The high surface area of the framboidal minerals led to increased reaction rates which resulted in the rapid corrosion of the galvanized steel.

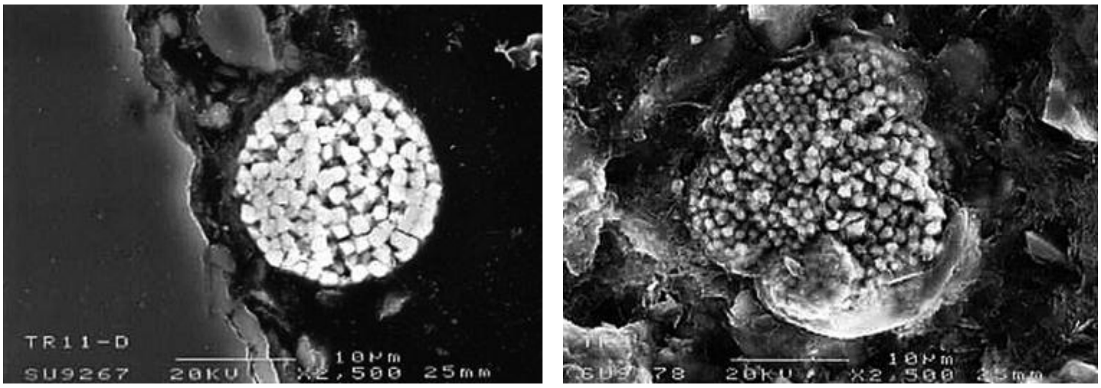

Figure 5: Framboidal Pyrite from alluvial sand (From: Reid *et al*. 2005)

2.1.3 Sulfates within the UK

It is currently problematic to establish which soils, within a UK context, pose a risk regarding sulfate concentration as their values are not widely recorded. This has highlighted a possible area of future research that needs undertaking in order to better assess soils for their corrosive potential. Royse *et al*. (2009) have suggested using the British Geological Surveys G-BASE (geochemical database) and Prop-Base data for statistically mapping the occurrence of sulfates (and chlorides) within soils and drift geology. Currently within the assessment of soil corrosivity (Appendix 1), sulfates are characterized as being 1) present, 2) a trace or 3) not present. The soil parent material is often known and this allows the presence of sulfates to be estimated.

2.1.4 Concrete corrosion

Concrete corrosion was under consideration prior to World War Two (Bessey, 1953), however attacks on concrete structures as a result of soil attack were previously thought to be rare in occurrence. Unlike metallic objects that are subject to electrochemical corrosion, cementitious structures and pipes undergo ‘degenerative chemical reactions’ (Boxhall *et al*. 2007). Sulfate processes within soils can impact on concrete infrastructure, with sulfates having an intraneous/extraneous origin or a combination of the two. In this review we are principally concerned with the extraneous component, more specifically that [sulfates] derived from soil.

Erlin and Stark (1966) were first to discover the significance of deteriorated concrete and their link to sulfates. Two types of sulfate attack have since been identified, these include ‘conventional sulfate attack’ that results in the formation of ettringite and gypsum (Zhou *et al*. 2003) and ‘Thaumasite Sulfate Attack’ (TSA), the latter having a more detrimental effect to cementitoious structures.

2.1.4.1 Primary risk factors for concrete corrosion

Portland based cement, so named for its colour association with Portland Limestone, is defined as a ‘hydraulic cement’. This is where limestone and clay are heated within a kiln and subsequently pulverized, then the addition and subsequent reaction with water causes it to harden. Five differing types of Portland cement are identified by ASTM International (ASTM, 2012), the primary risk factors for any Portland based materials to corrosion (degradation) being (Clark, 1999):

Presence of a source of sulfate, including sulfide that may decay to sulfate;
- Presence of mobile water (groundwater in the case of buried concrete);
- Presence of carbonate (generally in the aggregate);
- Low temperatures (generally lower than 15°C (Ideally 0-5°C (Bensted, 2003))).

However Sims and Huntley (2004) have since suggested that the four risk factors identified by Clark (1999) do not have to be ‘obviously’ present, with some overseas cases having seen as little as 1 in 4 of the factors present).

Clark (1999) identifies that mobile water is needed to initiate sulfate attack, this is generally in the form of ‘natural’ groundwater’s. However Leaking water mains and drainage systems have resulted in the mobilization of soluble sulfate compounds (calcium sulfate, magnesium sulfate, sodium sulfate and potassium sulfate) within underlying soils and fill (i.e. burnt shale from mining activities) that has caused significant damage to domestic concrete floor slabs (Longworth, 2008). Therefore adequate drainage that is not susceptible to leakage within highway areas that have buried concrete components (i.e. bridges and gantry’s) are required to ensure that water cannot mobilise sulfate(s) in relatively high sulfate bearing soils.

The aggressiveness of sulfates in soil to that of concrete has been identified by Paul (1994) as follows (Table 1):

Degree of attack	**Weak**	**Moderate**	**Strong**
Sulphate (mg SO_4^{2-}/l)	2000-6000	6000-12 000	12 000-24 000

Table 1: Chemical attack of concrete by soils containing sulphates: Assessment of degree of attack (From: Paul, 1994)

Only very low chloride levels are needed for concrete corrosion to take place (Daily and Kendell, 1998), however cement type has also been indicated as an influence in the corrosion resistance of concrete in relation to chloride concentrations (Maslehuddin *et al.* 2007). Glass and Buenfeld (1997) have identified that within UK bridge structures, chloride concentrations of <0.2% mean a low risk of corrosion, whereas >1.5% have a high risk of corrosion. There is currently limited knowledge with regards to the thresholds of Chloride needed to initiate the localized breakdown of the passive layer of reinforcing bar in concrete structures (Manera *et al*. 2008; Angst *et al.* 2009).

2.1.4.2 Thaumasite in concrete

The thaumasite form of sulfate attack is more serious than other types of sulfate attack because the main calcium silicate cementing phases (the main binding agent of Portland cement) are affected rather than only the portlandite and calcium aluminate phases (Longworth, 2008; Aguilera *et al.*, 2003). This ultimately leads to a complete loss of integrity and strength of the concrete structure, turning it in some cases to a ‘pulpy mass’ (Collepardi, 2001). Figure 6 shows the effect of thaumasite formation and its degrading effect within a motorway bridge structure in Gloucestershire. Portland based cements that were deemed to be resistant to sulfate attack were used in structures where the threat was high, however many studies have now shown that thaumasite has since developed in these ‘resistant’ cements (Crammond, 2003; MacPhee and Diamond, 2003).

Thaumasite is known as being a rare naturally occurring complex sulfate-bearing mineral usually originated from metamorphic rocks (Sims and Huntley, 2004). It is also a ‘cultivated reaction product’ as supported by laboratory findings (Collard-Jenkins *et al*. 2003).

Since 1988 over 80 UK field structures have been deemed to be under sulfate attack, with the thaumasite form of sulfate attack (TSA) being responsible for over 95% of these cases (Crammond, 2003). However relatively little published information and even fewer recorded/documented cases exist within the UK context prior to 1998 (IAN 48, 2003). The Thaumasite Expert Group (TEG, 1999) was established after many UK bridge structures were shown to be showing key signs of TSA, identifying that “TSA will only occur in buried concretes when all the primary risk factors are present simultaneously and developed to a significant degree”.

Hobbs and Taylor (2000) suggest that TSA is not generally the primary cause of concrete deterioration, but rather that the primary cause is sulphuric acid attack. Sulphuric acid is derived from pyritic oxidation (Guruprasad *et al*. 2011; White *et al*. 1997) within both natural or backfilled (disturbed) soil material, the formation of sulphuric acid then leads to a reduction in the pH of the groundwater. This reduction of pH in the groundwater allows the thaumasite to form, as shown in a previous study by Gaze and Crammond (2000), they suggest that thaumasite is not able to form in conditions with a pH less than 10.5. Yang *et al*. (2012) further this by reporting that when a pH of 11.5 is met then thaumasite will form but will subsequently readily dissolve in the solution. Once formed, thaumasite can withstand pH values as low as 7. It is this chemistry of the soil that is vital to the performance of concrete structures (Crofts, 2006).

The suggestion that the presence of acid generally promotes the growth of thaumasite (Hobbs and Taylor, 2000) has since been refuted by Hill *et al*. (2003). Hill *et al*. (2003) reported laboratory studies that have shown that except in certain concrete types where sufficient limestone provides enough carbonate ions to form thaumasite, then generally the acid results in the conversion of calcite to gypsum.

It has been argued that the concrete does not have to contain a significant amount of carbonate in the aggregate to be susceptible to thaumasite attack (Sims and Huntley, 2004). They consider this to be a concern as structures that do not contain high levels of carbonates may be missed from 'desk screening studies'.

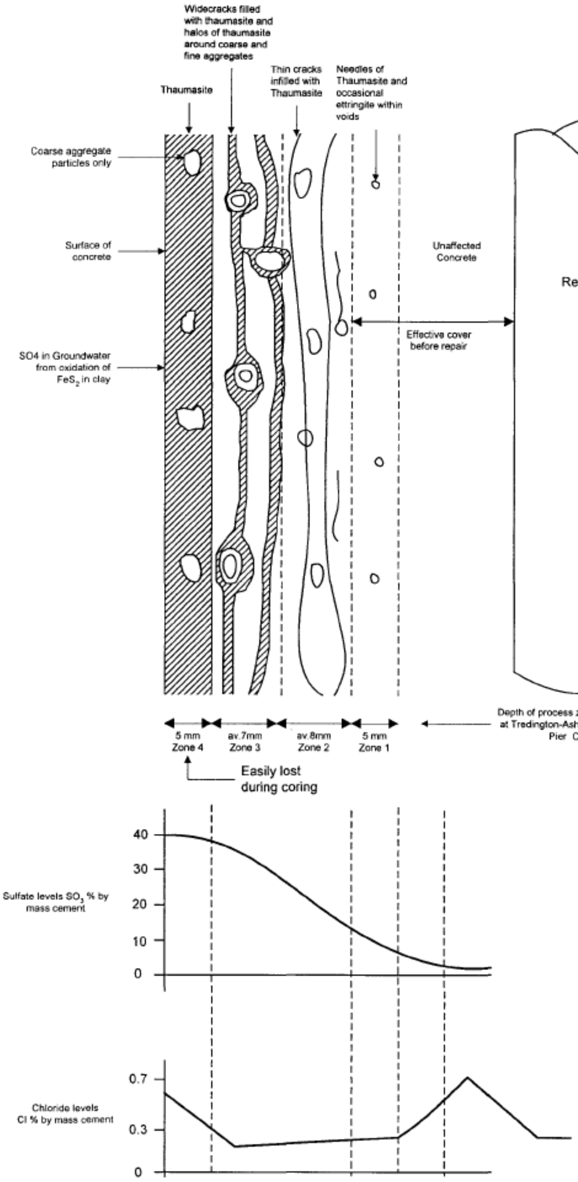

Figure 6: Example of Thaumasite attack in 'good quality' concrete: Tredington-Ashchurch Bridge, Gloucestershire (From: Halcrow, 1998)

Swenson and Mackenzie (1968) identified that the concentration of soil sulfates and soil-water sulfates could not always be a measurement for the degree of deterioration of the concrete structure, with capillary action and resulting evaporation being significant factors. Collard-Jenkins *et al*. (2003) showed in their study examining bridge structures on the M4 motorway that, due to the use of granular fill around the bridge foundations rather than sulfide contaminated [clay] soils and semi impervious protection of the concrete, that there were little sign of thaumasite formation.

2.1.4.3 Advancement of concrete research in aggressive ground

The Building Research Establishment (BRE) detailed the sulfate and acid resistance of concrete in aggressive ground (BRE, 1991). However, the methods of deducing sulfate content of the soil can sometimes produce misleading results. This is due in part due to the theory that when ground is disturbed, aerated and moved, often for the purpose of engineered fill, what was initially a low sulfate material may over time increase due to localized weathering processes (Sims and Huntley, 2004).

Although the risk factors identified by Clark (1999) have been recognised, the TEG made their recommendations without the knowledge of the pH, cation and sulfate ion concentrations of the groundwater. This was due to the fact that no data existed with regards to the backfill used adjacent to the concrete bridge foundations in their study (Hobbs, 2003).

This has since led to further expansion and amendment of the guidelines for using buried concrete in aggressive ground. Further work by Hobbs (2003) on this matter highlights that the current guidelines (BRE Special Digest) do not take into account the adverse effects of magnesium ions within groundwater on concrete attack. He concludes that near ‘neutral’ groundwaters have a low magnesium ion count and therefore generally pose a reduced risk of thaumasite attack on buried concrete. Reid et al. (2005) concluded that currently only water soluble sulfate is determined, not allowing for the oxidation of reduced sulfate compounds (i.e. pyrite). The Inadequacies in the 2:1 water/soil extractable sulfate in the BRE SD1 test for water soluble sulfate have been highlighted by Crammond *et al*. (2003) within Lower Lias Clay sediments and associated pyrite minerals. Therefore explaining why one may observe numerous cases of sulfate attack both on cementitious and metallic structures, particularly documented on highway infrastructures within the UK.

2.1.4.4 Further research in concrete corrosion

From this review regarding the degradation of concrete as a result of soil processes it can be observed that the mechanisms are extremely (chemically) complex and spatially highly variable. The risk posed to UK concrete infrastructure assets is great and many studies have been established as a result of this.

The important role of groundwater in mobilizing soluble sulfates has been stated and the failure of other infrastructure (i.e. water, sewerage and drainage pipes) have resulted in the mobilization of sulfates, resulting in corrosion of cementitious infrastructure assets. However knowledge of sulfate concentrations in UK soils remains relatively unknown on the regional/national scale, and further research is required to better understand the spatial distribution of sulfates.

2.2 Soil temperature

McNeill and Edwards (2001) suggest that temperature is often overlooked within corrosion studies, perhaps resulting from a previously stated assumption that soil temperature had no effect on corrosion rate (Pookote and Chin, 1979). However a later study by Nie *et al*. (2009) identifies that generally higher temperatures during the summer months have resulted in greater magnitudes of corrosion to carbon steel pipelines, a result of the oxidative-reductive potential being varied by temperature. It has been noted that for iron, a change in temperature of 1.0^{o}C relates to an electrical resistivity change of 0.5% (SeonYeob *et al.* 2007). It also ultimately has an impact on the soil moisture content, where higher temperatures will result in lower moisture contents, however this will be discussed in the next chapter.

2.2.1 Temperature effects on the 'passive film'

Temperature can also affect the semi conductive property of the passive film (protective layer) of the metal substrate, the presence of aggressive sulfide and chloride ions within the soil can then attack the metal surface (Li *et al*. 2007). Li *et al*. (2007) showed that with increasing temperature (30, 60 and 90^{o}C) and increasing chloride concentration the protective qualities of the passive film decreases. This is dissimilar to concrete based corrosion that is more susceptible under lower temperatures (<15^{o}C) (Clark, 1999).

Soil temperatures, alongside barometric pressure, can have the effect of the 'expansion-contraction' of soil gases (e.g. CO_2, O_2) that ultimately results in differing soil gas concentrations on a daily/hourly basis throughout the soil substrate, and is dependent on the mineralogy of the soil (Shreir *et al*. 2000). Pressure and temperature changes can result in leaking gas from fractured pipelines being drawn into properties and enclosed spaces, posing an explosive risk, if the soil strata are advantageous to this mechanism (Robinson *et al*. 1997).

2.2.2 Soil temperature gradients

After analysing data from the Met Office it is possible to see (Figure 7) that temperature gradients do vary throughout the soil profile, with generally deeper horizons having a slower response time to temperature change.

Figure 7: Soil temperatures for the year 2009: Drumburgh, Cumbria (Data sourced from: UK Metereological Office, 2012)

2.3 Moisture content

2.3.1 Soil moisture and water table fluctuations

Shrier *et al*. (2000) identify three types of soil moisture:

Free ground water: Essentially this represents the water table of the substrate, below which water is always present. The depth to free ground water can vary, dependent upon geological and climatic factors.

- *Gravitational water:* Whereby water, normally as a result of precipitation, enters the soil surface and percolates downwards. Eventually this water reaches the free ground water table, often rapidly, especially in coarser grained soils (i.e. sand and gravel).
- *Capillary water:* Water that is held within the 'capillary' spaces between clay and silt particles, this resource is what plants and animals living within the soil mass rely on for their water consumption. Generally sandy soils have a small amount of capillary water available.

Burton (2001) identifies that water table fluctuations, in particular their height and duration, are important factors in assessing the corrosivity of soils. The depth of the soil subject to periodic moisture change is usually referred to as the active zone (Fu *et al*. 2012).

Water content and water movement in soils can be seen as a factor of (Cole and Marney, 2012):

- Water flow patterns;
- Ground topography, soil profiles and the position of the water table;
- Soil type and water saturation limits.

2.3.2 Critical moisture content of soils and impact on corrosion

Even in the absence of oxygen, iron will still undergo corrosion by the process of oxidative reaction in water (Reardon, 1995). Gupta and Gupta (1979) estimated that the critical moisture content of soils in the corrosion of mild steel is when it is above 50% of its holding capacity. They go further to suggest that the corrosivity potential of soil should be deemed with an assumed water capacity of 65%, their study showed a direct correlation between mass loss in the pipework and moisture content of soils. However Ismail and El-Shamy (2009) have shown that 50-60% is the optimum moisture content for maximum corrosion rate (Figure 7). Norin and Vinka (2003) found higher corrosion rates with increased rainfall, especially if the precipitation is more conductive to corrosion (Kizhlo and Kanbergs, 2010).

Murray and Moran (1989) undertook laboratory and field testing assessing the impact of moisture content on pipeline steel. The study revealed that at near saturated condition (25 to 28wt% water) the corrosion rate was ~2 µA/cm^2, whereas for relatively dry soil case (<10wt% water) the rate was ~2x10^{-2} µA/cm^2. The two soil types that were studied, clay and a sandy loam, revealed similar corrosion rates when subjected to the two moisture content conditions. Ahmed (2011) suggests that soil humidity and consequently soil moisture is an important factor for corrosion rates in soils, which is intrinsically linked to the electrochemical properties of the soil mass essential for corrosional processes.

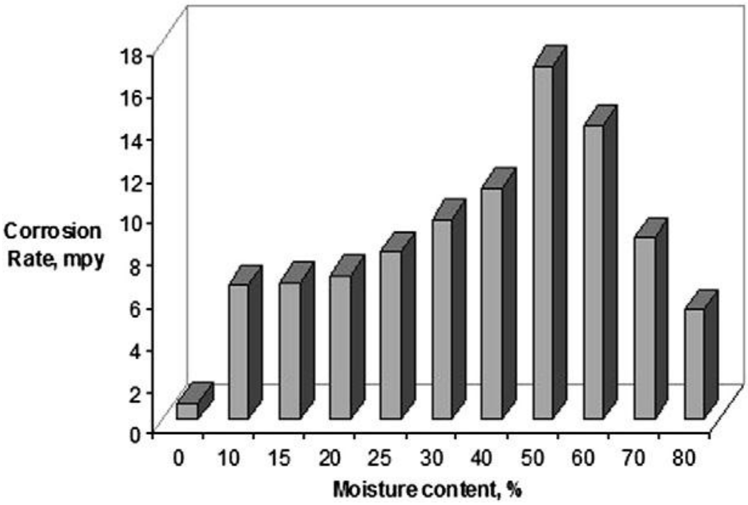

Figure 8: Effect of moisture content on soil corrosivity (From: Ismail and El-Shamy, 2009)

2.3.3 Case Study: Soil moisture in North London

Burton (2001) undertook a visual inspection of the mottles of the soils of North London. Under 'sealed' surfaces (indicated by mottling and greenish grey soil colours) he discovered that soil is not subject to significant summer drying, remaining in fact moist throughout the year. This allows for anaerobic conditions to prevail, except where under the influence of drying by encroaching tree roots.

However in Burton's (2002) study he sought to monitor *in situ* soil moisture changes. As a result of this monitoring study it was apparent that wetting/drying cycles did take place at and around pipe depth under sealed surfaces. Drying of up to 8% was seen in the London Clay over the summer months. Coarser textured soils (with better drainage) witnessed a gradual moisture decline over the summer months. Grassed surfaces showed a greater amount of drying. Grass transpiration resulted in drying to depths of 90-100cm in fine textured soils (i.e. silt and clay), and up to 80cm in coarse textured soils (i.e. sand and gravel). Therefore especially on grass surfaces it is apparent that drying will occur at or around pipe depth which could have a significant effect on corrosional processes. However this study was limited to North London sites, therefore further studies are needed in a range of geological/pedological settings in order to fully understand the soil moisture regime throughout the seasons under different climatic scenarios in a national context.

2.4 Soil Mineralogy/Texture

Soil mineralogy is an important factor regarding the moisture content of soils. A clay soil, due to its inherent molecular structure, is able to retain moisture more readily than a sandy soil (Figure 9). This means that water in clays is more easily retained and so has a greater exposure to any buried metal surfaces, facilitating the corrosive action of the soil (Jones, 1992). However over time clay soils can reduce in their corrosiveness due to the relative inability of these soils to transport oxygen through their mass. This may help to explain why disturbed soils have a considerably greater effect on corrosion rate, as oxygen is mixed back into the soil body. Eventually with settlement of the disturbed soil material, conditions could lead to slower corrosion rates (Oguzie *et al*. 2004).

Noack and Ulanicki (2007) demonstrated that sandy soils would allow leakage around the full circumference of the failed pipe, whereas a clay soil would constrain the leak and lower the flow rate of the escaping fluid.

Jeannin *et al*. (2010) undertook a study to understand the effect of clay mineralogy on corrosion processes. This revealed that clay minerals would interact strongly with the metal surface (especially montmorillonite) hindering oxygen diffusion and release of Fe (II) into solution which subsequently acts to partially block the electrode reducing general corrosion. However localized corrosion can occur within the pores of the mineral layer within clay soils.

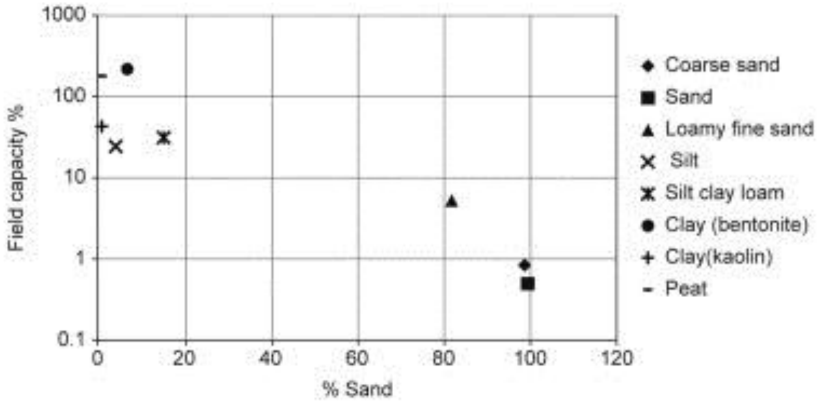

Figure 9: Field (moisture) capacity of soils as a function of sand content (From: Nelson-Neale *et al*. 2000)

2.4.1 Organic matter

Neff *et al*. (2006) suggest that organic matter and carbonate content of soils can initially cause an increase in the corrosion rate at the time of burial. This could be a result of humus rich and very cohesional clay soils inhibiting the formation of an anti-corrosion surface layer on the metal object, something that other soil environments allow (Nurnburger, 2012).

2.4.2 Soil particle angularity

The angularity of soil particles is also a key factor with regards to underground infrastructure resilience. Angular (sharp) particles can pierce the passive 'protective' film of underground metal structures that can leave the metal substrate exposed to the potentially aggressive soil mass (Sjogren *et al*. 2011). Angular particles can also lead damage of PVC corrosion-resistant pipes, as a result of abrasion. One particular case showed that the scratching of a bituminous coating on a cast iron pipe led to the increased corrosion and resultant failure, likely as a result of angular soil particles abrading the surface of the protective coating (Makar, 2000).

Majid *et al*. (2010) have studied the erosive slurry that can be formed when high pressure water mains fracture. In their study, this caused the protective coating of an adjacent steel gas pipe to be damaged, resulting in rapid corrosion and resultant failure of the second service. The soils at this location were sandy in texture which caused the slurry to be highly erosive of the surrounding pipes.

Soil mineralogy could also play a part in contamination migration, for example a gas leak in Teignmouth resulted in gas migrating through the substratum necessitating local businesses to evacuate due to the risk of fire and explosion (BBC, November 2012). A sandy soil would allow this to occur more readily than a clay soil.

2.4.3 Influence of differing soil environments

A pipe passing through differing soil environments can generally be anodic within clay due to the lack of oxygen in clay soils and cathodic in loamy soils (greater aerability). This results in the formation of a 'corrosion cell' (Bradford, 2001) as shown in Figure 10. Velazquez *et al*. (2009) suggest an increasing corrosiveness potential in sandy clay loam, clay loam and clay respectively. These corrosion cells can vary in size from very small (i.e. centimetres) to many miles depending upon the soil properties (Paul, 1994).

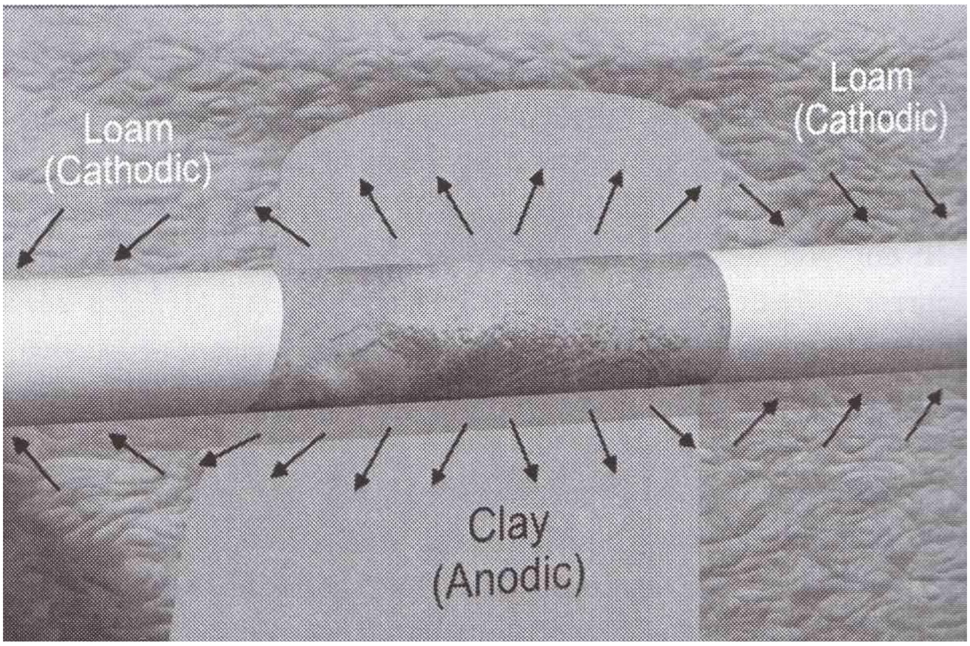

Figure 10: Corrosion cell formed by pipeline passing through differing soil types, arrows show direction of corrosion currents (From: Bradford, 2001)

2.4.4 Soil moisture deficit

Levlin (1996) discovered that during drought conditions clay soils that subsequently shrink and crack, would allow oxygen from the surface to reach the metal substrate through the cracks (that often reach the subsoil). This results in an increased corrosion rate.

The UKCIP (2002) have highlighted that by the 2080's the summer soil moisture deficit could be reduced by up to 40% if the highest emission levels are reached. Together with wetter winters this could result in a seasonally fluctuating groundwater level. The consequences of this could be the changing reducing-oxidising state of the soil being particularly aggressive to buried metal assets (Farewell *et al*. 2012; Kleiner *et al*. 2012).

2.5 Soil resistivity

Soil resistivity indicates the ability of a soil environment to carry corrosion currents. It is subsequently a function of the soil moisture content and the concentration of the current carrying soluble ions (Palmer, 1989).

Soil resistivity is generally controlled by 'spaces, fractures and the amount and composition of fluids that fill the pore spaces within a soil mass' (Alhazzaa, 2007).

Tiba and de Oliveira (2012) identify the following as influencing soil resistivity:

- Resistivity of the minerals and gas that fill the pores;
- Humidity;
- Porosity;
- Texture, shape and distribution of pores;
- The absorption of ions on the surface of the mineral particles.

Resistivity of soils varies widely due to these identified parameters, Busby *et al*. (2012) suggest that often these contributing factors are not measured alongside resistivity surveys so it is difficult to interpret 'the broad ranges of resistivity…for the broad soil texture classes'.

2.5.1 Resistivity measurement

The unit of soil resistivity is the ohm-centimeter (ohm(Ω)-cm) and is a measurement of the 'resistance of a cube of soil one centimeter in dimension as measured from opposite faces' (Parker, 1962). Measurements of resistivity can be made within the field or laboratory. Ferreira *et al*. (2007) identified that laboratory resistivity measurements within in an aqueous solution did not correlate well with field results. With coarse granular soils (i.e. gravels) and made ground with coarse fragments it has often been difficult to obtain reliable measurements due to lack of contact between resistivity probe and soil substrate (Burton, 2003).

2.5.2 Soil resistivity as a corrosion indicator

Mughabghab and Sullivan (1989) found soil resistivity to be relatively unimportant in the corrosion process compared to pH. Whereas Palmer (1989) suggests that resistivity is a major controlling factor in the corrosion rate. Later Bradford (2000) regards the method of soil resistivity as being the most commonly used indicator of soil corrosivity. Rudd (1995) suggested that resistivity alone was only capable of distinguishing between three of the five corrosivity classes for soils, and that seasonal variations had a significant impact. However Burton (2001) found in his study of North London sites that resistivity correlated well with the soil corrosivity classes identified in Table 2: Soil resistivity values and corrosivity effects (ASTM, 2012).

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

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

2.5.3 Stray currents in the corrosion system

Other critical infrastructures can also increase the corrosion of underground assets, via the principle of stray currents. For example electric powered mass transit railway systems and electricity transmission lines can create stray currents resulting in severe corrosion of underground assets (Wang *et al*. 2013; Flounders and Danilyak, 1995). Zhu *et al*. (2011) have suggested that soils with a higher resistivity can counteract the issue of stray currents by limiting the potential for the soil to carry the current.

2.6 Microbiologically Influenced Corrosion

In the absence of oxygen, it is generally assumed that metal corrosion is undertaken as a result of microbial activity (Pankhania, 1988), however it is more pronounced under the influence of a partial oxygen supply (Hamilton, 1998). The process of Microbially-Induced Corrosion (MIC) is deemed to constitute approximately 20% of corrosion costs to many industrialised countries (Mehanna *et al*. 2009). Fleming (1996) previously suggested that this could be as high as 50%. The measurement of redox potential is used to determine whether a soil is anaerobic (oxygen depleted) or aerobic (oxygen rich) (Palmer, 1989), with anaerobic conditions being favoured for MIC.

2.6.1 Sulfate reducing bacteria

Sulfate reducing bacteria (SRB) are considered the major bacterial group involved in MIC (Hamilton, 1985). The process of MIC is a result of any organism that metabolically reduces sulfate to H_2S (Hydrogen Sulphide) (Javaherdashti, 1999). Mehanna *et al.* (2009) have identified the SRB *Geobacter sulfurreducens* as being prolific within soils and sediments and therefore should be considered a great threat to corrosion of underground metals within the soil substrate.

However it is not just the presence of SRB's that provide the cause of anaerobic corrosion. Bio-corrosion has been shown to have occured even when SRB's are absent (Lopez *et al*. 2006). The full story of microbiologically influenced corrosion is yet to be fully understood (Mehanna *et al*. 2009).

2.6.2 Disturbed ground and Sulfate Reducing Bacteria

The study by Karpachevskii *et al*. (2011) revealed the impact of trench backfill and compaction on soil properties. Trench backfill and reinstatement practices can promote waterlogging that increases the likelihood of the presence of SRB, in turn increasing corrosion rates of buried metal substrates. Dexter (1987) highlighted that water saturated clay-type soils of near neutral pH with decaying organic matter and a source of SRB were a threat to the underground pipeline industry. However, a review by Corus (2005) did not identify SRB's to be a factor in the corrosion of driven steel piles, the reasoning to this has not yet been fully explained.

2.6.3 Pinpointing of MIC

The presence of MIC in environments that are considered non-corrosive have resulted in the determination of the likelihood of corrosive action on underground assets difficult (Little and Lee, 2007). Little and Lee (2007) also demonstrate that due to the very localized nature of MIC attack, often electrochemical detection methods (i.e. redox potential) which give an overall signal for the 'entire surface' are not suitable for accurate pinpointing of MIC.

2.7 Soil pH

Oguzie *et al*. (2004) suggest that buried metallic structures are susceptible to corrosion at any pH value. It is interesting to note that within the pH range of 4-8.5 that Iron can be immune, passive (corroding slowly) or corroding, as indicated in the Pourbaix diagram in Figure 8 (Tiba and Oliveira, 2012; Chaker, 1989). This is very much dependent on the [redox] potential of the iron or other metallic products within the soil.

The potential of a metal is the energy per unit charge needed to drive the redox reaction essential to electrochemical corrosion. A lower potential (negative) will therefore be more susceptible to corrosional processes.

2.7.1 Pipe pitting rates and pH concentration

Dafter (2008) suggests that pH data often corresponds poorly to pipe pitting rate. He demonstrates that other electrochemical methods (i.e. redox potential and resistivity) are more accurate for determining soil corrosiveness. However Doyle *et al*. (2003) considering water main corrosion in Toronto, Canada showed that the use of pH measurements increased the correlation coefficient of this resistivity based study. Bushman and Mehalick (1989) also suggest that soil pH bared a strong correlation with ferrous iron pipe pitting rates.

2.7.2 pH and the passive protection layer

At low pH values it has been suggested that the passive protection layer is unable to form, leading to a higher corrosion rates (Camitz and Vinka, 1989). At a near neutral pH the soil permits an amenable environment for SRB to develop (Dexter, 1987). This could possibly explain the identified high corrosion rates within North London (Burton, 2001). He identified North London soils as having a neutral/alkaline pH, although it should be noted that soil adhering to affected pipes tended to be slightly acidic (pH ~4.99). However this inherent acidity adjacent to the affected pipe could be a result of the corrosion process (Figure 11).

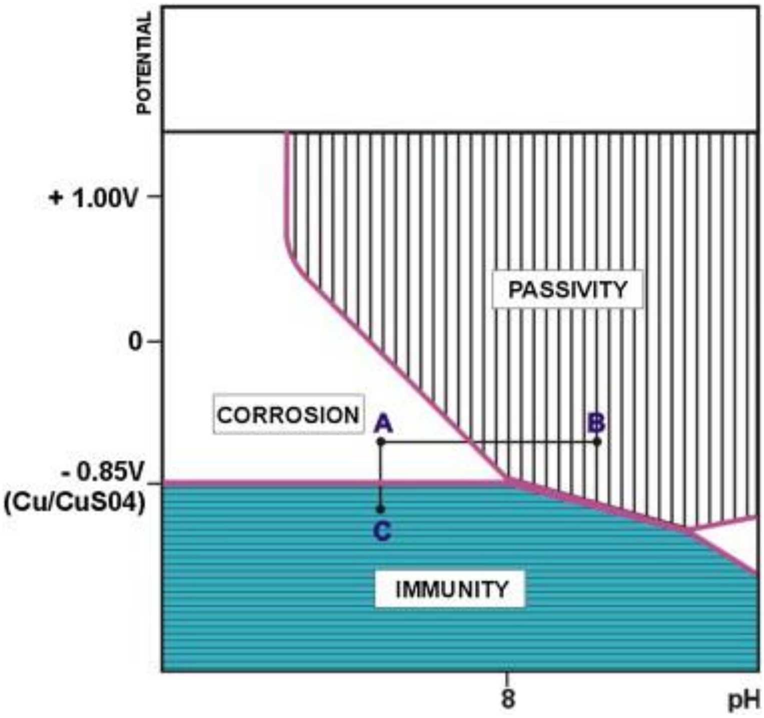

Figure 11: Simplified Pourbaix diagram ([Redox] Potential x pH) (From: Tiba and de Oliveira, 2012)

3. The impact of soil corrosion on UK infrastructure

3.1 Energy (Oil, Gas and Electricity)

3.1.1 Oil/fuel sector

The consequences of pipeline failure, especially in the case of pipelines carrying fuels and oils as well as other hazardous substances can be potentially harmful. For example, in July 1999 a tank at the Esso Petroleum in Fawley, Hampshire released some 400 m^3 of crude oil, a result of corrosion at the base of a storage tank (UKSHE, 2000). Subsequently if the soil easily permits the flow of liquids through it (i.e. a sandy/gravelly soil) then contaminants could easily enter ground waters and pollute wide areas (depending on the catchment area). The consequences of agricultural ground becoming contaminated could result in it potentially becoming unusable for many years (Moore and Hallmark, 1987).

Clark and Sims (1998) identify the presence of buried services as ‘pollution conduits’ whereby they allow the preferential flow of contaminants, this may be due to the backfilling of service trenches with sand sized materials.

3.1.2 Electricity sector

Both Ibrahim (1999) and Kirkpatrick (1988) have suggested the steel power line support structures will freely corrode and inevitably fail when in direct contact with the soil. This is aided by the copper grounding that coincides with the towers used for earthing the structures. The process of galvanic corrosion and the exacerbation by copper was discussed earlier in this review. A study by Fitzgerald and Kolb (1985) revealed that the Kentucky Power Company's overhead power line suffered considerable corrosion less than two years after construction. Hu *et al.* (2000) have identified that the corrosion of substation grounding grids are a large problem in China which are generally constructed from steel or galvanized steel. Whereas earthing grids within the UK are generally constructed from copper which has a greater resistance to corrosion. The corrosion of buried subsurface distribution transformers have also failed after a short period of time due to corrosion processes (Pittsfield and Hickary, 1972).

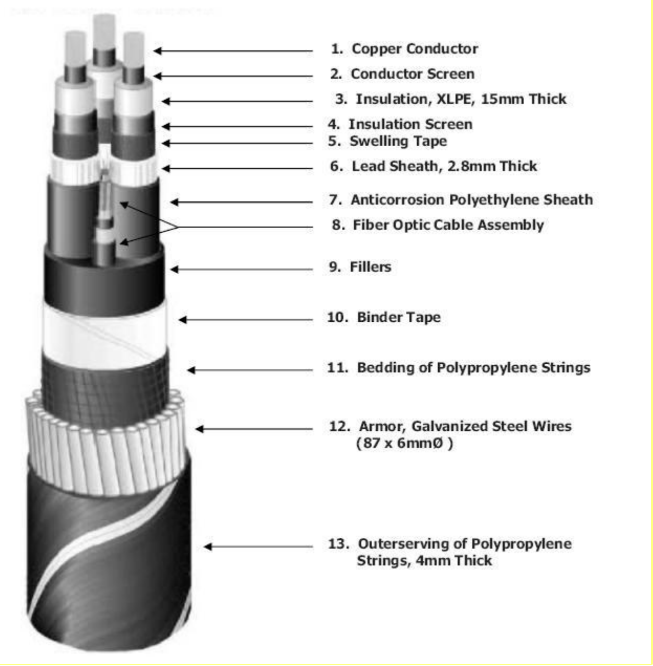

Figure 12: Typical construction of 3 phase electric cable (From: openelectrical.org)

There have been certain cases of MIC being a problem on buried underground cables in Spain. However this was deemed as a result of contamination of the materials used for cable construction and not as a result of bacteria sourced from the soil environment (Pintado and Montero, 1992). The construction of electric cables, at a distribution level often makes them hardy to corrosional processes as seen in Figure 12. The outer covering of polypropylene (plastic) serving to prevent corrosion (National Grid, 2009).

3.1.3 Gas sector

The Health and Safety Executive (HSE, 2001) issued an enforcement policy concerning the issue of iron gas mains failures, which subsequently established the Iron Mains Replacement Program (IMRP) (HSE, 2011). The HSE identified that some 91,000 km of remaining iron gas mains within 30m of buildings that could be deemed at risk as a result of failure were present (Table 3). Approximately 23,000 fractures and corrosion failures which had led to 600 'gas in building' events resulting in the fatalities of 1-2 people annually had occurred up to 2001 with most iron pipes being 40-100 years old. This sign of an 'aging' gas main infrastructure has led the fracture rate to rise from 13 per 100km in 1977 to approximately 14,5 per 100km in 1999.

Material	**Length of low pressure (Km's 000s)**	**Length of medium pressure (Km's 000s)**	**Total length (Km's 000s)**
Cast Iron	73	4.7	77.8
Ductile Iron	13	-	13
Totals	86	4.7	90.8

Table 3: Length of cast iron and ductile pipes affecting 'at risk' population (30m from gas main) (HSE, 2001)

An explosion at Bridge Street, Shrewsbury 2010 (Figure 13) prompted an investigation by the HSE (2010). It resulted in the destruction of six commercial properties in the town centre, luckily with no fatalities. The sandy-gravel soil type which was identified within the excavated trench was deemed to be very aggressive to moderately corrosive, the nine inch low pressure gas main was also surrounded by bricks and in some cases founded on an historic brick foundation which could have led to increased stresses on the pipe from traffic and loadings above. The soil type (sandy gravel) allowed the leaking gas to migrate to the nearby commercial properties that probably provided a source of ignition, there was no domestic gas supply to any of the affected buildings.

Figure 13: Result of gas explosion at Bridge Street, Shrewsbury, 2010 (From: BBC, 2010)

It is important to note that adjacent to the gas main were a number of other key infrastructure assets including water, electricity, telecommunications and traffic light cables. The HSE identified that both the telecoms and traffic light systems were damaged as a result of the explosion, which resulted in disruption to local services and businesses within Shrewsbury town centre.

Figure 14 shows the effects of corrosion on the failure of a large scale gas main which luckily was not in a populated area but still resulted in the destruction of two houses almost half a mile apart.

Figure 14: Explosion of a gas pipeline, deemed to be as a result of corrosion, Appomattox, Virginia. (From: http://protectingourwaters.wordpress.com/2012/04/05/pa-court-no-right-to-know-about-pipeline-saftey-problems/)

3.2 Telecommunications and ICT

With telecommunications and network cables often being wrapped in corrosion resistant materials (Figure 15) and then being placed within plastic ducting, soil corrosion is not often an issue and literature relating is very sparse.

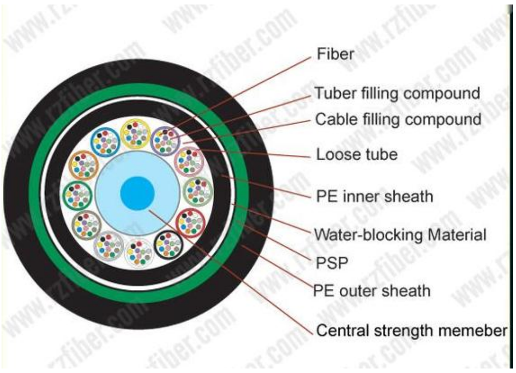

Figure 15: Typical design of a double armoured 96 core fibre optic cable (From: alibaba.com)

3.3 Highways

Sulfate attack identified on the M5 motorway (Hobbs and Taylor, 2000) has left the reinforcing bar within the concrete exposed to the soil, which has subsequently lead to its corrosion and weakening of the entire bridge structure(s).

The use of steel piles in a range of engineering activities (i.e. bridge foundations) have been reviewed on a global context, whereby unless the soil is strongly acidic (pH <4) then underground corrosion in disturbed soils is often neglible, independent of soil characteristics deemed a result of relatively low oxygen levels (Morley, 1978; Corus, 2005). Padilla *et al*. (2013) have found general agreement that the main reason for premature failure in steel reinforced concrete structures is the corrosion of the steel reinforcing bars. They go further identifying a large part of this issue to be related to road de-icing agents, which subsequently contaminate the soils with large quantities of sulfates. The cost of the direct association with the use of road deicing salts and their impact on road and bridge infrastructure within the USA have been estimated at between $2.5-5 billion per year (Padilla *et al*. 2013).

Soil nailing for mainly highways and rail embankments is a common occurrence within the UK, the process involves the reinforcement and strengthening of ground (especially slopes) by installing closely spaced steel bars (or ‘nails’) (Figure 16) (Yean-Chin and Chee-Meng, 2004). The nails are often made from unalloyed or low-alloyed steel (Nurnburger, 2012), therefore Prashant and Mukherjee (2010) suggest that soil nails can be particularly prone to corrosion. This is often a result of high groundwater levels, especially those soils with high quantities of acids and dissolved salts. Furthermore, in natural ground oxygen always reaches the surface of the metal independent of the ground conditions (Nurnburger, 2012). The overall result is failure of the soil nails and subsequent possible slope failure resulting in damage to the infrastructure asset. To protect against the degradation of soil nails, they are often coated in concrete (up to 20mm thick) but this can have inherent cracks and deformities which can lead to attack of soil directly onto the exposed steel surface (Phear *et al*. 2005; Nurnburger, 2012).

Figure 16: Slope pinning on the M1 Motorway (S.Hallett)

3.4 Water/Wastewater

Ashton *et al*. (2009) in their report outlining the leakage target setting for the Greater London authority highlight the serious potential impact that leakage could have on the underground transport network (i.e. London Underground Limited) and traffic congestion. The latter was recently witnessed at the Brent Cross Flyover when a water main burst flooding and closing the North Circular road, a main commuter road into Central London (BBC, 2012) (Figure 20).

The problem of a burst pipe could be a greater problem if other hazards are apparent, for example in July 2012, Severn Trent Water suffered two consecutive water main burst within their system which could not be pinpointed due to flooding of the area (BBC, July 2012).

Pipelines are evolving to counteract corrosional processes, the 1960’s marked the progression from spun gray iron pipes to that of spun ductile iron pipes in the UK water industry. However King *et al*. (1986) deduced that these two materials corroded at similar rates despite their metallurgical, chemistry and mechanical properties being very different. Newport (1981) suggested in the study of Severn Trent Water's pipe network that age was not always a factor in pipe corrosion, suggesting that spun iron pipes had a greater failure rate than the oldest cast iron mains. Iron pipes have sometimes been encased in polyethylene to extend their life by not allowing the metal to come into contact with corrosive soils (Crabtree *et al*. 2012).

Bradford (2001) comments on how the replacement of new sections of steel pipe can also increase corrosion action on the rest of the pipe. After replacement the new section of pipe becomes anodic in relation to the old section of pipe and the new section suffers from increased corrosion.

Pipe Type Class	Burst Rate
Cast Iron	1.12
Lead	0.60
PVC	0.33

Table 4: Failure rate of North East Water pipes in relation to pipe material (From Dufour *et al*. 1998)

The movement to PVC pipes has seen a large reduction in the amount of bursts in the water network (Table 4). Cohen and Brock (1995) undertook a study surveying the water distribution network in Billings, Montana, where copper pipes were assessed for corrosion in relation to their soil environment. However their study showed the general acceptance that copper is effective as a corrosion resistant material with maximum corrosion pit depths less than 5% of the wall thickness after 29 years of burial in the soil environment. Although the soils in Billing were relatively non aggressive, localized corrosive attack was deemed to be a result of the contamination by deicing salts and lawn fertilisers.

In a case of water pipe corrosion in San Diego, cast iron pipes were used as trunk mains and copper pipes as domestic supply lines, when the cast iron pipes became severely corroded they were replaced with asbestos cement pipes (this would now generally be polyethylene) which resulted in the copper pipes being severely corroded as they had been cathodically protected by the cast iron. Therefore often replacing certain sections of pipes with corrosion resistant materials could exacerbate or create new problems in other locations (Bradford, 2001).

3.4.1 Case study: London's Water Mains

With more than half of Thames Water's mains being over 100 years old, and approximately a third being over 150 years old (Greater London Authority, 2003), it is no surprise that they are under threat from attack from corrosive soils due to their relatively long exposure times. In the three years prior to 2000/01 leakages of mains in the London area was reduced by approximately 38%. However since this period leakage percentages have increased (Figure 17) but have since fallen due to the remedial measures imposed on Thames Water. The initial increase was factored as being a result of processes in London's clay soil on the aging water mains (Greater London Authority, 2003).

An earlier study undertaken at Cranfield University followed Thames Water in their investigation and repair of water pipes within the North London area. This allowed assessment of the soil profile and *in situ* testing, characterisation and sampling to be undertaken around the failed pipe(s).

The geology of London consists predominantly of the London Clay Formation. Cast iron gas and water mains are susceptible to corrosion as a result of the aggressive behavior of the London Clay (Schmidt *et al*. 2008). Palmer and Bunyan (1999) showed within their work that lime contamination of soils as a result of material used for backfilling of service trenches has increased the pH value of the soil(s). Undisturbed soils, however, were determined to be slightly acidic to neutral compared to that of neutral/alkaline of the undisturbed soils. These clays are also prone to shrinkage, which generally occurs in the dry summer months, and swelling, which generally occurs in the autumn months. Illite is the main clay mineral within the London Clay, with smectite also being present. The very high surface area of illite makes it susceptible to the shrink/swell process. It is also interesting to note that within Burton's (2001) study of North London soils that generally below 60cm depth the soil profile remained recognisable (Windsor Series).

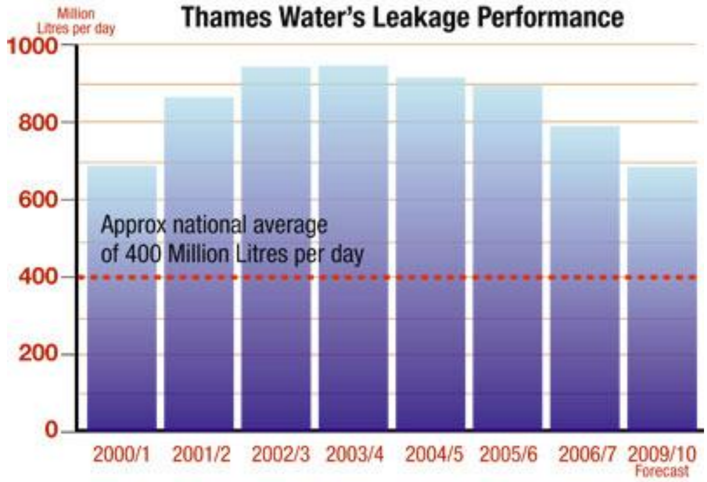

Figure 17: Thames Water's leakage performance between 2000-2010 (From: www.abingdonreservoir.org.uk/popup/tw_leakages.html)

The consequences of the action of corrosion and shrink/swell clays are that underground pipe networks (water and gas) are highly susceptible to fracture (Figure 19). Figure 18 shows an application of remote sensing (satellite monitoring) in identifying the ground movement within the London metropolis. The north west of London (white box) appears to be more susceptible to vertical movement more than the southern and eastern areas of the city. The cyclic annual vertical movement has been estimated at approximately 50mm (Boyle *et al*. 2000). These processes result in a high intensity of pipe breakages, something that has been especially witnessed within the northern area of London.

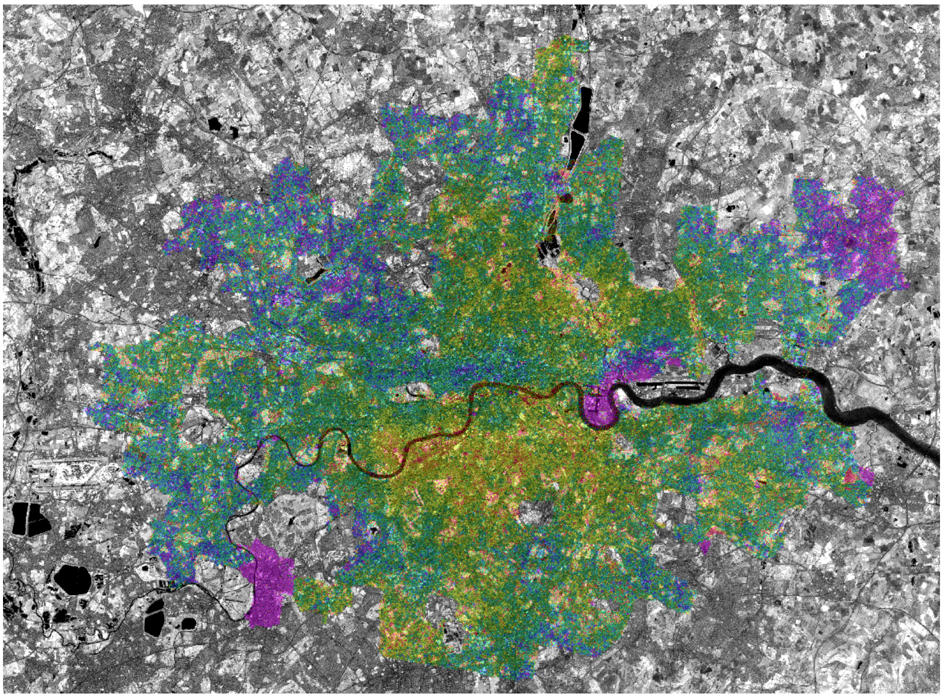

Figure 18: A height change (degree of movement downwards) image derived from a differential interferogram overlain on a landsat TM image. Blue represents a greater movement than red (purple areas are incorrectly wrapped) (From: Boyle *et al*. 2007)

Figure 19: Close up of pipe fracture in situ (From: Burton, 2004)

Figure 20: Consequences of pipe burst at Brent Cross Flyover, North Circular, London, 5th September 2012. (From: BBC, 2012)

The cascading effects of a water pipe burst on the North Circular, near to the Brent Cross flyover in September 2012 could be clearly seen (Figure 20). Not only did it cut off the supply to approximately 1,300 homes, but it also caused the closure of one of London's busiest commuter routes (BBC, September 2012).

3.5 Nuclear Waste containment

The process of nuclear power generation is good from the perspective of immediate carbon emissions, however the storage of the resultant nuclear waste is problematic (i.e. Sellafield, Cumbria (BBC, 2013) and presents a current issue for many nuclear countries (Cattont *et al*. 2008).

After their use in the generation of power, high level radioactive wastes will be stored within metallic containers and buried. Therefore the metal containers can come into contact with soils, more specifically clay minerals. This association with clay soils could allow them to be susceptible to the action of corrosive ground. The depth to which they are stored is likely to be great so could be suggested to be of little interest to soil science, however as Neff *et al*. (2005) suggest, many studies of archaeological iron in shallow soils have been facilitated as a result of this issue, particularly in France. The study of archaeological iron allows for the assessment of iron materials that have been in contact with soils, often for many centuries, suggesting a key role that the understanding of shallow soil deposits and their corrosivity plays in the decision making of key geological containment of radioactive wastes.

4. A 'stand-alone' issue?

Pipes do fail due to corrosion alone, however pipes that are weakened by corrosion processes are often then susceptible to other externally applied stresses (Schmidt et al. 2006), discussed elsewhere.

4.1 Ground movement

The formation of cracks in drying clay soils (Brady and Weil, 2002) could exacerbate the process of corrosion by allowing oxygen to reach the metal surface. The formation of cracks also provides an efficient medium for the transport of contaminants through the soil mass if a pipe were to fail (Oostindie and Bronswijk, 1995; Farewell *et al*. 2012). Additionally with the formation of cracks, surface soils are likely to be deposited in the formed cracks, later rainfall events will then result in the swelling and closing of the cracks in the clay soil. The increased surface volume as a result of the presence of infilled material within the cracks results in both lateral and upward soil movement (Farewell *et al*. 2012) that along with corrosion processes could cause the underground asset to fail.

The resultant failure of drains and water mains can also result in ground movement that could affect other services that are in close proximity, Burton (2001) noted that often other services were encountered 10-50cm away from the affected service that was being investigated/replaced. For example if a water pipe or drain were to develop a leak in a clay soil then the subsequent wetting could result in the swelling of the soil, of up to 10% of original soil volume (Nelson and Miller, 1992). This would result in significant movement that could damage other services that have been subject to corrosion processes (Jones and Jefferson, 2012).

Damage costs to foundations and infrastructure as a result of ground movement have been estimated to reach costs of £500 million in 1991 (Jones and Terrington, 2011). Oliff *et al*. (2001) regard the settlement of soil as both inducing failure in older pipelines but also the most common cause of failure in modern (plastic) pipelines. Leaking (high pressure) pipes could also have the effect of eroding the supporting substrate, especially when in a sandy soil, often resulting in longitudinal failure of the pipe (Balkaya *et al.* 2012). A gas explosion that occurred at Buckstone Road, Edinburgh in 2005 was the result of a number of soil factors. Firstly the four inch diameter cast iron gas main had suffered fissure corrosion at its base. Secondly the resultant leak had allowed gas to migrate through the permeable soil where it collected within the basement of one of the properties in Buckstone Road, which finally resulted in an explosion. It was identified at this site that ground instability had played a major role in the pipes failure (HSE, 2006).

The Cranfield study on London water mains revealed that under concrete and tarmac, clays are not likely to undergo shrink-swell processes (Burton, 2002). The only instance where this may be an issue is where tree roots encroach upon the soil system. Trees extract moisture from the ground to depths of between 1.5 and 2.0m in the UK, causing settlement of clays, especially in areas that are paved and are not subject to evapotranspiration (Biddle, 2001; Clayton *et al*. 2010). Tree roots can also have the opportunity to directly affect underground pipes and cables by putting increasing stresses on them, especially for larger sized roots (BRE, 1999), however this was not deemed to be a significant cause of damage to services in Burton's (2001) study.

4.2 Human error

Construction and or repair of other infrastructures could also result in pipe leakage, especially where mechanical excavation techniques are employed. If the pipe has already undergone corrosional processes then the action of disturbing the local soil profile may result in premature pipe failure (Sosa and Alvarez-Ramirez, 2009). Likewise during backfill of the service trench, if not properly compacted, settlement (perhaps differential) could result which would put stress on the buried service and possibly lead to its failure.

5. Soil mapping and calculation for corrosion risk potential in soils

Principally the aim of soil surveys and resultant soil mapping is to obtain and provide information about the soil underneath our feet (Avery, 1987). The use of soil mapping to assess the corrosivity of soils was originally introduced as the risk assessments of pipeline operator's needed to be bettered in order to reduce the likelihood of asset failure in regards to corrosion (Figure 21). The method of soil corrosivity mapping is becoming increasingly prevalent as it provides a clear visual interpretation for regional characterisation. Often mapping is used alongside in situ measurements of soil characteristics during the design phase of pipeline construction (Gimelfarb, 1990). Within the USA, soil surveys were being undertaken to map soil corrosivity as early as 1935 (Denison and Ewing, 1935).

Soil maps are better able to distinguish the potential degree of corrosiveness than a geological (drift/bedrock) map. Corcoran *et al.* (1977) undertook a survey of soils in south Oxfordshire, they found that geological maps interpreted the study area as being underlain entirely by the Oxford Clay Formation. However three distinct soil series (Evesham, Denchworth and Langley) were identified in the study area that had large variations in terms of corrosivity. The importance of understanding the characteristics of the individual soils was made clear in this study, rather than solely assessing drift geology.

Penhale (1971) argued that soil corrosivity mapping based upon soil characteristics are subject to errors due to the number of soil factors that may influence corrosion. Argent and Furness (1979) support this suggesting that small scale maps are generally only suitable for a brief assessment of corrosive soils, whereas the use of large (national) scale soil maps have proven to give considerable precision. The role of a changing climate is likely to significantly alter soil characteristics in future scenarios, this also needs to be accounted for (Kumar and Imam, 2013).

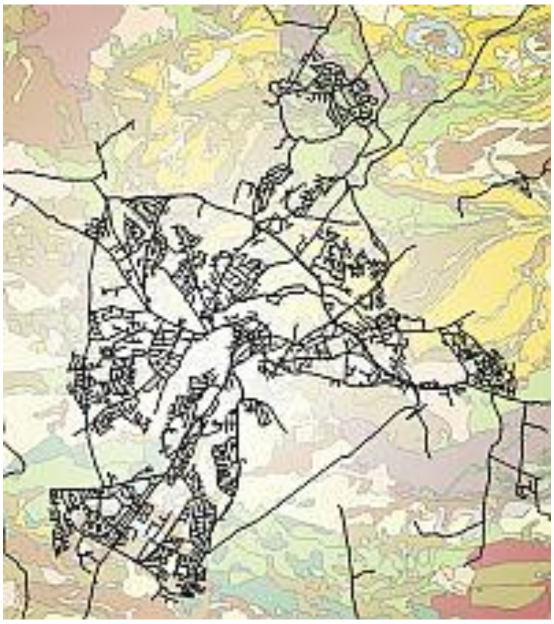

Figure 21: Example of a pipe network overlain on a soil variability map (From: www.landis.org.uk/services/leacs.cfm)

5.1 NSRI and the Leacs model

The National Soil Resources Institute, Cranfield University has developed a commercial geo-spatial tool to assess and visualise the corrosivity potential for underground-buried infrastructure assets (i.e. water/gas mains). This tool, regarded as the main source of soil corrosion information (Royse *et al*. 2009), known as Leacs (Leakage assessment from corrosivity and shrinkage) is primarily aimed at the water industry but is invaluable to any infrastructure operator managing shallow underground assets. The Leacs model was derived from Palmer's (2007) calculations for corrosion risk potential at depths of 0.4 and 1.0m (Appendix 1). The Leacs system assesses not only the corrosivity potential of the soil but also the shrink/swell properties of predominantly clay soils incorporating over 60 years of accumulated soil data for England and Wales, it was identified in the previous chapter that pipe failure is often a result of these two phenomenon.

Royse *et al*. (2009) have suggested that the Leacs model does not fully encompass the 'very complicated' nature of soils within the UK in regards to corrosivity. A lack of data available for urban areas could also be problematic for assessing risk to buried services in the urban environment.

The Leacs model has proven to be useful in directly correlating infrastructure assets with potential hazardous soil conditions, especially in the water industry. Along with breakage records the system has the possibility to give a clear identification of key problem corrosivity areas, aiding technological solutions for future mitigation of soil related geohazards on buried infrastructure. Pyne's (2007) study in the Northumbrian Water region assessed the comparison of the Leacs model with breakage rates for the region. It was shown that more bursts occurred in the 'lower' risk areas than in the 'high', with Pyne concluding that other factors apart from corrosivity and subsidence must be a factor in water mains failure for this region.

6. Solving the problem….

It would be the ideal of the subsurface infrastructure engineer to stop and protect against corrosional processes within soils, however the issue of corrosivity on buried infrastructure is often a difficult problem to address and one that cannot be entirely solved (Ibrahim, 1999). This report shows that there are many inter related soil properties contributing to the problem of metal corrosion within the buried environment.

Corcoran *et al*. (1977) identify that the prediction of soil corrosivity in soils is important for pipeline engineers because; a) it allows the estimation of performance and life of newly installed pipelines and subsequent methods for protecting them and; b) the anticipated failure of existing pipelines can be established.

However leaks from buried pipes, especially potable water supplies can often be difficult to trace as often they drain into storm/sanitary sewers, porous underground formation(s) and absorbent soils (Walker and Schaefer, 2009). The techniques listed in Table 5 offer some possible solutions to both monitoring and detecting failing/failed buried water and sewage pipes. Although as Ratiliffe *et al*. (2009) describe, 'buried pipelines often operate in a state of anonymity with respect to corrosion until deterioration is severe enough to cause failure'. In some cases severe pitting corrosion can occur without any significant metal loss or change in the resistance, which results in electrical resistance sensors not successfully predicting corrosion rate of a buried asset (Zivica, 2000).

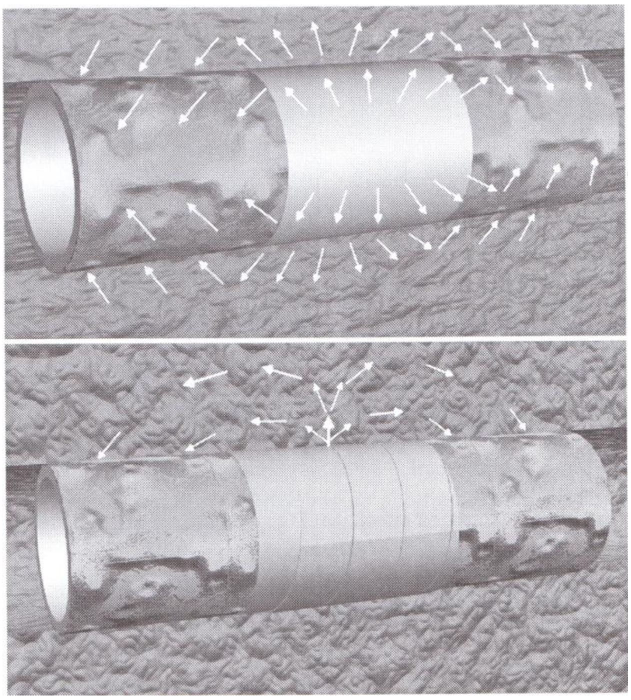

Figure 22: New steel pipe (lighter colour) section connected to rusted steel pipe (darker, pitted pipe). Top picture shows pipe without coating and bottom has coating with more concentrated attack in coating flaw(s) (From: Bradford, 2001)

Alamilla *et al*. (2009) suggest that both the evaluation and estimation of corrosion for buried metals is often complex and should not rely on the values of in situ measurements themselves, but also consider the soil properties (i.e. texture, water content, resistivity, pH, redox potential, composition and concentration of chemical species).

With corrosion occurring at different rates for each asset (i.e. pipeline), and across individual assets due to the dynamic soil environment, often the age of the buried service is not always a factor (Marlow *et al.* 2011). In certain cases the replacement of pipe sections can have a detrimental effect, resulting in the new section acting as an anode with the older pipe acting as a cathode (Figure 22). Also if the pipe is protectively coated this can result in extremely localized corrosion due to the inevitable flaws in pipe coatings, often this will lead to penetration of the new pipe within weeks, perhaps a reason for continuing failures after pipe repair (Bradford, 2001). Similarly Corbett (1998) suggests that using replacement pipe (metal) of the same type as the existing buried infrastructure can have an increased effect on corrosion of the new section of pipe. This is due to the new pipe not having developed a 'passive' protective film compared to that of the old section, so preferentially corrosion takes place on the new section of pipe first.

This review has shown that it is often a combination of other soil factors that have led to the failure of corroded pipes, such as the shrink swell of clays and loading of the ground surface with transport and paved surfaces.

Technology	Asset type(s)	Relevant failure event(s)	Primary stress indicator and pathway
Optical fibre monitoring for structural condition	Gravity sewer, sewer rising mains, water	Sewage spill, leak, burst main	Soil movement, pipe deformation, joint leak, surge pressure/cyclic pressure
Soil temperature/moisture/ pressure sensing to infer structural condition	Gravity sewer, sewer rising mains, water	Sewage spill, leak, burst main	Soil environment change, soil movement
In situ linear polarization resistance to monitor soil corrosivity	Sewer rising mains, water	Sewage spill, leak, burst main	Soil environment change, external corrosion
Surface based resistivity to monitor soil corrosivity	Sewer rising mains, water	Sewage spill, leak, burst main	Soil environment change, external corrosion
Infrared thermography	Gravity sewer, water	Sewage spill, leak, burst main	Loss of support/voiding, exfiltration, leak, burst main
Ground penetrating radar	Gravity sewers	Sewage spill, infiltration	Loss of soil support/voiding

Table 5: Monitoring technologies identified for water and wastewater systems (From: Davis *et al*. 2013)

7. Conclusion

With the cost of corrosion within the UK estimated to cost 4-5% of the GNP (Uhlig, 1985) it can be seen that this is a real issue facing buried critical infrastructure within the UK.

The heterogeneous nature of UK soils and the presence of 'made ground' (especially in urban areas) and service trench backfill has often resulted via anthropogenic alteration of in situ and imported soils in adding to the soil's corrosive nature, ultimately providing additional stresses on the UK's underground infrastructure assets.

This review has critically assessed the soil factors that are deemed to affect soil corrosivity of which; 1) are very complex; 2) do not act in isolation; 3) are intrinsically linked and interrelated. Future climatic change and increasingly extreme weather events as highlighted by the UKCIP (2002) and HSE (2011) could result in changes in soil conditions that could exacerbate soil corrosivity within the UK. On the contrary it could also result in the improvement of some soil series with respect to soil corrosivity.

Corrosion alone can result in the failure of buried infrastructure assets, however it is often due to a series of supporting event(s) that leads to inevitable asset failure; i.e. 1)shrink/swell clays, 2) loss of support (soil erosion), 3) Use of mechanical machinery in cohesive material to investigate failure, 4) Influence of tree roots (indirect and direct).

From review of available literature it appears that the gas and water and to a lesser extent the highways sectors are most affected by corrosional processes. The electricity and telecommunications sectors have proven little affected by subsurface corrosional processes as cable design has often mitigated against this risk. Electricity pylons have been subject to corrosional processes, however the use of cathodic protection has often greatly reduced this risk over recent decades.

The identification of corroded underground infrastructure assets are often hard to monitor due to the large expense and impracticability of excavating service trenches, which are often situated adjacent to or within busy highway networks. However corrosion can result in the contamination of soils and groundwaters that not only affect potable water supplies but also can have a significant effect on agricultural land quality for future years. Fire and explosion caused by rupturing fuel lines has the potential to cause great harm, especially within urban areas.

Investment in underground infrastructure needs to be a continual process so as to decrease the assets functional failures due to corrosivity of the surround soil. However from identified replacement programs within the UK such as the IMRP, the replacement of mains is not often based upon soil factors, but rather diameter and pressure of pipes (HSE, 2011). This approach could explain the continued failure of particular water and gas mains within the UK as a result of corrosional processes. It is hoped that better integration of soil corrosivity mapping can hope to further identify potential areas of risk to the infrastructure network of the UK.

To finally conclude; while Butlin (1952) suggests that a product placed within the earth (soil) will ultimately revert, by deterioration and corrosion, to their original form, Ibrahim (1999) comments that 'corrosion of most metals is inevitable and corrosion prevention all but impossible… fortunately corrosion control is possible'

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Appendix 1 – Calculator for corrosion risk potential in soils

The following table provides a set of criteria for determining a soil corrosivity rating at soil depths of 0.4m, 1.0m, plus overall rating scoring system.

Factor (at 0.4m depth)	Rating	Criteria	Score
Texture ***(taken from** soil **series definition)***	Clay <27%		0
	Clay >27%		1
Soil water regime ***(taken from Avery (1980) subgroup definitions)***	Well drained	No gley mottling present	0
	Stagnogleyic	No distinct gley mottling above 40cm (‘g’ horizon criteria – Avery 1980) plus slowly permeable layer.	2
	Stagnogley	Distinct gley mottling above 40cm plus slowly permeable layer.	3
	Super-Stagnogley (WC V & VI)	Distinct gley mottling above 40cm plus, peaty surface layer; slowly permeable layer.	3
	Gleyic	Distinct gley mottling only below 40cm; no slowly permeable layer.	0
	Gley	Distinct gley mottling above 40cm; no slowly permeable layer	2
	Super gleys (WC V & VI)	As gley criteria above but peaty layers present, at least at the surface.	4
Acidity/Alkalinity ***(taken from surveyors best estimates)***	pH >4.5		0
	pH <4.5		1
	Calc at 40cm	Only assessed in well drained soils	-1
Sulphates ***(Refer to geology and surveyors best estimate)***	None present		0
	Trace		1
	Present		2

Calculator for risk corrosion potential at 40cm depth (After Burton, unpublished)

Factor (at 1.0m depth)	Rating	Criteria	Score
Texture ***(Taken from series definition)***	Clay <27%		0
	Clay >27%		1
Soil water regime ***(Taken from Avery (1980) subgroup definitions.***	Well drained	No gley mottling present	0
	Stagnogleyic	No distinct gley mottling above 40cm (‘g’ horizon criteria – Avery 1980) plus slowly permeable layer	1
	Stagnogley	Distinct gley mottling above 40cm plus slowly permeable layer.	2
	Super- Stagnogley (WC V &VI)	Distinct gley mottling above 40cm plus, peaty surface layer; slowly permeable layer.	3
	Gleyic	Distinct grey mottling only below 40cm; no slowly permeable layer	2
	Gley	Distinct gley mottling above 40cm depth; no slowly permeable layer.	3
	Super gleys (WC V &VI)	As gley criteria above but peaty layers present, at least at the surface	4
Acidity/Alkalinity ***(Taken from Surveyors best estimate)***	pH >4.5		0
	pH <4.5		1
	Calc at 1m	Only assessed in well drained soils	-1
Sulphates ***(Refer to geology and surveyors best estimate)***	None present		0
	Trace		1
	Present		2

Calculator for corrosion risk potential at 1.0m depth (After Burton, unpublished).

Corrosion class Number.	Corrosion class name	Score
1	Non aggressive	0-1
2	Slightly aggressive	2
3	Moderately aggressive	3
4	Highly aggressive	4
5	Very highly aggressive	>4
6	Impermeable rock	

Corrosion potential classes. (After Burton, unpublished)