Shrink–Swell Soils

Introduction

Shrink-swell soils are one of the most costly and widespread geological hazards globally, with costs estimated to run into several billion pounds annually. These soils present significant geotechnical and structural challenges to anyone wishing to build on, or in, them. Shrink-swell occurs as a result of changes in the moisture content of clay-rich soils. This is reflected in a change in volume of the ground through shrinking or swelling. Swelling pressures can cause heave, or lifting, of structures whilst shrinkage can cause differential settlement.

This chapter aims to give the reader a basic understanding of shrink–swell soils. To do this, we will review the nature and extent of shrink-swell soils, both in the UK and worldwide, discuss how they form, how they can be recognised, the mechanisms and behaviour of shrink–swell soils, and the strategies for their management (including avoidance, prevention and mitigation). This Chapter also includes a glossary of terms and is illustrated throughout with references and recommendations for further reading, in order to help the reader's understanding of the subject.

Properties of shrink–swell soils

A shrink–swell soil is one that changes in volume, in response to changes in its moisture content. The extent of the volumetric change reflects the type and proportion of swelling clay in the soil. More specifically, expansive clay minerals expand by absorbing water and contract, or shrink, as they release water and dry out. Clays range in their potential to absorb water according to their different structures (Table 1). For the most expansive clays, expansions of 10% are common. (Chen 1988; Nelson & Miller, 1992).

In practice, the amount by which the ground shrinks and/or swells is determined by the water content in the near-surface (active) zone. Soil moisture in this zone responds to changes in the availability of atmospheric recharge and the effects of evapo-transpiration. These effects usually extend to about 3 m depth, but this may be increased by the presence of tree roots (Driscoll, 1983; Biddle, 1998; Biddle, 2001). Characteristically fine-grained clay-rich soils soften, becoming sticky and heavy following recharge events such as rainfall and commonly they can absorb significant volumes of water. Conversely, as they dry, shrinking and cracking of the ground is associated with a hardening of the clay at surface. Structural changes in the soil during shrinkage, e.g. alignment of clay particles, ensure that swelling and shrinkage are not fully reversible processes (Holtz & Kovacs, 1981). For example, the cracks that form during soil shrinkage are not perfectly annealed on re-wetting. This volume increase results in a decrease in the soil density, thereby providing enhanced access by water for subsequent episodes of swelling. In geological time scales shrinkage cracks may become in-filled with sediment, thus imparting heterogeneity to the soil. Once the cracks have been in-filled in this way, the soil is unable to move back, leaving a zone with a network of higher permeability in-fills.

When supporting structures, the effects of significant changes in water content on soils with a high shrink–swell potential can be severe. In practical civil engineering applications in the UK, there are three important time dependent situations, each with different boundary conditions, where shrink–swell processes need to be considered:

1. Following a reduction in mean total stress; the most notable effects are found adjacent to cut slopes, excavations, and tunnels, (Vaughan & Walbancke, 1973; Burland et al, 1977; Grob, 1976; Madsen & Muller-Vonmoos, 1985; Einstein, 1979).

2. Subsurface groundwater abstraction or artificial/natural recharge under conditions of constant total stress in both unconfined and confined aquifers. Regional subsidence or heave can be induced by this process.
3. Surface climatic/water balance fluctuations related to land-use change under conditions of constant total stress. The most notable effects follow the development of seasonally desiccated soils, (shrinkage) which can cause structural damage to existing shallow foundation, (Driscoll, 1983; Taylor & Smith, 1986).

As well as effective stress changes, some deformation may be caused by bio-geo-chemical alteration and dissolution of minerals, as a result of 'steady state' fluid transport processes. Although surface movements and engineering problems can occur, due to a loss, or addition of solid material; these are not strictly shrink–swell soils. However, these processes are often combined with effective stress changes and/or fluid movements and hence they may be difficult to separate from true shrink–swell processes which might be taking place at the same time.

The chief factors controlling shrink–swell susceptibility in geological formations are material composition (clay mineralogy), initial in-situ effective stress state and stiffness of the material. Variations in the 'initial condition' caused through processes such as original geological environment, climate, topography, land-use and weathering affect in-situ effective stresses, stiffness and hence shrink–swell susceptibility. Clays belonging to the silicate family comprise the major elements silicone, aluminium and oxygen. There are many other elements that can become incorporated into the clay mineral structure (hydrogen, sodium, calcium, magnesium, sulphur). The presence and abundance of these dissolved ions can have a large impact on the behaviour of the clay minerals. The clay minerals are defined by the ratio of silica tetrahedra to alumina, iron or magnesium octahedra (Figure 7).

Table 1. Clay minerals: their properties and sources.

	Group	Clay minerals	Physical Properties	Principal sources
Increasing swelling potential →	Smectite 2:1 phyllosilicates	Montmorillonite, beidellite, nontronite, talc, hectorite, saponite and sauconite	Weakly linked by cations (Na and Ca). Na montmorillonite particularly prone to swelling	Alteration of mafic igneous rocks rich in Ca and Mg
	Vermiculite 2:1 phyllosilicates		Also expansive upon heating	Decomposition of micas
	Illite 2:1 phyllosilicates	Phengite, brammalite, celadonite, glauconite and hydrous micas	Predominate in marine clays and shales. Characteristic of weathering in temperate climates or high altitudes in the tropics.	Decomposition of micas and feldspars
	Kandites 1:1 phyllosilicates	Kaolinite, dickite, nacrite and halloysite		Decomposition of orthoclase feldspar

Subsidence also occurs in superficial deposits such as alluvium, peat and laminated clays that are susceptible to consolidaton settlement (e.g. in the Vale of York, east of Leeds, and in the Cheshire Basin), but these are not true shrink-swell soils.

Costs associated with shrink-swell clay damage

Clay shrink-swell is a global problem and many of the world's major towns and cities are founded on clay-rich soils and rocks. In the UK the effects of shrinkage and swelling of clay soils, with respect to foundation and building damage, were first recognised by geotechnical specialists following the dry summer of 1947. Following the drought of 1975–76 insurance claims in the UK came to over £50 million, and since then the cost of has risen dramatically. In 1991, after a preceding drought, claims peaked at over £500 million. Over the past 10 years the adverse effects of shrink–swell behaviour has cost the economy an estimated £3 billion, making it the most damaging geohazard in Britain today, with as many as one in five homes in England and Wales at risk from ground that swells when it gets wet and shrinks as it dries out (Jones, 2004), although susceptible ground conditions are perhaps less severe under a temperate UK climate than in some other countries. The Association of British Insurers (ABI) has estimated that the average cost of shrink–swell related subsidence to the insurance industry stands at over £400 million a year (Driscoll & Crilly, 2000). The ABI stated that the 350% increase in the value of claims during July to September 2018 was the highest quarterly jump since records started, more than 25 years ago. In the US the estimated damage to buildings and infrastructure exceeds $15 billion annually. The American Society of Civil Engineers estimates that one in four homes have some damage caused by shrink–swell soils. In a typical year they cause a greater financial loss to property owners than earthquakes, floods, hurricanes and tornadoes combined (Nelson & Miller, 1992).

Formation processes

Clay minerals (Table 1) are a product of weathering. They mostly form on land but are often transported to the oceans (Eberl, 1984). They can form through three mechanisms: inheritance (sediment transport), neoformation (from solution or reaction of amorphous material) and transformation (retaining some of the inherent structure whilst undergoing chemical reaction). As weathering proceeds silica and potassium are gradually leached, e.g. Eberl (1984) cites a number of case studies that demonstrate how wet climates are associated with kaolinite rich soils, whilst dry environments are characterised by smectite clays. Thus the distribution of clay minerals at the surface reflects both the underlying geology and the nature of weathering.) In addition to the material composition (clay mineralogy; Table 1) the main factors controlling shrink-swell susceptibility in geological formations are: depositional environment, diagenesis, stress history and weathering. These factors influence the in-situ effective stress state and stiffness of the material and therefore its propensity to swell.

Ultimately the clay minerals derived from weathering are transported to the ocean, where they undergo little reaction, except for ion exchange and neoformation of smectite, which is associated with volcanic activity in the oceans and demonstrates the influence of geotectonic setting on clay mineral distribution. Clay mineralogy is also affected by diagenesis and stress history (Eberl, 1984; Keller, 1963, and Merriman, 2005). Broadly, diagenesis takes the form of smectite to illite transformations. Illitization proceeds through a series of reactions involving intermediate mixed layers of illite and smectite of varying compositions (Lanson et al., 2009). Near surface weathering can reverse this process leading to the formation of mixed layer clays. Whilst the stress history can be important in influencing clay mineralogy it has been argued that the influences of burial depth on engineering properties is less significant than that of stratigraphical position, e.g. Jackson and Fookes (1974).

Distribution

Shrink–swell soils are found throughout many regions of the world, particularly in arid and semi-arid regions, as well as where wet conditions occur after prolonged periods of drought. Their distribution is dependent on geology (parent material), climate, hydrology, geomorphology and vegetation and renders them susceptibility to environmental change, e.g. Harrison et al. (2012).

Countries where shrink–swell soils occur and give rise to major construction costs include: Ethiopia, Ghana, Kenya, Morocco, South Africa and Zimbabwe in Africa; Burma, China, India, Iran, Israel, Japan and Oman in Asia; Argentina, Canada, Cuba, Mexico, Trinidad, USA and Venezuela in the Americas;

Cyprus, Germany, Greece, Norway, Romania, Spain, Sweden, Turkey and UK in Europe; and Australia (Figure 1). In these countries, or significant areas of them, the evaporation rate is higher than the annual rainfall so there is usually a moisture deficiency in the soil. When it soil suction increases the potential for heave. In semi-arid regions a pattern of short periods of rainfall followed by long dry periods (drought) can develop, resulting in seasonal cycles of swelling and shrinkage.

In humid climates problems with shrink–swell soils trend to be limited to those soils containing higher plasticity clays. In arid/semi-arid climates soils that exhibit moderate shrink–swell potential can cause distress to residential property. This occurs as a direct result of the relatively high suction that exist, in these soils, and the larger changes in water content regimes that results when water level changes.

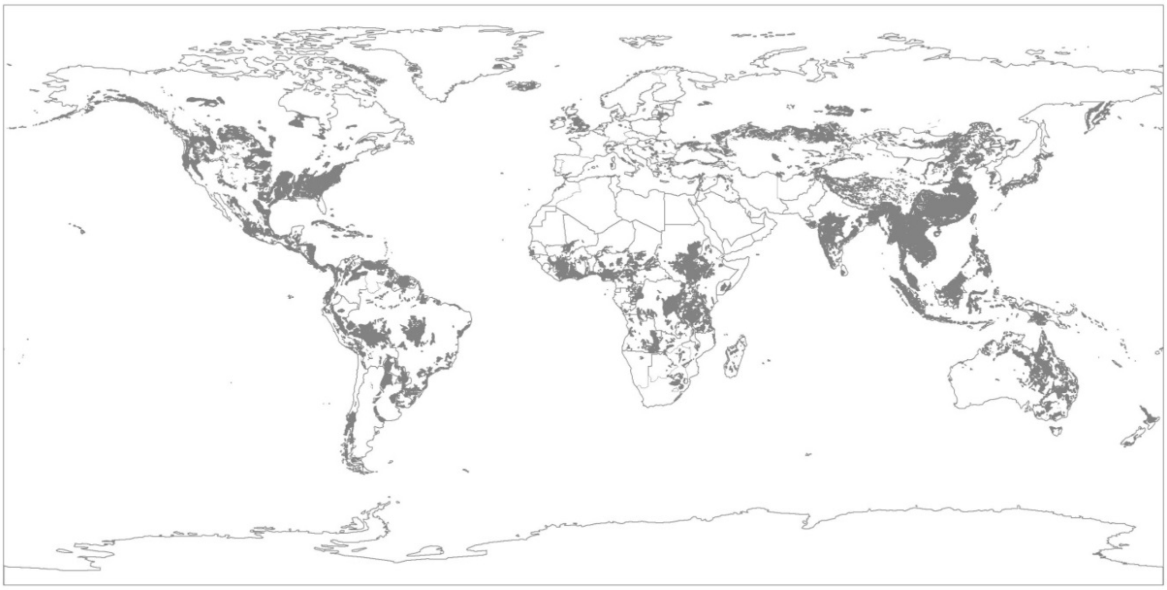


Figure 1 – Global distribution of shrink–swell soil where major construction costs occur (by region)

Reflecting the broad younging of the UK stratigraphy to the south-east, the clay-rich soils most susceptible to shrink–swell behaviour predominate in the south-east of the country, primarily distributed to the east of a line from Dorset to Birmingham, Nottingham and North Yorkshire (Figure 2). In this zone the near-surface Jurassic, Palaeocene and Eocene clays are less indurated than their older counterparts and retain a greater propensity to absorb and lose moisture. These mudrocks are normally firm to very stiff clays or very weak mudstones that weather to firm to stiff clays near the surface. Indurated clays are less prone to shrink-swell behaviour because of the clay transformations that occur during diagenesis.

The transformations associated with diagenesis are attributable to the changes in the stress, fluid pressure, geochemistry and temperature as a consequence of burial. Associated with the clay transformation are compaction and fluid migration, development of diagenetic bonds, mineralization and cementation, recrystallization and pressure solution. In some areas of the UK (e.g. around The Wash, northwest of Peterborough, and under the Lancashire Plain) the mudrocks are deeply buried beneath other (superficial) soils that are not as susceptible to shrink–swell behaviour, although consideration should be given for the potential for swelling and heave in deep excavations in these soils.

Whilst the 2-D distribution of the the UK clay soils is relatively well known in 2-D, e.g. Loveland (1984), Jeans (2006 a and b) and Wilson et al. (1984), the 3-D distribution is less well known. There is significant potential for furthering this understanding through the use of 3D geological models, e.g. Jones and Terrington (2011). Indications are that climate change will have an increasingly adverse effect on the moisture conditions that UK soils experience and therefore on the damage caused to the homes, buildings, roads and services founded on them with further potential for the application of 3D geological modelling.

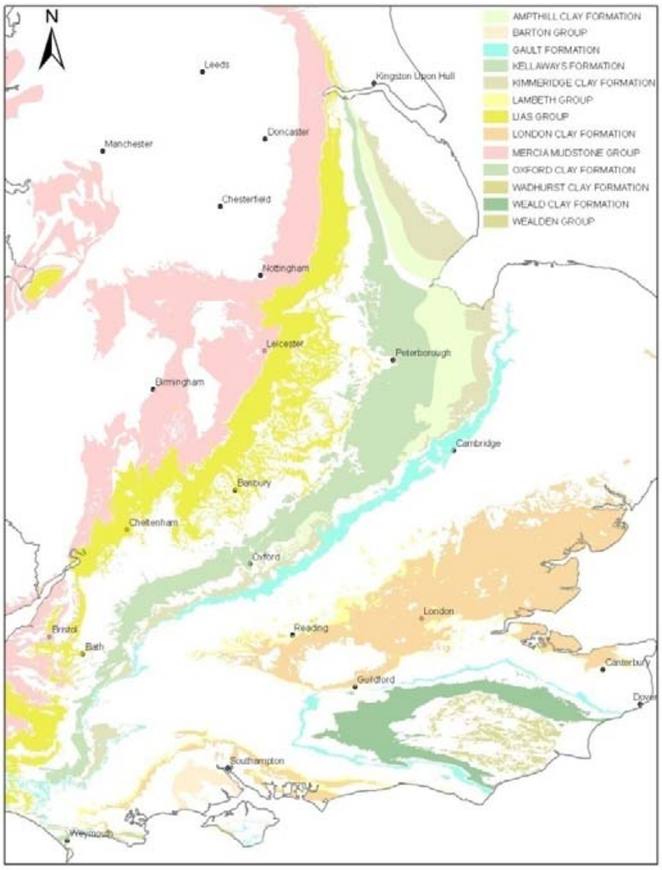


Figure 2 – Distribution of UK clay-rich soil formations (after Jones & Jefferson, 2012)

A meaningful assessment of the shrink–swell potential of a soil in the UK requires a considerable amount of high-quality and well-distributed spatial data of a consistent standard (Jones & Jefferson, 2012) and from this a Volume Change Potential (VCP) map can be constructed. However, looking at soils on a national scale (although giving a good indication of potential problem areas) does not tell the whole story. No two clay soils are the same in terms of their behaviour or their shrink–swell potential, therefore it is better to look at them on a more regional scale. Jones and Terrington (2011) discuss a methodology for creating a 3D VCP interpolation of the London Clay, visualising plasticity values at a variety of depths, relative to ground level, across the outcrop (Figure 3).

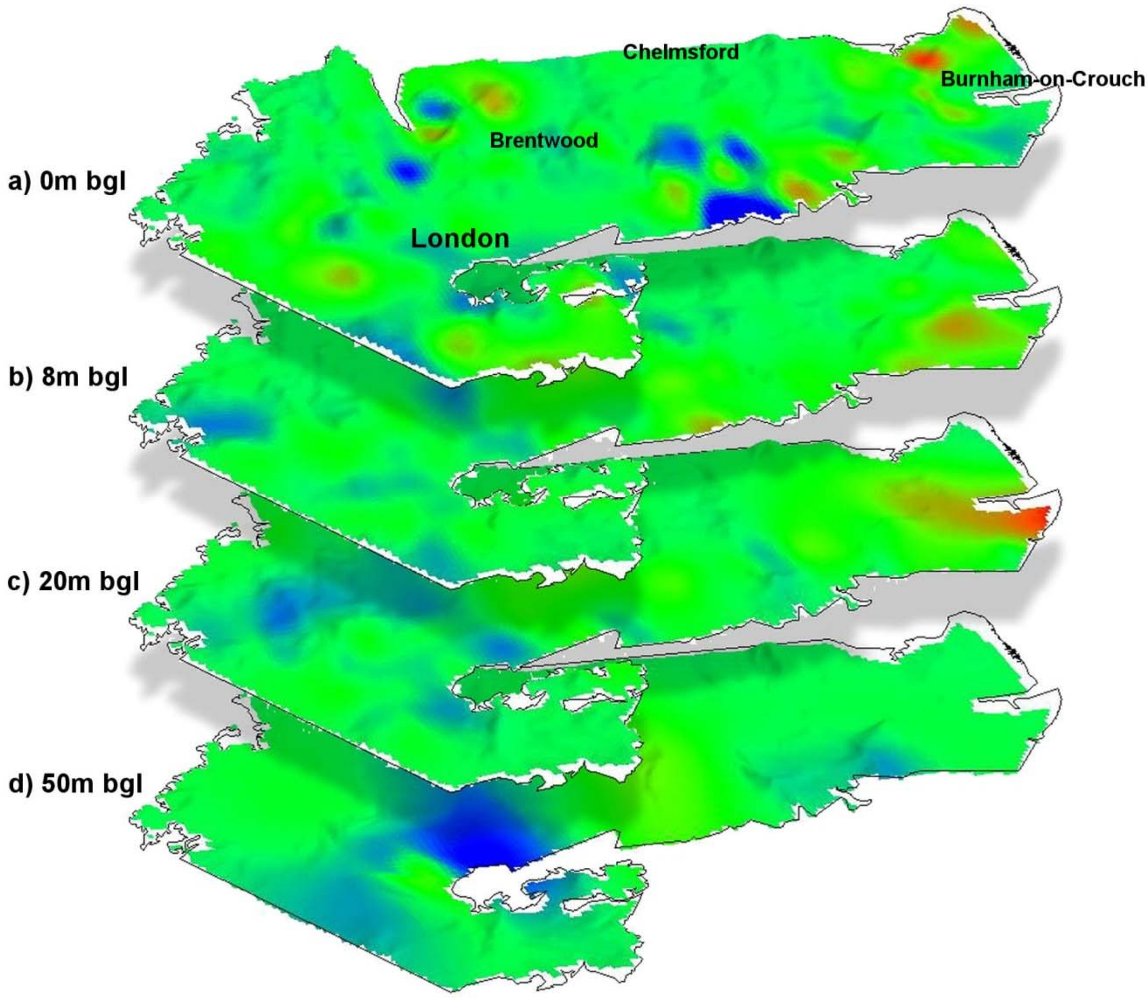


Figure 3 - Interpolation of 'Area 3' showing surfaces at 0 m, 8 m, 20 m and 50 m bgl (Jones & Terrington, 2011) [***Note***: blue: medium, green: high, red: very high]

Characterisation of shrink swell soils

Shrink swell soils can be recognised from either geological and geotechnical characterisation, or from the damage incurred by buildings and infrastructure. Typically, swelling pressures can cause heave, or lifting, of structures whilst shrinkage can cause differential settlement. Damage to a structure is possible when as little as 3% volume expansion takes place (Jones, 2002). Failure results when the volume changes are unevenly distributed beneath the foundation. For example, water content changes in the soil around the edge of a building can cause swelling pressure beneath the perimeter of the building (Figure 4), while the water content of the soil beneath the centre remains constant. This results in a failure known as end lift. Conversely, soil shrinkage around the perimeter may result in centre lift. Subsidence problems are easier to recognise than heave problems; this may occur on a dry clay soil and the only obvious sign might be irregular crack patterns, wider at the bottom than at the top, with no obvious cause.

Figure 4 – Swelling beneath perimeter of building causing heave in porch (© David Noe)

Another major contributing factor to ground shrinkage is tree growth, more specifically tree roots. Roots grow in the direction of least resistance and where they have the best access to water, air and nutrients (Roberts 1976). The actual pattern of root growth depends upon, amongst other factors, the type of tree, depth to water table and local ground conditions. Trees will tend to maintain a compact root system. However, when trees become very large, or where trees are under stress, they can send root systems far from the trunk. Damage to foundations resulting from tree growth occurs in two principal ways: physical disturbance of and shrinkage of the ground by removal of water. Physical disturbance of the ground caused by root growth is often seen as damage to pavements and broken walls (Figure 5). Shrinkage, caused by water removal can lead to differential settlement of building foundations. Vegetation induced changes to water profiles can also have a significant impact on other underground features, including utilities. Tree induced movement has the potential to be a significant contributor to failure of old pipes located in clay soils near deciduous trees (Clayton et al., 2010) and can also cause physical disturbance to services.

Potential shrinkage and/or swelling from these causes can usually be anticipated in most engineering circumstances. However, because of the differences between natural and tree-induced shrink–swell, and varying initial conditions, the relative susceptibility to volume change at any place may not necessarily always be the same for a given geological formation or soil type. Spatial generalisation is thus difficult, and a prediction of the severity of potential deformation often requires site specific subsurface investigations and in-situ monitoring.

Therefore, to summarise the main environmental causes of shrink–swell:

1. Normal seasonal movements associated with changes in rainfall and vegetation growth
2. Enhanced seasonal movement associated with trees, severe pruning or removal of trees or hedges
3. Long-term subsidence, as a persistent water deficit develops
4. Long-term heave as a persistent water deficit dissipates
5. Increased susceptibility of the near surface soils as its density is reduced

Figure 5 - Damage to kerbstone and paving caused by root growth

Whilst much research has been carried out worldwide to infer shrink–swell behaviour from soil index properties, few direct data are publically available in UK geotechnical databases (Hobbs et al., 1998). Two schemes that are commonly used to assess shrink-swell properties within the UK are based on the Building Research Establishment (BRE) and National House-Builders Council (NHBC) schemes. High shrinkage soils may not behave very differently from low shrinkage ones, because conditions in the UK do not allow full potential to be realised (Reeve et al., 1980).

Potential shrink–swell soils are initially identified, by soils engineers, from particle size analyses to determine the percentage of fine particles in a sample. If more than 35% of the particles are able to pass through a 63 μm sieve, the sample is classified as a fine soil comprising either silt or clay, or a combination of both (BSI, 1999). Clay sized particles are considered to be less than 2 μm (although this value varies slightly throughout the world) but the difference between clays and silts is more to do with origin and particle shape. Silt particles (generally comprising quartz particles) are products of mechanical erosion whereas clay particles are products of chemical weathering and are characterised by their sheet structure and composition.

Although there are a number of methods available to identify shrink–swell soils, each with their relative merits, there are no universally reliable methods available (Jones & Jefferson, 2012), and they are rarely employed in the course of routine site investigations in the UK. This means that few data are available for data-basing the directly measured shrink–swell properties of the major clay formations, and reliance has to be placed on estimates based on index parameters, such as liquid limit, plasticity index, and density (Reeve et al., 1980; Holtz & Kovacs, 1981; Oloo et al., 1987). No consideration has been given to the saturation state of the soil and therefore to the effective stress or pore pressures within it.

The most widely used parameter for determining the shrinkage and swelling potential of a soil is the Plasticity Index (I_P). Such plasticity parameters, being based on remoulded specimens, cannot precisely predict the shrink–swell behaviour of an in-situ soil. However, they do follow established procedures, being performed under reproducible conditions to internationally recognised standards (Jones, 1999). A ‘Modified Plasticity Index’ (I_P’) is proposed in the Building Research Establishment Digest 240 (BRE, 1993) for use where the particle size data, specifically the fraction passing a 425μm sieve, is known or can be assumed as 100% passing (BRE, 1993). The Modified I_P’ takes into account the whole sample and not just the fines fraction, it therefore gives a better indication of the ‘real’ plasticity value of an engineering soil (Jones & Terrington, 2011).

Such empirical correlations may be based on a small data set, using a specific test method, and at only a small number of sites. Variation of the test method would probably lead to errors in the correlation. The reason for the lack of direct shrink–swell test data is that few engineering applications have a perceived requirement for these data for design or construction. However, the stages of investigation needed for shrink–swell soils follow those used for any site. See Simons et al. (2002) and Leroueil (2001). Indications are that climate change will have an increasingly adverse effect on the moisture conditions that UK clay soils experience and therefore on the damage caused to the structures founded on, or within, them. The Government has recognised that climate change is one of the biggest problems that the UK faces and, if current predictions are correct, we can expect hotter, drier summers and milder, wetter winters (UKCIP, 2009), with as many as 1 in 5 homes in England and Wales likely to be damaged by the shrinking and swelling behaviour of these clay soils (Jones, 2004). If the UK were to experience an increase in extended periods of dry weather, prior to rainfall events, costs caused by shrink–swell damage could rise significantly. It is, therefore, important to recognise the existence of shrink–swell soils at the earliest stage possible, during site and laboratory investigations, in order to ensure that the correct design procedures are put in place, before costly remediation is required.

Soil suction is a measure of the free energy or the relative vapour pressure (relative humidity) of the soil moisture. It can be defined by the suction required to remove the water from above the water table. There are two components: the matric potential, which is the moisture held in soil pores by capillary action, and the much smaller solute potential, which is the osmotic effect of dissolved salts. Soil suction characteristics vary between clay soils in accordance with the composition of the soil, particularly its particle size and clay mineral content. Figure 6 shows typical moisture content suction profiles for a variety of UK and North American mudrocks.

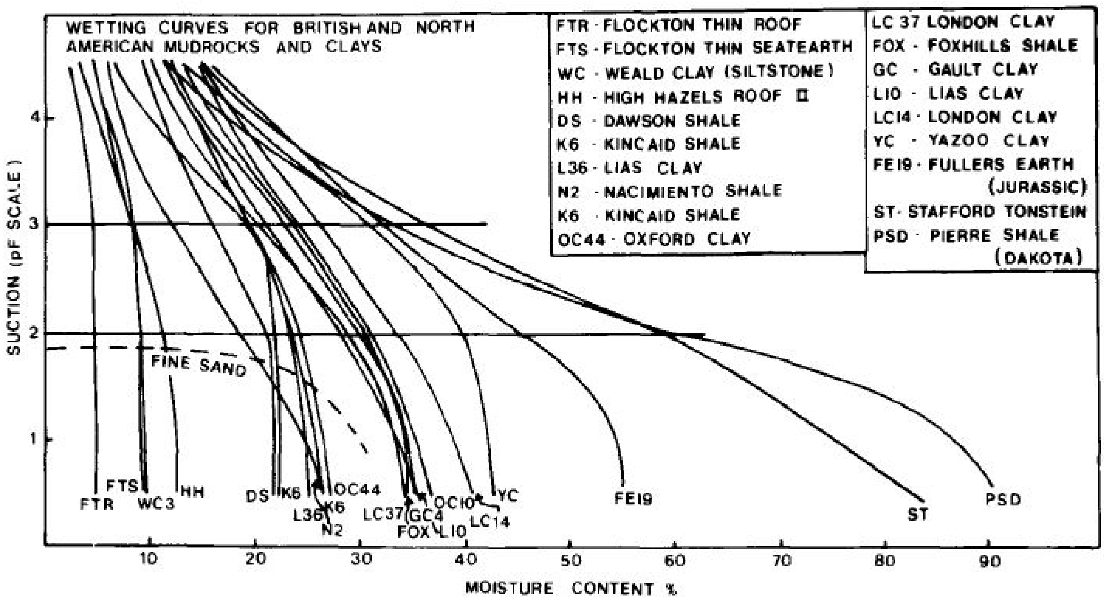


Figure 6 – Suction– MC relationship for UK and North American soils (Reproduced from Taylor & Smith, 1986. Mineralogical Society of Great Britain)

The hydraulic conductivity of a soil also varies with the suction, both seasonally and over longer timescales. Secondary permeabilities can be induced through fabric changes, tension cracking and shallow shear failure during the shrink–swell process which may influence subsequent moisture movements. For example, Scott et al. (1986) showed in a micro fabric study of clay soils that compression, (swelling) cracks tended to parallel ground contours and dip into the slope at c. 60°, and could usually be distinguished from shrinkage cracks which were randomly distributed. In the London Clay soils studied, they found that the ratio between shrinkage and swelling discontinuities was about 2:1. The actual mechanism of volume increase, (or decrease) and the differences in susceptibility to these processes which have been found between different sediments, has been attributed to a combination of both mechanical and physico-chemical processes, (Bolt, 1956; Mitchell, 1976; Taylor & Smith, 1986).

Mechanisms of shrink–swell

Ground deformation in response to a reduction in total stress can be considered in terms of:

1. An immediate, but time dependent elastic rebound.
2. Swelling due to the change in effective stress.

Changes in effective stress drive fluid movement into or out of the geological formation or soil. The magnitude of strains associated with this process depends on the drained stiffness, the extent of the stress change, the water pressures that are set up in the soil or rock, and the new boundary conditions. The rate of volume change depends on the compressibility, expansibility and hydraulic conductivity of the sediment and surrounding materials. In stiff homogeneous materials with a low hydraulic conductivity several decades may be necessary to complete the process. The same physical parameters and processes control the swelling that accompanies atmospheric driven aquifer recharge, although without a total stress change there is no elastic rebound of the soil/rock structure.

Shrinkage by evaporation is similarly accompanied by a reduction in water pressure and development of negative capillary pressures; deformation follows the same principles of effective stress. The processes of shrinkage due to evaporation have been reviewed in detail, using effective stress concepts, by Sridharan & Venkatappa Rao, (1971), Bishop et al. (1975) and Alonso et al. (1990).

At any time the 'equilibrium' water content in a geological formation or weathered soil represents a balance between the clay minerals need to suck in water, and the tendency for applied stresses to squeeze out water. A clay/soil mass initially in equilibrium will swell if a transient change in geo-environmental boundary conditions results in unloading or an increase in water pressure. As corollaries to the three situations of shrink–swell associated with anthropogenic interference (engineering works) there are also three comparable groups of natural causes:

1. From a total stress change following erosion, tectonism or mass movement.
2. From climatically controlled hydrodynamic processes, associated with sea-level change, and groundwater recharge and discharge.
3. From biogenic/chemical/physical weathering under conditions of almost constant total stress.

Freeze-thaw involves effective stress changes, and is also a natural cause of shrink–swell. It is extremely important in northern latitudes; the top few metres of most weathered materials in the UK were affected by freeze-thaw processes during the late glacial period. However, examples of heave are known to have occurred next to some refrigeration plants; beneath road pavements; and it may also have contributed to some slope instability problems. Morgenstern (1981) reviewed research progress in this field and provides a good starting point and bibliography into the subject.

Civil engineering and other anthropogenic interference thus essentially mimic these natural effects through environmental changes connected with construction, artificial groundwater recharge, agriculture, waste disposal etc., but their effects are superimposed onto a range of initial time dependent conditions.

Shrink–swell behaviour

The shape of clay particles is determined by the arrangement of the thin crystal lattice layers that they form (Figure 7). The molecular structure and arrangement of the clay crystal sheets in shrink swell clays guides how water is attracted and held between the crystalline layers (and on their surfaces) in a strongly bonded 'sandwich' (Figure 7), an example of which is shown in Figure 8. The electrical dipole structure of water molecules drive an electro-chemical attraction to the microscopic clay sheets. The mechanism by which these molecules become attached to each other is called adsorption. Na-Smectite clays (such as montmorillonite) have the greatest affinity for water, and can adsorb very large amounts of water molecules between their clay sheets. In theory they can expand some 800 times by volume, causing dispersion of clay platelets by the elimination of repulsive interlayer forces. They therefore have a large shrink–swell potential, as do vermiculite and chlorite, which also exhibit crystalline swelling. For further details of mineralogy of clay minerals and their influence of engineering properties of soils see Mitchell & Soga (2005). Driscoll, (1983), Taylor & Cripps, (1984) and Taylor & Smith, (1986) provide useful reviews of the controls that clay mineralogy has on the drained compressibility/expansibility of geological materials and hence their susceptibility to large deformations from effective stress changes which lead to shrinkage and/or swelling.

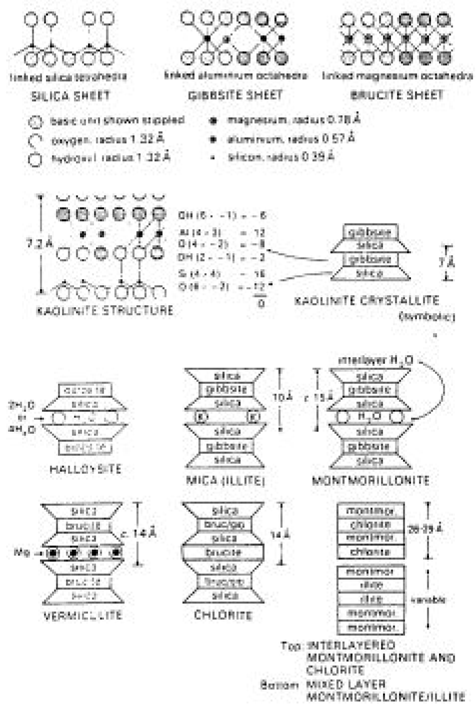
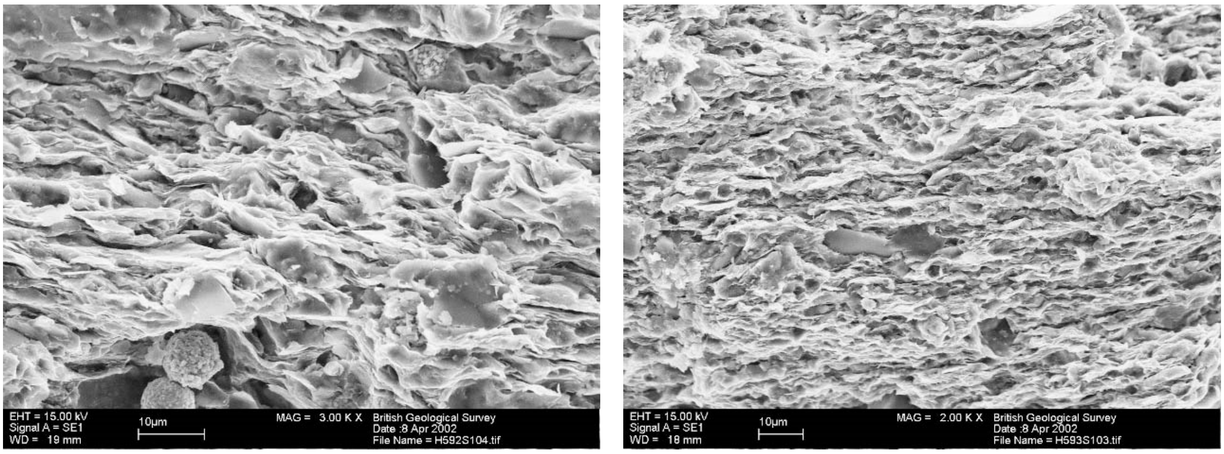


Figure 7 – Swelling clay mineral structures (Reproduced from Taylor and Cripps, 1984. Surrey University Press)



(a) (b)

Figure 8 – SEM images showing typical features of Lias Group clay. (a) Tightly packed, flat-lying, curved clay flakes, ~10 µm in diameter and <1 µm thick. (b) Well laminated, tightly packed, flat-lying clay flakes

Saturated clay shrink-swell soils contain water molecules between the clay sheets, causing the bulk volume of the soil to increase, or swell with changes in water content. This process of absorption weakens the inter-clay bonds and causes a reduction in the strength of the soil. As moisture is reduced, by evaporation or gravitational forces, the water between the clay sheets is released, causing the overall volume of the soil to decrease, or shrink. Features such as voids or desiccation cracks are associated.

Shrinkage and swelling usually occurs in the near-surface to depths of about 3 m, but this can vary depending on climatic conditions. The shrink–swell potential of expansive soils is determined by its initial water content; void ratio; internal structure and vertical stresses, as well as the type and amount of clay minerals in the soil (Bell & Culshaw, 2001). These minerals determine the natural expansiveness of the soil, and include smectite, montmorillonite, nontronite, vermiculite, illite and chlorite. Generally, the larger the amount of these minerals present in the soil, the greater the shrink–swell potential. However, these effects may become 'diluted' by the presence of other non-swelling minerals such as quartz and carbonite (Kemp et al., 2005).

Soils with high shrink–swell potential will not usually cause problems as long as their water content remains relatively constant. This is controlled by the soil properties (mineralogy); suction and water conditions; water content variations; and geometry and stiffness of a structure founded on it (Houston et al., 2011). In a partially saturated soil, suction or water content changes increase the likelihood of damage occurring. In a fully saturated soil the shrink–swell behaviour is controlled by the clay mineralogy.

Seasonal volume change generally takes place with the assistance of fractures and secondary macropores within the weathered horizons. If under-saturation is present at very shallow depths slaking by air breakage can also occur. Taylor & Smith (1986) described these processes, and the physico-chemical techniques for predicting structural breakdown. The depth of 'active' groundwater flow is thus an important control on the susceptibility of soils to volume change, because this affects the magnitude of that change in both the saturated and unsaturated groundwater zones.

Shrink–swell soil problems typically occur due to water content changes in the upper few metres, with deep seated heave being rare (Nelson & Miller, 1992). The water content in this zone, which are known as the active layer, is significantly influenced by climatic and environmental factors and is generally termed the zone of seasonal fluctuations or active zone as shown in Figure 9.

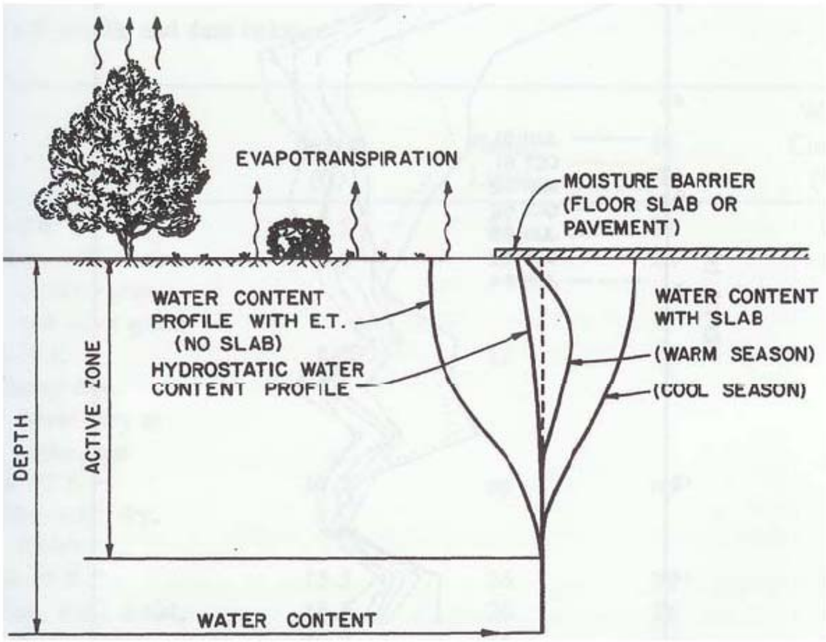


Figure 9 – Water content profiles in the active zone (Reproduced from Nelson & Miller, 1992. John Wiley & Sons Inc.)

In the zone of seasonal fluctuations, moisture contents range between negative and positive pore water pressures (Figure 9)., with further details provided by Nelson et al. (2001). It is important to determine the depth of the active zone during a site investigation in order to ensure adequate foundation design. This can vary significantly with climate conditions with depths of 5 to 6 m in some countries, whereas in the UK 1.5 to 2 m is typical (Biddle, 2001), extending to 3 to 4 m in some areas of the London Clay (Biddle, 2001). Depending on the relative significance of heave or subsidence, the term 'Active Zone' is defined in one of a number of ways, e.g. Nelson et al. (2001) defined: :

1. **Active Zone**: The zone of soil that contributes to soil expansion at any particular time.
2. **Zone of Seasonal moisture fluctuation**: The zone in which water content change due to climatic changes at the ground surface.
3. **Depth of wetting**: The depth to which water contents have increased due to the introduction of water from external sources and used to estimate heave by integrating the strain produced over the zone in which water contents change (Walsh et al., 2009).
4. **Depth of potential heave**: the depth at which the overburden vertical stress equals or exceeds the swelling pressure of the soil. This is the maximum depth of the active zone.

The natural, time-dependent physical and chemical changes which occur in a geological formation are inherent weathering processes. In a stiff clay the result is one of softening i.e. an increased water content, while in a soft clay a hardened crust is often formed in association with desiccation. Mesri et al. (1978) provide a useful summary of the reasons why softening and weathering processes are time dependent:

1. *Hydraulic conductivity of the clay*: The increase in water content, including the adsorbed double layer water requires flow into the clay, either from internal adjustments or from an external hydrological input.
2. *Particle rearrangement*: Structural readjustment including particle deformation and reorientation is a chain reaction process and hence time dependent.

3. *Progressive breakdown of diagenetic bonds*: Interlayer bonding and cementation is common in many stiff clays and shales, as evidenced by the difficulty of dispersing soils for index testing.
4. *Progressive development of structural discontinuities*: Inhomogeneous swelling and shear distortion may produce structural discontinuities, fissures, and slickensides, which in turn affect the breakdown of diagenetic bonding and mass hydraulic conductivity.
5. *Chemical changes*: Chemical changes of inorganic and organic compounds including bacterial oxidation.

Superimposed on these widespread climatic influences are local ones such as tree roots and leakage from water supply pipes and drains. The removal or severe pruning of trees may result in swelling problems, as man is unable to supply water to desiccated soil as efficiently as a tree originally extracted it through its root system (Cheney, 1986). The swelling of shrinkable clay soils after trees have been removed can produce either very large uplifts or very large pressures (if confined), and the grounds recovery can continue over a period of many years (Cheney, 1986).

Building, or paving, on previously open areas of land, such as the building of patios and driveways, can cause major disruption to the soil-water system. Sealing the ground in this way cuts off the infiltration of rain water and the trees that are dependent upon this water will have to send their roots deeper, or further afield, in order to find water. The movement of these root systems will cause a major ground disturbance and will lead to the removal of water from a larger area around the tree (Jones & Jefferson, 2012). Problems occur when structures are situated within the zone of influence of a tree (Figure 10).

Occasionally this situation may worsen as nearby trees continue to extract water during the growing months, when rainfall is low. If a more permeable type of surface, such as block paving, is used, more rain water can enter the ground and supply nearby tree roots. If an impermeable method of paving is used, it may prevent water from infiltrating into the ground. This can affect the shrink-swell behaviour of the ground and also the growing patterns of nearby trees. A well-designed impermeable paving system, in good condition may actually reduce the amount of shrink-swell activity in the ground immediately below it. Paving moderates variations in water content of the soil and thus the range of shrink-swell behaviour that might be expected. However, if the paving seal is broken, water can suddenly enter the system, causing swelling of the ground.

Nevertheless trees are a vital component of the environment and play an important role valued by the public at large for many different reasons. However, trees are also a very real problem when they shed their leaves, petals and fruit, block out sunlight and importantly their roots are associated with cracked pavements, blocked drains and where shrink–swell soils are present building subsidence occurs. If vegetation is involved, it produces a characteristic seasonal pattern of foundation movement; subsidence in the summer reaching a maximum usually in September, followed by upward recovery in the winter (Crilly & Driscoll, 2000 and Driscoll & Chown, 2001). This pattern provides clear evidence of clay shrink-swell as as no other cause produces a similar pattern and it can be concluded that soil drying by vegetation must be involved (unless the foundations are less than 300 mm).

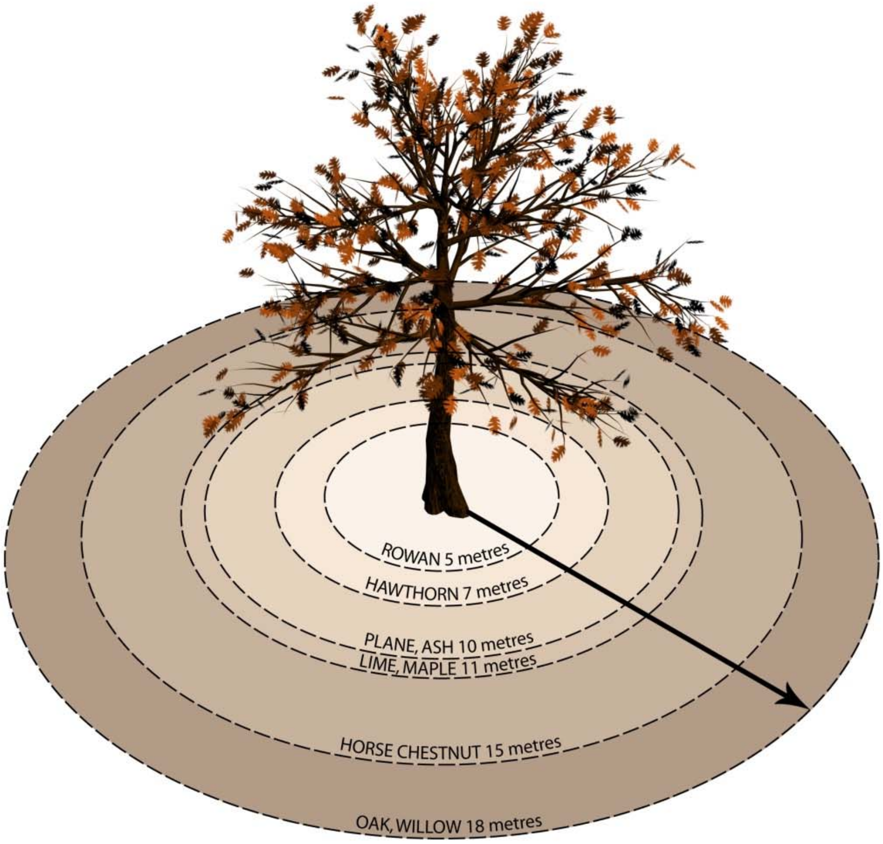


Figure 10 – The zone of influence of some common UK trees (after Jones et al., 2006)

Strategies for engineering management: avoidance, prevention and mitigation

The structures most susceptible to damage caused by shrink–swell soils are usually lightweight in construction. Houses and other low-rise buildings, pavements, pylons, pipelines and other shallow services are especially vulnerable to damage because they are less able to suppress differential movements than heavier multi-story structures. Due to the global distribution of shrink–swell soils many different ways to tackle the problem have been developed and these can vary considerably (Radevsky, 2001). The preferred methodology is country-specific, depending on technical developments, country specific legal frameworks and regulations, insurance policies and the attitude of insurers, experience of the engineers and other specialists dealing with the problem and, most importantly, the sensitivity of the owner of the property affected. A summary of these issues is provided by Radevsky (2001) in his review of how different countries deal with shrink–swell soil problems, and a detailed informative study from the United States has more recently been presented by Houston et al. (2011).

In order to make a proper characterisation of a site where shrink–swell soils exist two factors need to be identified:

1. The properties of the soil (e.g. mineralogy, soil water chemistry, suction, soils fabric).
2. Environmental conditions that can contribute to changes in water contents of the soil (e.g. water conditions and their variations (climate, drainage, vegetation, permeability, temperature) and stress conditions (history and *in-situ* conditions, loading and soil profile).

Shrink–swell soils require extensive site investigation in order to provide sufficient information, normal investigations, relating to the structures most affected by shrink–swell soils, are often not adequate. These investigations may involve specialist test programmes even for relatively light weight structures (Nelson & Miller, 1992).

Whilst the selection of the type of foundation can be critical in the mitigation of clay shrink-swell there are a number of factors that influence the selection of foundation types and design methods, including climate and local experience, financial and legal aspects, as well as technical issues and experience. Irrespective, if shrink swell clays have been identified the design should take account of the depth of the active layer and the understanding that shrink–swell behaviour often does not manifest itself for several months. Other issues such as financial can place strain on this and so early communication with all relevant stakeholders is essential. Often higher initial costs are offset many times over by a reduction in post construction maintenance costs dealing with expansive soils (Nelson & Miller, 1992).

Foundation alternatives when dealing with potentially expansive soils are likely to require one of a number of structural alternatives designed to either isolate the structure from soil movement, e.g. using drilled pier and beam foundations or introduce sufficient stiffness to resist movement, e.g. using stiffened slab on grade or modified continuous perimeter footings (Jones and Jefferson, 2012). The use of ground improvement techniques in isolation or in combination with these approaches may be a good alternative (Jones & Jefferson, 2012; Chen, 1988; Nelson & Miller, 1992, and Nelson et al., 2011). Of particular importance is the aim to minimise total and differential movements. Globally, the most common types of foundations used in expansive soils are drilled pier and beam systems, reinforced slabs-on-grade and modified continuous perimeter spread footings.

Pavements are particularly susceptible to damage caused by shrink–swell soils. Their vulnerability stems from their relative light-weight nature extended over a relatively large area. For example, Cameron (2006) described problems with railways built on shrink–swell soils where poor drainage exists, and Zheng et al. (2009) describes problems with highway sub-grade construction on embankments and on slopes, in China. Damage to pavements on shrink–swell soils manifest in a number of ways, including severe unevenness along significant lengths of pavement (sometimes evidenced by cracks); longitudinal cracking; lateral cracking developed from significant localised deformations, and localised pavement failure associated with disintegration of the surface. A detailed account of a range of treatment approaches is described by Chen (1988) and, Nelson & Miller (1992), with a detailed review of the use of stabilisation techniques over the last 60 years provided by Petry & Little (2002).

The philosophy of pavement design is essentially the same as that used for foundations. However, a range of different approaches are required to overcome the difficulty the pavement cannot be isolated from the soils and it is impractical to make pavements stiff enough to avoid differential movements (Jones & Jefferson, 2012). Pavement designs are considered based on either flexible or rigid pavement systems. See Manual of Contract Documents for Highway Works (DETR, 1993). Decision making with respect to pavement design in shrink swell soils should be based on comprehensive ground understanding, in the context of the project requirements.

Conceptual ground models should include, but not be limited by, characterising: the depth of the active zone, the potential for volume change, soil and soil water chemistry, the distribution and seasonality of moisture in the soil, soil permeability and soil structure. Failure to carry out an adequate site investigation can lead to false diagnoses and inappropriate remedial measures employed (Nelson & Miller, 1992).

A number of solutions are available for the management of shrink–swell soils (Table 1). As fluctuations in water contents are one of the primary drivers of shrink–swell problems, with non-uniform heave occurring due to non-uniformity of water contents, if moisture content change can be minimised over time, then shrink–swell problems can be mitigated. Moreover, if moisture content changes can be slowed down and moisture distributions made uniform, then differential movement can also be reduced. The lowest technology approach is avoidance and the selection of alternative routes. Engineered solutions include: replacement of expansive soil with a non-expansive alternative; a modified design based on a low strength with a requirement for regular maintenance; improvement of the expansive soils through disturbance and re-compaction; stabilisation of the expansive soil through chemical additives, such as lime treatment, or the high technology approach of moisture control over the life of a pavement. Details of these are provided in Chen (1988) and, Nelson & Miller (1992). There is a legacy of negative perceptions associated with some techniques, e.g. Houston et al. (2011) found that many geotechnical and structural engineers considered chemical stabilisation approaches such as the use of lime as ineffective for pre-treatment of shrink–swell soils for foundations.

Table 2 – Soil Stabilisation approaches applied to expansive soils (after Jones & Jefferson, 2012)

Improvement method		Outline of approach	Advantage	Disadvantage
Avoidance	Removal and replacement	Expansive soil removed and replaced by non-expansive fill to a depth necessary to prevent excessive heave Depth governed by weight needed to prevent uplift and mitigate differential movement	Non-expansive fill may increase bearing capacities Simple and easy to undertake Often quicker than alternatives	Impervious fill to prevent water ingress Thickness required may be impractical Failure can occur during construction due to water ingress
Stabilization (physical and chemical).	Remoulding and compaction	Less expansion observed for soil compacted at low densities above OWC than those at high densities and below OWC Standard compaction methods and control can be used to achieve target densities	On site resources eliminate cost of imported fill Relatively impermeable fill achievable to minimise water ingress Swell potential reduced without introducing excess water	Low density compaction may be detrimental to bearing capacity May not be effective for soil of high swell potential Requires close and careful quality control
	Remoulding and mixing	Variations on the above include mixing with non-swelling material to dilute swell potential, e.g. sand (Hudyma & Avar, 2006) or granulated tyre rubber (Patil et al., 2011).	Swell potential reduced without introducing excess water	Requires close and careful quality control
	Cation exchange	Exchangeable cations that originate in pore waters are attracted to the external and internal surfaces of the clay. The main cations in natural waters in order of abundance are calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}) and sodium (Na^{+}).	Cation exchange has been used in some situations to reduce swelling, for example using calcium to replace sodium. Rimmer & Greenland, (1976) have also shown how calcium carbonate suppresses the swelling behaviour of a clay through its effect on the diffuse double layer.	Requirement to understand soil chemistry and undertake laboratory trials. Requires close and careful quality control
	Chemical Stabilisation: lime/cement	Lime (3 to 8% by weight) common with cements (2 to 6% by weight) sometimes used, and salts, fly ash and organic compounds less	All fine grained soils can be treated by chemical stabilisers Is effective is reducing plasticity and swell	Soil chemistry may be detrimental to chemical treatment Potential health and safety issues and

Improvement method		Outline of approach	Advantage	Disadvantage
		commonly used Generally lime mixed into surface (~300 mm), sealed, cured and then compacted. Lime may also be injected in slurry form. Lime generally best when dealing with highly plastic clays	potential of an expansive soil Chemical stabilisation can be used to provide a cushion immediately below foundation placed on expansive soils, e.g. pavements (Murty & Praveen, 2008).	environmental risks Curing inhibited in colder temperatures Requires site specific design and quality control. Beetham et al. (2014) found that that if durability and/or long term performance are to be optimised, treatment of medium – high plasticity clay soils may require adaptations to standard working practices.
	Chemical Stabilisation: by by-products	By product stabilisers include cement/ lime kiln dust and pulverised fuel ash (pfa)	As above with the added potential for integrated sustainability	As above
	Chemical Stabilisation: non-traditional stabilisers	Non-traditional stabilisers include sulfonated oils, potassium compounds, ammonium compounds and polymers. electrochemical soil treatment approaches are being developed that utilise electrical current to inject stabilising agents into the soils (Barker et al., 2008).	Some of these methods are less bulky, reducing transport costs.	Requires site specific design and quality control Some emerging technologies can be expensive Health and safety considerations associated with some techniques
Water control methods	Pre-wetting or ponding	Water content increased to promote heave prior to construction. Dykes or berms used to impound water in flooded area Alternatively trenches may be used and vertical drains can be used to also speed infiltration of water into soil	Moves the edge effects away from the foundation/pavement to minimise seasonal fluctuation effects Used when soils have sufficiently high permeabilities to allow relatively quick water ingress, e.g. with fissured clays	May require several years to achieve adequate wetting Loss of strength and failure can occur Ingress limited to depth less than the active zone Water redistribution can cause heave after construction
	Vertical Barriers – polyethylene, concrete, impervious semi-hardening slurries		Lengthens the time for water content changes to occur due to longer migration paths under foundations	
	Horizontal Barriers – using membranes, bituminous membranes or concrete			

As with new construction on shrink-swell soils mitigation projects should be appraised in the context of a number of scoping questions (Lee and Jefferson, 2012) feeding into a good conceptual ground model. For example: are remedial measures needed – is damage severe enough to warrant treatment? What are the ground conditions and processes driving the damage? Has the problem stabilised and when should intervention take place? Is the full extent of the problem known? In the context of the ground model the detail with respect to the options available for remediation and its specification in terms of design and quality assurance can be addressed. Further to this the economic questions around funding sources and post remedial residual risks, e.g. in the context of localised treatment can also be addressed.

Examples of remedial measures employed for mitigation of foundations related failures in shrink-swell soils include (Jones and Jefferson, 2012):

1. Repair and replace structural elements or correct improper design features
2. Underpinning, particularly of key parts of the foundations (Buzzi et al., 2010)
3. Provision of structural adjustments of additional structural support e.g. post tensioning
4. Stiffening of foundations
5. Provision of drainage control
6. Stabilisation of water contents of foundation soils
7. Install moisture barriers to control water content fluctuations

For pavements the most common remedial measures are either removal and replacement or construction of overlays. Whichever method is used care is needed to ensure causes of the original distress are dealt with. Remedial measure should aim to minimise volume changes and options are: remove and replace expansive soil; use of additives to reduce volume change capacity; Application of surcharge to confine soils if swell pressures are not too great or minimising moisture content changes in the sub-grade. Many of the pre-construction approaches can also be applied to post-construction treatments and for pavements these include: moisture barriers; removal, replacement and compaction and drainage control (Table 2).

Shrink-swell soils and trees

Different problems are faced when considering the distinctly separate areas of designing new build structures or remediating existing damaged buildings. New build guidelines in the terms of domestic dwellings recognises the need for thorough ground investigations to design systems to cope with the hazards presented by the presence of existing trees or building following their recent removal. See NHBC Standards Chapter 4.2 Building Near Trees (NHBC, 2011) and NHBC Efficient Design of Foundations for Low Rise Housing, Design Guide (NHBC, 2010). In the case of existing dwellings a range of Reports and Digests are available from the BRE Digest 251 (BRE, 1995), 298 (BRE, 1999), 361 (BRE, 1991), 412 (BRE, 1996) and 471 (BRE, 2002) and in the Summary of Good Technical Practice by Driscoll & Skinner (2007).

In the case of existing structures the main cause of distress results from the effects of differential settlement where different parts of the building move by varying amounts due to variations in the properties of the underlying soil. Equal or proportionate movements across the plan area of a building, though significant in the terms of vertical movement may result in little by way of structural damage (IStructE, 1994). Biddle (2001) suggests one of four remedial options to deal with the adverse actions of trees:

1. Fell the offending tree to eliminate all future drying

2. Prune tree to reduce drying and the amplitude of seasonal movement
3. Control root spread to prevent drying under foundations
4. Provide supplementary watering to prevent soil from drying

Biddle (2001) states it is now recognized that in most situations underpinning is unnecessary and that foundations can be stabilized by appropriate tree management, usually felling the offending tree or carrying out heavy crown reduction. Site investigations should reflect this change, and be aimed at providing the information to allow appropriate decisions on tree management, in particular:

1. Confirmation that vegetation-related subsidence is involved
2. Identification of which tree(s) or shrub(s) are involved
3. Assessment of the risk of heave if a tree is felled or managed
4. Identification of need for any other site investigations
5. If the tree warrants retention, assessment of whether partial underpinning would be sufficient
6. Confirmation that vegetation management has it been effective in stabilising the foundations
7. Provision of information within an acceptable timescale

Tree pruning to reduce its water use and therefore its influence on the surrounding soil is often employed. However, if the trees are thereafter not subjected to a frequent and on-going regime of management the problem will very quickly return and problems continue. Whilst tree removal will ultimately provide an absolute solution in the majority of cases, there are situations where this is not an option (e.g. protected trees, adverse risk of heave, incomplete evidence in contentious issues, and physical proximity of trees). In addition pruning is only an appropriate option in some circumstances with details discussed by Biddle (2001). If vegetation is involved the greatest movement is usually closest to the culprit. Unless trees are very close to each other, the spatial distribution of movement can thus help to identify the culprit. The influence of trees is likely to be fairly widespread whereas shrubs are localised. The pattern of movement detected by level monitoring is sometimes unusual, e.g. no movement where it might be expected, or vice versa. If so, other investigations can be formulated to try to explain the anomaly. For instance, if part of a building closest to a tree is not moving whereas other parts are, it might be because of previous partial underpinning. Trial pits at relevant locations can provide an answer. However, these must be appropriate as information can be fraught with problems (Biddle, 2001).

If a mature tree is felled, consequential heave of a building on a clay soil can occur. Unfortunately the evidence is rarely available. However, a number of clues can help and include:

1. The house is new – less than 20 years old
2. There is expansive soil present
3. The crack pattern might appear a bit odd – wider at the bottom than the top, with no obvious cause
4. Cracks continue to open even in the wet months

Heave problems can be costly and always require thorough investigation, involving soil sampling, precise levels and aerial photographs. Heave is a threat but rarely a reality where established existing properties are involved and the structure pre-dates the planting of the tree. Ultimately, if the offending tree can be accurately targeted and dealt with rapidly, before next growing season, the extent of any damage and need for remedial work will be kept to a minimum (Biddle, 2001).

Conclusions

Subsidence and heave, caused by shrink–swell soils, are probably the most significant geological hazards to affect domestic properties and other low-rise structures worldwide, costing billions of pounds annually. In a typical year they cause a greater financial loss to property owners than earthquakes, floods, landslides, hurricanes and tornadoes combined. They are found throughout many regions of the world, particularly in arid and semi-arid regions, as well as in more humid regions, such as the UK, where their problematic behaviour only tends to occur in highly plastic clay soils, especially after prolonged periods of drought. This shrink–swell effect is induced by changes in the water content of the ground, causing subsidence or heave to occur, which can be exacerbated by external influences such as the presence of tree roots.

The shrink–swell hazard is controlled by a number of factors, primarily, the geology and mineralogy (high plasticity clays) and the climate (prolonged periods of dry weather). The seasonal volumetric behaviour of a desiccated soil is complex, and this complexity increases with severity of the shrinkage phenomena. The actual mechanism of volume increase (or decrease) and the differences in susceptibility to these processes can be attributed to a combination of both mechanical and physic-chemical processes. Shrinkage and swelling usually occurs in the near-surface to depths of about 3 m, water content in this upper layer is significantly influenced by climatic and environmental factors and is generally termed the active zone. The shrink–swell potential of expansive soils is determined by its initial water content; void ratio; internal structure and vertical stresses, as well as the type and amount of clay minerals in the soil. Clay particles are very small and their shape is determined by the arrangement of the thin crystal lattice layers that they form. In an expansive clay the molecular structure and arrangement of these clay crystal sheets has a particular affinity to attract and hold water molecules between the crystalline layers (and on their surfaces) in a strongly bonded ‘sandwich’, giving them a large shrink–swell potential. Seasonal volume change generally takes place with the assistance of fractures and secondary macropores within the weathered horizons.

Houses and other low-rise buildings, pavements, pylons, pipelines and other shallow services are especially vulnerable to damage from shrink–swell clays because they are less able to suppress differential movements than heavier multi-story structures. Normal site investigations are often not adequate and a more extensive examination is required to provide sufficient information. This may involve specialist test programmes even for relatively light weight structures. A large number of factors influence foundation types and design methods including attributes such as climate, financial and legal aspects as well as technical issues. Often higher initial costs are offset many times over by a reduction in post construction maintenance costs dealing with expansive soils. Pavements are highly susceptible to damage caused by shrink–swell soils, their vulnerability stems from their relative light-weight nature extended over a relatively large area. Building, or paving, on previously open areas of land can cause major disruption to the soil-water system. Sealing the ground in this way cuts off the infiltration of rain water and the trees that are dependent upon this water will have to send their roots deeper, or further afield, in order to find water. The movement of these root systems will cause a major ground disturbance and will lead to the removal of water from a larger area around the tree. Tree pruning to reduce its water use and therefore its influence on the surrounding soil is often employed. However, if the trees are thereafter not subjected to a frequent and on-going regime of management the problem will very quickly return and problems continue. Whilst tree removal will ultimately provide an absolute solution in the majority of cases, there are situations where this is not an option.

Definitions and glossary

ABSORB: Take in or soak up (energy or a liquid or other substance) by chemical or physical action.

ADSORB: To hold molecules as a thin film on the outside surface or on internal surfaces within the material.

ATTERBERG LIMITS: Consistency criteria for defining key water contents of a clay soil. They are: liquid limit, plastic limit and shrinkage limit.

BEARING CAPACITY: The ability of a material to support an applied load. Ultimate bearing capacity is the pressure at which shear failure of the supporting soil immediately below and adjacent to a foundation. A foundation is usually designed with a working load that is some proportion of the bearing capacity.

CLAY: A naturally occurring material which is a plastic material at natural water content and hardens when dried to form a brittle material. It is the only type of soil/rock susceptible to significant shrinkage and swelling. It is made up mainly, but not exclusively, of clay minerals. It is defined by its particle-size range (< 0.002 mm). Clay does not have to be the dominant component of a soil in order to impart clay-like properties to it.

CLAY MINERALS: A group of minerals with a layer lattice structure which occur as minute platy or fibrous crystals. These tend to have a very large surface area compared with other minerals, thus giving clays their plastic nature and the ability to support large suction forces. They have the ability to take up and retain water and to undergo base exchange.

DENSITY: The mass of a unit volume of a material. Often used (incorrectly) as synonym for Unit weight. Usually qualified by condition of sample (e.g. saturated, dry).

DIAGENESIS: The physical and chemical changes occurring during the conversion of sediment to sedimentary rock.

DISCONTINUITY: Any break in the continuum of a rock mass (e.g. faults, joints).

DRAINED: Condition applied to strength tests where pore fluid is allowed to escape under an applied load. This enables an effective stress condition to develop.

DROUGHT: A prolonged period of abnormally low rainfall, leading to a shortage of water.

EFFECTIVE STRESS: The total stress minus pore pressure. The stress transferred across the solid matter within a rock or soil.

ELASTICITY: Deformation where strain is proportional to stress, and is recoverable.

EXPANSIVE: A clay that is prone to large volume changes that are directly related to changes in water content. The mineral make-up of this type of soil is responsible for the moisture retaining capabilities. Expansive soils typically contain one or more of these clay minerals: montmorillonite, smectite, illite.

FILL: Material used to make engineered earthworks such as embankments and capable of acquiring the necessary engineering properties during placement and compaction.

FORMATION: The basic unit of subdivision of geological strata, and comprises strata with common, distinctive, mappable geological characteristics.

GLACIAL: Of, or relating to, the presence of ice or glaciers; formed as a result of glaciation.

GROUNDWATER: Water contained in saturated soil or rock below the water-table.

GROUP: A stratigraphical unit usually comprising one or more formations with similar or linking characteristics.

HEAVE: Upwards movement of the ground and the corresponding movement of the affected foundations. Heave of low-rise structures occurs when a clay is able to absorb more water than it had previously contained and expands. This can occur when trees or hedges, which take moisture from the soil, are severely pruned, or removed, resulting in the soil increasing in moisture content in the affected area.

HYDRAULIC CONTINUITY: Juxtaposition of two or more permeable deposits or rock units such that fluids may pass easily from one to another.

ILLITE: A 2:1 clay mineral, common in sedimentary rocks, not noted for susceptibility to shrink–swell behaviour.

INDEX TESTS: Simple geotechnical laboratory tests which characterise the properties of soil (usually) in a remoulded, homogeneous form, as distinct from ‘mechanical properties’ which are specific to the conditions applied.

INDURATE: The process of making a hardened mass of material, possibly in distinct horizons.

JURASSIC: The middle period of the Mesozoic (208.0 to 145.6 Ma.).

LINEAR SHRINKAGE (LS): The percentage length reduction of a prism of remoulded clay subjected to oven drying at 105^{o} C.

LIQUID LIMIT (LL): The moisture content at the point between the liquid and the plastic state of a clay. An Atterberg limit.

MINERAL: A naturally occurring chemical compound (or element) with a crystalline structure and a composition which may be defined as a single ratio of elements or a ratio which varies within defined end members.

MOISTURE CONTENT: See Water content.

MONTMORILLONITE: A s:1 clay mineral, member of the smectite family, highly susceptible to shrinkage and/or swelling.

MUDROCK: A term used by engineers, synonymous with mudstone.

MUDSTONE: A fine-grained, non-fissile, sedimentary rock composed of predominately clay and silt-sized particles.

OUTCROP: The area over which a particular rock unit occurs at the surface.

OVERBURDEN: Material, or stress applied by material, overlying a particular stratum. Unwanted material requiring removal (quarrying).

OVER-CONSOLIDATED (OC): Deposit, such as clay, that in previous geological times was loaded more heavily than now and consequently has a tendency to expand if it has access to water and is subject to progressive shear failure. The moisture content is less than that for an equivalent material which has been normally consolidated.

PARTICLE-SIZE ANALYSIS (PSA): The measurement of the range of sizes of particles in a dis-aggregated soil sample. The tests follow standard procedures with sieves being used for coarser sizes and various sedimentation, laser or X-ray methods for the finer sizes usually contained within a suspension.

PARTICLE-SIZE DISTRIBUTION (PSD): The result of a particle-size analysis. It is shown as a ‘grading’ curve, usually in terms of % by weight passing particular sizes. The terms ‘clay’, ‘silt’, ‘sand’ and ‘gravel’ are defined by their particle sizes.

PERMEABILITY: The property or capacity of a rock, sediment or soil for transmitting a fluid; frequently used as a synonym for ‘hydraulic conductivity’ (engineering). The property may be measured in the field or in the laboratory using various direct or indirect methods.

PLASTICITY INDEX (PI): The difference between the liquid and plastic limits. It shows the range of water contents for which the clay can be said to behave plastically. It is often used as a guide to shrink–swell behaviour, compressibility, strength and other geotechnical properties.

PLASTIC LIMIT (PL): The water content at the lower limit of the plastic state of a clay. It is the minimum water content at which a soil can be rolled into a thread 3mm in diameter without crumbling. The plastic limit is an Atterberg limit.

PORES: The microscopic voids within a soil or rock.. The non-solid component of a soil or rock.. May be filled with liquid or gas.

PORE PRESSURE: The pressure of the water (or air) in the pore spaces of a soil or rock. It equals total stress minus effective stress. The pore pressure may be negative.

QUARTZ: The most common silica mineral (SiO_2).

SAND: A soil with a particle-size range 0.06 to 2.0 mm. Typically consists of quartz particles in a loose state.

SATURATION: The extent to which the pores within a soil or rock are filled with water (or other liquid).

SETTLEMENT: The lowering of the ground surface due to an applied load (see consolidation).

SHALE: A fissile mudstone.

SHEAR STRENGTH: The maximum stress that a soil or rock can withstand before failing catastrophically or being subject to large unrecoverable deformations.

SHRINKAGE: The volume reduction of a clay (or clay-rich soil or rock) resulting from reduction of water content. Shrinkage may cause subsidence of shallow foundations.

SHRINKAGE LIMIT (SL): The water content below which little or no further volume decrease occurs during drying of a clay (or clay-rich soil or rock). The laboratory tests which measure shrinkage limit have largely fallen into disuse in the UK. An Atterberg limit.

SILT: A soil with a particle-size range 0.002 to 0.06 mm (between clay and sand).

SMECTITE: A group of 2:1 clay minerals noted for their high plasticity and susceptibility to shrink–swell behaviour (e.g. montmorillonite).

STIFFNESS: The ability of a material to resist deformation.

STRAIN: A measure of deformation resulting from application of stress.

STRESS: The force per unit area to which it is applied. Frequently used as synonym for pressure.

SUBSIDENCE: The settling of the ground or a building in response to physical changes in the subsurface such as underground mining, clay shrinkage or drained response to overburden (consolidation).

SUCTION: The force exerted when fluid within pores in a soil or rock is subjected to reduced atmospheric (or other environmental) pressure.

SUPERFICIAL DEPOSITS: A general term for usually unlithified deposits of Quaternary age overlying bedrock; formerly called ‘drift’.

SWELLING: The volume increase of a clay (or clay-rich soil or rock) resulting from an increase in water content. Swelling behaviour may cause heave of shallow foundations.

SWELLING INDEX (SI): The rebound (unloading) equivalent of the Compression index.

TILL: An unsorted mixture which may contain any combination of clay, sand, silt, gravel, cobbles and boulders (diamict) deposited by glacial action without subsequent reworking by meltwater.

WATER CONTENT: In a geotechnical context: the mass of water in a soil/rock as a % of the dry mass (usually dried at 105º C). Synonymous with moisture content.

WATER TABLE: The level in the rocks at which the pore water pressure is at atmospheric, and below which all voids are water filled; it generally follows the surface topography, but with less relief, and meets the ground surface at lakes and most rivers. Water can occur above a water table.

WEATHERING: The physical and chemical processes leading to the breakdown of rock materials (e.g. due to water, wind, temperature).

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Useful web addresses

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British Geological Survey www.bgs.ac.uk

Institution of Civil Engineers www.ice.org.uk

International Society of Arboriculture www.isa-arboriculture.org

Royal Institution of Chartered Surveyors www.rics.org

Subsidence Claims Advisory Bureau www.subsidencebureau.com

The Clay Research Group www.theclayresearchgroup.com

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