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COLLAPSIBLE SOILS IN THE UK

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ABSTRACT

Metastable soils may collapse because of the nature of their fabric. Generally speaking, these soils have porous textures, high void ratios and low densities. They have high apparent strengths at their natural moisture content but large reductions of void ratio take place on wetting and, particularly, when they are loaded because bonds between grains break down on saturation. Worldwide, there is a range of natural soils that are metastable and can collapse, including loess, residual soils derived from the weathering of acid igneous rocks and from volcanic ashes and lavas, rapidly deposited and then desiccated debris flow materials such as some alluvial fans, for example, in semi-arid basins, colluvium from some semi-arid areas and cemented, high salt content soils such as some sabkhas. In addition, some artificial non-engineered fills can also collapse. In the UK, the main type of collapsible soil is loess, though collapsible non-engineered fills also exist. Loess in the UK can be identified from geological maps but care is needed because it is usually mapped as 'brickearth.' This is an inappropriate term and it is suggested here that it should be replaced, where the soils consist of loess, by the term 'loessic brickearth.' Loessic brickearth in the UK is found mainly in the south east, south and south west of England, where thicknesses greater than 1 m are found. Elsewhere, thicknesses are usually less than 1 m and, consequently, of limited engineering significance. There are four steps in dealing with the potential risks to engineering posed by collapsible soils: (1) identification of the presence of a potentially collapsible soil using geological and geomorphological information; (2) classification of the degree of collapsibility, including the use of indirect correlations; (3) quantification of the degree of collapsibility using laboratory and/or *in situ* testing; (4) improvement of the collapsible soil using a number of engineering options.

WHAT ARE COLLAPSIBLE SOILS?

Soils that have the potential to collapse generally possess porous textures with high void ratios and relatively low densities. At their natural moisture content these soils possess high apparent strength but they are susceptible to large reductions in void ratio on wetting, especially under load. In other words, the metastable texture collapses as the bonds between the grains break down as the soil becomes saturated. Jefferson & Rogers (2012) pointed out that as collapse was controlled both microscopically and macroscopically, both these elements need to be understood if the true nature of collapse was to be determined. The potential for soils to collapse is clearly of geotechnical significance, particularly with respect to the potential distress of foundations and services (for example, pipelines) if not recognised and designed for.

The collapse process represents a rearrangement of soil particles into a denser state of packing. Collapse on saturation usually occurs rapidly. As such, the soil passes from an under-consolidated condition to one of normal consolidation.

This definition is similar to the first part of that of Rogers (1995) who gave two basic requirements for a soil to be collapsible:

> “A collapsible soil is one in which the constituent parts have an open packing and which forms a metastable state that can collapse to form a closer packed, more stable structure of significantly reduced volume.
>
> “In most collapsible soils the structural units will be primary, mineral particles rather than clay minerals.”

The latter part of Rogers (1995) second basic requirement of collapsibility is, perhaps, a little confusing (what is meant by primary, mineral particles?) Jefferson & Rogers (2012) made it clearer by defining collapsible soils as: “…soils in which the major structural units are initially arranged in a metastable packing through a suite of different bonding mechanisms.” This can include both individual primary minerals (non-clay) and ‘peds’ comprising individual primary minerals with clay mineral coatings and/or clay ‘bridges’ to other particles.

The most widespread naturally collapsible soils are loess or loessic soils of aeolian origin, predominantly of silt size with uniform sorting. The majority of these soils have glacial associations in that it is believed that these silty soils were derived from continental areas where silty source material was produced by glacial action prior to aeolian transportation and deposition.

Vast spreads of loess have accumulated over large areas of North America, Europe, Russia and China during the last two to three million years, for example, the Wucheng loess of China occurs over most of the Lower Pleistocene (c. 2.4 – 1.15 million years BP) (Liu *et al*. 1985). However, it is not found exclusively in these regions. For example, it also occurs in Thailand and New Zealand. Jefferson *et al.* (2001) estimated that loess covered about 10% of the Earth's landmass while Dibben (1998) estimated the figure at 15%.

The term 'loesch' (also 'lȍsz' in Jari & Badura [2013], 'schwemmlöss' or 'löss' in Pye [1995]) was used by countrymen from the Upper Rhine region (south-west Germany) to describe the friable silt deposits along the Rhine Valley near Heidelberg. Although the term was literally introduced by Karl Caesar von Leonhard in 1820, it was only brought into the scientific literature in 1834 by Charls Lyell (Smalley *et al*., 2001). In Britain, loess has been known as ‘Brickearth’ (D'Archiac 1839, Prestwich 1863, Fink 1974). Brickearth was used in Roman buildings (for example, in the Roman London Amphitheatre and timber buildings discovered in the Walbrook Valley [Arkell & Tomkeieff 1953 and Lee *et al*. 1989]) and was described as homogeneous, structure-less loam (Deakin 1986).

Pye (1995) proposed that there were four fundamental requirements necessary for the formation of loess; minor additions have been made to these:

- a dust source;
- adequate wind energy to transport the dust;
- a suitable depositional area (or reduced wind speed [Pye 1987]);
- sufficient amount of time for its accumulation and epigenetic evolution (Trofimov 1990).

These requirements are not specific to any one climatic or vegetational environment. Whilst much loess was formed in glacial/periglacial environments, derived from the floodplains of glacial braided rivers where glacially-ground silts and clays were deposited, windblown deposits can be derived in other environments described by Iriondo & Krohling (2007) as volcanic, tropical, desert and gypsum loesses and climatically-controlled ones referred to as trade-wind and anticyclonic.

However, soils other than loess have the potential to collapse. Haskins *et al*. (1998) referred to collapsible soils from Mpumalanga Province, South Africa that had been derived from weathered granite. Assadi (2014) observed the formation of a collapsing structure in superficial kaolinite deposits (sub-200kPa pre-consolidation stress) with a moisture content of 1-5%, and also in accumulated wet kaolinite (40-45% moisture content) of similar stress history as it dried. Northmore *et al.* (1992a) summarised the geological and geotechnical characteristics of tropical red clay soils derived from volcanic ash deposits in Kenya, Indonesia and Dominica, including their potential to collapse. In further reports, more detailed information on the geology of the sampled areas (Northmore *et al.* 1992b), mineralogy (Kemp 1991), geotechnical index properties (Northmore *et al.* 1992c), strength and consolidation properties (Hobbs *et al.* 1992), pit sampling (Culshaw *et al.* 1992) and borehole sampling (Hallam & Northmore 1993) were presented and discussed. Other potentially collapsible soils include rapidly deposited and then desiccated debris flow materials (such as some alluvial fans, for example, in semi-arid basins of inland California [Waltham 2009]), colluvium in Colorado and other semi-arid areas of the western USA [for example, White & Greenman 2008]), cemented, high salt content soils such as some sabkhas (for example, El-Ruwaih & Touma 1986), non-engineered fills (compacted dry of optimum) and waste materials such as fly ash (Jefferson & Rogers 2012). Many of these soils do not occur in the UK and are not considered further here except for non-engineered fills.

LOESS IN THE UK

In Great Britain, loessic deposits are mapped by the British Geological Survey mainly as ‘brickearth’. Such deposits occur mainly as a discontinuous spread across southern and eastern England, notably in Essex, Kent, Sussex and Hampshire (Fig. 1a and b). The extent of brickearth shown on this map is derived from British Geological Survey (BGS) geological mapping originally at a scale of 1:10 000 or 1:10 560 and includes only those deposits that are at least 1 m thick. This distribution is comparable with the extent of loess greater than 1 m thick shown by Ballantyne & Harris (1994) (their Figure 8.21) after Catt (1977, 1985) and was derived from pedological and geological maps, as well as other sources. This latter map also shows “Cover sands” and “Loess 0.3 – 1.0 m thick.” Fig. 2a and b shows the distribution of loessic deposits greater than 1 m thick and between 300 mm and 1 m thick, derived from Soil Survey 1:250 000 soil maps. Assadi (2014) has reviewed the geographical distribution of loess soils in the UK. In addition, material similar to brickearth occurs in widened fissures (gulls) in deposits such as the Hythe Beds in Kent (Bell *et al*. 2003) and in a sinkhole in the Chalk north-west of London (Gibbard, P., pers. comm.). Whether such fill is of windblown origin or whether it is derived locally from pre-existing silty clay deposits that have undergone solifluction is still a matter of debate. Patchy loessic deposits have also been described in south-west England, around the Lizard Peninsula in Cornwall (Ealey & James 2008, 2011) and around Torbay in Devon (Cattell, 1997).

The use of the term 'brickearth' for loessic deposits on geological maps may seem strange. However, the reason is quite simple and obvious – the loesses usually had significant clay contents and were very suitable for the manufacture of bricks. However, care is needed when using the term 'brickearth' to identify loesses, as some so-called brickearths are not loess. For example, William Smith used the term on his 1815 geological map of Britain (Smith 1815) – he was referring to what we now know as

Lambeth Group deposits and also East Anglian Crag deposits. Similarly, the Norwich Brickearth of East Anglia, UK, is an Anglian sandy glacial till (Rose *et al.* 1999) (the Happisburgh Till Member). The terminology used on geological map legends is confusing as the BGS does not use the term 'loess' and the term 'aeolian' is used only on map sheets 316 (Fareham), 317/332 (Chichester and Bognor) and 331 (Portsmouth). As well as tills, 'brickearth' may also refer to glaciolacustrine deposits and colluvial deposits. Based on the BGS Lexicon of Rock Names, Bell & Culshaw (2001) described the main brickearth units (the first five terms in Table 1). All of them should be assumed to be loessic as first deposited, though they may have been reworked. More recently, other terms have been used (see the remainder of Table 1). Initially, all of them should be assumed to be loessic as first deposited, though they may have been reworked, and so potentially collapsible. The term ‘brickearth’ has become so entrenched in the geological literature that it will probably never be superseded entirely, despite new nomenclature being suggested by the British Geological Survey (McMillan & Powell 1999). As such, the more appropriate general term of ‘loessic brickearth’ is recommended for those deposits in the UK that are clearly of aeolian/loessic origin.

According to Kerney (1965), almost all the loessic brickearth soils in the UK are probably of late Devensian age (c. 14 to 30 ka BP). Parks & Rendell (1992) carried out thermoluminescence dating of loessic brickearth deposits from 26 locations in south east England and reported that they seemed to have resulted from at least three depositional phases during the Late Pleistocene (10-25 ka BP, 50–125 ka BP and >170 ka BP). However, most of the samples were of Late Devensian age but with isolated pockets of older material found throughout the area. Using the optically stimulated luminescence (OSL) method, Clarke *et al.* (2007) dated the lower ‘calcified’ loessic brickearth at Pegwell Bay, Kent at 17.2±1.3 ka BP and at Ospringe, Kent at 23.8±1.3 ka BP. The upper ‘non-calcareous’ loessic brickearth at Pegwell Bay had an age of 15.0±0.9 ka BP. At Ospringe, the age of the upper, non-calcareous loessic brickearths was 18.7±2.3 ka BP but Clarke *et al.* believed this to be an overestimate of the true age because the deposit probably contains grains of mixed ages. The loess of the Lizard Peninsula was dated by Ealey & James (2011) at around 15.9 ka BP. These dates imply that calcareous loessic brickearth was deposited more than once both at around the time of the Late Glacial Maximum and during deglaciation. The deposition of the upper non-calcified material may correspond to a period of rapid climatic warming.

HOW TO RECOGNISE LOESSIC BRICKEARTH

Description and mineralogy

Given that identifying loess deposits from geological maps may be problematical, it is essential to obtain and geotechnically test samples suspected of being loessic to determine their index properties and their susceptibility to collapse.

Generally in the UK, loessic brickearth comprises a discontinuous blanket deposit of yellowish brown, friable, slightly plastic, poorly bedded, clayey and sandy silt with well-developed vertical jointing. It has a very open, low density structure. With regard to loessic brickearths in Kent, UK, Milodowski *et al.* (2015) described their fabric as being characterised by “an open-packed arrangement of clay-coated, silt-sized quartz particles and pelletised aggregate grains (peds) of compacted silt and clay, supported by an inter-ped matrix of loosely packed, silt/fine-grained sand, in which the grains are held in place by a skeletal framework of illuviated clay.” Similarly, Fig. 3 shows three silt-size particles with two of them bridged by platy clay particles from South Essex, UK. It now seems that loessic brickearth in south-eastern England may not consist of an upper part that has been leached of carbonate material and a lower calcareous part. Rather, Clarke *et al.* (2007)

and Milodowski *et al*. (2015) argued that in Kent and south-east Essex there have been at least two phases of brickearth/loess deposition in the Late Devensian, the older, deeper deposits being calcareous, with the presence of an old soil horizon at the top of it. However, Catt (2008) challenged this interpretation and it seems that systematic dating of various loessic brickearth deposits is needed.

The lower parts of a deposit tend to be more rigid and better consolidated than the upper parts. Quartz is the most abundant mineral in loessic brickearth ranging between 12% and 54%, with an average of 33%, followed by feldspar. Of the clay-type minerals, mica is generally more abundant than montmorillonite that, in turn, is more abundant than illite and kaolinite. For example, Northmore *et al*. (1996) found that montmorillonite averaged some 15% in the loessic brickearth of south Essex with a maximum of 39% and kaolinite constituted generally less than 5%. Calcium carbonate occurs as grains, thin tube infillings, buttress/bridge units and as concretionary nodules. When present it tends to account for less than 10% of the soil. However, in Kent, values quoted by Derbyshire & Mellors (1988) were as high as 20%.

The principal mineral in some gull-fills found in Kent is quartz, it comprising as much as 85% (Bell *et al*. 2003). The quartz grains are sub-angular and sub-rounded to rounded. The degree of roundness tends to increase with increasing size of grains. The remainder of the fill usually consists of sub-angular flint grains, hornblende, some glauconite and traces of heavy minerals and micaceous material. The carbonate content varies between 0.03 and 0.46%, which is very low compared with loessic brickearths from south Essex and Kent. The small amount of calcium carbonate may be due to the material having been leached.

Geotechnical properties

Particle size distribution

Loess deposits, generally, consist of 50 to 90% silt size particles. The particle size distributions of loessic brickearth from South Essex and Kent are shown in Fig. 4a, from which it can be seen that they are similar. Clayey, silty and sandy brickearth/loess can be recognized (using Holtz & Gibbs' [1952] chart). The clay content in the loessic brickearth from south Essex ranges from 4 to 42%, with an average of 21%. This compares with an average silt content of 59% (range 26 to 84%), silt being the most important size fraction in this deposit (Northmore *et al.* 1996). Loess with 5-40% clay content may exhibit collapsibility (Dudley, 1970, Lawton *et al*. 1992) but collapsibility potential rises significantly in loess containing 11 to 24% clay constituents. On Holtz & Gibbs' chart, the South Essex loessic brickearths fall within all three classes (clayey, silty and sandy loess). The particle size distribution of gull-fill material from Allington, Kent is illustrated in Fig. 4b. This indicates that it falls within the clayey loess and silty loess zones of Holtz & Gibbs (Bell *et al.* 2003). This means that it has affinities with loessic brickearth from Pegwell Bay, Kent, as reviewed by Fookes & Best (1969), as well as with those from other locations in Kent and in south Essex. It is well sorted, with uniformity coefficients ranging from 4 to 11.

Density

Most bulk densities of loessic brickearth fall within the range 1.7 and 2.1 Mg m^{-3} (Table 2), with most dry densities varying from 1.37 to 1.74 Mg m^{-3}. The relatively low densities of are similarly reflected in high void ratios (0.56 to 0.90), indicative of an open microstructure. Grain densities are quite variable, from 2.61 to 2.72. Assallay (1998) noted dry densities and void ratios of 1.15 Mg m^{-3} and 1.61, respectively, for non-British loesses.

Plasticity

Loess soils are slightly to moderately plastic, the plasticity increasing as the clay content increases. Loessic brickearth of South Essex has a natural moisture content that usually varies from 13 to 21%; that of the gull-fill material from Allington, Kent is similar but with a slightly higher range, that is, 16 to 24%. These soils are of variable plasticity, ranging from low to occasionally high but most are of low plasticity. The spread of liquid limits ranged from 27 to 64% and that of plastic limits was from 17 to 24% (Table 2). These are broadly similar to values for Kent loessic brickearths quoted by Derbyshire & Mellors (1988). According to their liquid limits (range 31 to 34%), the gull-fill has a low plasticity. Its plastic limits also have a limited range from 18 to 23%. Most loessic brickearths have negative liquidity indices indicating that they are in a fairly brittle condition.

Whilst being a function of mineral components of a soil, plasticity changes with the inflow of cationic solutions into the soil. For British loessic brickearth, Boardman *et al.* (2001) showed an increase in plasticity index when loess is wetted with dilute solutions of $FeCl_3$ or NaCl. The increase in plasticity was relatively more marked in non-calcareous sequences when wetted with Na^+-enriched water, and more pronounced in calcareous sequences when wetted with Fe^{+3}-enriched water. The critical water content at which loess collapses is inversely proportional to the plasticity index.

Strength, consolidation and permeability of brickearth/loess

The strength of loess is dependent on the initial porosity and moisture content, the degree of deterioration of the bonds and the increase in granular contacts under consolidation, as well as changes in moisture content. When loess with many macro-pores and high water content is loaded, the cementing bonds are first broken resulting in a lowering of the apparent cohesion and, eventually, softening of the soil. With further loading the grains are brought more and more into contact, thereby increasing friction, so giving rise to a hardening effect. As far as the angle of shearing resistance of loess is concerned, this usually varies between 30^0 and 34^0. As the liquidity index of loess increases, the shear strength decreases, becoming essentially zero at around a liquidity index of one.

The results obtained from undrained triaxial tests on loess from South Essex by Northmore *et al.* (1996) showed that the shear strength was between 10 and 220 kPa. Such a range indicates the variability in undrained shear strength. However, Northmore *et al.* noted a general tendency for shear strength to decrease with increasing depth. They suggested that this might be partly due to the variable composition of the deposit that tends to vary from a stiff sandy silty clay (relatively dry) near the surface, to a clayey silty loam with increasing depth. The higher values of shear strength may reflect the desiccated 'crust-like' nature of the soil near the ground surface. Consolidated drained triaxial tests also indicate variable effective shear strengths. Peak values of internal angle of shearing resistance may be between 19^0 and 34^0, and those of effective cohesion from between 10 to 70 kPa. Residual values drop to between 16^0 and 25^0, and zero, respectively. Recent detailed investigation of the mineralogy and structure of loessic brickearths in Kent (Milodowski *et al*., 2015) also suggest that the variable formation of secondary calcium carbonate cementation will also influence shear strengths in the lower ‘calcareous’ loessic brickearths..

Loess can support heavy structures with small settlements if loads do not exceed the apparent preconsolidation stress and natural moisture content is low in comparison with the plasticity index. On the other hand, loess can compress substantially if the apparent preconsolidation stress is exceeded. Primary and secondary compression are similar to that of saturated clay. Primary settlements generally occur rapidly, with much of the settlement occurring during the actual application of load. Loess also may exhibit creep deformation under loading.

The compression index indicates that the degree of compressibility of loess is high and, generally, the value of coefficient of volume compressibility decreases with increasing load.

Tests on loess from South Essex carried out by Northmore *et al.* (1996) exhibited rapid consolidation that is reflected in the high coefficients of consolidation. In many instances, all the primary consolidation may take place within a half minute of loading that is essentially showing collapse of the soil fabric. The primary consolidation, that is, the wetted collapse, for the upper calcareous loess at Pegwell Bay, Kent, Sittingborne, Kent and Star Lane, South Essex was as high as 6.3%, 16.9% and 9.4%, respectively (Dibben 1998).

Loess has a much higher vertical than horizontal permeability, which is enhanced by long vertical 'voids' in the loess structure that are formed by fossil root-holes and vertical fissures. Because of this, deposits of loess are better drained (their permeability ranges from 10^{-5} to 10^{-8} m s^{-1}) than are true silts.

NON-ENGINEERED FILLS

Non-engineered fills are a commonly occurring collapsible deposit found in many parts of the UK as well as across the globe. In the UK, collapse settlements can be particularly problematic for cohesive fills that have been placed dry of optimum or, more generally, on non-engineered fills that have been poorly compacted. The subsequent placement of overburden on these fills, often with an increase in water content, can trigger significant collapse. For example, clayey silt loams, placed dry-of-optimum, were found to exhibit collapse settlement of up to 600 mm (Assadi & Jefferson 2015)

The magnitude of the actual collapse that occurs is a function of the soil properties, the degree of compaction and the thickness of the layer that becomes saturated post-construction settlement (Nowak & Gilbert 2015) and this can be significant for settlement sensitive structures. Case histories recorded by Blanchfield & Anderson (2000); Charles & Skinner (2001) and Charles (2005) indicate that collapse settlements in excess of 1 m can occur in deep, backfilled quarries. In these deposits collapse typically occurs after infilling and is often associated with the re-establishment of true groundwater conditions post-construction or, more localised conditions through leaking drains or poorly located soakaways. Collapse potential can remain from some considerable time post-construction, for example, the Clifford embankment is York. Here, collapse was trigger by a flooding event hundreds of years after the construction. Further details are provided by Charles & Watts (2001) and Skinner (2012). It would be true to say that almost any soil can exhibit a collapse potential under the right stress environment and, so, collapse potential should be viewed in the light of an open metastable fabric, which has the potential for increased packing of particles (and subsequent volume change) when placed under load and/or through a significant increase in water content through inundation. The next section discusses various aspects that need to be taken account of when identifying potentially collapsible soils.

IDENTIFYING COLLAPSIBILITY

Collapse Potential

Soils such as loess have the potential to collapse when wetted or wetted under loading. This process is frequently referred to as 'hydro-consolidation' (for example, Rogers *et al.* 1994). Jefferson & Rogers (2012) summarised the main geotechnical and micro-fabric characteristics required of the most collapsible soils:

- an open, metastable structure;
- a high voids ration and low dry density;
- a high porosity;
- a geologically young or recently altered deposit;

- a soil with inherent low inter-particle bond strength.

In addition to these, favourable conditions for porous granular soils to collapse include:

- a well sorted soil, where grains connect together via two points (Bolton 1999);
- a sub-angular shape and rough texture for silts;
- a low degree of saturation (structure-based) and hence a high apparent cohesion;
- a prolonged application of load smaller than fragmentation load.

In an environmental sense, collapse potential is also related not only to the origin of the material, to its mode of transportation and to the depositional environment, but also to weathering. For example, Gao (1988) pointed out that the weakly weathered loess of the north west of the loess plateau in China has a high potential for collapse, whereas the weathered material of the south east of the plateau is relatively stable and the features associated with collapsible loess are gradually disappearing. In Poland, Grabowska-Olszewska (1988) observed that collapse is most frequent in the youngest loess and that it is almost exclusively restricted to loess that contains slightly more than 10% particles of clay size (less than 0.002 mm). These soils are more or less unweathered and possess a pronounced vertical pattern of fissuring. Assadi & Jefferson (2013) maintained that maximum collapsibility is likely to occur in loess with 10-15% clay and 20% carbonate inclusions. However, this high degree of collapsibility was found to significantly decrease in the presence of amorphous silica precipitates, an indication of quartz weathering. Assadi (2014) reported further observations on the decreased collapsibility after slow precipitation of amorphous silica in clayey silts of <25% clay content (particularly at clay contents below 15% in the presence of metal-based sulphates) and fast precipitation of amorphous silica in silty clays of >45% clay content. So, it appears that those older deposits, in which the fabric and mineral composition have been altered by weathering, are not nearly as susceptible to collapse as young, unweathered soils.

Popescu (1986) stated that there was a limiting value of pressure, defined as the collapse pressure, beyond which deformation of soil increases appreciably. The collapse pressure varies with the degree of saturation. He defined truly collapsible soils as those in which the collapse pressure is less than the overburden pressure. In other words, such soils collapse when saturated since the soil fabric cannot support the weight of the overburden. When the saturation collapse pressure exceeds the overburden pressure, soils are capable of supporting a certain level of stress on saturation. Popescu defined these soils as conditionally collapsible soils. The maximum load that such soils can support is the difference between the saturation collapse and overburden pressure. Based on observations on loess from Thailand, Phien-wej *et al.* (1992) concluded that the critical pressure at which collapse of the soil fabric begins was greater in soils with smaller moisture content. So, during the wet season, when the natural moisture content could rise to 12%, there was a reduction in the collapse potential to around 4%.

However, to help understand better which loess soils might be more susceptible to collapse, Jefferson *et al.* (2003) developed the concept of the provenance (P), transportation (T) and deposition (D) (PTD) model. They argued that it is the PTD sequence that a particular deposit goes through that determines whether the soil will have an open, metastable structure and relatively high voids ration, hence making it more likely to collapse. Jefferson *et al.* illustrated the approach with a number of examples. One example that would include the brickearths/loesses of South Essex is reproduced in Table 3. The different depositional situations explain, in part, the different litho-stratigraphic names used on BGS geological maps (see Table 1).

Jefferson & Rogers (2012) summarised the link between the PTD sequence and collapse potential as follows: “The alternating nature of loess formation significantly influences the engineering behaviour and ultimately the nature of collapse, and the location (depth) where collapse occurs. This will dictate the nature of the infiltration pattern of water into the soil and as a result can yield collapse in unexpected locations. Moreover, this can influence the effectiveness of any ground improvement approach used to remove collapsibility."

Broadly, loesses have three zones of relative collapsibility (Jefferson & Rogers 2012):

- a surface desiccation crust that doesn't collapse without additional loading;
- a collapsible zone;
- a zone at depth that has collapsed due to overburden pressure.

For collapse to happen, the following are required:

- an open structure with relatively large voids;
- a source of strength to keep the particles in position.

This strength is provided by one or more of the following:

- capillary or matric suction forces;
- clay and silt particles at coarser particle contacts;
- cementing agents, for example carbonates or oxides.

For cemented loesses, Milodowski *et al.* (2015) said that there were three stages of collapse after inundation (when any suction will be lost):

- first, dispersion and disruption of clay bridges between larger silt particles leading to initial rapid collapse of loose-packed inter-ped silt/sand;
- rearrangement and closer packing of compact aggregate silt/clay peds as the load is taken up via the particle contacts;
- progressive deformation and shearing of the silt/clay peds and collapse into unsupported inter-particle areas.

STRATEGIES FOR ENGINEERING MANAGEMENT: AVOIDANCE, PREVENTION AND MITIGATION

Popescu (1986) proposed that there were four steps required when dealing with collapsible soils:

- Identification of the presence of a potentially collapsible soil using geological and geomorphological information. For the UK, the use of geological maps has been discussed above. Also, the BGS's GeoSure geohazard information system (Culshaw & Harrison 2010) includes a map layer for collapsible soil that shows areas of moderate and significant collapse potential (http://www.bgs.ac.uk/products/geosure/collapsible.html). Other approaches have been recently presented, for example, a collapse-risk-specific non-conflicting fine soil classification framework such as one recently proposed by Assadi (2014).

- Classification of the degree of collapsibility, perhaps using indirect correlations. A wide range of empirical collapse indices exist. Bell *et al.* (2003) compared seven of them plus liquid limit vs dry density plots of Gibbs & Bara (1962), with the results of oedometer tests to determine the coefficient of collapsibility. They concluded that while many of the indices broadly agreed with the oedometer test results, they should be regarded as only approximate indications of collapsibility. Differences between the indices may be the result of regional differences in the materials used.

- Quantification of the degree of collapsibility using laboratory and/or *in situ* testing. In the laboratory, the double or single oedometer test is used following the methodology of Jennings & Knight (1975) and modified by Houston *et al.* (1988). The amount of collapse strain developed when the test specimen is flooded under a given load indicates the susceptibility to collapse. Although, strictly, these methods should be seen as indicative of actual potential collapse. Table 4 shows Jennings & Knight's classification of collapse severity in terms of the percentage collapse derived from the relationship:

$$\text{Coefficient of collapse, } C_{col} = \frac{\Delta e}{1 + e_i} \qquad (1)$$

In situ tests that have been used include plate loading, pressuremeter and standard penetrometer. These, and other tests have been described by Jefferson & Rogers (2012).

Dynamic cone resistance, q_d, was measured by Northmore *et al.* (2008) for the loessic brickearth at Ospringe, Kent. They showed that q_d takes high values in granular, sandy, gravelly sequences and very low values in desiccated surface layers. Resistance was more or less constant through the loessic brickearth sequences, except a slightly decreasing trend with depth in the upper non-calcareous sequence followed by a slightly increasing trend in the lower calcareous sequence. This may suggest a history of leaching. The 1.5-2.5 MPa resistance through the upper non-calcareous and 3-4 MPa resistance through the lower calcareous sequence could be a means to identify loessic brickearth in a profile with top loam and bottom sand formations of >5MPa resistance.

In the last ten years, geophysical methods have been increasingly used. Northmore *et al.* (2008) described the use of electrical resistivity, shear wave profiles and electromagnetics (EM) to determine the depth and extent of collapsible and non-collapsible loessic brickearth at Ospringe, Kent. Shear wave velocities through the loessic brickearth sequences were reportedly lower than in the topmost loam and bottom sand formations. Owing to the heterogeneous nature of the lower calcareous loessic brickearth, shear wave velocities followed an erratic pattern. Northmore *et al.* also argued the capability of EM profiling to distinguish between the lower calcareous and upper non-calcareous loessic brickearth. At Ospringe, Kent, they measured an EM resistivity of 22 to 24 Ω-m for the lower calcareous sequence and greater than 70 Ω-m for the underlying Chalk formation. They measured an electrical resistivity of 20 Ω-m for the upper non-calcareous loessic brickearth, 22 to 30 Ω-m for the lower calcareous loessic brickearth and greater than 75 Ω-m for underlying Chalk formation.

- Engineering options to improve collapsible soils have been summarised by Jefferson & Roger (2012) and are summarised in Table 5.

For foundations Popescu (1992) suggested four approaches:

Very stiff raft foundations and a rigid superstructure to reduce differential settlement (expensive and not always successful).

Flexible foundation and superstructure to reduce damage.

Use of piles through the collapsible soil.

Soil improvement (see Table 5).

For roads and railways, some of the approaches in Table 5 may be applicable but care should be taken with roads because the pavement may reduce evaporation and hence alter the water content conditions compared with the surrounding ground.

Slope stability problems are unlikely in the UK because thicknesses of loessic brickearth are mostly not great enough.

More recently, Roohnavaz *et al*. (2011) discussed the use of unsaturated loess fills for earthworks, where standard methods are often insufficient to remove collapse potential (developed through inter-particle bonding). Instead, they suggested that repeated reworking and recompaction is required in combination with greater compactive effort and placement wet of optimum. Further details of the special attention needed when working with collapsible soils, in particular loess, are provided by Jefferson & Rogers (2012).

EXAMPLE OF DAMAGE CAUSED BY COLLAPSE

Surprisingly little is published about cases of damage caused by collapse of loessic brickearth in the UK. Cattell (1997) described the presence of loess and possibly soliflucted loess in the Torbay area in south Devon. Cattell (2000) said that the susceptibility of the soils to loss of strength on wetting is unusually high. Fig. 5 shows a derelict house in Torbay, situated on the loess that Cattell described, that has suffered foundation failure probably due to the leaking of a drain or downspout. However, given the extent of loess in south east England, it seems likely that other examples of failure exist, though they have not been identified as such, except for a few isolated cases.

However, even in the most loessic parts of South East England the risk of structural collapse effecting foundations, etc. would be low due to the relatively thin deposits of collapsible loess. For example, if foundations are excavated down to 2 m, they would probably cut through many, if not most, areas of collapsible loessic brickearth. Even if loessic brickearth was still found beneath the foundation, the thickness remaining to the underlying Chalk, river gravels or London Clay would be insufficient for significant collapse in most cases. Of course, this comment does *not* rule out undertaking adequate site investigation to determine the thickness and measure collapse potential on samples, if the thickness beneath a building or structure warrants it.

Nevertheless, the ‘seasonal’ collapse of loess-like soils including poorly engineered loam, and in particular calcareous loam fills/embankments has been long a well-known challenge for the construction of earthworks. The performance of the heavily used UK transport infrastructure relies, in part, on the performance of underlying embankments, many of which have been in service for over 150 years. Furthermore, new embankments will be built in the coming decades to improve the network, raising the need for a better understanding of the impact of placement conditions on planned maintenance costs. The revised British Code of Practice for Earthworks was published in 2009 and includes compliance with Eurocode 7 (Anon. 2009a). This places emphasis on fill classification and compaction specifications, while setting the Specification for Highway Works 600 series (Anon. 2009b) as the default approach for earthworks in the UK. However, the revised earthworks British Standard (and earlier documents such as Charles & Watts [2001]) lack consideration of unexplained ground movements in compacted earthworks, particularly when material from nearby cuttings is used as fill materials. Unexplained settlements include sudden and long-term subsidence particularly in transient loading environments, when fills are built from sand/silts with small clay inclusions, as well as seasonal subsidence in fills with <20% carbonates. Assadi & Jefferson (2015) recently examined dry and wet compressibility of a suite of calcareous and non-calcareous clayey silts and silty clays against the BRE recommendations, as a baseline for UK earthworks practice.

CONCLUSIONS

Globally, a relatively wide range of soil types have the potential for collapse under suitable conditions. However, regardless of provenance, virtually all are characterised by porous textures, high void ratios and low densities with collapse triggered by water inundation and saturation. In the UK, loessic brickearth is the predominant collapsible natural soil along with certain non-engineered (or inadequately engineered) fills. Collapsible soils, including loess, are materials that ‘standard’ soil mechanics stress-strain principles fail to adequately explain in terms of their engineering behaviour. For the ground engineering industry to avoid and mitigate the risks associated with collapse, a first significant step is to correctly identify the presence of collapsible soils. Once identified, appropriate laboratory testing procedures and, where necessary, follow-up field tests can be applied to assess collapse potential, and the possible need for mitigation measures. This chapter has highlighted current geological-geotechnical-geochemical-mineralogical and geomorphological understanding of UK collapsible soils and may serve as a guide to aid engineering ground investigation in those areas where such natural (loessic) soils and potentially collapsible man-made fills may be present. Current techniques to help mitigate the risks associated with collapse are also described. As planned expansion of the UK’s road and rail infrastructure progresses it becomes ever more important that the collapse potential of poorly- or non-engineered fills, including old Victorian railway embankments, is considered by ground engineers, and that the use and appropriate engineered placement of potentially metastable materials is more fully understood and designed for.

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GLOSSARY AND DEFINITIONS

Brickearth: a term used in the UK on British Survey Geological maps to describe materials that have been commonly used to make bricks. Deposits mapped as ‘brickearth’ are mainly, but *not exclusively*, loess deposits.

Loessic brickearth: a new term that applies to the UK. It consists of materials mapped by the British Geological Survey as brickearth but which comprise deposits of loess.

Collapse: a sudden change in soil structure from an initial open state to a final dense state when grain-to-grain connections fail in the event of wetting or loading (Assadi 2014).

Collapsible soil: a soil in which the constituent parts have an open packing and which forms a metastable state that can collapse to form a closer packed, more stable structure of significantly reduced volume (Rogers 1995).

Loess: a widespread water-sensitive soil with at least one cycle of Aeolian deposition and a possible history of post depositional modifications. The metastable aspect of loess is due to its air-fall sedimentation history, while the post-depositional modifications are responsible for the collapsibility of the metastable structure (Rogers 1995, Smalley *et al.* 2006).

Hydrocompaction/hydro-consolidation: a process by which fine grained, low density soils restructure and compact due to the addition of water or the addition of water under load (Waltham 2009/Rogers *et al.* 1994). See also ‘Collapse.’

Metastability: a metastable soil has an open structure, that is, the granular frame of the solid particles must be in an open packing that is capable of achieving rapidly a significantly closer packing, producing a stable structure (Assallay 1998).

Non-engineered fill: The term 'fill' (or 'made ground') is used to describe material that has been deposited by human processes. The material could be natural, or have been altered artificially prior to deposition. Fill is either engineered or non-engineered depending on whether any specific treatment during deposition takes place. As a result, a number of engineering challenges may exist and will require different remediation approaches to improve and mitigate problematical behaviour. Non-engineered fill may consist of domestic waste, building waste, slag, mining and quarry waste, industrial waste and soil waste. Non-engineered fills may settle variably, have poor bearing capacity and may suffer significant movements due to causes other than the imposed loading. Other problems associated with some wastes include contamination, spontaneous combustion and the emission of gas. The extent to which non-engineered fill will be suitable as a foundation material depends largely on its age, composition, uniformity, properties and the method by which the material was placed (Bell *et al.* 2012).

FIGURE CAPTIONS

Fig. 1a and b	Surface distribution of loess/brickearth in the southern UK based on Soil Survey 1:250 000 scale soil maps (1983). Loess >1 m thick in black; loess >300 mm thick (and often partly mixed with subjacent deposits) shown stippled (after Catt 1985); a) Wales and western England; b) Eastern England.
Fig. 2a and b	Distribution of brickearth deposits in south eastern and southern England based on British Geological Survey 1:50 000 scale geological maps; a) South east England; b) Southern England. Contains Ordnance Data © Crown Copyright and database rights [2019]. Ordnance Survey Licence no. 100021290.
Fig. 3a	Photomicrograph showing silt-size particles with two of them bridged by platy clay particles; sample from Pegwell Bay, Kent.
Fig. 3b	Photomicrograph showing large open voids and silt-size particles bridged by platy clay particles; sample from Ospringe, Kent.
Fig. 4	(a) Particle size distribution plots of brickearth/loess from Allington, and Pegwell Bay, Kent. (From Bell *et al.* 2003). (b) Particle size distribution plot for gull-fill material from Allington, Kent. This indicates that it falls mainly within the silty loess zone of Holtz & Gibbs (1952) (From Bell *et al*. 2003).
Fig. 5	Derelict house in Torbay, situated on loess, which has suffered foundation failure probably due to the leaking of a drain or downspout.

Fig. 1a

Fig. 1b

Fig. 2a

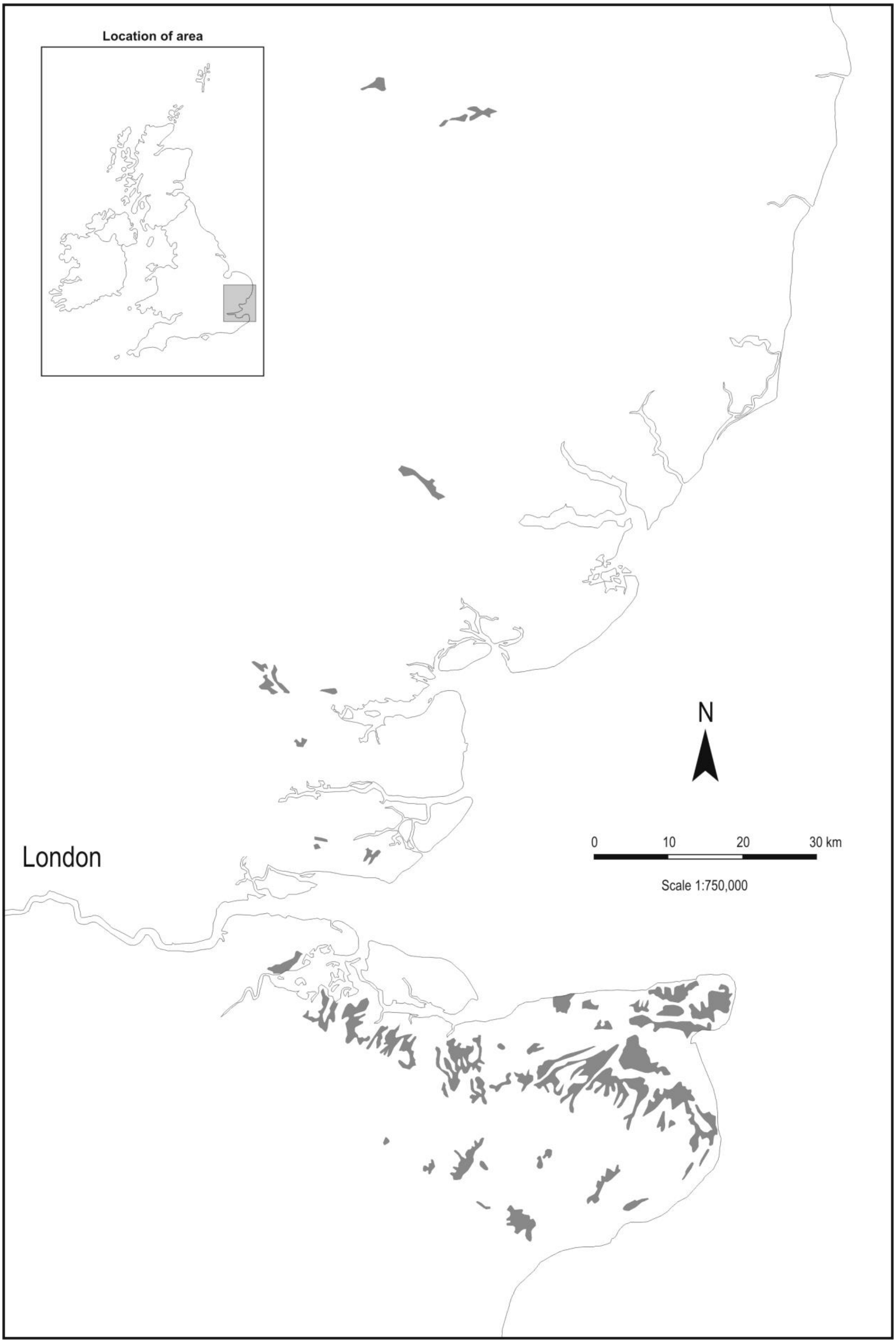
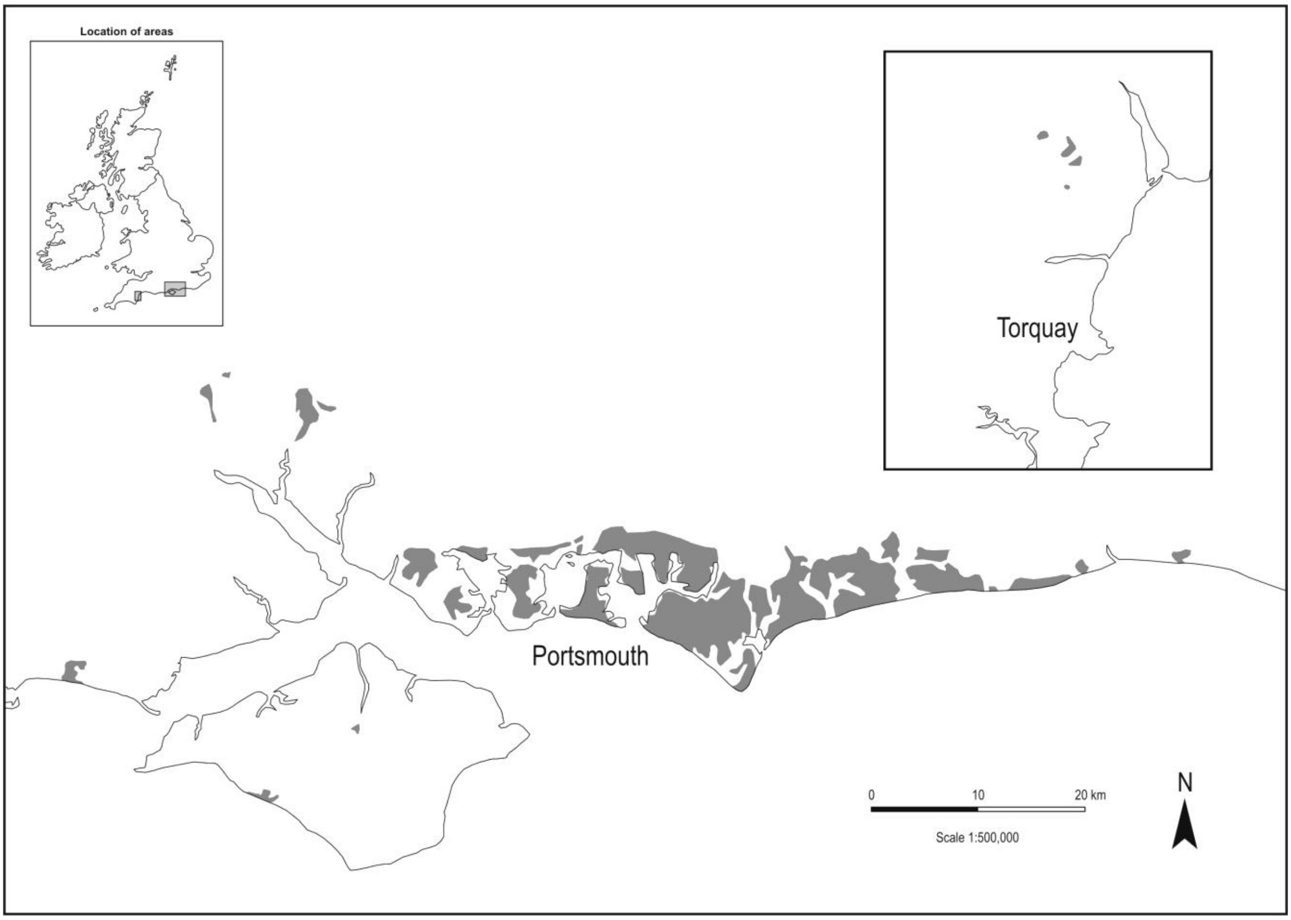


Fig. 2b


Location of areas
Torquay
Portsmouth
0
10
20 km
Scale 1:500,000
N

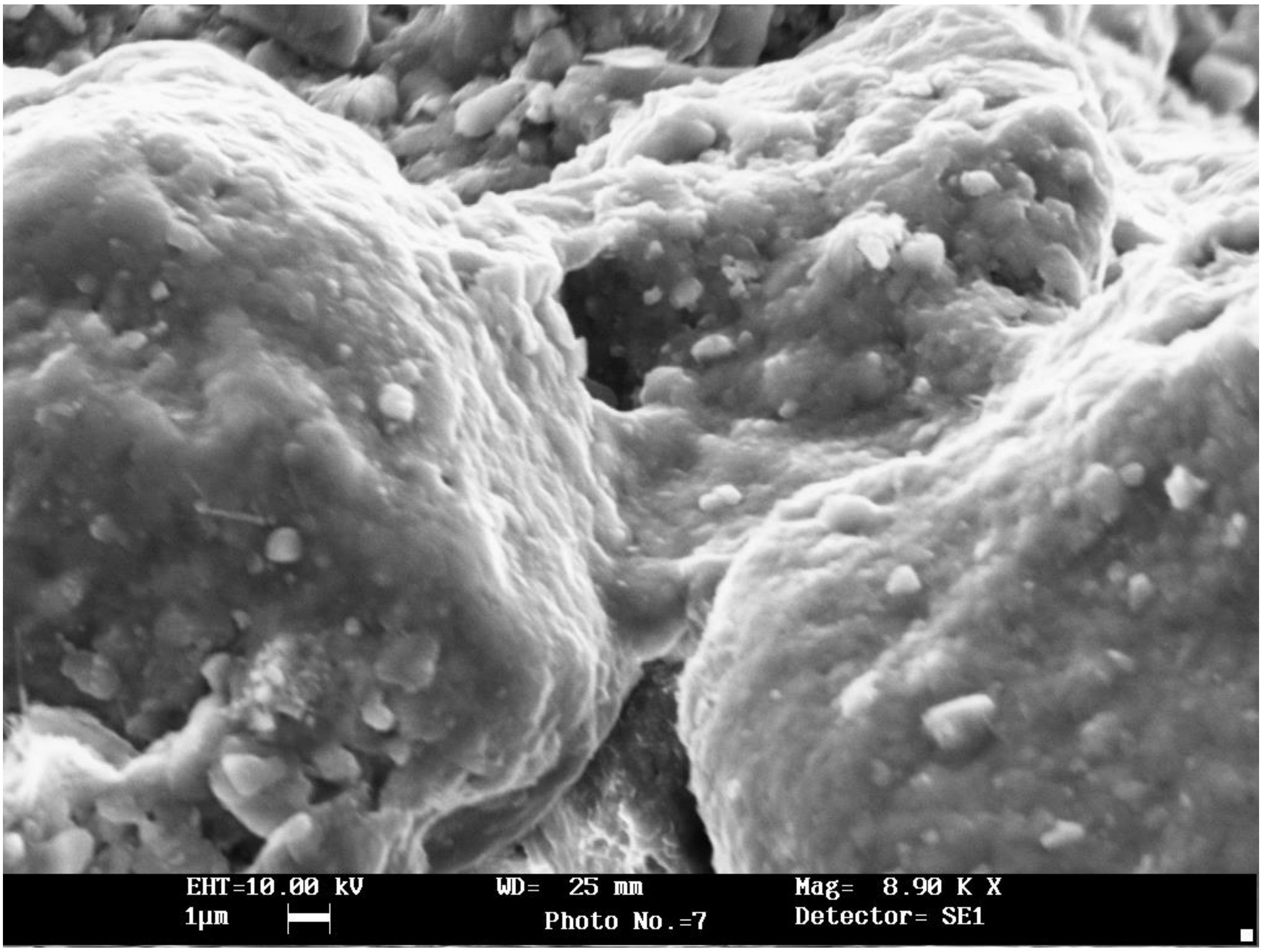


Fig. 3a

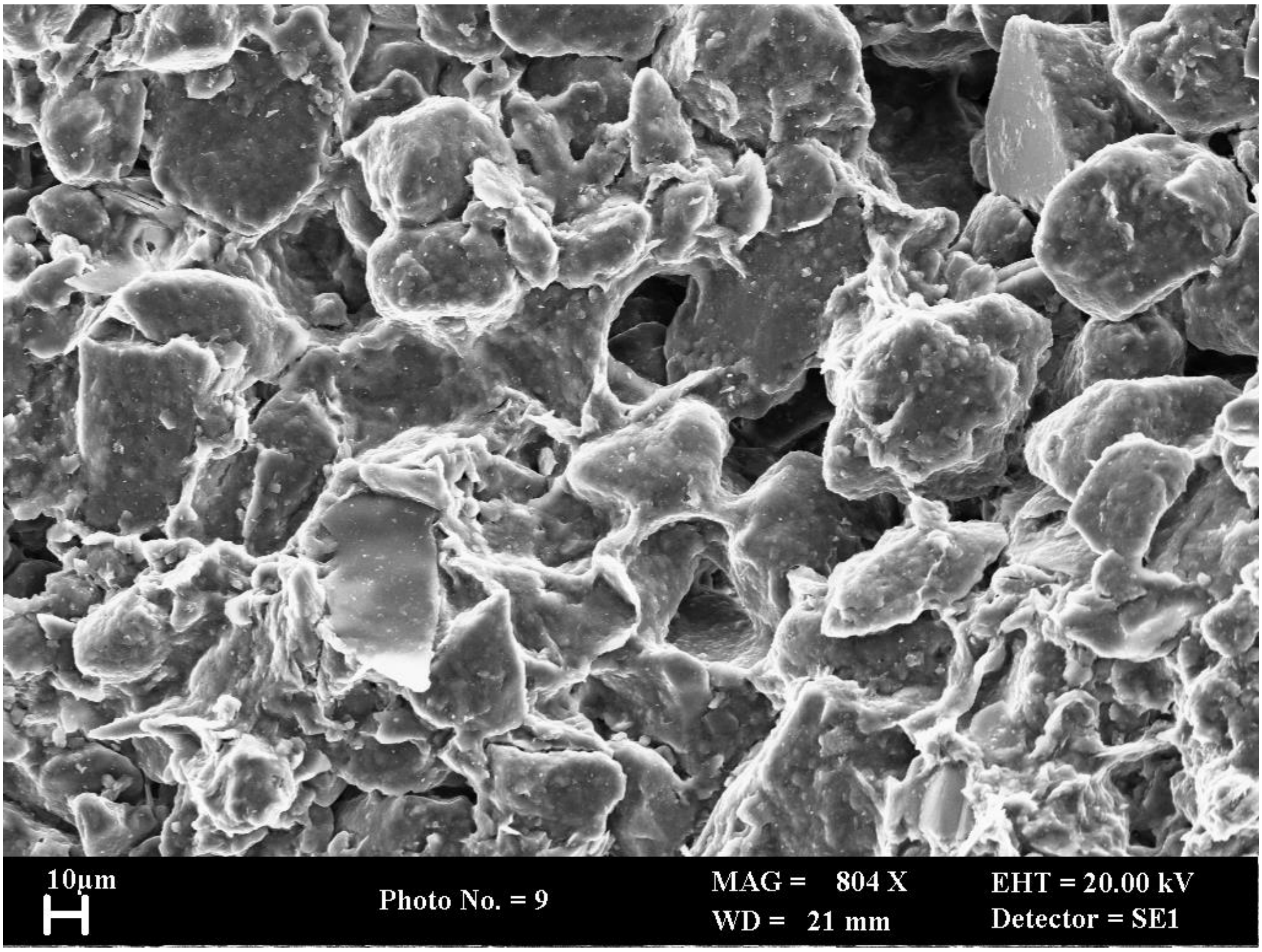


Fig. 3b

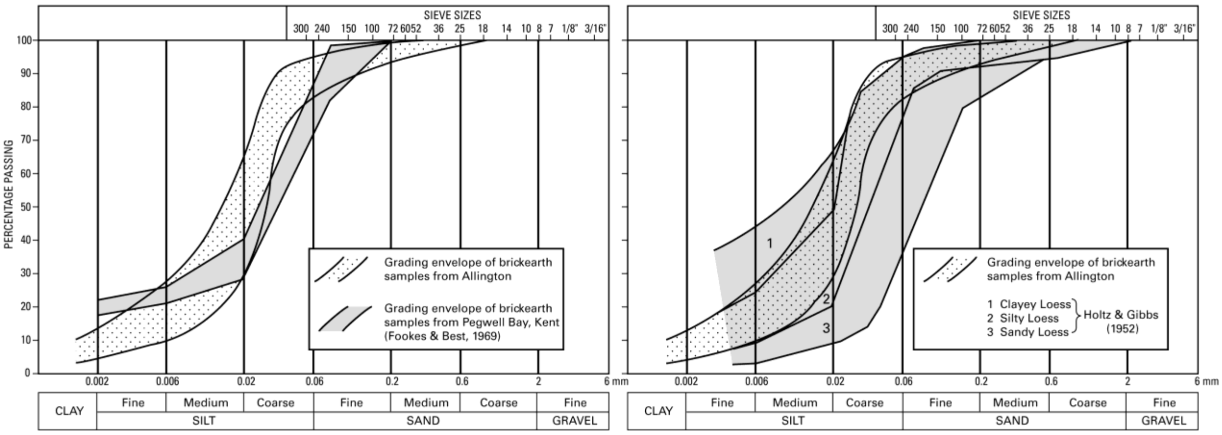

SIEVE SIZES
300 240 150 100 72 60 52 36 25 18 14 10 8 7 1/8" 3/16"
PERCENTAGE PASSING
0
10
20
30
40
50
60
70
80
90
100
0.002
0.006
0.02
0.06
0.2
0.6
2
6 mm
CLAY
Fine
Medium
Coarse
SILT
Fine
Medium
Coarse
SAND
Fine
GRAVEL
Grading envelope of brickearth samples from Allington
Grading envelope of brickearth samples from Pegwell Bay, Kent (Fookes & Best, 1969)
1
2
3
1 Clayey Loess
2 Silty Loess
3 Sandy Loess
Holtz & Gibbs (1952)

Fig. 4

Fig. 5

Table 1. Terminology used on British Geological Survey 1:50 000 scale geological maps that may be indicative of the presence of loess.

Stratigraphic name	Description
Brickearth	Varies from silt to clay, usually yellow-brown and massive
River Brickearth	Varies from silt to clay, usually yellow-brown and massive; of fluvial origin
Head Brickearth	Varies from silt to clay, usually yellow-brown and massive. Poorly sorted and poorly stratified, formed mostly by solifluction and/or hillwash and soil creep.
Head Brickearth, Older	Varies from silt to clay, usually yellow-brown and massive. Poorly sorted and poorly stratified, formed mostly by solifluction and/or hillwash and soil creep. Older than 'Head Brickearth' in the same map area.
Head Brickearth, Younger	Varies from silt to clay, usually yellow-brown and massive. Poorly sorted and poorly stratified, formed mostly by solifluction and/or hillwash and soil creep. Younger than 'Head Brickearth' in the same map area.
Aeolian deposits (‘Brickearth’)	Mainly fine sandy silt or silt, locally contaminated with gravel.
Langley Silt – 'Brickearth'	Sandy clay and silt.
Enfield Silt – 'Brickearth'	Sandy clay and silt.
Roding Silt – 'Brickearth'	Sandy clay and silt.
Ilford Silt – 'Brickearth'	Sandy clay and silt.
Crayford Silt – 'Brickearth'	Sandy clay and silt.
Dartford Silt – 'Brickearth'	Sandy clay and silt.
Silt	-
Glacial Silt	-
Glacial Silt and Clay	-

Table 3. Progress of a loess particle that falls in the headwater of the River Thames catchment (after Jefferson *et al.* 2003).

P1	Particles are formed by cold phase glacial action
T1	Loess material is blown generally southwards
D1	Deposits over midland and southern Britain
D1t	Deposits in River Thames catchment, headwaters region
T2t	Carried into River Thames by slope wash and streams. Short transport may deliver it to the Langley Silt
T3t	Carried by the River Thames into the estuary region
D2t	Deposited on northern bank as a floodplain deposit
T4t	Blown inland to form loess
D3t	Loess deposit formed, perhaps in South Essex

Table 4. Collapse percentage as an indication of potential severity (after Jennings & Knight (1975).

Collapse	**Severity of problem**
0 - 1	No problem
1 - 5	Moderate trouble
5 - 10	Trouble
10 - 20	Severe trouble
> 20	Very severe trouble

Table 5. Methods of treating collapsible loess ground (after Jefferson *et al.* 2005).

Depth (m)	Treatment method	Comments
0-1.5	Surface compaction with vibratory rollers, light tampers	Economical but requires careful site control, for example, limits on water content.
	Pre-wetting (inundation)	Can effectively treat thicker deposits but needs large volumes of water and time.
	Vibroflotation	Needs careful site control.
1.5-10	Vibrocompaction (stone columns, concrete columns, encased stone columns).	Cheaper than conventional piles but requires careful site control and assessment. If uncased, stone columns may fail with loss of lateral support on collapse.
	Dynamic compaction; rapid impact compaction	Simple and easily understood but requires care with water content and vibrations produced.
	Explosions	Safety issues need to be addressed.
	Compaction pile	Need careful site control.
	Grouting	Flexible but may adversely affect the environment.
	Ponding/inundation/pre-wetting	Difficult to control effectiveness of compression produced.
	Soil mixing lime/cement	Convenient and gains strength with time. Various environmental and safety aspects; the chemical controls on reactions need to be assessed.
	Heat treatment	Expensive.
	Chemical methods	Flexible; relatively expensive.
>10	As for 1.5-10 m, some techniques may have a limited effect.	(see above)
	Pile foundations	High bearing capacity but expensive.

Table 2. Some geotechnical properties of loessic brickearth soils. The figure in brackets indicates the number of samples tested.

Property	**South Essex[1]**	**Allington, Kent[2]**	**Allington, Kent (gull-fill)[3]**	**Ospringe, E of Faversham Kent*[4]**	**Pegwell Bay, Kent[5]**	**Pegwell Bay, Kent[6]**	**Ford, NE of Canterbury, Kent[6]**	**Pine Farm Quarry, E of Maidstone, Kent[6]**	**Reculver, E of Herne Bay, Kent[6]**	**Northfleet, Kent[6]**	**Sturry, NE of Canterbury, Kent[6]**
Natural moisture content (%)	13-21	-	16-24	15-20 (9)	2-10 (9)	-	-	-	-	-	-
Particle density (Mg m^{-3})	2.61-2.77	-	2.61-2.62	2.60-2.71 (8)	-	2.69	2.70	2.70	2.68	2.70	2.69
Bulk density (Mg m^{-3})	1.78-2.25	-	1.71-2.04	-	1.55-1.78 (9)	-	-	-	-	-	-
Dry density (Mg m^{-3})	1.43-1.99	-	1.38-1.70	-	1.52-1.65 (9)	1.64-1.73	1.49	1.48	1.62	1.61	1.69
Void ratio	0.57-0.82	-	0.54-0.90	-	0.63-0.77 (9)	0.55-0.64	0.81	0.82	0.65	0.68	0.59
Porosity (%)	36-45	-	35-48	-	-	36-39	45	45	39	41	37
Grain-size distribution (%)											
Sand	4-54	12-31 (3)	5-17	5-20 (9)	12-27 (9)	-	-	-	-	-	-
Silt	26-84	67-86 (3)	78-86	43-70 (9)	51-70 (9)	>65	>65	>65	>65	>65	<65
Clay	4-42	<3 (3)	5-14	19-39 (9)	14-22 (9)	-	-	-	-	-	-
Plastic limit (%)	17-24	23-25 (2)	18-23	20-24 (9)	18-21 (11)	17-21	17-20	21-22	19-21	19-20	21-23
Liquid limit (%)	27-64	28-29 (2)	31-34	33-39 (9)	26-32 (11)	28-33	31-45	30-32	32-33	31-33	41-46
Plasticity index (%)	7-40	4.5 (2)	9-16	9-17 (9)	8-12 (11)	11-14	11-28	9-11	12-13	12-13	20-25
Activity	-	-	-	0.23-0.68 (9)	0.48-0.59 (2)	-	-	-	-	-	-
Coefficient of collapsibility	-0.009-0.038	-	-0.0003-0.029	-	-	-	-	-	-	-	-
Angle of friction	11-36	-	-	-	-	-	-	-	-	-	-
Calcium carbonate content (%)	0-16.5 (12)	7.9-8.3	<0.5	-	0-19 (9)	16.2	12.7	14.0	6.0	9.4	-

1 Northmore *et al.* (1996)
2 Lill (1976)
3 Bell *et al.* (2003)
4 Northmore *et al.* (2008)
* Non-calcareous brickearth only
5 Fookes & Best (1969)
6 Derbyshire & Mellors (1988)