A Conceptual Model for Loess in England: Principles and Applications

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Abstract

PTD, an acronym for Provenance - Transport - Deposition, is a multilayer geomorphotechnical system, the combination of geomorphology, Quaternary Sciences, and geotechnical consequences of its implementation in groundworks and other crosscutting disciplines. Embedded in its three layers are geographical, geochemical, geophysical, mineralogy, dating, lithological and geotechnical inputs. In this state-of-the-art review contribution and for Loess in England, Syngenetic and Epigenetic mechanisms are drawn out and used to generate the three constitutive layers for three conceptual PTD models and the interrelationships among them. The developed models are then deployed to inform earthworks design for three HS2 embankments in Chiltern Hills.

Key words

Loess; Syngenetic; Epigenetic; Quaternary; Earthworks

1. Introduction

Patchily scattered loess successions in basins and valleys, on hills and around rivers over Southern England were first reported in Prestwich (1863). Sequences of Loess across Midland, South and South East England with greater than 1m thickness have significant hiatuses and are restricted to Thames Estuary in North Kent (Catt, 1978). Loessic sequences of up to 8m thickness have been reported in South Essex across as area of approximately 10Km in diameter and centred around Stambridge (Northmore et al., 1996), and sequences of up to 4m thickness in subsurface buried erosional channels (Milodowski et al., 2015). Major English loessic accumulations also include ca. 1.6m thick deposits in North Kent near Halling (Cook, 1914), ca. 2.6m thick deposits in Ospringe (Zourmpakis et al., 2006), and ca. 1.3m thick deposits in Pegwell Bay (Milodowski et al., 2015), East Kent (Derbyshire and Mellors, 1988), and Sussex coastal plains (Clarke et al., 2007). Thickness of loess sequences reaches 10m (Shepherd and Randell, 2010) in East Sussex Seaford Head, 3 to 5.5m in Chiltern Hills (Avery et al., 1982), and 3 to 5.5m in Salisbury of Hampshire (West and Mills, 2009). One metre thick loess accumulations have reportedly occurred across South East and South West Hampshire (Reynolds et al., 1996).

Loess is generally not prevalent within the UK, thereby poses limited risk to infrastructures, unless when they apply large or transient loads to the loess sequence beneath. Discovery of loess profiles close to key heavy transport infrastructures in the late 90s necessitated the British loess research to extend beyond its traditionally restricted South East England region. Examples of such discoveries include the works of Elsden (1997) and Rose et al (2000) on identification of several sequences of intact loess profiles – up to 3.8m deep - at the London Heathrow Airport site. In 1839, D'Archaic discussed geographical and morphological similarities between loess drapes of identical source across western Europe, and also between loess in Continental Europe, particularly North France and England (Fall, 2003). This relationship was later expanded in Prestwich (1863) and Parks and Rendell (1992). Delage et al (2005) discussed the geotechnical problems associated with building the TGV High Speed rail on Loess in Northern France following the removal of humus horizons and top soil in 1993. They referred to 43 sinkhole incidents along 50km where rail was immediately built on the loess stratum, 19 of which were linked to natural wetted collapse. In the UK, the first phase of the UK National High-Speed Rail 2 (HS2) between London and Scotland is an initial London to West Midlands line, which could be operational by 2026, and will cut into thin and patchily distributed loess and loess-like drifts (classified by the British Geological Survey as brickearth or head brickearth, head silt, or as silt formations including the Langley silt and Dartmouth silt formation) across Buckinghamshire and Hertfordshire. Given the broadly agreed similarities between the loess sequences at two sides of the English Channel, geotechnical problems similar to that associated with the TGV project could arise in the UK. Three main embankments will underpin the HS2 within Chiltern Plateau between Luton and High Wycombe i.e. West Hyde, Colne Valley North, and Aylesbury, whereby a considerable load will act to the underlying shallow natural loessic stratum. Although collapse (upon wetting) appears to be unlikely for the loess beneath the three embankments, transient traffic loading may cause collapse, particularly where loess contains a degree of calcium carbonate (Assadi-Langroudi and Jefferson, 2013). The risk to this and similar major infrastructure projects across South and South East England necessitates a systematic study of relationships between loess and loess-like accumulations, allowing a better use of comparable experience. Smalley (1966) developed a framework for loess formation comprising three basic actions: P-actions (i.e. provenance), T-actions (i.e. transport) and D-actions (i.e. deposition). Formation of loess, as a Quaternary sedimentary deposit, involves quartz particle generation (P-action, also referred to as Aufbereitung in Penck 1953), followed by several stages of transport (T-action) and deposition (D-action). A robust understanding of loess demands each of the 'actions' to be independently identified and the interrelationships amongst them to be fully explored (Smalley and Krinsley, 1978). Wright et al (1998) argued the distinction between quartz sand/silt production and transport mechanisms and suggested that P- and T-actions interact. Jefferson et al (1997) and Kumar et al (2006) contested that interaction. Assadi-Langroudi et al (2014) retested the idea and suggested such interactions may exist should quartz particles contain crystalline cleavage-like defects. The three actions combined are termed "Loess cycle" in Gardner and Rendell (1994), "pathway approach" in Wright (2001), and "stage approach" or PTD model in Jefferson et al (2003), who extended the approach into a conceptual geomorphological model for the Arun catchment in the Weald and Thames catchment. As it happens, these hitherto geomorphological models are restricted to regions demarcated in South East England and loess in midland England has lacked appreciation.

This paper intends to bring the PTD to earthworks industry attention, with stimulus coming from two directions. First, incorporating the PTD approach in desk study can inform the earthworks design practice in absence of large ground datasets, through systematic use of comparable experience. Patches of Quaternary drifts that share similar formation mechanisms (thereby common composition and packing) are likely to share common engineering properties. Adopting the PTD approach can explain spatial variability of ground data and bring confidence to a project, not just around design but predicted long-term serviceability too. A second stimulus has come from the growing need to predict landform changes stemmed from erosional actions of river streams. Multiple P- T- and D-actions are laid as constitutive layers in PTD models and offer a visual representation of continuous landform and sediment change. This paper builds on the previous contributions and proposes a suite of new and refined models for the Loess in midland, south and south-eastern England. Interrelationships between the Great Ouse and Thames Catchment Systems are discussed and tested, and geotechnical applications are drawn out and discussed in the context of the planned High-Speed Rail 2 earthworks in Buckinghamshire and Hertfordshire.

2. The Great Ouse and Thames Catchments (North Kent and South Essex)

2.1 Syngenetic Events

The loess of Essex, North Kent, and probably London resemble the classic loess of Western Europe more than the debris left by the British Ice. The northward retreating British Ice is unlikely to have had any pronounced effect on silt of loess landforms across South East England (Parks and Rendell 1992): Loess in North West France and South East England are genuinely similar and the thickness of loess in South East England is significantly greater than that in the south, south west and north England. Lill and Smalley (1978) emphasised on the dominant role of strong easterly winds stemmed from the anticyclonic conditions over Scandinavia in spreading the first silt. Easterly winds carried the glacial silt over large distances across Europe. The cyclonic conditions operating on the western British Isles diminished the easterly air flow, leading to deposition of silt in sparse and thin layers over South East England. This agrees with Avery et al (1982), who reported on the distinctly finer silts in deposits of North West London (i.e. north of River Thames – Chiltern Hills), with a pronounced mode size on 16 to 32µm as compared with the typical 32 to 44µm size silt, broadly reported for the Devensian loess of East England. Finer silt to the west is a signature of long-distance movement of silt. Hypothesised here and underpinned with the silt population across the Wealden are a suite of secondary/tertiary short-distance Aeolian systems that are likely to have refined the silt distribution to today’s patterns: silt is likely to have deflated (or soliflucted) from Allington and spread multilaterally to south west, north west, and north east. This ties in with the steady decrease of silt content along these directions. Silt is also likely to have deflated from east coast of Pegwell Bay and Reculver Cliff and have been blown towards south west, and north west. This agrees with the easterly wind flow conditions detailed in Lill and Smalley (1978).

Derbyshire and Mellors (1988) and Northmore et al (1996) reported relatively higher sand content and larger sand mean diameter for loessic accumulations north of the Wealden area (in comparison with loess in Southern Wealden). Given the sand content distribution pattern across the Wealden, the origin of sand in Wealden loess is likely to be the retreating British Ice which was distributed, following a long-distance travel, by strong prevailing north-west to south-east winds. This contrasts the contribution of easterly and north-easterly winds, addressed as T1 stage (i.e. 'T' for Transport) in Jefferson et al (2003), highlighting a fundamental difference between the origin and transport system for Wealden silt and sand. A secondary short-distance Aeolian system is likely to have refined the sand distribution to today's patterns across the Wealden, commencing from a catchment area near Oxted towards adjacent regions (to an approximate radius of 60km i.e. an area between Arundel to the west, Molash to the east, and Stambridge to the north east).

In brief, the silt across South East England is relatively finer than silt in East England and reduces in size towards western Wealden, suggesting a Scandinavian ice retreat origin that was primarily carried by easterly winds and subsequently by two local wind systems. Sand content and mean size decreases from north to south across Wealden, suggesting a British Ice retreat origin and a primarily NW-SE wind transport system, spreading the sand in and around Oxted, before a final deflation and Aeolian transportation to an approximate diameter of 60km by local wind systems.

2.2 Epigenetic Events

Loess across North Kent is loosely defined as homogenous porous silty sediments comprising marks of illuviums (migrated fines) in form of inter-particle bridge units, that suggests a cryoturbation history, in coarse quartz grains are capped with a thin layer of silt/clay in a stable packing (Milodowski et al 2015). Signatures of soft pellets, little clay bridge/buttress connector units and disturbed cryogenic fabrics together with generally low plasticity indices can represent a history of solifluction, which eventually shaped the present-day upper non-calcareous brickearth (i.e. loess). Abundant in the upper brickearth sequence are primary detrital carbonates, which downplay likelihood of carbonate dissolution/leaching in the upper non-calcareous layer. For the lower calcareous loess, Milodowski et al (2015) observed loose open-packed ped structures, possibly formed after a spell of cryoturbation, and probably a product of cyclic Periglacial freeze-thaw. Contrasting the mineralogical composition of the lower loess sequence and the Tertiary substrata, they suggested that a significant proportion of the quartz silts (particularly in Pegwell Bay) could have been generated through frost shattering within the underlying chalk and Thanet Sand Formation (also see Derbyshire and Mellors (1988)).

Bell et al (2003) looked into the regional post-depositional processes for the Maidstone loess in North Kent. The valley-ward movement of the underlying Atherfield Clay Formation and the dissolution of the overlying Hythe Beds Formation have formed gullies along fissures. Gullies were filled with river gravel, loess, and solifluction remnants, which then gently subsided into depths following the end of the Periglacial conditions (i.e. melting of the Devensian ice). Similar events have influenced the landform, to the west. Looking into further north and north-west, Avery et al (1982) tentatively correlated the Chiltern Hills deposits to the loess of South and East England. They listed a set of post-depositional events which have affected these deposits, including cryoturbation, solifluction and temperate weathering: According to their account, local footprints of cryoturbation are evident in form of irregular composites of loess, stones and fines in underlying sequences that are described as drifts and clay-with-flint. The high clay content in loess of Chiltern Hills was attributed to cryoturbation (linked with nearby clay formations including Reading Beds or Plateau Drift). Weathering, slumping, cryoturbation and solifluction of the Plateau Drift decreased the thickness of the Reading Bed Clay strata and exposed the chalk to weathering. On consequent dissolution of chalk, a series of funnels and slumps formed and accommodated deep profiles of loess materials. This is generally consistent with Northmore et al (1996) observations: The loess across north and north east of the South Essex. Loess overlies the Quaternary terrace gravel and Eocene London Clay formations following episodes of solifluction and rapid slope degradation in outcrops of Tertiary deposits.

According to Fall (2003), the clay-sized fragments in Wealden Loess increases from east to west, between Pegwell Bay and Teynham, then locally decreases to a low order at Allington (Maidstone, Kent) before increasing along the west margin of the Wealden. Fall's observations tie in with higher clay contents observed in brickearth sequences at Ospringe (upper sequence) comparing to Pegwell Bay (Table 1). In Table 2, the plasticity index (PI) of South East England loess increase from 13% at Pegwell Bay and Recurver to 22% at Sturry and 35% at South Essex. Near Maidstone, PI decrease to 13% at Northfleet. Milodowski et al (2015) attributed the low clay content of the Pegwell Bay upper non-calcareous brickearth to a history of solifluction reworking and colluvial-alluvial activities. Bell et al (2003) attributed the low clay content in Allington to its unique reworking background. Clay could be of an in-situ weathering or Eocene origin, or a product of decalcified chalk around Molash and south of the River Thames (Gallois, 2009). Flints are probably a product of chalk dissolution. Nonetheless, it is likely that aeolian silts were originally mixed with clay and clay-with-flint fragments, by modification through cryoturbation and solifluction.

Table 1 Quantitative mineralogical analysis of loess at Kent and South Essex see McKervey and Kemp (2001), Bell et al (2003) Miller (2002) and Milodowski et al (2015)

Location	Bulk Minerals: %															Clay minerals: %			
	quartz	Mica	chlorite	K-feldspar	albite	calcite	dolomite	smectite	kaolinite	hematite	rutile	plagiocalse	Glauconite	Muscovite	Flint	Smectite	Illite	Chlorite	Kaolinite
Lower Pegwell Bay	66	3	1	5	5	14	2	1	3	nd	<1	-	-	-	-	50	27	7	16
Upper Pegwell Bay	62	16	<1	3	6	1	nd	1	11	<1	<1	-	-	-	-	40	30	9	21
Ospringe	67	2	nd	7	8	<1	<1	3	14	nd	<1	-	-	-	-	43	22	0	36
Pegwell Bay	77	-	-	19	-	-	-	-	-	-	-	-	1	1	2	-	-	-	-
Ford, Kent	82	-	-	14	-	-	-	-	-	-	-	-	1	2	1	-	-	-	-
Allington, Kent	85	-	-	11	-	-	-	-	-	-	-	-	1	2	1	-	-	-	-
Ashford, Kent	84	-	-	12	-	-	-	-	-	-	-	-	1	2	1	-	-	-	-
Teynham, Kent	79	-	-	18	-	-	-	-	-	-	-	-	1	1	1	-	-	-	-
Star Lane	56	-	-	-	-	-	-	-	-	-	-	8	-	-	-	28		0	4
Upper Ospringe	66	13	-	7	7	-	0.7	1.2	13	-	-	-	-	-	-	53	22	8	19
Lower Ospringe	59	14	-	5.5	5	8.4	3.1	1.3	4.4	-	-	-	-	-	-	58	21	6	16
Upper Pegwell Bay	62	13	0.5	4.4	5.7	0.5	-	1.5	7	0.5	-	-	-	-	-	62	17	7	14
Lower Pegwell Bay	63	11	-	5	3.5	-	1.7	1	2	-	-	-	-	-	-	55	25	6	14

Table 2. Consistency limits of loess at South Essex and Kent – see Derbyshire and Mellors (1998), Boardman et al (2001), Milodowski et al (2015), Assallay (1998), Northmore et al (1996, 1999)

Location	LL (%)	PL (%)	PI (%)
Pine Farm Quarry, Kent	32.0	22.0	10.0
Ford, Kent	34.0	19.0	15.0
Pegwell Bay, Kent	29.0	18.0	11.0
Pegwell Bay buried channel, Kent	33.0	20.0	13.0
Reculver, Kent	33.0	20.0	13.0
Sturry, Kent	44.0	22.0	22.0
Northfleet, Kent	32.0	19.0	13.0
Kent (average)	34.0	20.0	14.0
Pegwell Bay, upper non-calcareous	25.6	18.6	7.0
Pegwell Bay, lower calcareous	26.6	18.5	7.1
Ospringe, upper non-calcareous	36.0	23.0	13.0
Ospringe, lower calcareous	28.0	NP	NP
Britain (average)	28-46	17-23	9-28
South Essex (average)	35.2	19.8	15.0
Upper Claygate Beds, South Essex	60.0	25.0	35.0
Middle Claygate Beds, South Essex	60.0	27.0	40.0
Lower Claygate Beds, South Essex	70.0	25.0	45.0

3. The Southampton Catchment (Hampshire Basin)

3.1 Syngenetic Events

According to Lill and Smalley (1978), the silt component of loess of East Yorkshire, East Lincolnshire, North Norfolk and Devon is from outwash deposits remained after retreatment of the Weichselian glaciers. This could be deemed the main source of quartz in the Hampshire Basin. The loess in the east end of Hampshire Basin contains relatively lower sand contents, which is consistent with the trend of sand content distribution across the South Wealden (Fall, 2003). For the late Devensian loess of West Hampshire, Reynolds et al (1996) suggested a westward decrease in modal size of aeolian silt (blown by easterly winds from the North Sea Basin). The long-distance aeolian transport of sand may account for the sand drape at Lepe Point, Ocknell Plain, and Wootton Heath (Reynolds et al., 1996), but has marginal control on the most of the surface sandy drape at the Hampshire Basin. This is reflected in relatively greater sand content to the west (Fall, 2003). Thereby, sand is deemed a product of fluvial secondary and tertiary river actions (in local rivers and river mouths - also see Smalley et al (2009)), and the subsequent localised short-distance aeolian transport. This hypothesis ties in with the observations of Reynolds et al (1996) for loess deposits at New Forest in South Hampshire, so too the more recent observations detailed in West and Mills (2009) and West et al (2010) for loess at High Cliffe, Barton-on-Sea, Chilling Cliff, Brownwich Cliff, and Hill Head.

3.2 Epigenetic Events

Unlike the Wealden area, the clay content in loess sequences across the Hampshire basin generally decrease from east to west (Reynolds et al., 1996, Fall, 2003). A <35cm thick, often discontinuous, late Devensian loess caps a continuous nearly impermeable pre-Devensian loess in South West Hampshire, a region between Southampton Water and Avon Valley (i.e. the New Forest). The upper brickearth contains footprints of historical surface runoff and erosion, while its sand fragment is mineralogically identical to that in the Tertiary bed (Reynolds et al., 1996). Flint fragments could be a product of frost heave or cryoturbation. For Holbury (i.e. east margin of the region) Reynolds et al (1996) suggested that a relatively older brickearth deposit was gelifluction over the lower younger deposit from nearby but slightly higher parts of the terrace, and sandwiched a stone line or a discontinuous fragipan. According to the simplified geological map of Hampshire Basin (described in West and Mills (2009)), Hampshire Basin is surrounded by Reading, London Clay, and Chalk Formations, and is in association with local river system (e.g. River Meon, River Hamble, River Itchen, River Test, River Avon, and River Stour), which suggests the control of solifluction reworking on the formation of clay constituents, where these are found in abundance. Derbyshire and Mellors (1988) also insisted on the interaction between quaternary brickearth and Tertiary beds. This agrees with the findings of Fall (2003), which attributed the generally high plasticity of South England Brickearth to the highly plastic Sussex deposits in Hampshire Basin. West et al (2010) pointed to the mineralogical resemblance between the Hill Head Brickearths at east margins of Southampton Water and the chalk formations. This suggests a history of solifluction in Chalk outcrops of Portsdown Hill. This area (between Hill Head and Southampton water) is covered with a thin 1m thick non-calcareous loess blanket (i.e. in Chilling and Brownwich Cliffs according to West and Mills (2009)), which caps the Pleistocene river Gravel Terrace, a sequence on top of the Middle Eocene bioturbated marine sandy clay formation. Given the resemblance of clay mineral assemblages with that of chalk, clay may have been washed or blown as dust over the cliffs. To the north, the thickness of brickearth increases to 3 to 5.5m in Salisbury. These deposits are calcareous and possess variable masses of flint and chalk, Late Pleistocene fauna, containing signatures of solifluction reworking. To the west, head brickearths of Barton-on-Sea and High Cliffe possess cryoturbation structures.

4. Provenance-Transportation-Deposition model

The conceptual PTD system is built through a speculative study of the pre- and post-depositional soil formation mechanisms as discussed in Section 3. The model employs a range of micro-morphological, geochemical and physical indicators. Geotechnical inputs are then plugged into the developed PTD models to seek the interrelationships between the Great Ouse and Thames Catchments models, which can then tentatively offer a chance to transfer geo-data from a site in Ospringe, Kent, to three major embankments' sites in Chiltern Hills, where the HS2 track is to be laid on an arguably similar type loess (Fig 1). For loess in Wealden, Hertfordshire, and Hampshire basins, three conceptual PTD models are developed and set out in Table 3. Based on the association of local river systems with loess (Smalley et al., 2009), the models here categorize the English loess into three main groups of Thames, Southampton and Great Ouse catchments.

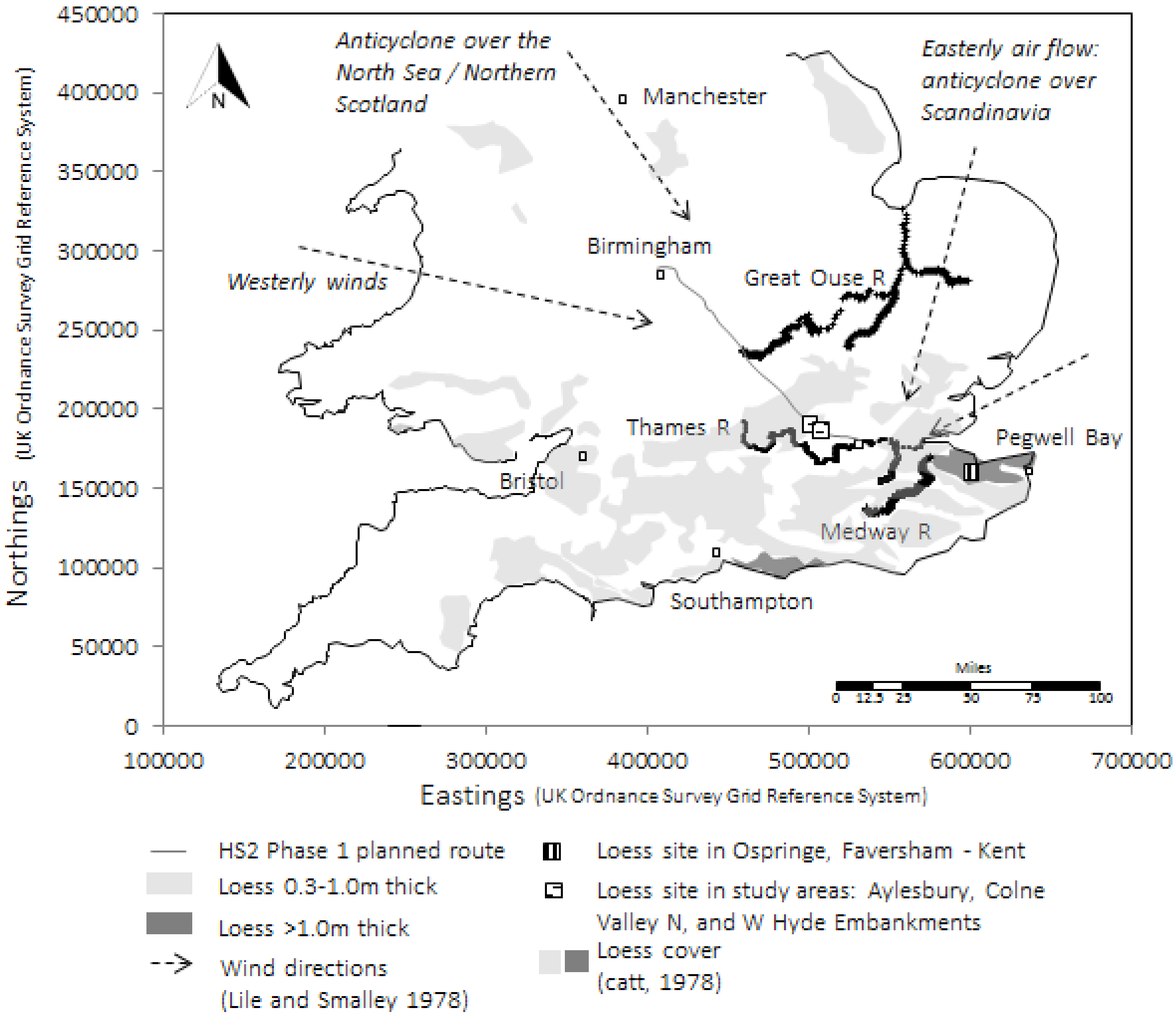


Fig. 1 Extent of the loess in South East England and HS2 Phase 1 planned route

Table 3. PTD scenarios for English loess across the Thames, Great Ouse, and Southampton catchments

Thames Catchment for Wealden Loess in North Kent						Great Ouse Catchment for Loess in Hertfordshire, Buckinghamshire		Southampton Catchment for Loess across Hampshire basin	
Jefferson et al (2013)		Proposed in this work							
P1	Fine sand/silt formation on the cold phase glacial action	P1	Fine sand/silt formation on the cold phase glacial action	P1	Fine sand/silt formation on the cold phase glacial action	P1	Fine sand/silt formation on the cold phase glacial action or frost shattering of Thanet Sand	P1	Fine sand/silt formation on the cold phase glacial action at the Weichselian Glacier, North Sea Basin
T1	Dust blown southwards by Hobbsean anti-cyclonic winds	T1	Dust blown by the south easterly winds	T1	Dust blown by easterly winds	T1	Dust blown by the south easterly winds	T1	Dust blown by southward winds to Southampton wetlands
D1	Deposited over midlands and southern England								
D1t	Deposited in the Thames catchment, headwaters	D1t	Deposited in the Thames catchment and midlands	D1t	Deposited in the Thames Catchment	D1g	Deposited in the Great Ouse catchment	T1s	River streams carried Quaternary flinty gravels from higher to lower Terraces
T2t	Carried into River Thames by slope wash and streams	T2t	Slope washed to Langley by Medway stream	T2t	Slope washed to Westerham by River Darent	T2t	Slope washed/blown inland southwards about 50-60 km	D1s	Deposited in Southampton catchment
T3t	Carried by River Thames into estuary region	D2t	Deposited in Langley	D2t	Deposited in Westerham	D2t	Deposited on chalk in valleys and in funnel/basin depressions clay-lined sinkholes	T2s	All direction silt/fine sand inland aeolian distribution via Southampton Water
D2t	Deposited on northern bank in floodplain form	T3t	Blown to Oxted by easterly winds	T3t	Solifluced to west, north east and east	T3t	Local fluvial tertiary distribution (local river systems including River Colne, River Chess and River Gade), Cryoturbation and temperate weathering	T3s	Local river system carrying clay and flint from northern, north-western, north-eastern outcrops to lower Terraces
T4t	Blown inland	D3t	Deposited in Oxted					D2s	Deposited in New Forest, west/east of Southampton Water, High Cliff coasts, Barton-on-Sea, Chilling, Brownwich and Hill cliffs
D3t	Loess deposit formed across the region	T4t	Soliflucted to west, north east (Stambridge), east (Molash)						

The three HS2 embankment sites will be built on patchily distributed loess-like drifts across the Chiltern plateau between Luton and High Wycombe; the area predominantly falls in the Great Ouse Catchment system: West Hyde (route element ID 030-L1 chainage 30+350 to 31+050), and Colne Valley North (route element ID 029-L1 chainage 29+400 to 29+650) are to be divided from one another by the Tilehouse Lane Cutting and on the Hertfordshire-Buckinghamshire border (Fig 2a). The Aylesbury embankment (route element ID 60+400 to 61+700). Despite geographical differences, common provenance and secondary aeolian transport systems (T2) as well as common chalk formation (on which the airfall material deposited) suggest synergies between the Wealden loess (i.e. Thames Catchment) and the loess-like drifts at the embankment sites (Great Ouse Catchment).

Figure 2b and 2c show the likely loess cover across the Chiltern plateau. Loess deposits appear to be stiff to very weak (Fig 2f), predominantly silty (Fig 2e) and calcareous. Calcium carbonate in loess typically is in form of long-range bonds and can supply reasonable degrees of small strain stiffness.

The soil profile in embankment sites generally consists of 0.5 to 6.5m of clayey silt, silty sand, and sandy to very silty clay over weathered Chalk. Per the British Geological Survey (BGS) borehole online repository, the standard penetration number (N SPT) averages around 10 across the region, indicating the friable nature of deposits. The loam is described on logs as “hoggin”, “friable brown grey silt with some fine to coarse flint sand, occasional cobbles and occasional snail shells”, and “firm to stiff very friable brown grey closely fissured slightly sandy silt with roots and occasional snail shells, highly bioturbated”. In Avery et al (1982), the latter drift deposits are described as “greyish brown passing down into light yellowish-brown silt loam to silty clay loam, containing about 15% sub-angular flint fragments and rare flint pebbles”. The descriptions match those of upper non-calcareous loess in Ospringe (Northmore et al., 2008) that reads: “olive-brown silt with some carbonaceous sub-vertical root channels, containing small fragments of chalk and flint (and primary detrital carbonates Milodowski et al (2015)) and rare small angular pebbles of flint at the base.”

Near Aylesbury, the BGS log record NGR 480490 show a 0.6m thick loamy topsoil (wind-blown reworked silt) overlying a grey brown sand with clay inclusions. At NGR 479260 212230, loess sits on a weathered limestone bedrock, 2.8m below ground level (mbgl). Limestone is highly weathered, mixed with quartz silt and sand (clastic Leighton Buzzard) and has a very fine-grained chalky texture. At NGR 481084 211810, upper and lower loess sequences are described as medium dense yellowish-brown silt and very fine sand (1.6-2.1mbgl) and very soft to very stiff “cemented” silt (>2.1mbgl), respectively. The trial pit records show that the cementation is likely to be of calcium carbonate type. This realisation is verified, for an institute of Geological Sciences note on a NGR 479260 212230 borehole log at 3.8m depth, reading “silt composed of angular quartz grains with some green mineral (glauconite), yellowish brown and greenish grey with calcareous cement; irregular shaped lumps at several unconnected levels”. Few centimetres beneath (4.61mbgl), the same log reads “laminations coarsening upward at several levels, with cream coloured calcite passes up into dark brownish grey silty quartz”. The confusion comes when this clearly loess sequence is described in simplified terms on borehole logs as ‘Portland beds’, ‘Kimmeridge Clay’ or ‘Wealden Sands’. This might be due to the resemblance of Kimmeridge Clay with loess. The former was used for brick works in Hartwell. The two loessic sequences at the location of planned Aylesbury embankment closely resemble, in description, the sequences in the benchmark loess site. The lithological and stratigraphic similarities between the benchmark loess site in Kent and the three embankment sites are summarised in form of a schematic vertical profile in Fig 3. Loess is predominantly a product of glacial abrasion. The reduction of rock to soil under high glacial energies and the subsequent aeolian transportation give Loess an identical well-sorted particle size distribution with a predominant silt fragment, in an open packing. Four main indicators of loess are, therefore, the marked mode size, void ratio, silt, and clay fraction contents. Table 4 summarizes the range of these four indicators for the Upper Sequence Loess in the two catchments.

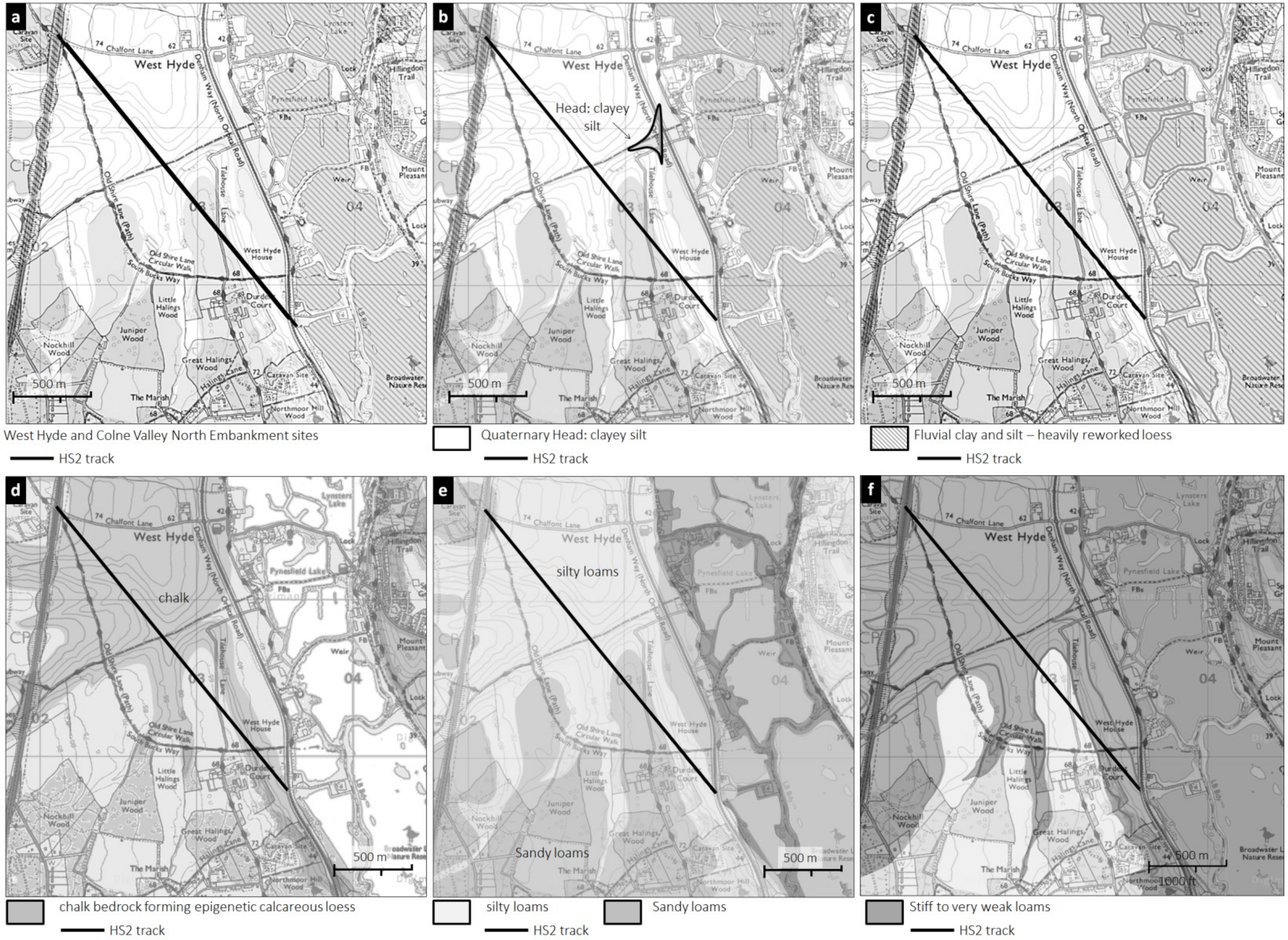


Fig. 2 Ground properties in Chiltern plateau (EDiNA Digimap, 2015)

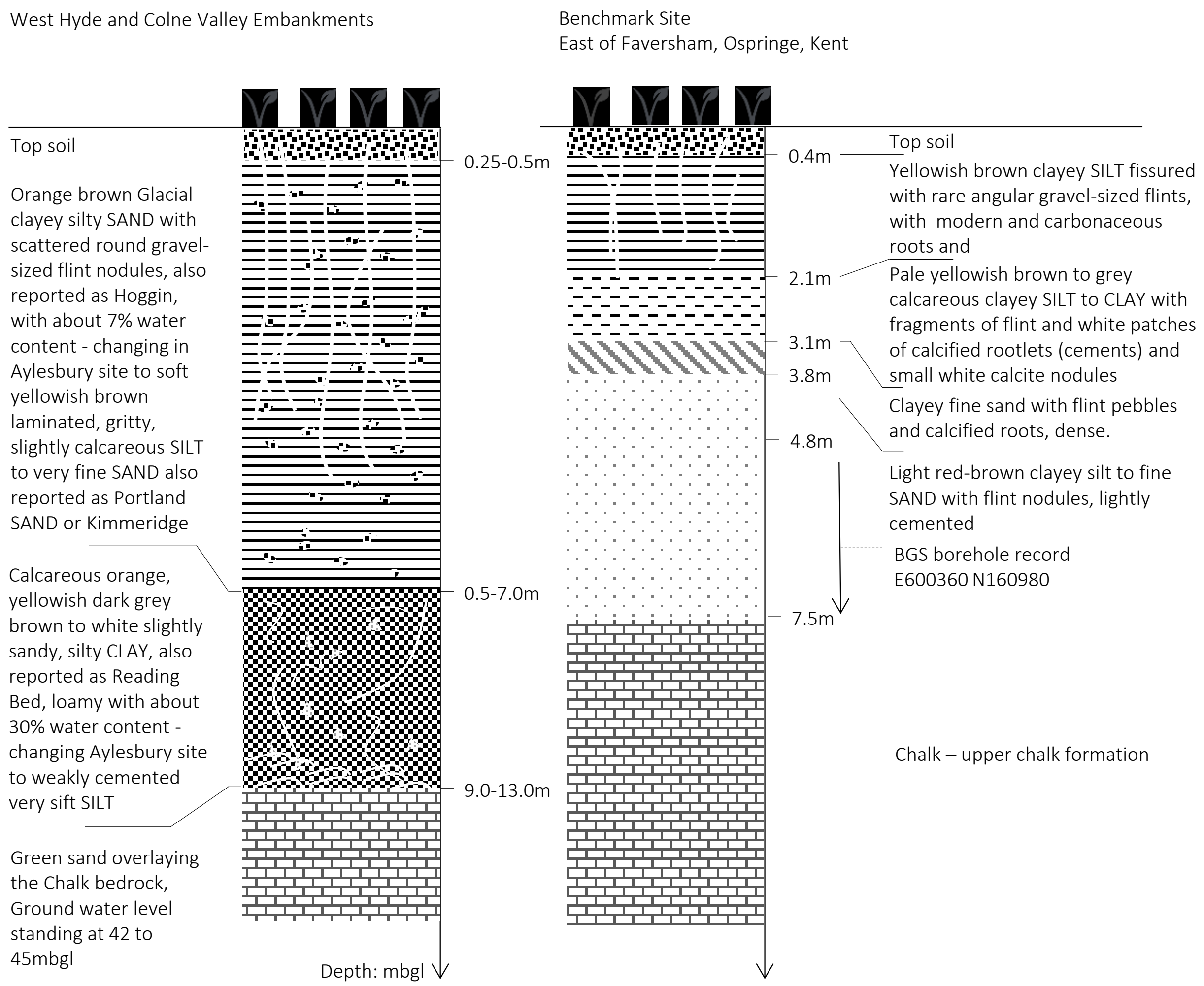


Fig 3. Summary lithological vertical profiles for loess based on BGS scanned borehole logs at (a) West Hyde, Colne Valley and Aylesbury embankment sites (Great Ouse Catchment) at UK Ordnance Survey Grid Reference E502105 N191540; E502118 N191494; E502500 N191350; E502550 N191350; E503260 N190860; E503330 N189610, (b) Benchmark sites, Ospringe Kent (Thames Catchment) at UK Ordnance Survey Grid Reference E599700 N161200

Table 4. Similarities between loess deposits from two catchment areas

Thames Catchment: Faversham Ospringe, Kent at NGR TQ 599700 161164														
		Physical properties					Grain size distribution				Whole-soil XRD[1]			
Soil	D: m	w: %	PI: %	G_s	e	γ_b: kNm^{-3}	>2mm: %	63µm-2mm:%	63µm-2µm:%	<2µm: %	C : %	K : %	S : %	Mode: µm
U.B	0.6	20.5	16	2.74	0.72	19.1	0.0	5.5	69.9	24.6	nd	6.3	0.7	32-40
	0.82	18.2	14	2.61	0.61	19.1	0.1	11.4	58.7	29.8	nd	5.1	0.7	
	1.08	18.7	11	2.65	0.68	18.7	0.0	11.2	61.5	27.3	nd	4.5	1.1	
	1.28	17.9	13	2.71	0.71	18.7	0.0	20.2	60.6	19.2	nd	3.2	1.7	
	1.48	20.1	17	2.60	0.72	17.2	0.1	16.5	48.9	34.5	nd	4.9	1.5	
	1.83	19.1	13	2.70	0.73	18.6	0.0	15.8	54.0	30.2	nd	4.9	1.6	
	2.00	14.9	9	2.71	0.75	17.7	0.0	18.1	43.0	38.9	nd	5.1	1.3	
L.B	2.20	14.4	6	2.71	0.74	17.8	0.0	16.5	68.6	14.9	12.8	4.7	1.0	
	2.40	10.9	0	2.71	0.64	18.3	0.1	26.9	55.5	17.5	8.7	4.5	1.5	
	2.90	11.9	0	2.65	0.72	17.3	11.3	34.9	35.4	18.4	4.0	5.2	1.2	
T.S	3.39	17.5	12	2.69	0.64	19.3	0.0	21.6	56.8	21.6	0.5	5.1	2.6	
	3.70	19.9	11	2.68	0.64	19.6	0.7	12.0	68.9	18.4	0.5	5.1	2.6	
South Essex[2]		18.0	15	2.70	0.69	19.0	0.0	20	59	21	10.4	-	-	-
Allington[3]		20.8	12	2.61	0.74	18.2	0.0	9.7	80.5	9.7	0.18	-	-	-

Great Ouse Catchment: Hertfordshire														
H.D	0.5-4.0	10-23	17-23	2.63-2.7	0.6-0.7	-	-	12-25	>50	<40	-	-	-	16-32

Thames Catchment: Faversham Ospringe, Kent at NGR TQ 599700 161164											
Soil	D:m	Silt mineralogy	Clay mineralogy		N_{SPT}	Strength[2] - original			Strength[2] - flooded		
		Quartz/Feldspar	Kaolinite:%	Illite:%		$\text{Ø}'_p$: °	$\text{Ø}'_r$: °	C': kPa	$\text{Ø}'_p$: °	$\text{Ø}'_r$: °	C': kPa
U.B[4]	0.82	9.4	19	22	16-20	22	26	35	-	25	-
L.B[5]	2.20	10.7	16	21	20-30	28	33	10	31	35	0
Great Ouse Catchment: Hertfordshire											
H.D	0.5-4.0	5-11	15-25	5-30	-	-	-	-	-	-	-

T.S: Thanet Sand; L.B: Lower calcareous brickearth; U.B: upper non-calcareous brickearth; H.D: head deposit; D: Depth; w: Water content; PI: Plasticity index; G_s: Specific gravity; e: void ratio; γ: bulk unit weight; C: Calcium Carbonate; K: Kaolinite; S: Smectite; N_{SPT} Standard Penetration blow number

[1] Millodowski et al (2015) [2] Northmore et al (1996) [3] Bell et al (2003) [4] Triaxial CD for South Essex calcareous brickearth, analogous to Ospringe (D=2.1-2.45m, G_s=2.6, γ_b=1.9, e=0.6, w=18, C<3) [5] Triaxial CD for South Essex calcareous brickearth, analogous to Ospringe (D=2-2.4m, G_s=2.71, γ_b=1.76, e=0.756, w=14, C=16.1)

The sub-angular to angular grains of loess from both catchments comprise quartz (9-11%), Kaolinite (19-25% of clay fragment) and illite (22 to 30% of clay fragment). Void ratio varies with depth, typically ranging between 0.61 and 0.75 in the Thames Catchment, which closely matches the 0.6 to 0.7 range of the Great Ouse Catchment. Predominant mode size takes an average of 32µm, tends to 40µm in the benchmark sequence and falls to 16µm in deeper sequences beneath the planned embankments. Per the grading data, silt fraction is 50 to 70% in the upper-sequence of the Thames Catchment loess, which well matches the >50% range reported for the Great Ouse Loess.

The Loess-like deposits in embankment sites appear to be identical to that in Ospringe Kent. The resemblance fundamentally lies in similarities in depositional and post-depositional history of the deposits in the two catchments. The most recent and robust ground investigation carried out on the Ospringe Loess is detailed in Jackson et al (2006), Zourmpakis et al (2006), Clarke et al (2007), Gunn et al (2006). Figure 4 illustrates the location and ground conditions of the benchmark site in Ospringe Kent, which cuts through the loamy deposits of the Thames Catchment (Fig 4b and 4e). Like the loess of the Great Ouse catchment, deposits are of stiff to very weak strength (Fig 4f) and with calcareous composition in the lower sequence (Fig 4d).

Fig. 4 Ground properties in the benchmark site – Faversham Ospringe (EDiNA Digimap, 2015)

Loess profile in Ospringe consists of an upper non-calcareous layer overlaying the calcareous loess. In Figure 5, the physical properties and shear wave velocity profile for Ospringe Loess are plotted against depth. Equations presented in Rampello et al (1997) are here used to convert the shear wave velocity data into small strain stiffness (G_{max} - labelled as 'measured' on Fig 4f). More detailed account of these equations is given in Likitlersuang et al (2013). As with the predicted G_{max} values, preliminary estimates of shear modulus at small strain are made as a function of the mean effective stress, drained shear strength and void ratio, within a framework proposed in Bui (2009) for sand and clay. The framework correlates the normalised small strain stiffness (by the effective stress) and void ratio. The method formulates the G_{max} as a function of effective stress to the power of ⅓ for a constant value C_p. These are in line with earlier works of Duffy and Mindlin (1956) and Goddard (1990). For structured Leighton Buzzard sand, Clayton et al (2010) have recommended a 450MPa value for C_p. For Eocene London clay west of London, C_p is about 300MPa. Cresswell, and Powrie (2004) suggested a 1200MPa value for C_p for Lower Cretaceous locked sand. For cemented loam (i.e. calcareous loess), they suggested the slightly higher 1900MPa for C_p. Relatively lower values of small strain stiffness were captured in the calcareous loess. One plausible explanation is the relatively lower population of angular silt-sized particles for larger sub-angular sand-sized fragment in the calcareous loess (Table 4). Given the established links between particle roundness and size (Assadi-Langroudi et al 2014), lower degrees of interlocking are expected in sand particles. One other possible reason is the presence of non-clastic calcium carbonate in clastic sand-sized fraction in the lower sequence in the form of occasional nodules and scaffolding micro-tubes (Milodowski et al 2015). Non-clastic particles contain greater degrees of internal imperfections, that appear in form of pseudo-cleavages.

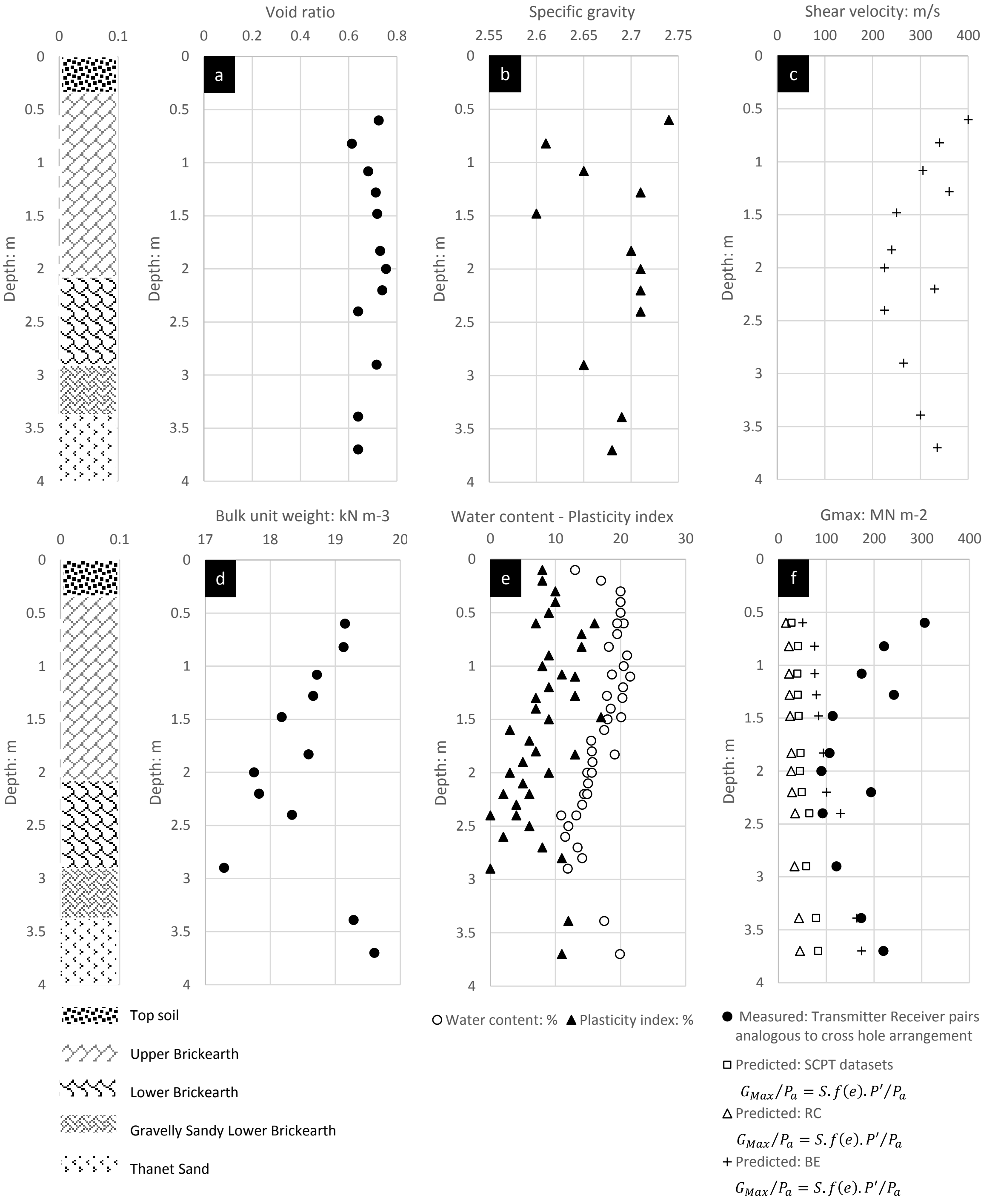
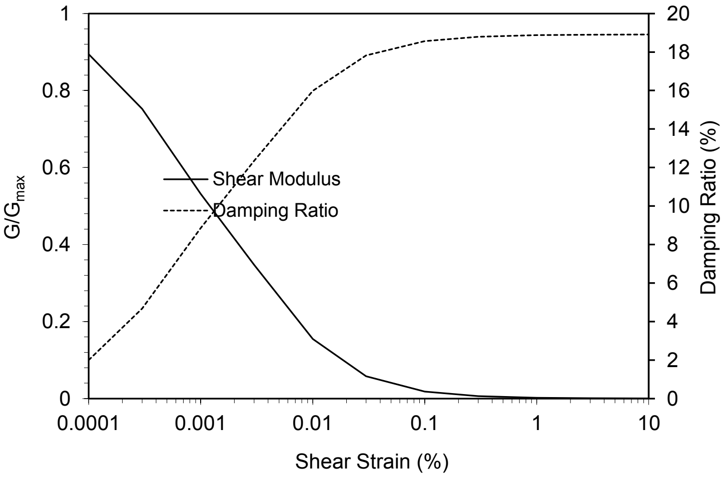


Fig. 5 Physical properties and maximum small strain stiffness profile at natural state: measured V_s were initially reported in Gunn et al (2006)

For the benchmark site, small strain stiffness in cemented loess appears relatively lower than that in non-calcareous loess (Fig 5f). The lower stiffness of calcareous loess, in part, is due to the presence of carbonate sands of limited crystalline integrity and sub-rounded texture (Assadi-Langroudi et al 2014). In Fig 5, the measured G_{max} decreases with depth through the non-calcareous upper sequence. As the borehole reaches the deep-lying lower calcareous sequence (at about 2m depth), small strain stiffness increases with depth through the cemented loess profile. This may imply the suitability of the lower cemented sequence in carrying the overhead traffic load and hence the suitability of cemented loess as a subgrade for future embankments. The upper sequence appears to be an inappropriate load bearing medium due to the relatively likely risk of punching shear failure.

The modified Kelvin-Voigt equivalent linear approach (Bardet et al 2000) was used to approximate the hysteretic stress-strain behaviour of soil in two sequences during high-speed traffic loading. Modulus reduction curve (i.e. variation of G/G_{max} and damping ratio with shear strain amplitude) is plotted for upper non-calcareous sequence (D=1.08mbgl – Fig 6a) and lower calcareous sequence (D=2.20mbgl – Fig 6b). In Fig 6, the equivalent linear damping ratio, is the damping ration that produces the same energy loss in a single cycle as the hysteresis stress-strain loop of the irreversible soil behaviour. Immediate findings are consistent with earlier discussions: At very small strains, the initial shear modulus appears to be closer to the maximum or small strain shear modulus in the calcareous (cemented) loess sequence. Modulus degradation gets momentum at slightly greater shear strain values (as compared to the similar trend for non-calcareous loess); once reaching the critical strain, modulus degradation appears to be sudden, indicating the brittle response of cemented loess to excitations. Yet, the G/G_{max} in the cemented loess sequence appears to be slightly greater than that in non-calcareous loess at similar and high strains. This further supports the suitability of the lower calcareous sequence as the relatively more reliable subgrade beneath future embankments.



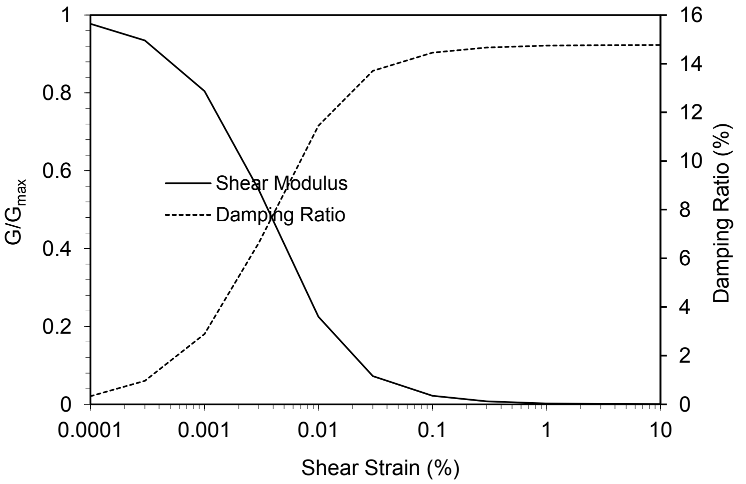


Fig. 6 Modulus reduction curve (a) upper non-calcareous loess sequence, (b) lower calcareous loess sequence

5. Concluding Remarks

Loess is generally not prevalent within the UK, and except when experiencing large and transient loads, pose limited risk to infrastructures. The first phase of the UK National High-Speed Rail 2 (HS2) between London and Scotland will cut into thin and patchily distributed loess and loess-like drifts across Buckinghamshire and Herefordshire (i.e. Chiltern Plateau between Luton and High Wycombe). The conceptual PTD models developed in this contribution establish interrelationships between these drift deposits and the Wealden Loess, which itself is broadly agreed to resemble the loess sequences in Northern France, where TGV embankments were reportedly heavily distressed during the 90s following a series of sinkhole incidents.

Since its introduction in 1966, the PTD system have been concocted to systematically explain the formation of quaternary loess deposits. In the UK, the hitherto PTD models are restricted to regions demarcated in South East England. This paper has brought the PTD to earthworks industry attention, with stimulus coming from two directions. First, incorporating the PTD approach in desk study can inform the earthworks design practice in absence of large ground datasets, through systematic use of comparable experience. Patches of Quaternary drifts that share similar formation mechanisms (thereby common composition and packing) are likely to share common engineering properties. Adopting the PTD approach can also explain spatial variability of ground data and bring confidence to a project, not just around design, but predicted long-term serviceability too. A second stimulus has come from the growing need to predict landform changes stemmed from erosional actions of river streams. Multiple P- T- and D-actions are laid as constitutive layers in PTD models and offer a visual representation of continuous landform and sediment change. This paper has deployed and developed three PTD models for Loess in England and implemented it to assess the possible implications of building three embankments as part of the national High-Speed Rail 2 project.

The small strain stiffness depth profile for upper non-calcareous and lower calcareous loess sequences cast doubt on the unsuitability of loess - as a general conception - as a medium to carry traffic load. Whilst building the transport infrastructure on upper non-calcareous loess is generally not advisable, lower calcareous layer could underpin the rail track provided being well drained.

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