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Periglacial discontinuities observed in Jurassic mudstones between Buckinghamshire and Warwickshire

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Abstract: Evidence for periglacial weathering in the shallow subsurface is widespread throughout the lowland southern British Isles. However, the geological indicators can be quite subtle and not always apparent during ground investigation. Narrow (0.3–0.6 m wide) trial pit excavations are a cost-effective way to investigate periglacial discontinuities, but they can mechanically disturb the ground and obscure the geometry of small-scale features. The aim of this study was to identify and record discontinuities, including relict shear surfaces in periglacially affected ground along the route of the HS2 railway between Wendover in Buckinghamshire and Southam in Warwickshire. Five case studies in full-scale earthwork excavations show that observed sheared surfaces occurred at a range of scales between millimetres to single discontinuities with a persistence of 10 or more metres. All individual discontinuities occurred within fields of disturbed ground extending up to hundreds of metres. The observations show that a classification scheme developed for Eocene clays is broadly applicable to Jurassic-aged mudstone strata examined across an extensive length of excavations (~60 km).

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Multiple phases of Quaternary glaciation are known to have deposited sequences of glacial deposits throughout much of the UK (Gibbard and Clark 2011). South of the Pleistocene glacial limit, glaciogenic deposits are absent but the bedrock has been widely affected by cold-climate, periglacial conditions (Hutchinson 1991; Berry *et al.* 2020; Moore *et al.* 2022). Periglacial conditions have affected unlithified superficial deposits resulting from earlier ice advances or non-glacial deposits, as well as underlying bedrock. This can influence the engineering properties of the ground supporting the construction of buildings and infrastructure (Griffiths and Giles 2017; Martin *et al.* 2017).

In mudstone-dominated terrains, periglacial processes have created weathered *in situ* clay and clay-rich head deposits with the potential to contain extensive periglacial discontinuities, including relict shear surfaces. Periglacial discontinuities can negatively affect the performance of earthworks during their construction and operation (Moore *et al.* 2022). For example, the 'daylighting' of unfavourably oriented shear surfaces during ground excavation or the re-activation of existing shear surfaces during construction can lead to reduced bearing capacity or increased ground deformation (Skempton and Weeks 1976; Berry *et al.* 2020). There are historic precedents for the failure of earthworks due to the inadequate understanding and mitigation of relict periglacial shears (Martin *et al.* 2017). In the UK, these include failures in periglacially-affected clays at Sevenoaks Bypass in Kent (Weeks 1969; Skempton and Weeks 1976), Daventry Bypass in Northamptonshire (Biczysko and Starzewski 1977), Carsington Embankment in Derbyshire (Skempton *et al.* 1991) and Flint Hill Farm in Surrey (Davies *et al.* 2003).

Figure 1 shows the route of the High Speed 2 (HS2) railway between Wendover in Buckinghamshire and Southam in Warwickshire. The HS2 railway includes mainline earthworks (cuttings and embankments), landscaping bunds and non-mainline earthworks for third-party rail and highway crossings. This part of the route is underlain by Jurassic, mudstone-dominated strata and crosses the mapped southern limit of Pleistocene glaciation east of Bicester near Twyford (Booth *et al.* 2015; Murton *et al.* 2015). There are an array of weathering features, mass-movement features, aeolian features and evidence of periglacial fluvial activity (Giles *et al.* 2017).

The aim of this paper was to visually identify, record and classify periglacial discontinuities in clay-rich deposits in wide earthwork excavations along the route of the HS2 railway between Wendover and Southam. The clay-rich deposits included weathered clays located in Jurassic-aged mudstone outcrops of the Ancholme Group and Lias Group, and in overlying clay-rich superficial deposits resulting from mass movement. Classification of the type, depth and lateral extent of periglacial discontinuities was compared to the schema for periglacial discontinuities developed by Spink (1991) for Eocene clays.

Periglacial shears as hazards

Periglacial mass movement processes generate periglacial slope deposits including head deposits. These mainly consist of (1) granular head deposits and (2) clay-rich head deposits (Murton and Ballantyne 2017). Granular head deposits are derived from non-argillaceous rocks and were therefore not examined in this study. Clay-rich head deposits are reworked (i.e. partially remoulded) clayey debris derived locally from argillaceous rocks and other material (e.g. Quaternary and pre-Quaternary deposits) that have been reworked or transported downslope to a location in periglacial conditions. Clay-rich head deposits can contain a range of relict periglacial features formed by shallow translational sliding in a process that is similar to active-layer detachment slides during warm summers in the Arctic (Harris 2013). This can generate persistent, low-angle shear planes within the clay-

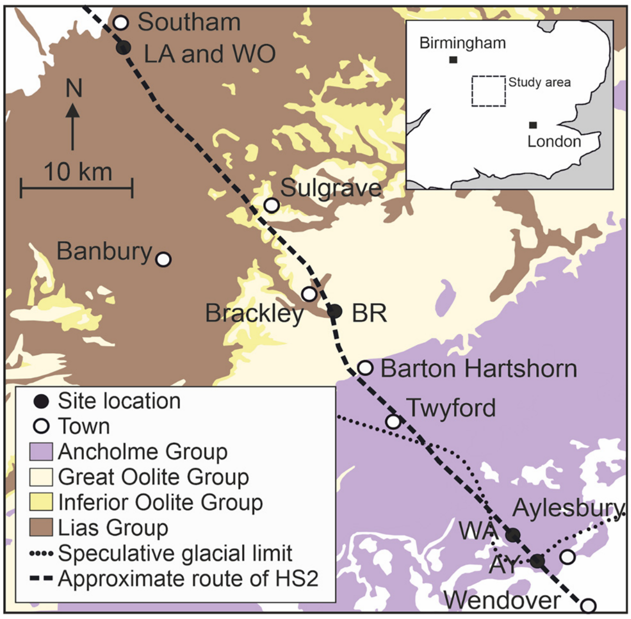

Fig. 1. The location of earthworks near Ladbroke (LA), Wormleighton (WO), Brackley (BR), Waddesdon (WA) and Aylesbury (AY) along the route of the HS2 railway between London and the West Midlands. The speculative glacial limit of Murton *et al.* (2015) and Booth *et al.* (2015) is shown. The outcrop locations of Jurassic-aged geological Groups are based on BGS maps, with the permission of the British Geological Survey.

rich head deposits and the underlying *in situ* soils along the direction of mass movement. In addition, smaller discontinuous shears can form due to internal deformation within the displaced soil mass (Hutchinson 1991; Spink 1991).

When summer ice melt within a soil cannot escape through drainage because of the underlying permafrost layer, there can be widespread loss of support in the soil matrix. This later process is termed gelifluction, which describes the gravity-induced, elasto-plastic shear deformation of fine-grained, frost-susceptible soils caused by high pore water pressures during thawing of ice-rich, frozen ground (Harris 2013; Ballantyne 2025). Measurements from a modern periglacial environment in Yukon Territory, Canada (Kinnard and Lewkowicz 2005) showed that gelifluction occurred as abrupt and discrete displacements near the thaw plane, followed by retrograde movement. The rapid and localized displacements were interpreted as resulting from micro-shearing of the soil. In clay-rich head deposits on sloping ground the micro-shears generated by gelifluction are likely to be obscured and overridden by the larger, more extensive shears generated by shallow translational sliding (Murton pers. comm.).

Brecciation can develop in frost-susceptible rocks, including mudstones, subjected to perennial and/or seasonal freezing and thawing. The growth of segregated ice lenses and frost heave results in the development and propagation of cracks and fissures that weaken the *in situ* rock (Murton and Ballantyne 2017).

Relict periglacial shears are shear surfaces within cohesive bedrock or clay-rich head deposits that are no longer active in present-day environmental conditions (Giles 2025), but may be reactivated during construction (Culshaw *et al.* 2017). Surface evidence of periglacial, shallow translational sliding can be obscured by modern land use such as ploughing. However, the underlying metastable planes of reduced shear strength can remain in the near subsurface and reactivate during construction activity (Culshaw *et al.* 2017; Moore *et al.* 2022). For example, the daylighting of low-strength shear planes in a cutting excavation can destabilize the overlying slope. Equally, the construction of embankments across sloping, periglacially sheared ground can induce displacement across underlying shear surfaces.

Culshaw *et al.* (2017) describe typical mitigation measures for earthworks in periglacially-affected terrain as including (1) reducing the slope gradient; (2) excavating weakened material and replacing it with engineered fill; and (3) employing harder engineering solutions including basal reinforcement, piling or soil nails. In the present study, a staged mitigation approach was adopted during the construction of earthworks between Wendover and Southam. This included (1) inspection of earthwork excavations, (2) field observations during construction and (3) the implementation of a pre-planned mitigation solution to excavate and replace material where necessary. For example, weakened material was removed and replaced with engineered fill before embankments were constructed across sloping ground. For permanent cuttings, the slope crest was over-excavated if required and replaced with a rock buttress. Notably, some over-steepened (~1 in 2), temporary slopes in periglacially sheared ground exhibited signs of instability during the observation stage, within one day of excavation. Any displacement was rapidly activated and could be remediated during construction. Therefore, they did not present a longer-term hazard to construction and operation of the railway.

Glacial and Periglacial terrains between Wendover and Southam

The route of the HS2 railway leaves the Chiltern Hills and the underlying Chalk bedrock NW of Wendover, where it enters the low-relief plain of the Vale of Aylesbury (Fig. 1). The Vale of Aylesbury is underlain by Upper Jurassic and Cretaceous mudstone-dominated strata and is a periglaciated landscape that includes the maximum limit of Quaternary glaciation (Moore *et al.* 2022). The geomorphology is characterized by the effects of repeated phases of periglacial processes, with smooth slopes and thick sequences of gelifluction deposits. The HS2 route through the Vale of Aylesbury rarely exceeds a slope angle of 1–3° and avoids the hillier ground ~1 km west of Waddesdon (WA in Fig. 1), which shows geomorphological evidence of mass movement.

North of Barton Hartshorn in Buckinghamshire, the Upper Jurassic strata are underlain by the mixed oolitic limestones, mudstones, sandstone and ironstones of the Middle Jurassic, Greater Oolite and Inferior Oolite groups. These outcrop along the route of HS2 for a further 17 km as far as Sulgrave, east of Banbury. The Middle Jurassic strata form the series of low hills which defines the Buckinghamshire–Oxfordshire–Northamptonshire borders in this area. In this region, natural slope angles within the route corridor increase marginally to a maximum of 3–5°. Where the bedrock changes from Ancholme Group mudstones to the Greater Oolite and Inferior Oolite groups, the terrain is formed by the differential erosion of hard and soft bedrock types, which act as a preparatory factor for cambering and valley bulging processes (Moore *et al.* 2022).

The terrain north of Twyford was glaciated at least once previously within the last 450 ka (Clark *et al.* 2004; Murton *et al.* 2015; Rose *et al.* 2021) and then experienced periglacial conditions. Deposits of Middle Pleistocene till occur as far south as Twyford, which is just south of the Northamptonshire Hills and the southern margin of the Greater Oolite Group outcrop (Fig. 1). Glaciofluvial deposits underlie slope-capping Middle Pleistocene till.

East of Banbury and heading north towards Southam the route is underlain by weathered surfaces of exposed Lias Group mudstones, overlain by a dissected and weathered till plain (Moore *et al.* 2022). This region experienced periglacial conditions during the Last Glacial Maximum (~26–19 ka) and was previously glaciated at least once in the last 450 ka (Shotton 1953; Clark *et al.* 2004; Rose *et al.* 2021). Natural slope angles within the railway corridor north of the Buckinghamshire–Oxfordshire–Northamptonshire border area reduce to match those of the Vale of Aylesbury.

The identification and classification of periglacial discontinuities

Downslope movement need not occur over a significant distance for the formation of internal and basal shearing (Hutchinson 1991). Therefore, it can be difficult to identify the boundary between transported, reworked material and the underlying, *in situ* residual weathered material derived from the same source mudstone strata. Often the only evidence of reworking is the inclusion of occasional foreign gravel material (Skempton *et al.* 1991), pinhole air bubbles (Murton and Ballantyne 2017) and thin, overturned and entrained organic residue. Therefore, it is important to examine the weathering profile through the affected zone to contextualize observations of periglacial discontinuities.

Spink (1991) provided a schema for the characterization of periglacial discontinuities that was developed from observations in Eocene clays. This was compared to observations obtained from the similar but older, Jurassic-aged, clay-rich deposits between Wendover and Southam. Spink (1991) identified seven different discontinuity types in London Clay Formation (Thames Group) and Reading Formation (Lambeth Group) clays exposed in trial pit excavations on gently sloping ground around Denham, Buckinghamshire. There was no occurrence of all seven types in the same location and the reference schema shown in Figure 2 is a composite. Spink (1991) also noted that some periglacial discontinuities can be confused with fissuring, which was also present in the *in situ* clays.

The Spink (1991) periglacial discontinuity types shown in Figure 2 are:

- Type 1 subhorizontal solifluction shears (up to 40° dip) that occurred within reworked and destructured upper material. Trial pit excavations showed that the shears had a persistence of 0.5–2.0 m and dipped at 0–40°, commonly subparallel to the ground surface.
- Type 2 basal solifluction shears were individually laterally extensive and found at or close to the base of the reworked material only. These shears represent a planar basal surface and the highest level of geohazard in construction.
- Type 3 discontinuous solifluction accommodation shears comprised very closely spaced (<200 mm) and randomly oriented networks of discontinuous (<100 mm) minor shears in the reworked clay. The shears were attributed to internal adjustment movements associated with solifluction.
- Type 4 high angle thaw collapse shears were high-angle shears found in the *in situ* destructured clays below the reworked material. They had lengths of 1–2 m, fading out downwards and truncated at the top by the overlying reworked clay. These shears were attributed to collapse associated with localized pockets of thawing within and beneath low-relief features of the palaeo topography. The thaw collapse shears did not occur on slopes angles greater than about 5°.
- Type 5 subhorizontal principal underthaw shears (described as ∼7° dip) were identified beneath the Type 4 shears close to the boundary between the weathered and unweathered clay. These were continuous, planar shear surfaces. They were bedding parallel and occurred in discrete, more plastic clay beds between more silty layers. Spink (1991) attributed types 5 and 6 shears to upward thaw of permafrost generating pore pressures in excess of hydrostatic, leading to the overlying frozen ground sliding en-masse downslope, possibly combined with lateral stress relief associated with valley formation.
- Type 6 undulose secondary underthaw shears were discontinuous (2–3 m persistence) near the boundary between the weathered and unweathered clay. However, Type 6 shears were low-angle accommodation shears (generally less than 30°) with no preferred orientation. Both types 5 and 6 shears commonly occurred at depths of several metres below the ground surface (i.e. significantly deeper than types 1–4).
- Type 7 subvertical contraction cracks were observed in the weathered *in situ* clay, to depths of up to 5 m below ground level (bgl), but not within the reworked uppermost zone. Spink (1991) attributed them to tensile failure rather than shearing. The cracks were not infilled by silt or foreign material, as observed in brecciated mudstone (Murton *et al.* 2001; Hutchinson 2010) and in thermal contraction cracks in present-day periglacial environments.

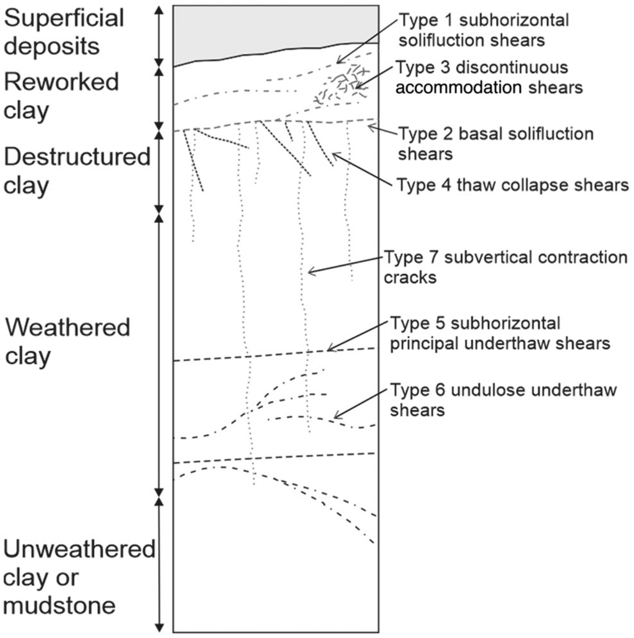

Fig. 2. Types of periglacial discontinuities in weathered Eocene clay, redrawn from Spink (1991).

Spink (1991) described the types 1, 2 and 3 shears in clay-rich material as solifluction shears whilst attributing them to periglacial mass-movement processes, including translational 'slab slides'. Mass movements in clay-rich head deposits on low-gradient slopes due to translational sliding are similar to 'active-layer detachment slides' observed in Arctic regions (Harris 2013; Ballantyne 2025). This differs mechanistically from downslope movement due to solifluction, which occurs in granular head deposits (Ballantyne 2025). Therefore, the characteristics of the types 1, 2 and 3 shears identified by Spink (1991) in clay-rich materials remain unchanged but they can now be attributed to translational sliding including (1) shallow, active-layer detachment above permafrost, (2) shallow or deeper seated thaw collapse (or gelifluction), or (3) mass movement of the permafrost layer itself.

Site selection and method

Geomorphological desk studies showed that periglacial discontinuities, including relict shear surfaces, may be present in the shallow surface on the HS2 alignment between Wendover and Southam. A risk assessment for this section of the route identified the most critical locations for further investigation, visual confirmation of disturbance and the use of mitigation measures where necessary.

Table 1. A summary of the case study sites shown in Figure 1

Location name	Superficial geology	Bedrock Geology	Topography
Ladbroke (LA)	Head deposits and glacial till	Charmouth Mudstone Formation (Lias Group)	Flat to very gently sloping ground at the base of a slope, with slope angles of 10° within 300 m of the observed sheared ground.
Wormleighton (WO)	Head deposits	Charmouth Mudstone Formation (Lias Group)	Flat ground, adjacent to slopes of 3°
Brackley (BR)	Alluvium and head deposits	Whitby Mudstone Formation (Lias Group)	At the base of a slope of 3°
Waddesdon (WA)	Head deposits	Ampthill Clay Formation strata (Ancholme Group)	Flat ground, flanked within 500 m to the west by higher ground with slope angles of 10°
Aylesbury (AY)	None	Kimmeridge Clay Formation (Ancholme Group)	Cresting the brow of a low hill, maximum 3° slope

These included locations in weak mudstone strata where an initial ground investigation had identified high-plasticity clays and/or the presence of a polished shear surface close to the ground surface (<5 m bgl). Additional contributory factors to earthwork construction risk were also considered. These included sloping ground, the inferred presence of adjacent faults, elevated groundwater, the presence of nearby surface water bodies and the likelihood of periodic flooding.

Following the pre-construction ground investigation, additional observations were undertaken during earthworks excavation to record periglacial discontinuities that were present in the shallow subsurface. Five sites were selected as case studies (Table 1) showing the typical periglacial discontinuities that were observed from within the full-scale excavations during construction, rather than from narrow (0.3–0.6 m) trial pits. For each of these sites, the location, parent rock type, shear and discontinuity type and their persistence were described and illustrated with photographs. The observations of periglacial discontinuities were compared to the types described in the Spink (1991) schema.

Results

A series of case studies is presented from five exemplar sites where observations were compared to the seven types of periglacial discontinuity described in the Spink (1991) classification. The location and type of structures within the ground profile at each site are summarized in Figure 3.

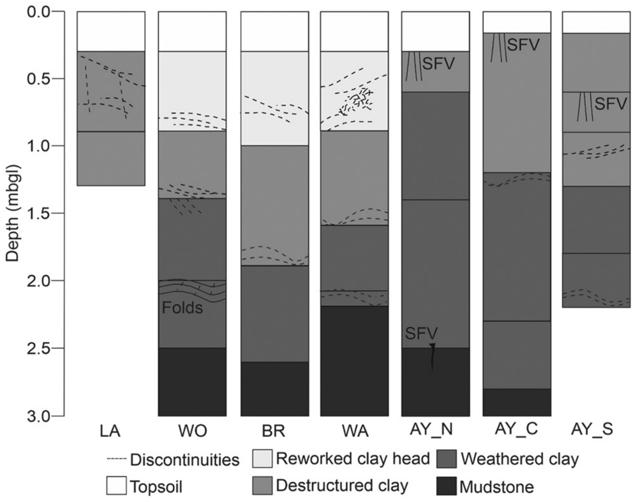

Fig. 3. Schematic ground profiles from excavations at earthwork sites near Ladbroke (LA), Wormleighton (WO), Brackley (BR), Waddesdon (WA), Aylesbury north (AY_N), Aylesbury central (AY_C) and Aylesbury south (AY_S), showing the location of observed discontinuities, folds and sand-filled veins (SFV). The site locations are shown in Figure 1.

An earthwork near Ladbroke, Warwickshire

The first case study site (LO in Fig. 1) was located on flat to very gently northward sloping ground at the base of a steeper hill to the east of the village of Ladbroke in Warwickshire. The primary slope had a maximum gradient of 10–11° and was located within 300 m of the observed periglacial discontinuities. From the ground investigation the ground profile was predicted to consist of generally 1 m and rarely up to 2 m of undifferentiated head deposits and glacial till, underlain by clays and mudstones of the Charmouth Mudstone Formation (Lias Group). Shallow excavations to remove surficial materials for the placement of landscaping bunds revealed swathes of sheared ground which extended across the full width of the earthwork and for at least a further 300 linear metres away from the slope toe. The sheared ground occurred within the upper 0.5–1 m of the excavation in firm to stiff greyish brown, mottled orange, slightly sandy, slightly gravelly clay with fine subrounded to angular fine gravel-sized (2–6.3 mm) lithorelicts of mudstone. The material was destructured clay but it was difficult to confirm if it was reworked clay and therefore represents head deposits. Borehole records showed that below the sheared clay the strata were stiff and very stiff, orange bluish grey mottled and bluish grey, destructured and distinctly weathered slightly sandy clays with fine to coarse gravel-sized (2–63 mm) and cobble-sized lithorelicts, becoming extremely weak thinly laminated dark bluish grey mudstone at a minimum of 2–2.5 m bgl.

Figure 4 shows that the shear planes took the form of undulose, hummocky ‘pillow-like’ polished surfaces within the clays. Individual shear surfaces (Fig. 5) appeared to have a persistence

Fig. 4. Shears in the form of undulose pillow-like polished surfaces at *c.* 0.6 m bgl in the Charmouth Mudstone Formation (Lias Group) near Ladbroke (LA), Warwickshire. The hammer is 280 mm long.

Fig. 5. An individual discontinuity surface at 0.6 m bgl in the Charmouth Mudstone Formation (Lias Group) near Ladbroke (LA), Warwickshire.

of between 0.5 and 2 m, but the outer limit of one ‘pillow’ form was often very closely to closely underlain or overlain by an adjacent ‘pillow’. Individual patches and fields of overlapping shears in this form extended for up to 100 m. Reliable orientation data were difficult to obtain, but undulose shears at *c.* 5–15° dip were intersected by steeper shears of similar persistence with dips of up to 60°. The higher angle shears had a clear southward-dipping orientation, toward the hill.

An earthwork near Wormleighton, Warwickshire

The second case study site (WO in Fig. 1) was located on flat ground near Wormleighton, Warwickshire. A ground investigation showed head deposits 1– 2 m thick, overlying weathered clay from the Charmouth Mudstone Formation (Lias Group, see Briggs *et al.* 2022). This location was surrounded by low hills to the west, south and east which opened up into a plain toward the north. Slope angles here reached *c.* 3° within 100 m of the location and 10° within 900 m to the east.

During excavation of the ground, numerous undulose ‘pillow-shaped’ shear surfaces were encountered within reworked firm brown and grey slightly gravelly clay head deposits at depths of *c.* 0.9 m bgl. Shears were also present through the underlying destructured weathered clay to the probable base of this stratum at 1.4 m. The head deposits and destructured clay were underlain by weathered stiff brown grey and yellow mottled clay with occasional orange sand pockets, lithorelicts and indistinct traces of laminated fabric. Closely spaced higher angle (30°) planar tight discontinuities were observed in the sidewall of the excavation within this stratum, below the destructured clay (Fig. 6). Below the design base of the excavation, at *c.* 2.0–2.5 m bgl, distinctly weathered stiff grey and grey-brown thinly and thickly laminated and fissured clay with gravel-sized (2–63 mm) agglomerations of fine sand sized yellow saccharoidal selenite was encountered. These laminated clays were folded with wavelengths of *c.* 0.5 m and individual lamination surfaces were frequently polished. Figure 7 shows that higher angle accommodation shears and thrusts were present within the folded clays cross-cutting the bedding structure.

An earthwork near Brackley, Northamptonshire

The third case study site (BR in Fig. 1) was located south of the town of Brackley, Northamptonshire. This site is in the northern Northamptonshire Hills and just north of the outcrop of the Inferior Oolite Group. The location was immediately at the base of the south facing slope of the River Great Ouse Valley and the ground sloped gently toward the south. Strata consisted of superficial alluvium and head deposits, which were underlain by over-consolidated clays and mudstones of the Whitby Mudstone Formation (Lias Group). Relict periglacial shear surfaces were anticipated in the head deposits and Whitby Mudstone, so trenches were excavated during construction along the base of the earthwork to a depth of 3–5 m. Periglacial shear surfaces were encountered mainly at upper layers up to a depth of 1 m below original ground level. These were localized and randomly oriented, formed in both head deposits (where present) and also destructured clay described as firm, fissured, brown mottled grey silty clay (Fig. 8). The shear surfaces were shallow dipping (up to 20° dip), undulose, closely spaced at 0.6–0.8 m maximum depth, similar to the Type 1 shears described by Spink (1991). Occasional, deeper minor shear surfaces were also encountered to depths of up to 2.0 m bgl.

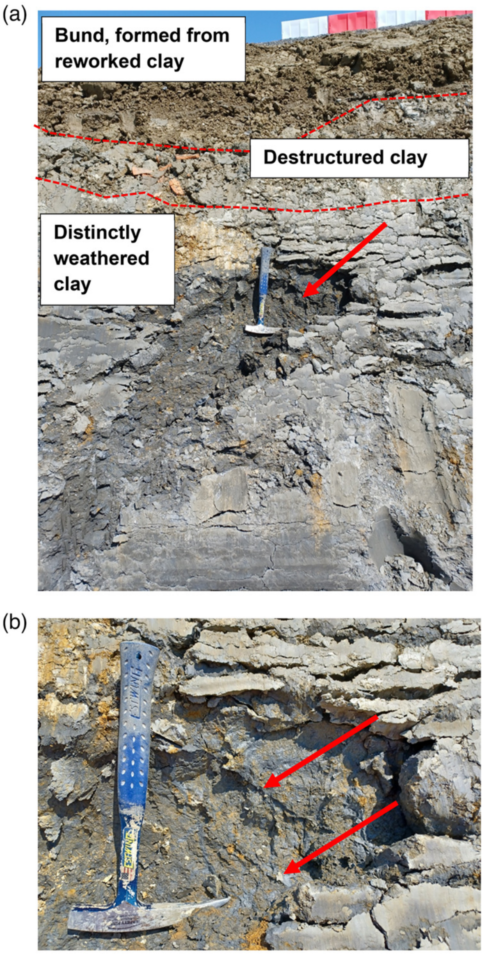

Fig. 6. (**a**) Closely spaced, higher angle (30°) planar tight discontinuities (Type 4 shears) at the base of the destructured clay (at 1.4 m below original ground level) in the Charmouth Mudstone Formation (Lias Group). (**b**) Close-up view of Type 4 shear. The images are from excavations near Wormleighton (WO), Warwickshire. The hammer is 330 mm long.

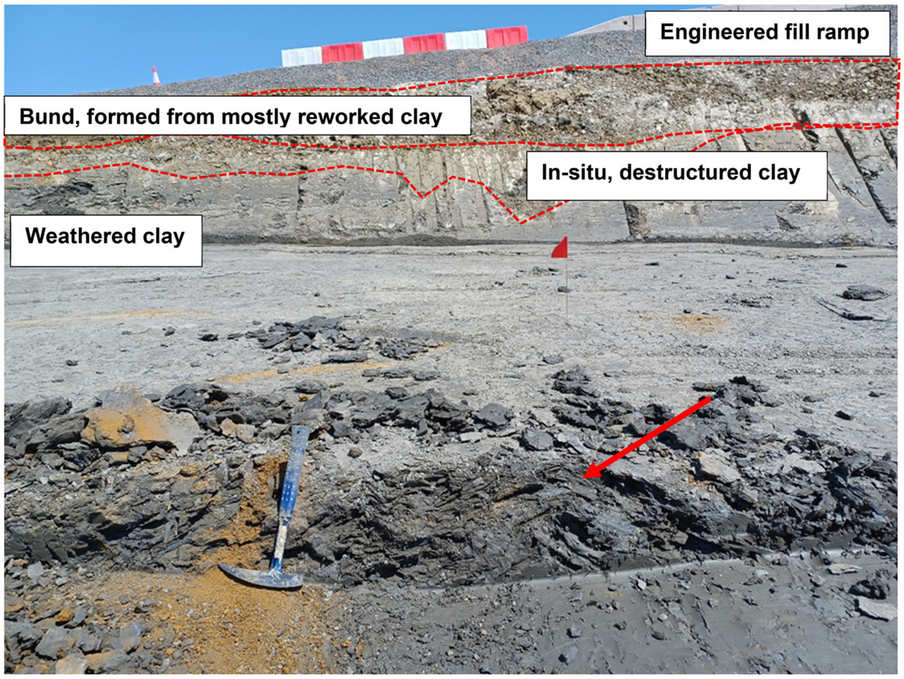

Fig. 7. Laminated, folded clays with higher angle accommodation shears at 2–2.5 m below the original ground level in the Charmouth Mudstone Formation (Lias Group) at excavations near Wormleighton (WO), Warwickshire.

An earthwork near Waddesdon, Buckinghamshire

The fourth case study site (WA in Fig. 1) was located SE of Waddesdon in Buckinghamshire, close to the town of Aylesbury. The site was on flat ground in the Fleet Marston area and was underlain by Ampthill Clay Formation strata (Ancholme Group). The site was flanked to the west by higher ground forming low hills of uppermost Jurassic Portland Group strata and capped with the dense sands of the Cretaceous Whitchurch Sand Formation. The hills to the west of Waddesdon run parallel to the route alignment and rise to *c.* 50 m higher than the valley floor. Slope angles were up to 10°. Mapping by the British Geological Survey (British Geological Survey 1991) identified mass-movement deposits on the upper slopes. The valley floor of the Vale of Aylesbury is widely covered by head deposits up to 3.5–5 m thick. Part of the earthwork was to be located on head deposits, which sit at the base of Waddesdon Hill, the crest of which is *c.* 0.5 km to the west. The firm to stiff grey and light brown mottled slightly sandy slightly gravelly clay contained bivalve shells (*Gryphaea* spp.), occasional black fibrous woody material and up to medium gravel-sized (2–20 mm) chert, orange sandstone and siltstone lithorelicts. Also entrained within the head deposits were occasional thin laminae and small pockets of black carbonaceous material.

Excavation of the upper 2 m revealed numerous periglacial discontinuities both within the head deposits and at the base of the destructured clay below (Fig. 9). Periglacial discontinuities were present in multiple locations of the complete linear excavation, with

Fig. 8. Shallow dipping, undulose, closely spaced shears (Type 1) at 0.6 m below the original ground surface in orange to brown mottled grey silty clay of destructured Whitby Mudstone (Lias Group) near Brackley (BR), Northamptonshire.

Fig. 9. Frequent shallowly becoming steeply dipping, undulose, closely spaced shears (Type 1) in head deposits at 0.6–0.8 m depth below original ground level in excavations near Waddesdon (WA), Buckinghamshire. The hammer is 330 mm long.

Fig. 10. The base of a 2 m excavation near Waddesdon (WA), Buckinghamshire. Some deeper shear surfaces are evident over a 40 m length after initial proof rolling with a vibrating roller.

each area of multiple discontinuities extending up to 200 linear metres, before disappearing and then re-appearing several hundred metres farther along. The excavation showed that the head deposits were mostly 1 m thick and underlain by 1–1.5 m of destructured and weathered clay. Sheared surfaces within the head deposits had a persistence length of up to several metres and a morphology very similar to the site near Ladbroke, far to the north and within a different source material. The 'pillow-shaped' shears occurred within a thicker zone than at Ladbroke. The surfaces were sinusoidal with overall dip slightly steeper than at Ladbroke and becoming up to 50–60° at an edge, defining the pillow surfaces themselves, rather than in cross-cutting shears. Between the dominant shears there were frequent, closely spaced low persistence undulose shears which terminated against the dominant shears. The deepest of the shears (at 2 m bgl) dipped at 5–25°, were widely spaced and more persistent at up to 10 m exposed length at the designed base of the excavation. Figure 10 shows that the deepest sheared surfaces became more evident after proof rolling at the base of the excavation with a vibrating roller. Some temporarily over-steep (~1 in 2) excavation sidewalls showed instability within one day of excavation, including an ~100 m long, 1–2 m deep mass in the head deposits and the destructured clay (Fig. 11). This was activated along numerous, discontinuous shear surfaces, rather than a planar basal (Type 2) shear surface.

An earthwork near Aylesbury, Buckinghamshire

The fifth case study (AY in Fig. 1) site was located to the west of Aylesbury, immediately south of the river Thame in Buckinghamshire. The site crested the brow of a low hill and was underlain by clays and mudstones of the Kimmeridge Clay

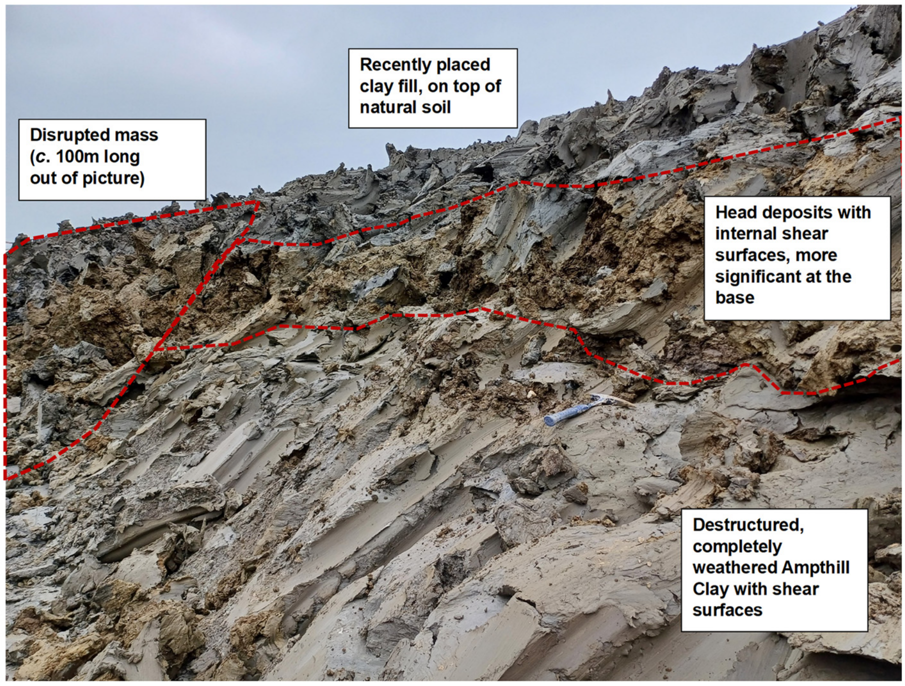

Fig. 11. A network of discontinuous shear surfaces was activated following the excavation of a temporarily steep (~1 in 2) slope near Waddesdon (WA), Buckinghamshire.

Fig. 12. Orange yellow silt and sand filled thin subvertical veins (Type 7 contraction cracks) in extremely weak mudstone (at *c.* 2.5 m below original ground level) become folded and irregular as they terminate in the overlying weathered clays of the Kimmeridge Clay Formation (Ancholme Group) in an excavation near Aylesbury (AY), Buckinghamshire. The hammer is 330 mm long.

Formation (Ancholme Group). Excavations revealed a periglacially-affected ground profile including polished shear surfaces, bedding disturbance and dewatering structures.

Three ground profiles are described showing a range of periglacial features. At the southern end of the site, excavations exposed a weathering profile of (1) a 1.3 m thickness of destructured mottled clays with rare small, sand-infilled vertical veins in the upper 1 m, crystallization of very fine selenite, and minor sub horizontal listric shear surfaces from *c.* 1.2 m bgl; (2) between 1.3 and 1.8 m distinctly weathered grey brown clay and (3) brown and blue weathered clay with lithorelicts and tightly contorted involuted relict lamination below 2 m bgl, underlain by small-scale polished listric shear surfaces with a dip of less than 10°.

Near the centre of the site, the excavations exposed a 1.2 m thick layer of destructured orange and brown silty occasionally sandy clay with intensely folded involuted pseudo-bedding and thick sand-filled veins. This was underlain by distinctly weathered bluish grey and brown silty clay with a very irregular weathering profile and undulose minor shear surfaces toward the top. The weathered clay transitioned to partially weathered extremely weak thinly laminated and contorted mudstone at *c.* 2.8 m bgl.

Towards the north of the site, extremely weak bluish grey and brown laminated mudstone at 2.5–3 m bgl contained orange and yellow silt and sand-filled thick subvertical veins. These veins became folded and irregular upward as they terminated in the weathered clays above (Fig. 12).

Interpretation

The five case study locations show relict shear features and other periglacial phenomena and their relationship with the weathering profile. In all five locations there were shallow dipping (<25°), highly undulose shears at a range of scales. These were often associated with steeper dipping shears with cross-cutting relationships. Periglacially reworked clay head deposits can be hard to identify over weathered clay and mudstone bedrock. Whilst not always being present, observation of entrained foreign gravel material and organic stringers provided the best definitive evidence of transportation.

At Ladbroke (LA), extensive areas of sheared clay occupy flat ground at the base of a hillslope. Although gravel-sized (2–63 mm) mudstone was identified within the clay matrix it seems most likely these are lithorelicts and this is *in situ* destructured clay and not clay head deposits. The hummocky undulose shear surfaces had a dip of less than 15°, were cross-cut and were intersected by steeper shears. At Wormleighton (WO), undulose shears were present within both reworked head and underlying destructured *in situ* clay to depths of up to 1.4 m bgl. Below this, higher angle planar discontinuities were present in stiff mottled clays, and laminations in the underlying distinctly weathered clays were folded with minor shear surfaces also present. At Waddesdon (WA), the sheared clay was identified as head deposits due to the inclusion of occasional foreign gravel and carbonaceous wisps. Shears in the head deposits were less than 25° dip, undulose but becoming steeper at their outer extent (up to 65°), rather than being cross-cut by a different set of discontinuities as at Ladbroke (LA). At Aylesbury (AY), the minor shearing was subsidiary to involution and soft sediment deformation of destructured to distinctly weathered strata and the formation of sand filled veins.

The Spink (1991) schema describes shear morphologies developed through shallow active layer detachment, thaw collapse, thermal contraction and underthaw. Additionally, Hutchinson (1991) showed an indicative cross section of the development of active, passive, sub horizontal and thaw collapse shears within and below the active layer detachment. These can be used to interpret the shears encountered at the case study locations.

Of the locations described, only Waddesdon (WA) and Brackley (BR) clearly show head deposits with active layer detachment. At both locations the undulose shears in the head deposits were interpreted as Type 1 shears connected by closely spaced smaller Type 3 shears. At Waddesdon (WA) the shape of the surfaces would suggest all of the Type 1 shears represent the formation of a network of shallow to moderately dipping active and passive shears within the reworked head. The deepest of the shears (with a dip of 0–25°) encountered at both Waddesdon (WA) and Brackley (BR) were toward the base of destructured clay, without the development of intervening Type 2 shears at the base of the head deposits.

At Ladbroke (LA) by contrast, the shears with a dip less than 15° were intersected by steeper cross-cutting shears which could represent thaw collapse (Type 4) across a tract of lower lying ground. The sheared material was not proven to be reworked head deposits and did not have a clear basal discontinuity, so these shears did not fit the Spink (1991) definition for Type 2 shears. The location at the base of a steeper slope fits the morphology of active layer detachment, but it is difficult to categorize the shears as Type 2, without a confirmed veneer of head deposits. As such the periglacial discontinuities encountered at Ladbroke could result from gelifluction rather than mass movement and lateral displacement.

A deeper cross section through the weathering profile was exposed at Wormleighton (WO). This exposed Type 4 thaw collapse shears in distinctly weathered clays, below head deposits which contained Type 1 shears (without the formation of Type 2 shears at the base), and destructured clays. At the base of the exposed profile, the laminated clay/mudstone was folded with polishing of lamination surfaces. This could be interpreted as the result of freeze–thaw of segregated ice lenses, although the possibility of an unloading origin cannot be discounted.

Involution at Aylesbury (AY) occurred in the near surface destructured *in situ* clay to depths of *c.* 1.2 m bgl, and distinctly weathered clay below this to depths of *c.* 2.1 m bgl. Thermally induced cracking as sand filled veins occurred throughout and was also present in the underlying weathered mudstone where the veins became disturbed at the top at the boundary with the involuted clays. As with the folded laminated mudstone at Wormleigton (WO), minor shearing was likely associated with bedding disturbance rather than active layer detachment.

The periglacial discontinuities observed at the case study sites broadly compare with the schema of Spink (1991). However, there were many examples of undulose and shallow dipping shears (less than 25° dip) within the destructured clay, rather than the reworked head. These do not fit the Spink (1991) schema as they are neither 'continuous', as required for Type 2 discontinuities, nor deep enough into the weathering profile to be types 5 or 6 discontinuities. These shears occurred within plastic clays, with little evidence of relict structure. Proven, continuous Type 2 shears between the reworked head and destructured clays were notably absent from the case study locations and were not encountered in any strata between Wendover and Southam. An extensive Type 2 shear band would represent the greatest hazard to constructed works. However, it would appear that the boundary between the transported and the *in situ* clays is defined by connected networks of undulose shear surfaces within both layers, rather than as a single boundary shear surface. It was these networks of discontinuous shear surfaces that activated instability in over-steep temporary slopes, shortly after excavation.

Conclusions

Periglacial weathering and conditioning of mudstone outcrops is widespread throughout the lowland southern British Isles. The geological indicators in the shallow subsurface are quite subtle and not easy to identify through ground investigation. Clear identification and classification are essential to ensure that appropriate mitigation is considered and to avoid periglacial relict shears from reducing the stability or serviceability of engineered structures, such as railway earthworks.

Periglacial discontinuities are prevalent in the Jurassic strata along the HS2 corridor and there is evidence for shear surfaces consistent with downslope movement at some locations with sloping topography. Full excavation through weathering profiles suggests that the Spink (1991) schema originally developed for Eocene clays is broadly applicable to periglacial discontinuity morphologies in Jurassic mudstone strata. However, there are two notable differences. The shears would no longer be described as solifluction shears because they are in clay-rich materials (Ballantyne 2025), but their characteristics remain unchanged from those identified in Spink (1991). There were also many examples of undulose, shallow dipping shears (up to 25°) within the destructured clay of the Jurassic mudstone strata that do not fit the Spink (1991) schema.

The case studies show that sheared surfaces occur at a range of scales between very closely spaced surfaces measured on a millimetric scale to single discontinuities with a persistence of 10 or more metres. These individual discontinuities occur within fields of disturbed ground with an extent into the hundreds of metres. The nature of the shears is best understood in relation to surrounding topography and their depth within the weathering profile. The two most extensive areas of ground in which periglacial shears were encountered were on the clay plains, suggesting widespread periglacial displacement at the toe of steep slopes or mass disruption on flatter ground.

Earthwork excavations in periglacially affected terrain between Wendover and Southam contained areas of periglacially reworked head material covering hundreds of linear metres. No single shear surface extended greater than 10 m and in most cases, they were highly undulose. Extensive Type 2 shears (Spink 1991) present the greatest risk of remobilization during construction, but these were not identified. However, networks of discontinuous shears in the vicinity of slope toes activated instability of some over-steep, temporary excavations while under observation during construction. These occurred within one day of excavation and could be remediated. Therefore, they can be anticipated during excavation but do not present a longer-term hazard to the construction and operation of the railway.

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Author contributions

GH: data curation (lead), formal analysis (equal), investigation (lead), methodology (equal), writing – original draft (equal), writing – review & editing (equal); **KB**: conceptualization (lead), data curation (equal), formal analysis (equal), investigation (equal), methodology (lead), writing – original draft (equal), writing – review & editing (equal); **HS**: writing – review & editing (supporting); **KR**: writing – review & editing (supporting); **SB**: supervision (lead), writing – review & editing (supporting).

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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