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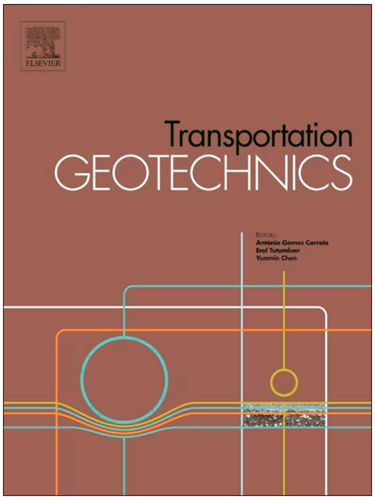

Evidence for the weather-driven deterioration of ageing transportation earthworks in the UK

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Title: Evidence for the weather-driven deterioration of ageing transportation earthworks in the UK

Authors: Kevin M. Briggs[1*], Peter R. Helm[2], Joel A. Smethurst[3], Alister Smith[4], Ross Stirling[2], Aleksandra Svalova[5], Yuderka Trinidad González[6], Fleur A. Loveridge[7] & Stephanie Glendinning[8]

*Corresponding author: k.m.briggs@bath.ac.uk

1. Faculty of Engineering & Design, University of Bath, Bath, BA2 7AY, UK.
2. School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.
3. School of Engineering, Faculty Engineering and Physical Sciences, University of Southampton, Southampton, SO17 1BJ, UK.
4. School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough, LE11 3TU, UK.
5. School of Mathematics, Statistics and Physics, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.
6. Department of Civil, Construction, and Environmental Engineering, Iowa State University, Ames, IA, United States.
7. School of Civil Engineering, Faculty of Engineering and Physical Sciences, University of Leeds, Leeds, LS2 9JT, UK.
8. Faculty of Science, Agriculture and Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK.

ORCID: KMB: 0000-0003-1738-9692, PRH: 0000-0001-6866-5568, JAS: 0000-0001-8175-985X, ASm: 0000-0003-3363-300X, RS: 0000-0002-0069-6621, ASv: 0000-0001-9455-3471, YTG: 0000-0003-3715-9712, FAL: 0000-0002-6688-6305

Abstract: Seasonal, weather-driven pore pressure cycles alter and degrade the hydro-mechanical engineering properties of earthworks as they age. The accumulating effects of deterioration over many years can lead to the excessive deformation or failure of earthworks; requiring interventions to ensure their reliable performance. This paper reviews the evidence for the weather-driven deterioration of ageing transportation earthworks, with a focus on clay earthworks in the UK. These include earthworks of various ages (up to ~200 years old), formed from a range of clay-rich strata and at various stages of deterioration. Evidence is considered for both past behaviour and projected behaviour in response to continued ageing and a changing climate. There is clear evidence that some clay earthworks are influenced by the cumulative effect of seasonal weather cycles over many decades. Simulations show that seasonal slope ratcheting will become an increasingly dominant driver of shallow failures in high-plasticity cut slopes as they age and in response to projected climate change. The evidence can inform performance curves describing the deterioration of individual earthworks in response weather-driven ageing. This can help identify earthworks with the highest likelihood of failure and inform decisions made by earthwork asset managers.

Keywords: earthworks; transportation; infrastructure; deterioration; ageing; climate change

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Introduction

Earthworks (cut slopes and embankments) support transportation infrastructure including roads, railways and associated building structures (Perry et al., 2003a; Perry et al., 2003b). They are formed from or within the ground and are therefore influenced by processes associated with the intersection of the Earth's lithosphere with the atmosphere, hydrosphere and biosphere (Huggett 2022; Fookes, 1997). Of these, weather-driven hydrological and mechanical processes are the most relevant to earthwork behaviour and their performance as engineering structures. Records show that earthworks formed from natural clay (i.e., cut slopes) or clay fill (i.e., embankments) are particularly susceptible to weather-driven deterioration, leading to a loss of performance or failure (Skempton, 1996; Leroueil, 2001; Ridley et al., 2004; O'Brien, 2007; Loveridge et al., 2010).

Pore pressures within earthworks can rapidly increase or decrease in response to individual weather events and alter more slowly and cyclically in response to seasonal weather changes (Leroueil, 2001; Ridley et al., 2004; O'Brien, 2007; Loveridge et al., 2010; Briggs et al., 2017). Hydrological loading that is induced by pore water pressure changes can be in excess of the mechanical loading from overlying traffic on an earthwork slope (Scott et al., 2007). Both pore pressure changes and physical weathering effects (e.g., desiccation cracking) can alter and degrade the engineering properties of earthworks as they age. After a period of time (generally on a decadal scale), this leads to a reduction in the resistance of some earthwork slopes to excessive deformation or failure.

Transportation earthworks in the UK range from those constructed for railways in the 1830s to those constructed since the 2000s for highways and high-speed railways (Perry et al., 2003a; Perry et al., 2003b; Spink, 2020). Many are formed on clay-rich outcrops ranging from the carboniferous Mudstones in Wales, central England and northern England, to Tertiary Clays and Mudstones in southeast England and Quaternary deposits distributed across the UK (Figure 1; Reeves et al., 2006). Therefore, the UK's transportation infrastructure includes earthworks of various ages, formed from a range of clay-rich soils and rocks and at various stages of deterioration (Briggs et al., 2019). The changing behaviour and deterioration of assets, such as transportation earthworks, can be described using an inverted 'bathtub' performance curve (Klutke et al., 2003; Thurlby, 2013). The curve (Figure 2) has four broad stages consisting of (i) a bedding-in period of improving performance following construction, (ii) a period of reliable performance, where deterioration has not yet significantly affected an asset, (iii) a period of reducing performance, where deterioration starts to negatively affect an asset without interventions such as increased maintenance and (iv) a period where deterioration has progressed to the extent that the asset becomes unreliable or fails. Figure 2 shows that there are transportation earthworks in the UK at each of these four stages of performance and deterioration. Recent research into the weather-driven deterioration of ageing earthworks in the UK therefore presents an opportunity to understand the key drivers, indicators and forecasts of earthwork deterioration as they age. This can be used to inform long-term assessment and management strategies for infrastructure owners, both in the UK and elsewhere.

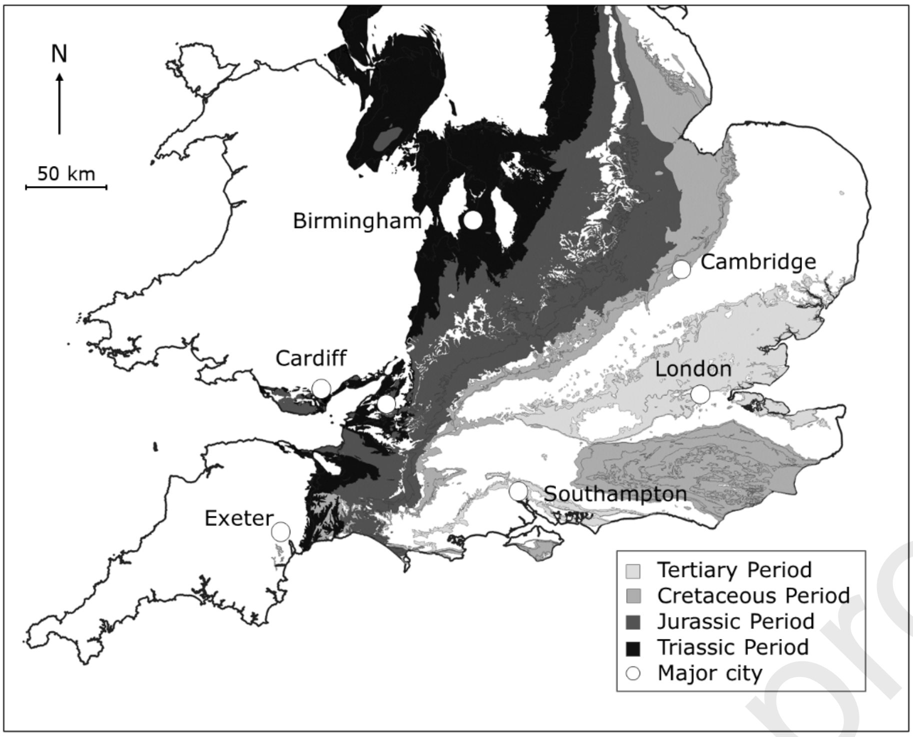

Figure 1: Clay-rich outcrops underlying major cities and transport networks in south and central England and Wales, categorised by Geologic Period (As categorised by Reeves et al., 2006). Quaternary deposits omitted for clarity. Contains British Geological Survey materials © UKRI 2023.

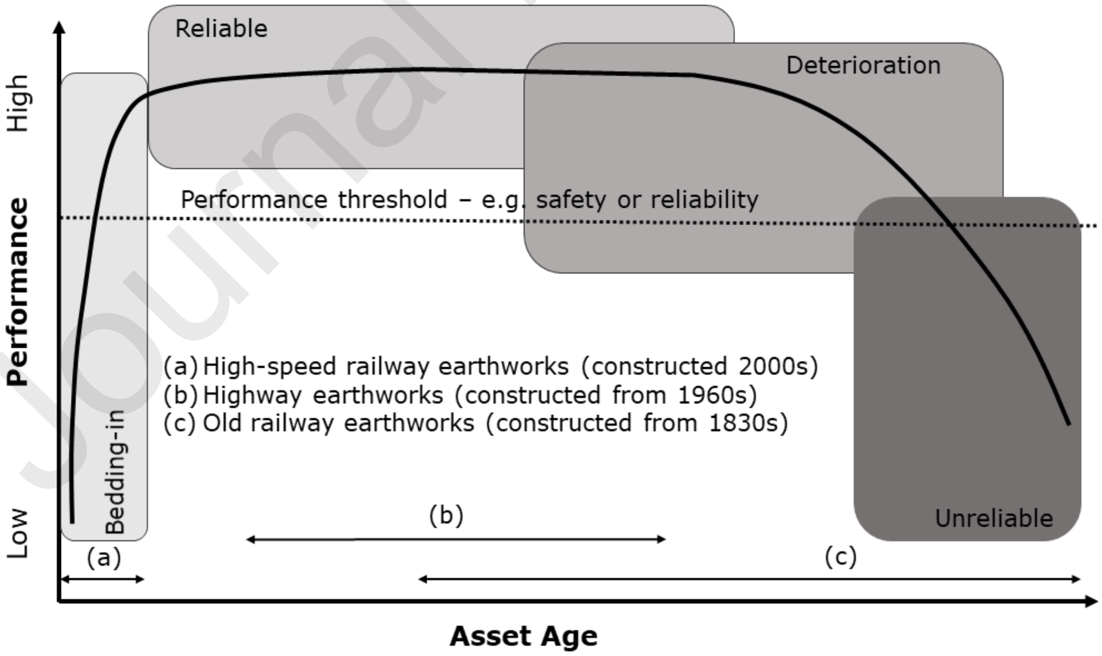

Figure 2: The UK's transportation network includes earthworks constructed since the 1830s that are now at various stages of deterioration (adapted from Briggs et al., 2019)

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The aim of this paper is to evaluate evidence for the long-term, weather-driven deterioration of ageing transportation earthworks and to present a conceptual model for these processes. First, the conceptual model is presented. Then, the subsequent sections summarise the supporting evidence. This evidence includes results from failure records, field-observations, *in situ* monitoring, full-scale trials, *in situ* testing, laboratory experiments and numerical simulations. The objectives are to evaluate (i) the evidence for weather-driven deterioration in clay earthworks, to inform the conceptual model (ii) how weather-driven deterioration will influence the deformation and stability of earthwork slopes as they age, (iii) the influence that projected climate change will have on the mechanism and rate of weather-driven deterioration in earthwork slopes.

A conceptual model of weather-driven deterioration processes in ageing transportation earthwork slopes

In temperate climates such as the UK, near surface soil moisture content and pore water pressures are often lowest at the end of summer (August/September) and highest at the end of winter (March/April). Water removal and drying of the soil occurs during the summer months when rainfall and soil water are evaporated or transpired. Rainfall infiltration and soil wetting occurs more easily during the winter months when evaporation and transpiration are significantly reduced. Seasonal fluctuations in soil moisture content and pore pressures are greatest near the ground surface, while fluctuations at greater depth occur in response to longer-term changes in weather, climate or groundwater conditions (Freeze & Cherry, 1979; Blight, 1997). These changes are known to affect the material properties, the deformation and the failure of natural slopes, cut slopes and embankments in a range of materials and climates (Leroueil, 2001).

A conceptual model of the weather-driven deterioration processes affecting ageing clay transportation earthwork slopes can be considered from the material-scale behaviour through to the slope-scale behaviour (Figure 3). This forms a subset of a wider deterioration framework for geotechnical infrastructure that includes additional human or environmental drivers of deterioration (Briggs et al., 2019) and earthworks used in other applications such as for flood defence (Vardon, 2015), that are not considered in this paper.

Stirling et al., (2021) described the weather-driven deterioration of clay fills based on extensive laboratory testing and a programme of field-based experiments. A conceptual model of weather-driven deterioration in clay fills was developed to include changes in material properties ranging from micro-scale cracking, to changes in soil water retention and strength. This formed the basis for a new conceptual model describing the weather-driven deterioration of clay earthworks (embankments and cuttings) at the slope-scale (Figure 3). The slope-scale conceptual model includes evidence from laboratory testing, field monitoring and *in situ* experiments; supplemented with insights from numerical simulations.

The conceptual model (Figure 3) includes four inter-related quadrants describing types of deterioration at the slope-scale that have been reported in experiments, simulations or from field observations for ageing clay cuts, clay embankments, or their constituent materials (i.e., clay fills or natural clays). The deterioration process in each quadrant is

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supported by summary statements describing published results and conclusions. The evidence to support these statements is described in the subsequent sections of this paper. Figure 3 shows that the four quadrants describing the weather-driven deterioration of ageing, clay earthworks and their constituent materials (natural clay or clay fill) are:

1) The irrecoverable, micro-scale deformation and altered fabric of the clay forming an earthwork.
2) The macro-scale deformation and altered fabric of the clay forming an earthwork, or of the earthwork itself.
3) Permanent changes in the hydraulic and water-retention properties of the clay forming an earthwork.
4) The irrecoverable loss of strength in the clay forming an earthwork; that then reduces the stability of an earthwork slope.

These weather-driven deterioration processes are in response to repeated cycles of wetting and drying, and the associated cycles in pore pressure, driven by predominantly seasonal weather changes. However, they may be applicable to ageing transportation earthworks in other geographical locations, or in newer earthworks that are now entering the stage of deterioration and reducing performance (Figure 2).

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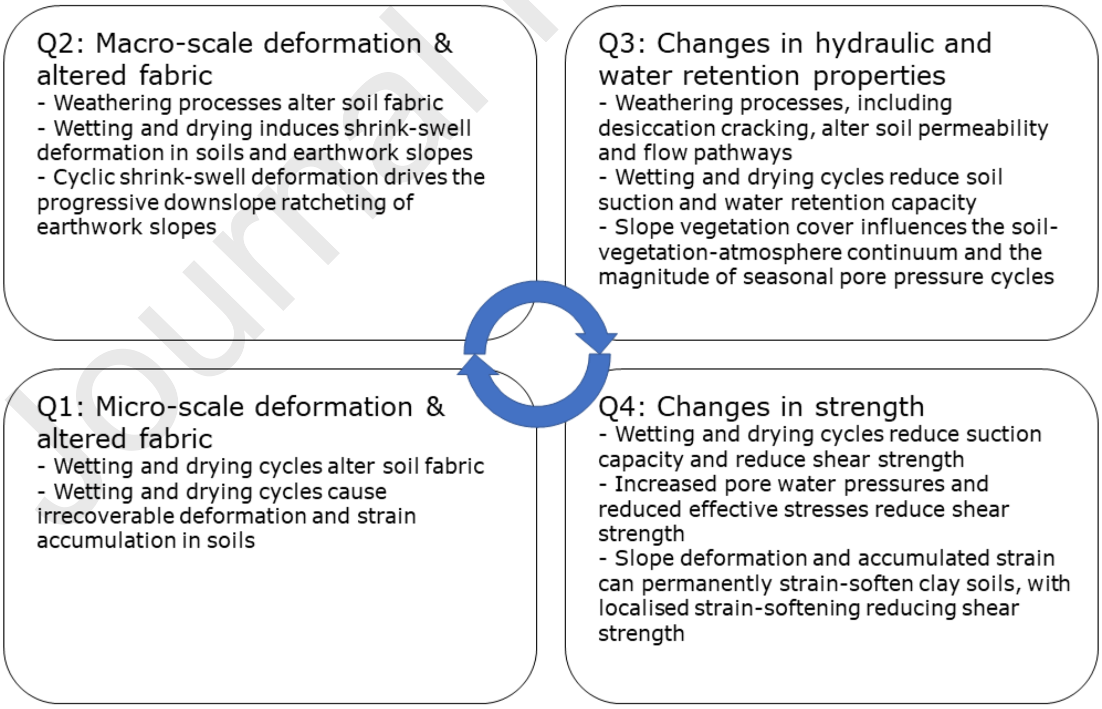

Q2: Macro-scale deformation & altered fabric
- Weathering processes alter soil fabric
- Wetting and drying induces shrink-swell deformation in soils and earthwork slopes
- Cyclic shrink-swell deformation drives the progressive downslope ratcheting of earthwork slopes

Q3: Changes in hydraulic and water retention properties
- Weathering processes, including desiccation cracking, alter soil permeability and flow pathways
- Wetting and drying cycles reduce soil suction and water retention capacity
- Slope vegetation cover influences the soil-vegetation-atmosphere continuum and the magnitude of seasonal pore pressure cycles

Q1: Micro-scale deformation & altered fabric
- Wetting and drying cycles alter soil fabric
- Wetting and drying cycles cause irrecoverable deformation and strain accumulation in soils

Q4: Changes in strength
- Wetting and drying cycles reduce suction capacity and reduce shear strength
- Increased pore water pressures and reduced effective stresses reduce shear strength
- Slope deformation and accumulated strain can permanently strain-soften clay soils, with localised strain-softening reducing shear strength

Figure 3: A conceptual model for the weather-driven deterioration of ageing, clay transportation earthworks (adapted from the conceptual model for the deterioration of clay fill by Stirling et al., 2021)

Evidence for near-surface weathering in earthwork slopes

There is *in situ* evidence to show that weathering alters the fabric and structure of near-surface soils in earthwork slopes (Q1 & Q2 in Figure 3). This leads to changes in the material properties at shallow depth and facilitates water movement to greater depth.

Anderson & Kneale (1980) and Anderson et al., (1982) showed that desiccation cracks formed in a high-plasticity clay fill embankment and acted as preferential pathways for water flow into the embankment. Near-surface cracks of up to 25 cm depth opened during the summer months and closed during the winter months. But micro-discontinuities persisted after crack closure and permanently altered the fabric and permeability of the soil.

Detailed *in situ* crack measurements on a vegetated, intermediate plasticity clay fill embankment (Yu et al., 2021) showed that the process of crack initiation, expansion, contraction and closure is an annual response to seasonal changes in weather, soil suction and moisture content (Figure 4). The measurements showed the formation of discrete, linear cracks up to 1 m in depth and 2 m in length, as opposed to the branching, connected polygonal cracking shown in laboratory experiments (Tang et al., 2008) and sparsely vegetated slopes (Dyer et al., 2009; Li & Zhang, 2011). Simulations by Stirling et al., (2017) showed that pervasive, fine cracking patterns were associated with low permeability marine clays with high air entry values (AEVs), while intermediate plasticity clays and tills were likely to exhibit permanent, deep cracking but less desiccated crust development.

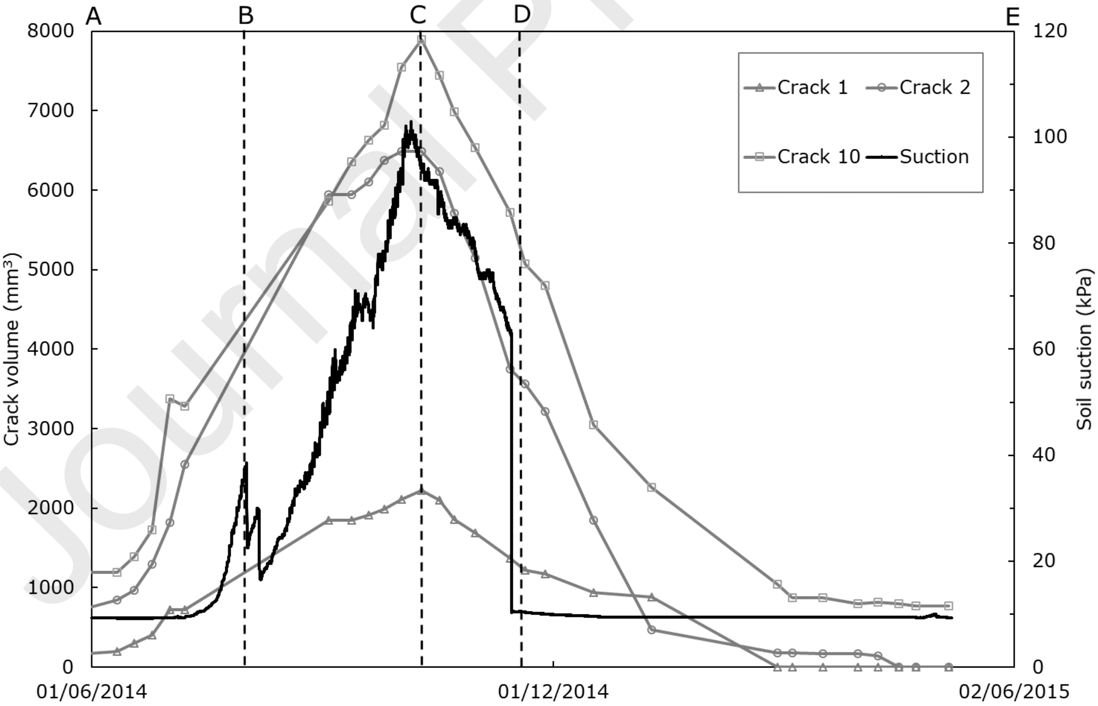

Figure 4: The annual variation of crack volume and soil suction from the lower slope of a clay fill embankment (adapted from Yu et al., 2020 and Yu et al., 2021), showing the process of crack initiation (A-B), expansion (B-C), contraction (C-D) and closure (D-E).

Laboratory measurements show that cyclic wetting and drying alters the fabric of compacted clay fills used to construct embankments. The altered fabric includes the formation of micro-scale cracks and led to a loss of suction generation capacity and a progressive loss of strength (Stirling et al., 2021; Azizi et al., 2019). The micro-scale fabric deterioration manifested as a macro-scale deterioration front in an embankment slope (Stirling et al., 2021). This was due to the crack propagation providing an enhanced pathway for water infiltration and removal at depth, which then induced soil volume change and the further propagation of the crack network into the slope surface. The crack propagation was limited by higher confining stresses and reduced suctions at greater depth, leading to a stable, near-surface zone of increased permeability within the clay fill.

Dixon et al., (2019) showed that in embankments, the permeability (saturated hydraulic conductivity, K_{sat}) varied by five orders of magnitude in the very near surface (0-0.3 mbgl) and by four orders of magnitude between 0.3 m and 1.2 m depth (Figure 5). This compared to measurements from cut slopes showing a four orders of magnitude change in permeability in the very near surface, and a two orders of magnitude reduction between 0.2 m and 0.6 m depth. These measurements, taken from six exemplar UK transport earthwork sites, showed that the main factor influencing the large variation in permeability was the near surface changes in soil fabric, driven by desiccation, root growth and root water abstraction. The greater permeability in the near surface increased the rate and magnitude of moisture content and pore pressure cycles, both within this zone and the relatively unaltered underlying zone within the earthwork.

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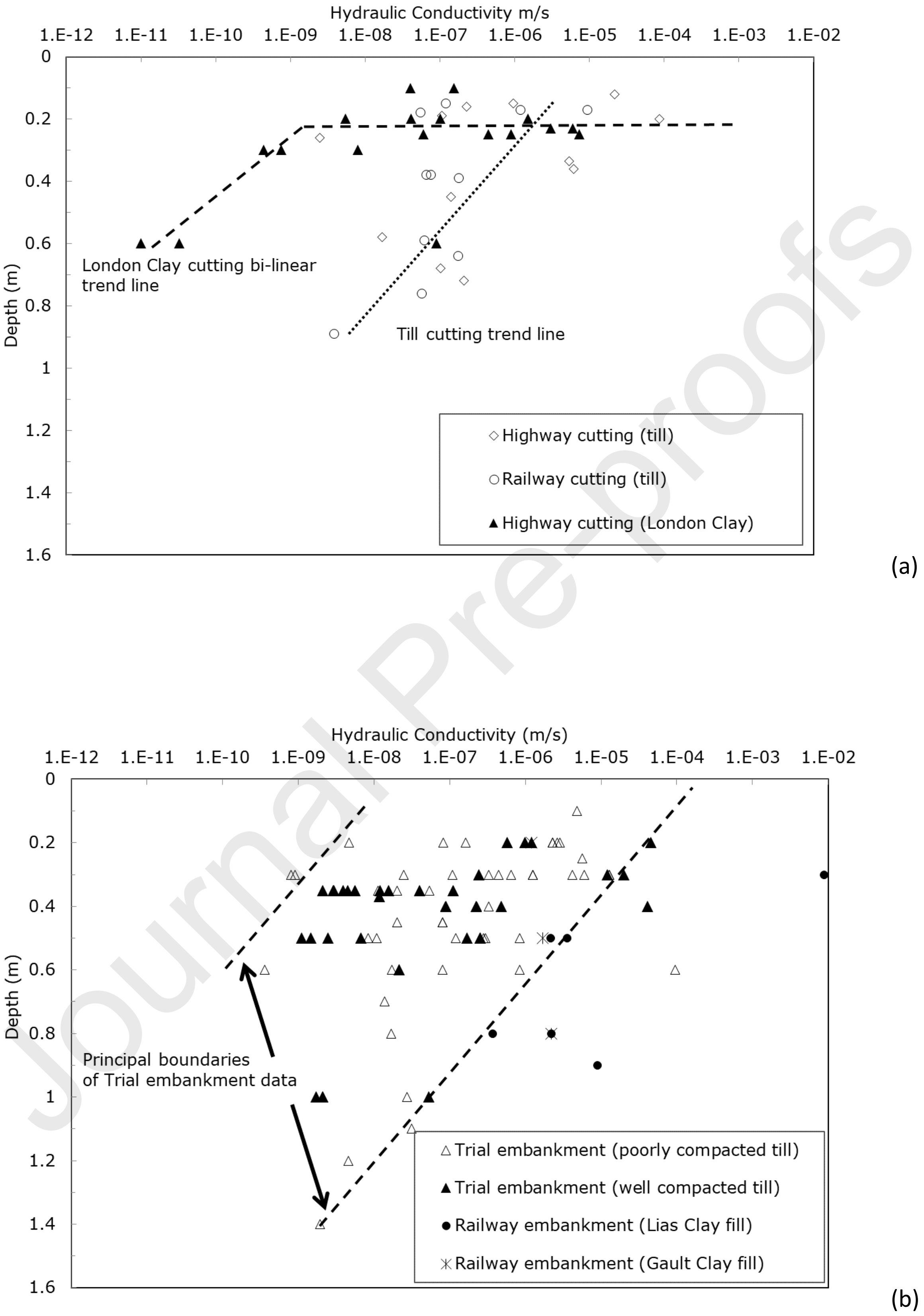

Figure 5: Near surface permeability measurements (saturated hydraulic conductivity, K_{sat}) at UK exemplar earthwork sites, from (a) cutting slopes and (b) embankment slopes. (redrawn from Dixon et al., 2019)

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Observations of weather-driven water movement in earthwork slopes

Seasonal weather changes alter the water balance at the ground surface, driving near surface changes in soil moisture content and pore pressure (Blight, 1997; Moene & van Dam, 2014). There is evidence of weather-driven deterioration and increased soil permeability at the near-surface that facilitates water flow (Q2 & Q3 in Figure 3). This can be increased by the formation of cracks, fissures and other changes in soil fabric during periods of dry weather.

Measurements from instrumented earthworks show how their construction material, construction method and the presence of surface vegetation cover can influence ground water movement. For example, the magnitude and frequency of pore water pressure change in old clay embankments is greater than in cuttings, due to the increased permeability of the embankment clay fill, relative to the *in situ* clay of a cutting (Loveridge et al., 2010). Similarly, the depth of significant seasonal moisture content variation in clay cuttings and low permeability, well-compacted fill embankments (typically 0.3-0.6 mbgl; Anderson & Kneale 1980; Cui et al., 2010; Smethurst et al., 2006; Smethurst et al., 2012) is much shallower than in more loosely compacted, ageing embankments, where it extends to a greater depth of up to 2-3mbgl (Hughes et al., 2009; Dyer et al., 2009; Glendinning et al., 2014; Chambers et al., 2014; Dixon et al., 2019). *In situ* measurements show that tree-covered slopes can generate large suctions throughout the tree root zone (up to approximately 3 mbgl). These suctions extend to greater depth than in grass covered slopes, due to the ability of trees to extend a deeper root system from which to remove water (Vaughan et al., 1978; Scott et al., 2007; Loveridge et al., 2010; Smethurst et al., 2015; Holmes et al., 2022). In some cases, mature trees are able to maintain a persistent suction and a persistently low moisture content at depth (>1 mbgl) throughout the winter months. This persistent moisture deficit is maintained at a depth that is below seasonal fluctuations closer to the near surface (Biddle, 1983; Biddle, 1998; Smethurst et al., 2015; Briggs et al., 2016).

There are several instrumented sites in the UK with long-term monitoring data showing weather-driven water movement within earthwork slopes, and the influence of seasonal weather extremes (e.g. a wet winter or dry summer, relative to the long-term average). Long-term monitoring at a grass covered, high-plasticity clay cut slope near Newbury (Figure 6) included moderate extremes of wet and dry summers and winters (Smethurst et al., 2012; Blake et al., 2022; Smethurst et al., 2022). Smethurst et al., 2012 showed that the annual totals of potential and actual evapotranspiration were relatively consistent and that pore water pressure changes were mainly affected by variations in annual and seasonal rainfall. The occurrence of extremely wet or dry summers had the most significant effect on the magnitude of seasonal pore water pressure cycles, with the largest suctions developing during periods of low rainfall between June and August. However, the grass vegetation was not able to maintain suctions during the winter months, even during drier winters. The measurements at Newbury continued for more than 20 years and continue to show pore water pressure cycles that vary in response to seasonal changes in the surface water balance of rainfall and evapotranspiration (Blake et al., 2022; Smethurst et al., 2022).

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Similarly, long-term monitoring of an instrumented, compacted clay fill embankment (Hughes et al., 2009; Toll et al., 2012; Glendinning et al., 2014; Stirling et al., 2021) has been used to contextualise climatic conditions for *in situ* experiments on the embankment slopes. This includes measurements showing that surface water infiltration during an extreme rainfall event is greater during a dry summer than it is during a relatively wetter summer or during the winter months (Dixon et al., 2019; Stirling et al., 2021).

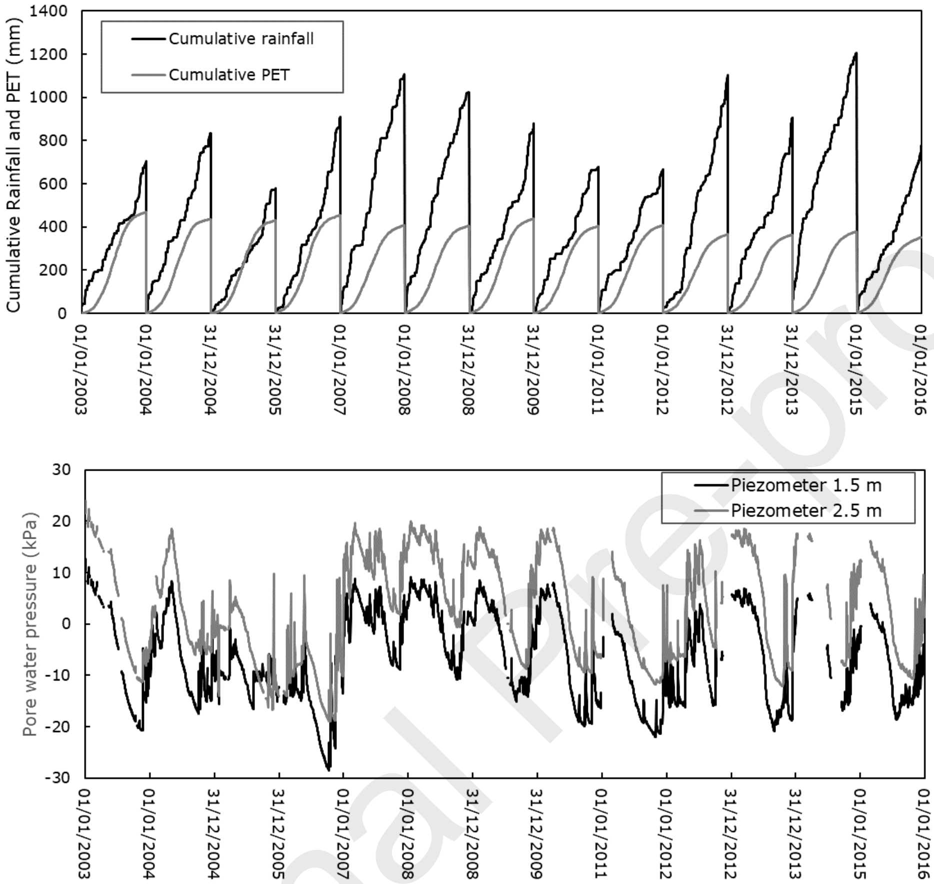

Figure 6: Measurements at Newbury cutting between 2003 and 2016, showing changes in (a) annual cumulative potential evapotranspiration (mm), rainfall (mm) and (b) pore water pressure (kPa) at 1.5 mbgl and 2.5 mbgl. Adapted from Smethurst et al., (2012) and Smethurst et al., (2022).

Observations of the weather-driven deformation and failure of earthwork slopes

Weather-driven pore water pressure and moisture content changes can cause volume change and both temporarily and permanently reduce the strength of the natural clay or clay fill forming an earthwork. This can lead to slope deformation, accumulated strain and the failure of earthwork slopes (Q2 & Q4 in Figure 3).

During construction of the early railways from the 1830s, there were failures in clay cut slopes and clay fill embankments following periods of wet weather during construction, or in subsequent winters. Skempton (1996) attributed the embankment failures to softening of the clay fill by the absorption of rainwater. Superficial failures in cut slopes were attributed to wet weather, but deep-seated failures were also identified in the years and decades after

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construction. The mechanism of these delayed, deep-seated failures was first described by Gregory (1844) and more fully explained by others (Henkel, 1955; Skempton, 1964; Vaughan & Walbancke, 1973; Chandler & Skempton, 1974; Cooper et al., 1998) as being triggered by stress relief and the long-term equilibration of negative pore water pressures following cut slope excavation. Over time, this reduced the strength of the clay by strain-softening and could lead to a progressive slope failure that was initiated at the slope toe. These deep-seated failures in clay cut slopes could be triggered by pore water pressure increases due to rainfall events or wet winter weather, but the weather-driven deterioration of strength was not the underlying cause of slope failure (Skempton, 1964; Vaughan & Walbancke, 1973; Hughes et al., 2007).

During the expansion of the UK's highway network in the decades following the 1950s, there were cut slope and embankment failures in overconsolidated clays that occurred in the decade post- construction (Garret & Wale, 1985; Greenwood et al., 1985; Parson & Perry, 1985; Perry, 1989). These were mainly shallow translational and rotational failures (<2m depth) that were triggered by pore water pressure increases during prolonged periods of rainfall. They most commonly occurred in earthworks constructed from or in high-plasticity clays (e.g., Gault, Kimmeridge, Oxford and London Clays).

In situ measurements obtained from high-plasticity clay fill embankments show the seasonal displacement of the embankment slopes in response to seasonal weather cycles and changes in surface vegetation cover. O'Brien (2007) showed railway track settlement on a clay fill embankment during the summer months, followed by heave during the winter months. Approximately two years of monitoring at the crest of a vegetated, high-plasticity clay fill embankment showed that seasonal deformations in a tree-covered part of the slope were more than ten times greater than those measured on a grass-covered part of the embankment (Scott et al., 2007; O'Brien, 2007). Inclinometer measurements from the midslope of a tree-covered, high-plasticity clay fill embankment showed a seasonal trend of outward displacement in the summer months, followed by inward movement during the winter months (Figure 7; O'Brien, 2013). During the two-year monitoring period there was a net outward, and apparently permanent, displacement of 10-15 mm per annum. The displacements were more closely aligned with changes in the soil moisture content and soil moisture deficit (SMD), than with individual rainfall events. The soil moisture deficit (SMD) describes the calculated or measured amount of moisture that has been depleted from a soil profile, relative to a reference amount such as the field capacity (Allen et al., 1998). Smethurst et al., (2015) showed that changes in soil moisture content measured within a tree-covered, high-plasticity clay fill embankment could be used to calculate vertical displacements at the embankment mid-slope. These compared well with *in situ* extensometer measurements from the same location. They showed that seasonal shrink-swell movements, pore water pressure changes and displacements were significantly reduced following the removal of mature trees from the upper two-thirds of the embankment slopes. This caused a gradual re-wetting of the embankment core, with an associated increase in pore water pressures and the upward and outward movement of the embankment slopes.

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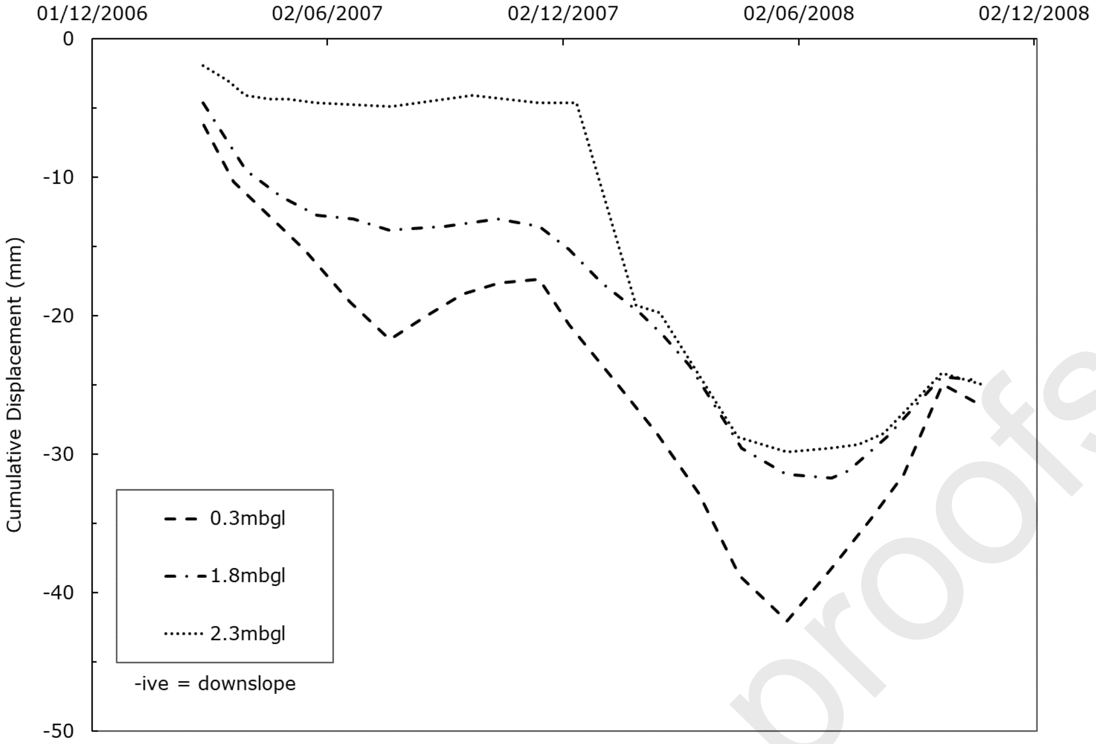

Figure 7: Inclinometer measurements from the midslope of a high-plasticity (Gault Clay) clay fill railway embankment with moderate water demand trees (redrawn from O'Brien, 2013)

Ridley (2012) showed *in situ* monitoring data linking climate, vegetation, pore water pressures and slope displacements in cut slopes. Inclinometer measurements from a heavily vegetated, cut slope in high-plasticity clay showed shallow (up to 3 m below ground level), shrink-swell movement in response to seasonal pore water pressure changes. Winter swelling of the slope occurred upward and outward in response to increased pore water pressures. Pore water pressures reduced in the summer, causing shrinkage that was downward and slightly inward. The shrink-swell movements showed net downslope displacement over successive annual cycles, leading to shallow instability. In another 5 m high cut slope, inclinometer and extensometer measurements showed summer settlement and winter heave displacements (Ridley, 2017) linked to reducing pore water pressures at shallow depth (1.5 mbgl) in the summer months and increasing pore water pressures in the winter months. This gave a net downward and outward slope displacement of more than 15 mm and 25 mm respectively, over three annual shrink-swell cycles.

Saffari & Ridley (2022) showed that mature trees created large cyclic, seasonal deformations and pore water pressures in a cut slope on the London Underground Ltd network (Figure 8). The trees on the high-plasticity clay slope induced seasonal pore water pressures cycles of up to 60 kPa and there was a clear pattern of cyclic, downslope displacement. The trees were later removed from the slope during remedial works and the seasonal deformations were reduced. However, the downslope displacements rapidly increased due to the reactivation of an existing shear surface that had been identified prior to the works.

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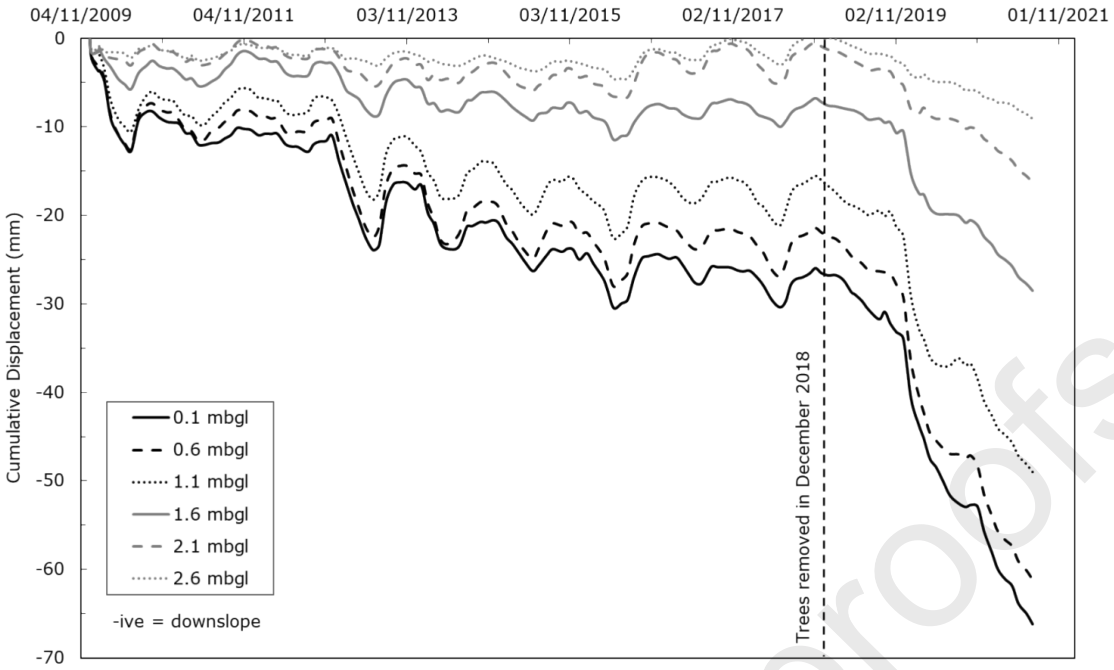

Figure 8: Inclinometer measurements at shallow depth in a high-plasticity cut slope on the London Underground Ltd network (redrawn from Saffari & Ridley, (2022), with data courtesy of Geotechnical Observations Limited).

Slope-scale simulations of the weather-driven deterioration of earthwork slopes

Slope-scale simulations show that weather-driven changes in moisture content and pore pressure within clay earthwork slopes can lead to cyclic and permanent slope deformation (Q2 in Figure 3), as shown by *in situ* observations and centrifuge modelling. Slope deformation and accumulated strain over many cycles can permanently strain-soften clay soils. This reduces their shear strength and reduces the stability of earthwork slopes (Q4 in Figure 3). However, current slope-scale simulations do not incorporate some of the material-scale deterioration processes outlined in Stirling et al., (2021). These include the simulation of macro-scale deformation features, irrecoverable micro-scale deformation and changes in soil water retention.

Numerical simulations of clay cut slopes have demonstrated the mechanism of deep-seated progressive cutting slope failure caused by the release of high lateral soil stresses and subsequent swelling following slope excavation (Potts et al., 1997; Ellis & O'Brien, 2007). The simulations showed that the rate of progressive failure was influenced by the hydraulic conditions at the slope surface and that the application of a suction delayed the development of slope failure. Simulations of progressive slope failure in clay fill embankments due to seasonal pore pressure cycling (Kovacevic et al, 2001; Nyambayo et al., 2004; Rouainia et al., 2009) showed that the time to slope failure was influenced by the saturated permeability (K_{sat}) of the soil and the hydraulic boundary conditions at the slope surface. Nyambayo et al., (2004) used a hydraulic boundary at the slope surface that cycled between conditions representative of summer (25-200 kPa suction for 6 months) and winter

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(10 kPa suction for 6 months). Sensitivity analyses showed that the progressive failure of relatively high-permeability earthworks (K_{sat} = 10^{-7} m/s or 10^{-8} m/s), such as clay fill embankments, could be accelerated by repeated pore pressure cycles. But this was less evident in simulations with lower-permeability fill ($K_{sat} < 10^{-9}$ m/s). Similar simulations and sensitivity analyses of clay fill embankments (O'Brien, 2013) showed that maintaining soil suction in the near surface (0-1 mbgl) of a slope for the winter condition reduced the deterioration rate of the soil strength and increased the number of winter/summer cycles required for slope failure. The simulations also showed ratcheting-type deformation of the embankment slopes prior to collapse and linked these to observations from the London Underground Ltd (LUL) network.

Rouainia et al., (2009) simulated the daily hydrological and mechanical behaviour of the clay cut slope at Newbury monitored by Smethurst et al., (2006) using weather data and material properties obtained from *in situ* and laboratory testing. The model showed that the pore pressures and cyclic slope displacements were responsive to daily weather conditions and were sensitive to prolonged wet winters and extremely dry summers. Further improvements to the hydrological part of the models were used to more accurately simulate *in situ* observations. These included the incorporation of unsaturated flow (Rouainia et al., 2009; O'Brien, 2013), vegetation at the slope surface (Scott et al., 2007; Briggs et al., 2016; Tsiampousi et al., 2017) and varied permeability with depth to represent surface weathering and the differences between clay fill and intact natural clay (Loveridge et al., 2010; Briggs et al., 2013; Rouainia et al., 2020).

Numerical simulations by Postill et al., (2020) showed that cyclic stress changes induced by wetting and drying at the surface of a clay slope could drive downslope ratcheting displacements (Figure 9) and progressive failure. A coupled hydro-mechanical model was validated against physical measurements from a 140 mm high, 1/60th scale, Speswhite Kaolin centrifuge model slope subjected to surface wetting and drying in a climate chamber (Take, 2003; Take & Bolton, 2011). Take & Bolton (2011) showed that cyclical variation in soil moisture content can drive effective stress changes in a Speswhite Kaolin clay slope and temporarily mobilise super-critical stress ratios in wet periods, causing successive dilatant softening, plastic strain accumulation, and leading to progressive failure. Postill et al., (2020) simulated the seasonal ratcheting deformations measured by Take & Bolton (2011) for different initial stress conditions. Additional sensitivity analyses by Postill et al., (2020) showed that the material stiffness controlled the rate of strength deterioration in the slope simulations, with stiffer materials showing a more gradual accumulation of irrecoverable strains and softening than less-stiff materials.

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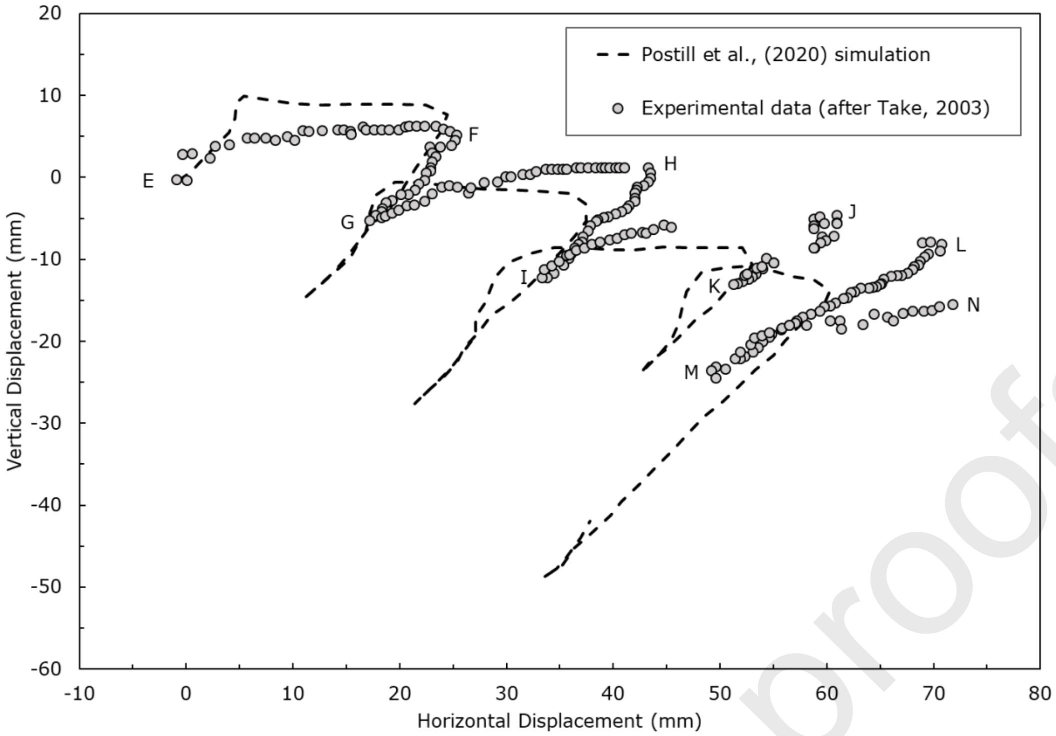

Figure 9: Vertical and horizontal displacements at the toe of a physical centrifuge slope model (grey circles) and numerical model (black dashed line) showing ratcheting deformations in response to wetting and drying cycles (E-N). Redrawn from Postill et al., (2020).

Postill et al., (2021) simulated displacements in a high-plasticity cut slope in response to seasonal pore pressure cycles, driven by a climate boundary condition. The coupled, saturated and unsaturated, hydro-mechanical model was validated using 16 years of monitoring data obtained from the cut slope at Newbury (e.g. Figure 6; Smethurst et al., 2012; Smethurst et al., 2022). It was then used to forecast the long-term deformation and failure of the cutting using 90 years of synthetic weather data. The synthetic weather data was calibrated to the regional weather baseline for 1961 to 1990 and therefore did not include climate change projections.

The simulations showed shrink-swell displacements at the mid-slope and toe of the cut slope in response to weather-driven pore water pressure cycles. They showed a cumulative upward and outward swelling of the slope at shallow depth during the first 15-20 years after construction and at greater depth (5 to 10 m below ground level) until approximately 50 to 80 years after construction. These displacements can be associated with post-construction stress relief and the dissipation of excess pore pressures generated during the construction of low permeability clay slopes (Vaughan & Walbancke, 1973). However, after approximately 15 years, the cut slope simulations also showed cumulative, downslope, near surface ratcheting deformation. These compare with the pattern of cumulative downslope displacements observed on high-plasticity cut slopes (Figure 8; Ridley 2012; Ridley 2017; Saffari & Ridley, 2022) and shown in similar simulations of embankment slopes (Morsy et al., 2023a; Morsy et al., 2023b). The Postill et al., (2021) cut slope simulations showed upward and outward mid-slope displacements in periods of wet winter weather, followed by downward, inward displacements in the drier summer months (Figure 10). The annual increments of downslope displacement increased with successive seasonal wetting and drying cycles. This caused the accumulation of plastic shear strains that initiated at the slope toe and were correlated with increased average pore water pressure. The plastic shear strains led to localised strain-softening, the redistribution of stresses and the progressive development of slope failure. A calculation of the slope factor of safety (FoS) at annual increments showed that it gradually reduced towards slope failure (FoS < 1) approximately 90 years after construction (Figure 11).

Postill et al., (2021) used a sensitivity analysis to compare the model behaviour with and without strain-softening. This confirmed that the initial reduction of the slope FoS was solely due to post-construction pore pressure dissipation, as described by Vaughan & Walbancke (1973). However, beyond the initial 10- to 15-year period, the reduction of the slope FoS (also shown as the magnitude of deterioration) was increasingly driven by material strain-softening in response to seasonal pore water pressure cycles (Figure 11). This demonstrates that the long-term reduction in slope stability was due to a permanent reduction in shear strength and not only in response to the reversible pore pressure changes. This reduction in the long-term slope FoS helps to explain *in situ* observations that cut slope failures can be triggered by wet winter weather conditions (and a subsequent pore water pressure increase) that are less onerous than past conditions.

Slope stability analyses carried out using a strength reduction approach at discrete points during the simulation showed that the critical slope failure surface changed from a deep seated, rotational failure mechanism during the first 25 years of the simulation, to a shallow translational failure mechanism in subsequent years (Figure 12). The shallow translational failure mechanism was driven by strain softening due to downslope ratcheting in the near surface of the cut slope, where seasonal pore pressure and stress cycles were greatest.

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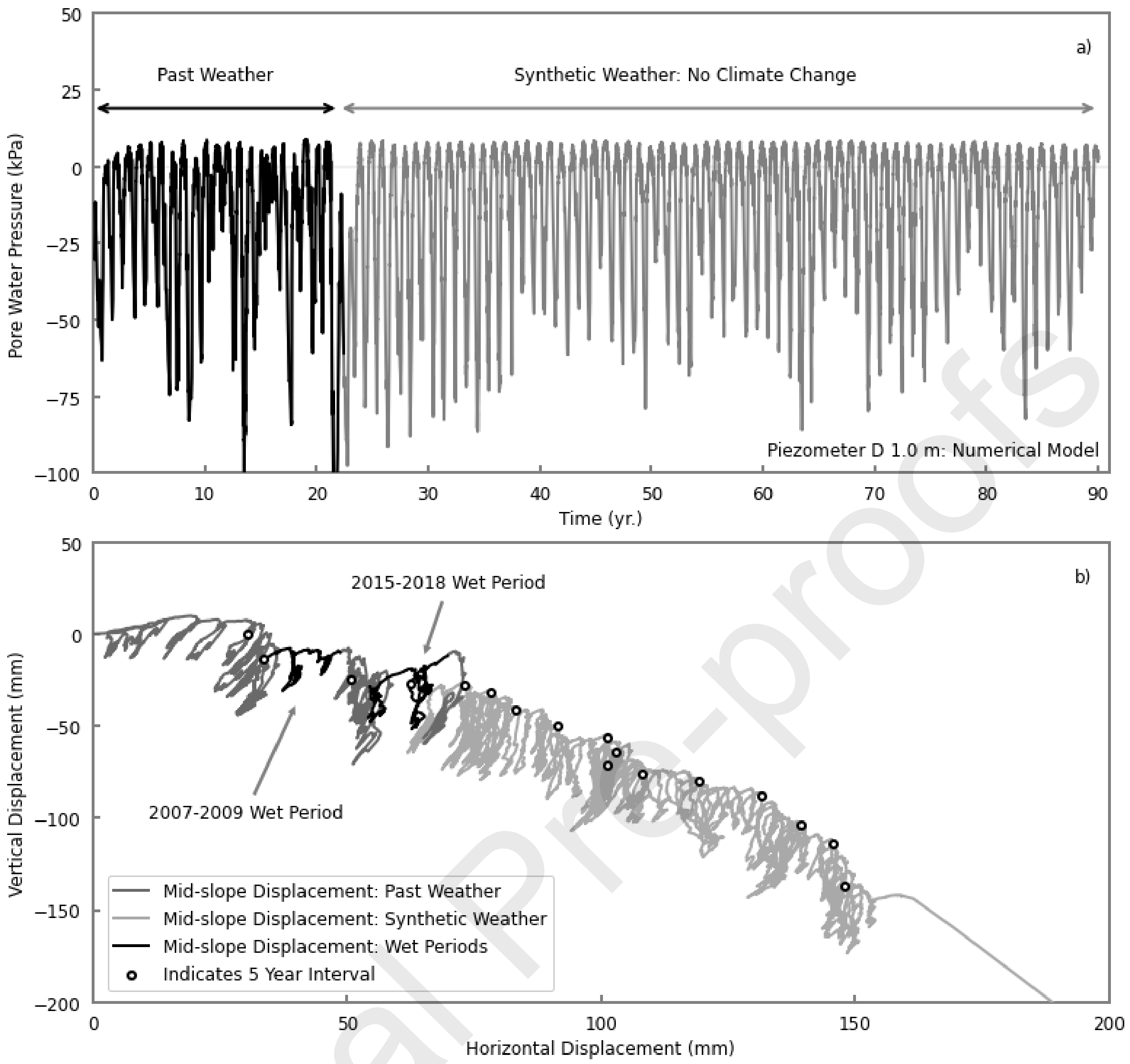

Figure 10: (a) Pore water pressures, and (b) mid-slope displacements simulated in a hydro-mechanical model of a high-plasticity clay cut slope, in response to measured weather data and synthetic weather data (from Postill et al., 2021 and Helm et al., 2023). (Courtesy of 4.0 International (CC BY 4.0))

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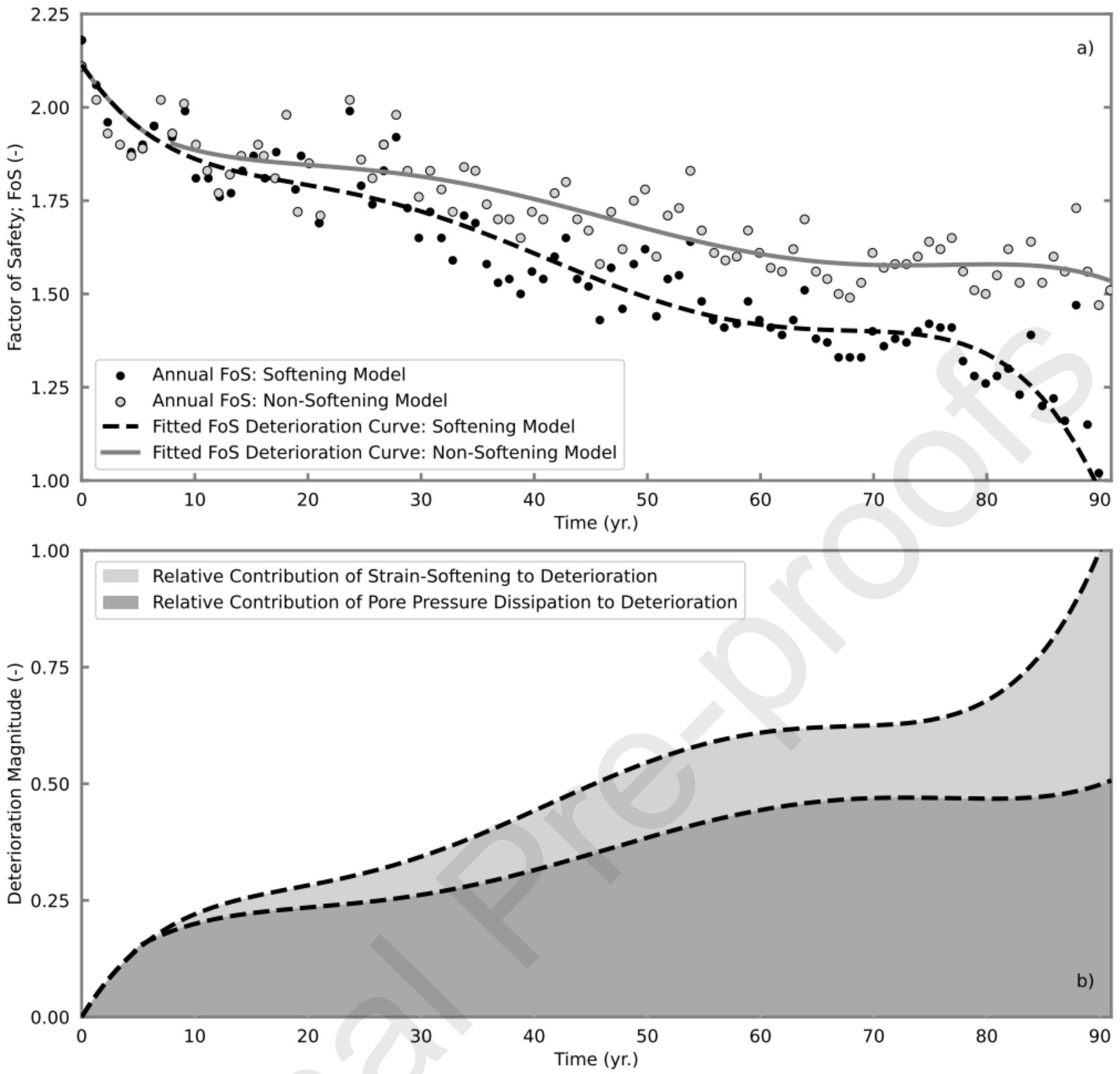

Figure 11: The change in cut slope (a) factor of safety and (b) deterioration for a softening and non-softening material model (from Postill et al., 2021 and Helm et al., 2023). Note that the deterioration magnitude is defined between the maximum factor of safety and the factor of safety at failure (Courtesy of 4.0 International (CC BY 4.0))

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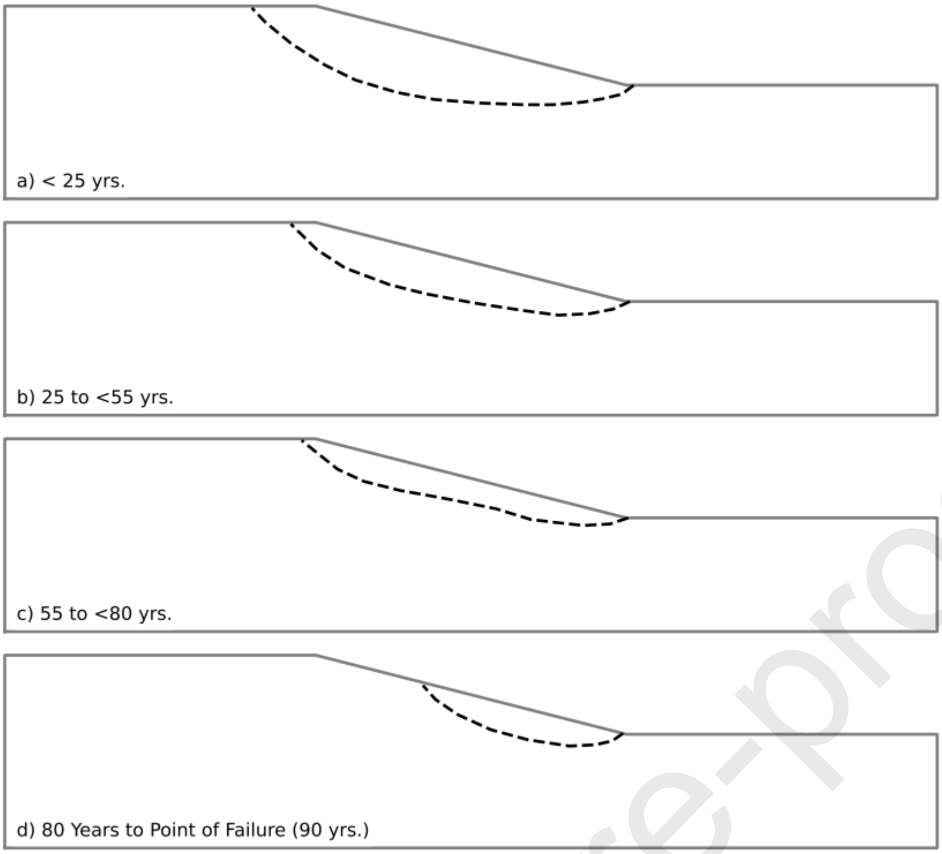

Figure 12: Critical failure surfaces in simulations of cut slopes after a) <25 years; b) 25 to < 50 years; c) 55 to <80 years and d) ≥ 80 years (from Postill et al., 2021). (Courtesy of 4.0 International (CC BY 4.0))

The impact of climate change projections on earthwork slopes

The evidence from the current climate shows that seasonal pore water pressure cycles drive progressive earthwork deterioration, while increased pore water pressures can trigger earthwork failures (Q4 in Figure 3). The projected change in future climate contributes to this in at least three ways: (i) long-term changes in weather and the soil water balance will alter the magnitude and frequency of pore water pressure cycles within earthworks; (ii) the increased magnitude of extreme weather events such as extreme rainfall events or evaporative drying will cause pore water pressure extremes that are in excess of historic values; (iii) a changing climate may alter the slope surface itself, including but not limited to creating more extensive desiccation cracking or changing the type of slope vegetation cover. The UK Climate Projections 2018 (UKCP18) show that the UK will experience warmer, drier summers (i.e. higher temperatures and less rainfall) and wetter winters (i.e. increased rainfall) than at present (Murphy et al., 2018). They also show an increased frequency of extreme weather events (Lowe et al., 2018; Murphy et al., 2018). This is also the projection for climate change across north-western Europe (Vardon, 2015). However, the impact of climate change on earthwork deterioration is dependent on water transfer in atmosphere-vegetation-soil interactions and on the condition of the earthworks themselves (Dijkstra & Dixon, 2010; Tang et al., 2018).

The historic evidence, for 2003-2020, shows a correlation between the rate of railway earthwork failures and extreme rainfall events or prolonged periods of wet winter weather

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(Mair, 2021). For example, there was significant disruption to the rail network in the southeast of England following the wet winter of 2000/2001, including 30 earthworks failures that caused line blockages (Birch & Dewar, 2002; Loveridge et al., 2010). This was the wettest winter since records began in 1766, with precipitation that was 196% of the long-term average (LTA). During the same winter (2000/2001), a 200 m long section of cut slope failed adjacent to the heavily trafficked M25 orbital motorway near London and threatened its closure (Davies et al., 2003; Power & Abbott, 2019). Heavy rainfall in the winter of 2019/2020 led to 250 earthworks failures across Great Britain in 2019/2020. The following summer, heavy rainfall led to an earthwork failure and a train derailment at Carmont, Scotland in August 2020 (Haines, 2021).

Observations show increased pore water pressures and slope instability within some earthworks following extreme rainfall events and prolonged periods of wet weather, but not in all earthworks. Measurements on the London Underground Ltd network following the wet winter of 2000/2001 showed that pore water pressures increased towards hydrostatic within the clay fill of some embankments, including those with trees on the embankment slopes. However, they also showed that in many cases this did not occur (Ridley et al., 2004). Briggs et al., (2013) reviewed these measurements and carried out simple hydrological simulations comparing pore water pressures generated for different extreme weather scenarios and embankment foundation conditions. This showed that pore water pressures could increase towards hydrostatic in clay fill embankments founded on a low permeability soil (such as London Clay), but that pore water pressures did not increase in clay fill embankments that were under-drained by a more permeable foundation (such as chalk or river terrace deposits), even during extremely wet winters.

Clarke & Smethurst (2010) used a water balance model and outputs from a weather generator (Kilsby et al., 2007) to consider the impact of projected climate change scenarios on long term soil moisture content changes in clay earthworks across England. The model considered the hotter, drier summers and wetter winters that were forecast in the UK Climate Impact Programme 2002 (UKCIP02) for the 2020s, 2050s and 2080s time periods (Hulme et al., 2002). The analyses considered clay earthworks, with grass slope cover, at four locations across England. The results showed that for the forecast time periods, relative to the baseline, the earthworks were drier; the maximum summer SMD increased, the duration of summer and autumn drying was longer and a larger SMD was sustained through the winter months (Figure 13). They also showed that the magnitude of seasonal soil moisture cycles increased for all three UKCIP02 time periods, relative to the 1961-1990 control period. Huang et al., (2023) used numerical simulations to consider the influence of climate change on earthwork pore water pressures using UKCP18 local projections (Murphy et al., 2018) for London. This showed that the projected increase in winter rainfall will not lead to more onerous pore water pressure conditions in earthworks across the London Underground Ltd network. However, in agreement with Smethurst & Clarke (2010), the simulations showed that there will be seasonal soil wetting and drying cycles of increased magnitude relative to the present condition, which may accelerate the weather-driven deterioration of earthworks. Similarly, Tang et al., (2018) showed that changing climatic conditions will increase freeze-thaw cycles, shrink-swell movements and alter pore water

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pressure cycles, leading to the accelerated deterioration of infrastructure earthworks across Europe.

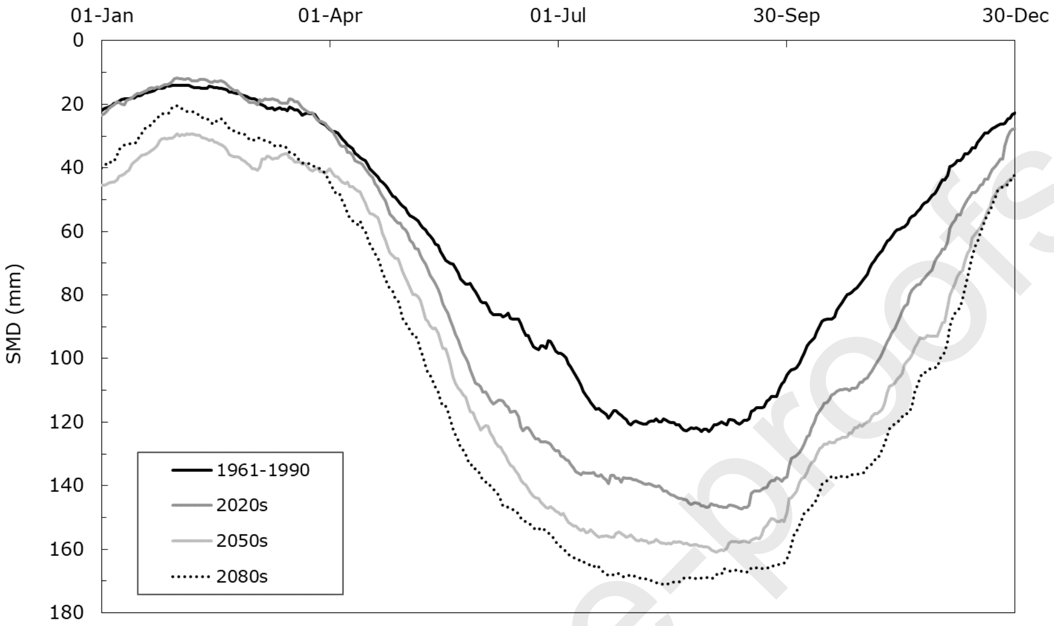

Figure 13: Average daily soil moisture deficit (SMD) for grass vegetation cover in London for 1961-1990 and for projections of the 2020s, the 2050s and the 2080s, under the UKCIP02 Medium High emission scenario (adapted from Clarke & Smethurst, 2010).

Numerical simulations have been used to consider the hydrological and mechanical response of earthworks to specific climate change scenarios. Rouiania et al., (2020) used surface pore water pressures from a hydrological model as inputs to a coupled fluid-mechanical model (Rouainia et al., 2009) of the high-plasticity clay cut slope in Newbury, England (Smethurst et al., 2006; Smethurst et al., 2012). The hydrological model used a weather generator to create 100 years of daily, synthetic weather data for a baseline time period (1961-1995) and for a drier, more variable, future climate scenario based on the UK Climate Projections 2009 (UKCP09) data (Jones et al., 2009). The results showed that the model subjected to the future climate scenario was drier (with lower moisture content and pore water pressures) than the model subjected to the baseline time period scenario. However, larger seasonal pore water pressure variations were generated in the model subjected to future climate. Over time, this increased the rate of mid-slope displacement, strain softening and strength reduction in the model subjected to future climate and decreased the time to failure, relative to the model subjected to the baseline time period. The Rouiania et al., (2020) simulations showing larger seasonal pore water pressure cycles for future climate scenarios is in broad agreement with models of earthwork hydrology in London and the southeast of England (Smethurst & Clarke, 2010; Huang et al., 2023). However, this is not necessarily applicable to other geographical locations with a different climate and underlying geology, or for natural slopes (e.g. Robinson et al., 2017; Pk et al., 2018).

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Discussion: Implications for the management of ageing earthworks

There are no commonly agreed standards for the management of earthworks as geotechnical assets in the UK (Power & Abbott, 2019). Therefore, major asset owning organisations such as those shown in Figure 2 have developed their own approaches in alignment with national and international standards (British Standards Institution, 2008; British Standards Institution, 2014) for the management of physical assets. Spink (2020) describes the risk-based approach adopted by transportation earthwork owners to identify the most vulnerable and critical earthworks within their networks. The risk assessment and management of ageing earthworks within these networks therefore benefits from an understanding of how weather-driven deterioration can alter the likelihood of an earthwork failure (safety or serviceability failure) occurring. Two examples are described, showing forecasts of the weather-driven deterioration and failure of ageing, clay cut slopes within a UK transportation network.

Postill et al., (2023) used numerical simulations of high-plasticity clay cut slopes (based on those of Postill et al., 2020) to compare the time to first-time failure for different slope geometries in response to scenarios of slope strength deterioration, driven by seasonal wetting and drying cycles. The simulations in Postill et al., (2023) included a strain-softening material model (Postill et al., 2020) and a hydrological flux surface boundary condition calibrated to produce summer (-40 kPa) and winter (0 kPa) pore water pressure conditions. They were validated by comparison with centrifuge modelling results (Take & Bolton, 2011; Postill et al., 2020). Postill et al., (2023) produced a framework relating the number of annual pore water pressure cycles (failure time) required to trigger the failure of the slopes, for varied slope geometries. The framework (Figure 14) relates the slope angle and slope height to the failure time in four categories ranging from 60 to 120 cycles. Figure 14 shows that short (< 3m) and relatively shallow (37.5^{o}) slopes did not fail after life seasonal cycles. But the failure time reduced for slopes that were steeper and/or taller than this. This framework does not provide forecasts, but can be used to identify the comparative impact of weather-driven slope deterioration on earthwork stability for different slope geometries.

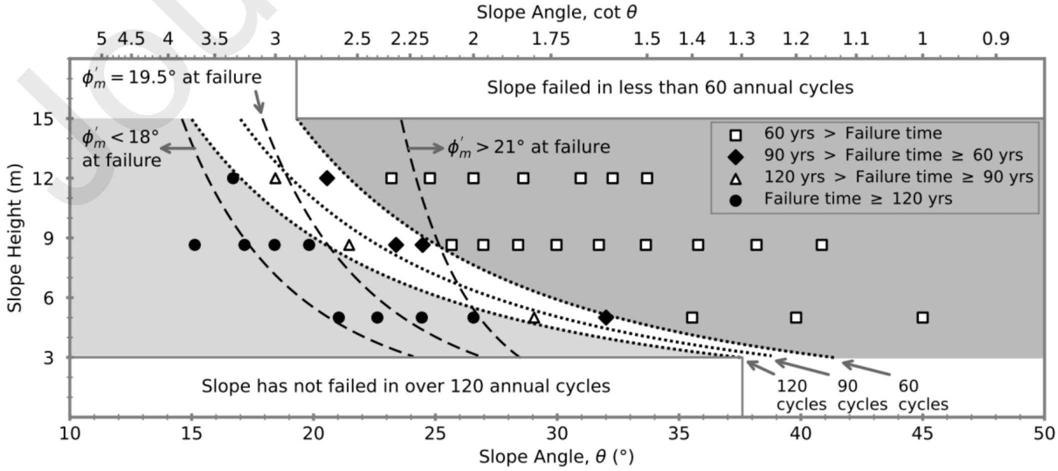

Figure 14: A framework for the number of cycles to failure in high-plasticity, strain-softening, clay cut slopes for varied slope geometries (from Postill et al., 2023 and Helm et al., 2021). Note that φ'$_m$ is the mobilised friction angle. (Courtesy of 4.0 International (CC BY 4.0))

Svalova et al., (2021) used a statistical emulator (a Gaussian process Bayesian surrogate model) to make time to failure predictions for high-plasticity clay cut slopes, based on 900 combinations of five slope geometry and material parameters. These parameters were the slope height (H), slope angle (θ), soil peak cohesion (c_p'), soil peak friction angle (ϕ_p') and the near surface reference permeability, controlling the permeability change with depth (k_{ref}). A Latin hypercube design was used to investigate the influence of these five parameters on the time to failure using a minimal number of numerical simulations. The emulator used training data from 76 numerical simulations of weather-driven deterioration in strain-softening, clay cut slopes in response to synthetic weather data, as developed in Postill et al., (2021). The range of slope geometries were chosen to be representative of 1,566 liDAR profiles for cut slopes on the M4 motorway and Great Western Railway between London and Bristol, UK. The Svalova et al., (2021) analyses showed that the time to slope failure was most sensitive to changes in the slope angle and slope height. For example, Figure 15 shows this result for a slope with peak strength material properties close to those reported for London Clay (Postill et al., 2021). The statistical surrogate model (emulator) can be used to compare the forecast time to failure for a range of idealised cut slope geometries and material properties. Given the assumptions in the model, the results can be used to compare the stability of earthworks within a whole transportation route or network. However, the consideration of site specific factors (e.g. the slope condition, composition, drainage condition) is required to understand the true stability of individual earthworks and to inform asset management decisions (Adey, 2019; Trinidad Gonzalez et al., 2023).

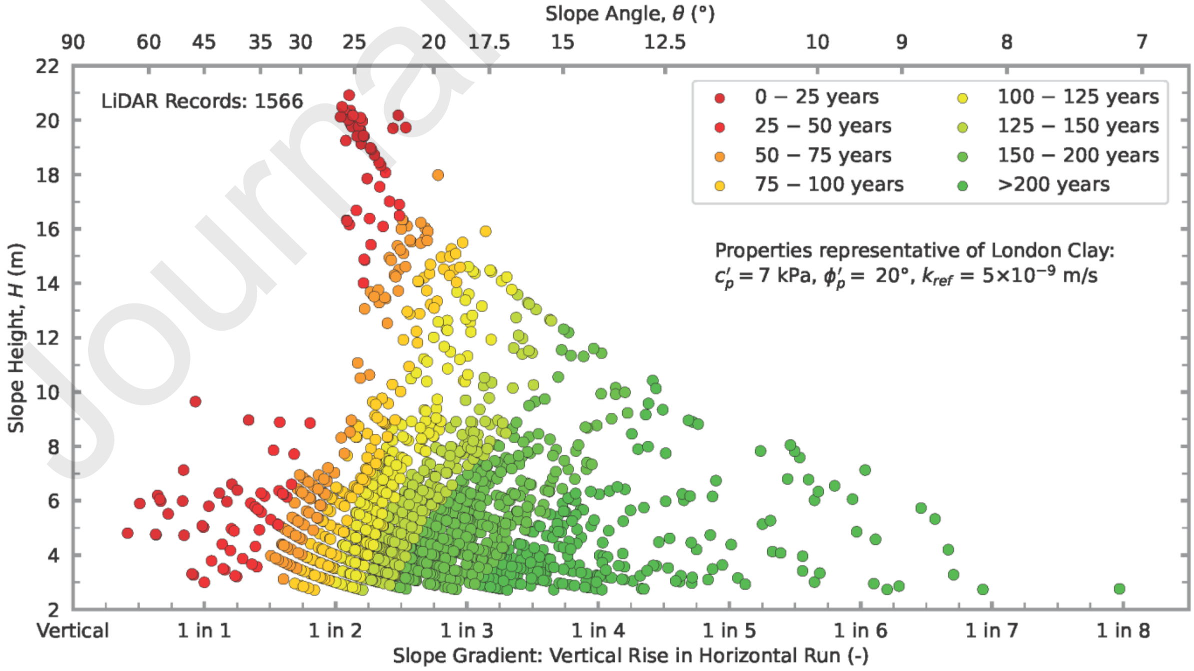

Figure 15: The expected time to failure (years) of high-plasticity earthworks representative of London Clay, for 1566 slope geometries on the London-Bristol transportation corridor (adapted from data in Svalova, et al., 2021). The material parameters for soil cohesion (c'$_p$), friction angle (φ'$_p$) and reference permeability (k$_{ref}$) are shown. (Courtesy of 4.0 International (CC BY 4.0))

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Conclusions

The results presented in this review show that ageing, clay transportation earthwork slopes deteriorate in response to weather-driven wetting and drying (Figure 3). Weather-driven deterioration becomes more significant as the earthworks age, after many seasonal wetting and drying cycles. The following conclusions can be drawn from these results:

1. There is clear evidence that earthworks (both cut slopes and embankments) supporting transportation infrastructure in the UK are influenced by seasonal weather cycles and their cumulative effect over many decades. The net infiltration of water during the winter months and the net removal of water during the drier summer months drives seasonal changes in moisture content and pore water pressure in the near surface, and longer-term changes at greater depth. The magnitude and depth of seasonal pore water pressure variation is influenced by the long-term weather conditions, the permeability of the earthwork soil and the type of slope vegetation. Critically, the soil permeability (the saturated hydraulic conductivity) can vary by up to four orders of magnitude within the near surface of earthwork slopes and can temporally change in response to the formation of surface cracks and fissures.

2. The mechanism of seasonal slope ratcheting will become an increasingly dominant driver of shallow failures in high-plasticity cut slopes as they age beyond the initial period of excess pore water pressure dissipation, swelling and risk of deep-seated slope failure (at approximately 80 years). Hydro-mechanical slope simulations show that irreversible, downslope, ratcheting displacements increased incrementally in response to annual wetting and drying cycles, with particularly large displacement increments during periods of prolonged wet weather. This is supported by *in situ* evidence showing seasonal ratcheting and downslope displacements in ageing, high-plasticity cut slopes.

3. Simulations of earthwork hydrology in London show that UK climate change projections will not make maximum pore water pressure conditions (a trigger for earthwork failure) more onerous. However, the magnitude of seasonal pore water pressure cycles will increase. Hydro-mechanical simulations of a cut slope in high-plasticity clay showed that greater pore water pressure cycles will increase the rate of strength reduction due to cyclic strain-softening. This will reduce the resistance to slope failure. Therefore, projected climate change may reduce the soil strength and the remaining time to failure for cut slopes in high-plasticity clays that have already experienced significant deterioration and loss of strength post-construction. Such slopes are more vulnerable to failure in periods of elevated pore water pressure than they were in less onerous weather conditions during the earlier, more reliable stage of their life.

4. Forecasts show that the time to failure of cut slopes in high-plasticity clay is sensitive to the slope geometry (i.e. the slope angle and slope height). Both a strength parameter framework and a statistical surrogate model (emulator) were used to forecast the time to failure of cut slopes representative of those on the UK's transportation network. The results showed that relatively low height and shallow slopes did not fail after 100 seasonal pore

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water pressure cycles, but the time to failure reduced for slopes that were steeper or taller. Such models can be used to forecast the rate of slope failures within a route of earthworks based on their age. This can allow asset managers to identify slopes with the highest likelihood of failure and prioritise planned investigations or assessments at individual sites.

5. Research into the failure of ageing transportation earthworks has mostly focused on high-plasticity clays in the southeast of England. This may be because they are associated with the greatest number of earthwork failures on the UK's highway and railway networks. Forecasts confirm that some of these slopes will continue to be vulnerable to failure as they continue to age and in response to long-term changes in climate. However, there is less information, less research and therefore less evidence for the changing vulnerability of other earthwork types in response to ageing and climate change. This includes earthworks formed from low and intermediate-plasticity clays and earthworks that are subjected to different, and often wetter weather conditions than the southeast of England.

6. Some processes that were identified in the conceptual model of clay fill deterioration (Stirling et al., 2021) have been observed *in situ*, but have not yet been incorporated into slope-scale simulations and forecasts of earthwork behaviour. These include, but are not limited to, the influence of changing soil water retention properties and changes in soil microstructure. There is limited evidence for the influence of these processes on forecasts of earthwork behaviour, and how they may change in the future.

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References

Adey, B.T. (2019). A road infrastructure asset management process: gains in efficiency and effectiveness. *Infrastructure Asset Management* 6(1): 2–14, https://doi.org/10.1680/jinam.17.00018

Anderson, M.G. and Kneale, P.E., (1980). Pore water pressure and stability conditions on a motorway embankment. *Earth surface processes*, 5(1), pp.37-46.

Anderson, M. G., Hubbard, M. G., & Kneale, P. E. (1982). The influence of shrinkage cracks on pore-water pressures within a clay embankment. *Quarterly Journal of Engineering Geology and Hydrogeology*, 15(1), 9-14.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. Food and Agricultural Organisation's Irrigation and Drainage Paper 56.

Azizi, A., Musso, G. & Jommi, C. (2019). Effects of repeated hydraulic loads on microstructure and hydraulic behaviour of a compacted clayey silt. *Can. Geotech. J.* 57, No. 1, 100–114, https://doi.org/10.1139/cgj-2018-0505.

Biddle, P. G. (1983). Patterns of soil drying and moisture deficit in the vicinity of trees on clay soils. *Géotechnique* 33, No. 2, 107–126, http://dx.doi.org/10.1680/geot.1983.33.2.107.

Biddle, P. G. (1998). *Tree root damage to buildings*. Wantage, UK: Willowmead Publishing.

Birch, G. P., & Dewar, A. L. (2002). Earthwork failures in response to extreme weather. In *Proceedings of the international conference railway engineering 2002*, held in London, UK, July 2002-CD ROM.

Blake, A., Smethurst, J., Yu, Z., Brooks, H., Stirling, R., Holmes, J., Watlet, A., Whiteley, J., Chambers, J., Hughes, P. and Smith, A., (2022). Long-term monitoring of long linear geotechnical infrastructure for a deeper understanding of deterioration processes. In *11th International Symposium on Field Monitoring in Geomechanics*. Imperial College London, UK, 4-7 September 2022.

Blight, G. E. (1997). Interactions between the atmosphere and the earth. *Géotechnique* 47, No. 4, 715–767.

Briggs, K.M., Smethurst, J.A., Powrie, W. and O'Brien, A.S., (2013). Wet winter pore pressures in railway embankments. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 166(5), pp.451-465.

Briggs, K.M., Smethurst, J.A., Powrie, W. and O'Brien, A.S., (2016). The influence of tree root water uptake on the long term hydrology of a clay fill railway embankment. *Transportation Geotechnics, 9*, pp.31-48.

Briggs, K.M., Loveridge, F.A. and Glendinning, S., (2017). Failures in transport infrastructure embankments. *Engineering Geology*, 219, pp.107-117.

Journal Pre-proofs

Briggs, K.M.; Dijkstra, T.A.; Glendinning, S. (2019). Evaluating the Deterioration of Geotechnical Infrastructure Assets Using Performance Curves. In *Proceedings of the International Conference on Smart Infrastructure and Construction 2019 (ICSIC)*, Cambridge, UK, 8–10 July 2019; pp. 429–435.

British Standards Institution, (2008). *Publicly Available Specification (PAS) 55, Asset Management*. *Part 1: Specification for the optimized management of physical assets*. London: British Standards Institution.

British Standards Institution, (2014). *BS ISO 55000: Asset management. Overview, principles and terminology*. London: British Standards Institution.

Chambers, J.E., Gunn, D.A., Wilkinson, P.B., Meldrum, P.I., Haslam, E., Holyoake, S., Kirkham, M., Kuras, O., Merritt, A. and Wragg, J., (2014). 4D electrical resistivity tomography monitoring of soil moisture dynamics in an operational railway embankment. *Near Surface Geophysics*, 12(1), pp.61-72.

Chandler RJ, Skempton AW (1974) The design of permanent cutting slopes in stiff fissured clays. *Geotechnique* 24:457–466. doi:10.1680/geot.1974.24.4.457.

Clarke, D. & Smethurst, J.A. (2010) Effects of climate change on cycles of wetting and drying in engineered clay slopes in England. *Quarterly Journal of Engineering Geology and Hydrogeology*, 43(4), pp.473-486.

Cooper MR, Bromhead EN, Petley DJ, Grant DI (1998) The Selborne cutting stability experiment. *Geotechnique* 48:83–101.

Cui, Y.J., Gao, Y.B. and Ferber, V., (2010). Simulating the water content and temperature changes in an experimental embankment using meteorological data. *Engineering Geology*, *114*(3-4), pp.456-471.

Davies, JP; Loveridge, F A; Perry, J; Patterson, D and Carder, D (2003). Stabilisation of a Landslide on the M25 Highway London's Main Artery. *12th Pan-American Conference on soil mechanics and geotechnical engineering*. 22-25 June 2003.

Department of Transport (2014). *Class investigation into landslips affecting Network Rail infrastructure between June 2012 and February 2013*. Rail Accident Investigation Branch, Department for Transport, 08/2014.

Dijkstra, T. & Dixon, N. (2010). Climate change and slope stability in the UK: challenges and approaches. *Quarterly Journal of Engineering Geology and Hydrogeology*, 43, 371–385, https://doi.org/10.1144/1470-9236/09.036.

Dixon, N., Crosby, C.J., Stirling, R., Hughes, P.N., Smethurst, J., Briggs, K., Hughes, D., Gunn, D., Hobbs, P., Loveridge, F. and Glendinning, S., (2019). In situ measurements of near-surface hydraulic conductivity in engineered clay slopes. *Quarterly Journal of Engineering Geology and Hydrogeology*, 52(1), pp.123-135.

Journal Pre-proofs

Dyer, M., Utili, S. and Zielinski, M., (2009), June. Field survey of desiccation fissuring of flood embankments. In *Proceedings of the Institution of Civil Engineers-Water Management* (Vol. 162, No. 3, pp. 221-232). Thomas Telford Ltd.

Ellis, E.A. and O'Brien, A.S., (2007). Effect of height on delayed collapse of cuttings in stiff clay. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 160(2), pp.73-84.

Fookes, P.G., (1997). Geology for engineers: the geological model, prediction and performance. *Quarterly Journal of Engineering Geology and Hydrogeology*, 30(4), pp.293-424.

Freeze, R.A. and Cherry, J.A. (1979) *Groundwater*. Englewood Cliffs ; London: Prentice-Hall. ISBN: 0-13-365312-9.

Garrett, C., Wale, J.H., (1985). Performance of embankments and cuttings in Gault Clay in Kent. From *Proceedings of the Symposium on Failures in Earthworks,* Organized by the Institution of Civil Engineers, Held in London, March 6–7, 1985.

Greenwood, J.R., Holt, D.A., Herrick, G.W., (1985). Shallow slips in highway embankments constructed of overconsolidated clay. From *Proceedings of the Symposium on Failures in Earthworks*, Organized by the Institution of Civil Engineers, Held in London, March 6–7, 1985.

Gregory, C.H., (1844). On railway cuttings and embankments; with an account of some slips in the London Clay, on the line of the London and Croydon Railway In *Minutes of the Proceedings of the Institution of Civil Engineers* (Vol. 3, No. 1844, pp. 135-145). Thomas Telford-ICE Virtual Library.

Glendinning, S., Hughes, P., Helm, P., Chambers, J., Mendes, J., Gunn, D., Wilkinson, P. and Uhlemann, S., (2014). Construction, management and maintenance of embankments used for road and rail infrastructure: implications of weather induced pore water pressures. *Acta Geotechnica*, 9, pp.799-816.

Haines, A., (2021). Resilience of rail infrastructure: Update report to the Secretary of State for Transport following the derailment at Carmont, near Stonehaven. *Network Rail: London*, UK.

Helm P, Postill H, Dixon N, El-Hamalawi A, Glendinning S, Take A. (2021). Dataset: Strength parameter selection framework for evaluating the design life of clay cut slopes. Newcastle University. Dataset. https://doi.org/10.25405/data.ncl.16598672.

Helm P, Postill H, Dixon N, Glendinning S, Smethurst J, Rouainia M, Briggs K, El-Hamalawi A, . Blake A. (2023). Data: Forecasting the long-term deterioration of a cut slope in high-plasticity clay using a numerical model. Newcastle University. Dataset. https://doi.org/10.25405/data.ncl.19762144

Henkel DJ, Skempton AW (1955) A landslide at Jackfield, Shropshire, in a heavily overconsolidated clay. *Geotechnique* 5:131–137.

Journal Pre-proofs

Holmes, J., Chambers, J., Wilkinson, P., Dashwood, B., Gunn, D., Cimpoiaşu, M., Kirkham, M., Uhlemann, S., Meldrum, P., Kuras, O. and Huntley, D., (2022). 4D electrical resistivity tomography for assessing the influence of vegetation and subsurface moisture on railway cutting condition. *Engineering Geology*, *307*, p.106790.

Huang, W., Loveridge, F.A., Briggs, K.M. and Smethurst, J.A., (2023). Effect of climate change on pore-water pressure regimes for design and assessment of clay earthworks. Published ahead of print in *Quarterly Journal of Engineering Geology and Hydrogeology. https://doi.org/10.1144/qjegh2023-015*

Huggett, R. and Shuttleworth, E., (2022). *Fundamentals of geomorphology*. Taylor & Francis.

Hughes, P.N., Glendinning, S., Mendes, J., Parkin, G., Toll, D.G., Gallipoli, D. and Miller, P.E., (2009). Full-scale testing to assess climate effects on embankments. In *Proceedings of the Institution of Civil Engineers-Engineering Sustainability* (Vol. 162, No. 2, pp. 67-79). Thomas Telford Ltd.

Hughes, D., Sivakumar, V., Glynn, D. and Clarke, G., (2007). A case study: delayed failure of a deep cutting in lodgement till. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 160(4), pp.193-202.

Hulme, M., Jenkins, G.J., Lu, X. Turnpenny, J.R., Mitchell, T.D., Jones, R.G., Lowe, J., Murphy, J.M. & Hassell, D. (2002). *Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report*. Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich.

Jones, P.D., Kilsby, C.G., Harpham, C., Glenis, V. and Burton, A. (2009). UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator. *UK Climate Projections science report*. Available at http://ukclimateprojections.metoffice.gov.uk/22530.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A. and Wilby, R.L., (2007). A daily weather generator for use in climate change studies. *Environmental Modelling & Software*, 22(12), pp.1705-1719.

Klutke, G.A., Kiessler, P.C. and Wortman, M.A. (2003). A critical look at the bathtub curve. *IEEE Transactions on reliability*, 52(1), pp.125-129.

Kovacevic, N., Potts, D. M., & Vaughan, P. R. (2001). Progressive failure in clay embankments due to seasonal climate changes. In *Proceedings of the international conference on soil mechanics and geotechnical engineering* (Vol. 3, pp. 2127-2130). AA Balkema Publishers.

Leroueil, S. (2001). Natural slopes and cuts: movement and failure mechanisms. *Geotechnique* 51 (3), 197–243.

Li, J. H. & Zhang, L. M. (2011). Study of desiccation crack initiation and development at ground surface. *Engng Geol*. 123, No. 4, 347–358, https://doi.org/10.1016/j.enggeo.2011.09.015.

Journal Pre-proofs

Loveridge, F.A., Spink, T.W., O'Brien, A.S., Briggs, K.M. and Butcher, D. (2010). The impact of climate and climate change on infrastructure slopes, with particular reference to southern England. *Quarterly Journal of Engineering Geology and Hydrogeology*, 43(4), pp.461-472.

Lowe, J.A., Bernie, D., Bett, P., Bricheno, L., Brown, S., Calvert, D., Clark, R., Eagle, K., Edwards, T., Fosser, G. and Fung, F. (2018). UKCP18 science overview report. *Met Office Hadley Centre: Exeter*, UK.

Mair, R. (2021). *A Review of Earthworks Management*, Network Rail. Report 2025/10005. Available at: https://www.networkrail.co.uk/who-we-are/our-approach-to-safety/stonehaven/

Moene, A.F. & van Dam, J.C. (2014). *Transport in the Atmosphere–Vegetation–Soil Continuum*. Cambridge University Press, Cambridge.

Morsy, A., Helm, P., El-Hamalawi, A., Smith, A., Hughes, P., Stirling, R., Dijkstra, T., Dixon, N. and Glendinning, S. (2023): Development of a multi-phase numerical modeling approach for hydromechanical behavior of clay embankments subject to weather-driven deterioration. *Journal of Geotechnical and Geoenvironmental Engineering*, 149(8). https://doi.org/10.1061/JGGEFK.GTENG-112

Morsy, A., Helm, P., El-Hamalawi, A., Smith, A., Hughes, P., Stirling, R., Dijkstra, T., Dixon, N. and Glendinning, S. (2023b). Data used for the validation of the BIONICS research embankment hydromechanical model 2023. Newcastle University. Dataset. https://doi.org/10.25405/data.ncl.22144442.v1

Murphy, J.M., Harris, G.R., Sexton, D.M.H., Kendon, E.J., Bett, P.E., Clark, R.T. and Yamazaki, K., (2018). *UKCP18 land projections. Exeter: Science Report*. Accessed at: www.metoffice.gov.uk/research/approach/collaboration/ukcp/science/science-reports

Nyambayo, V. P., Potts, D. M., & Addenbrooke, T. I. (2004). The influence of permeability on the stability of embankments experiencing seasonal cyclic pore water pressure changes. In *Advances in Geotechnical Engineering. The Skempton Conference. Thomas Telford, London* (pp. 898-910).

O'Brien, A. (2007). Rehabilitation of urban railway embankments: investigation, analysis and stabilisation. In: Cue'llar, V., Dapena, E., Alonso, E., et al., (Eds.), *Proceedings of the 14th European Conference on Soil Mechanics and Geotechnical Engineering*, Madrid. Millpress, Amsterdam, the Netherlands, pp. 125–143.

O'Brien, A.S. (2013). The assessment of old railway embankments – time for a change? Partial Saturation in Compacted Soils: *Géotechnique Symposium in Print 2011*, pp. 19–32 (http://dx.doi.org/10.1680/geot.sip11.ks)

Parsons, A.W., Perry, J. (1985). Slope stability problems in ageing highway earthworks. From *Proceedings of the Symposium on Failures in Earthworks*, Organized by the Institution of Civil Engineers, Held in London, March 6–7, 1985.

Journal Pre-proofs

Perry, J. (1985). Incidence of highway slope stability problems in Lower Lias and Weald clay. From *Proceedings of the Symposium on Failures in Earthworks,* Organized by the Institution of Civil Engineers, Held in London, March 6–7, 1985.

Perry, J., (1989). *A survey of slope condition on motorway earthworks in England and Wales*. Research Report-Transport and Road Research Laboratory 199.

Perry, J., Pedley, M., Reid, M. (2003a). *Infrastructure Cuttings – condition appraisal and remedial treatment*. C591. CIRIA, London.

Perry, J., Pedley, M., Reid, M. (2003b). *Infrastructure Embankments – condition appraisal and remedial treatment*. C592. CIRIA, London.

Pk, S., Bashir, R. and Beddoe, R. (2018). Effect of climate change on earthen embankments in Southern Ontario, Canada. *Environmental Geotechnics*, 8(2), pp.148-169.

Postill, H., Dixon, N., Fowmes, G., El-Hamalawi, A. & Take, W.A. (2020). Modelling seasonal ratcheting and progressive failure in clay slopes: a validation. *Canadian Geotechnical Journal*, 57(9), pp.1265-1279.

Postill, H., Helm, P.R., Dixon, N., Glendinning, S., Smethurst, J.A., Rouainia, M., Briggs, K.M., El-Hamalawi, A. & Blake, A.P. (2021). Forecasting the long-term deterioration of a cut slope in high-plasticity clay using a numerical model. *Engineering Geology*, 280, p.105912.

Postill, H., Helm, P.R., Dixon, N., El-Hamalawi, A., Glendinning, S. and Take, W.A. (2023). Strength parameter selection framework for evaluating the design life of clay cut slopes. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 176(3), pp.254-273.

Potts, D.M., Kovacevic, N. and Vaughan, P.R. (1997). Delayed collapse of cut slopes in stiff clay. *Géotechnique*, 47(5), pp.953-982.

Power, C.M. and Abbott, S. (2019). Introduction to ground-related risk to transportation infrastructure. *Quarterly Journal of Engineering Geology and Hydrogeology*, 52(3), pp.280-285.

Reeves, G.M., Sims, I. and Cripps, J.C. eds., (2006). *Clay materials used in construction*. Geological Society of London.

Ridley, A., McGinnity, B. and Vaughan, P. (2004). Role of pore water pressures in embankment stability. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 157(4), pp.193-198.

Ridley, A. M. (2012). Relationships between climate, vegetation, pore water pressures and the serviceability of clay slopes. *Rivista Italiana Geotecnica* 12, No. 3, 15–28.

Ridley, A. M. (2017). Monitoring the performance of clay slopes, John Mitchell Lecture. London, UK: Institution of Civil Engineers. See www.ice.org.uk/eventarchive/john-mitchell-lecture-2017 (accessed 18/03/2018).

Journal Pre-proofs

Robinson, J.D., Vahedifard, F. and AghaKouchak, A. (2017). Rainfall-triggered slope instabilities under a changing climate: comparative study using historical and projected precipitation extremes. *Canadian Geotechnical Journal*, 54(1), pp.117-127.

Rouainia, M., Davies, O., O'Brien, T., & Glendinning, S. (2009). Numerical modelling of climate effects on slope stability. *Proceedings of the ICE-Engineering Sustainability*, *162*(2), 81-89.

Rouainia, M., Helm, P., Davies, O. and Glendinning, S. (2020). Deterioration of an infrastructure cutting subjected to climate change. *Acta Geotechnica*, *15*, pp.2997-3016.

Saffari, N., & Ridley, A.M. (2022). Long-term field monitoring to manage performance of earth structures on the London Underground network. In *11th International Symposium on Field Monitoring in Geomechanics*. London, United Kingdom, 4-7 September 2022. https://www.issmge.org/publications/online-library

Scott, J.M., Loveridge, F., O'Brien, A.S. (2007). Influence of climate and vegetation on railway embankments. In: Cuellar, V., Dapena, E., et al., (Eds.), *Proceedings of the14th European Conference on Soil Mechanics and Geotechnical Engineering*. Millpress, Madrid, Amsterdam, pp. 659– 64.Croatian Geotechnical Society.

Skempton A.W. (1964) Long-term stability of clay slopes. *Geotechnique* 14:77–102. doi:10.1680/geot.1964.14.2.77

Skempton, A.W. (1996). Embankments and cuttings on the early railway. *Construction History* 11, 33–49.

Smethurst, J.A., Clarke, D. and Powrie, W. (2006). Seasonal changes in pore water pressure in a grass covered cut slope in London Clay. *Géotechnique*, 56, 523– 37.

Smethurst, J.A., Clarke, D. and Powrie, W. (2012). Factors controlling the seasonal variation in soil water content and pore water pressures within a lightly vegetated clay slope. *Géotechnique*, 62(5), pp.429-446.

Smethurst, J., Briggs, K., Powrie, W., Ridley, A., Butcher, D. (2015). Mechanical and hydrological impacts of tree removal on a clay fill railway embankment. *Géotechnique* 65 (11), 869–882.

Smethurst, J.A., Sellaiya, A., Blake, A.P., Powrie, W. (2022). A Long-Term Record of Water Content and Pore Water Pressure in a Vegetated Clay Highway Cut Slope. In: Tutumluer, E., Nazarian, S., Al-Qadi, I., Qamhia, I.I. (eds) *Advances in Transportation Geotechnics IV. Lecture Notes in Civil Engineering*, vol 166. Springer, Cham. https://doi.org/10.1007/978-3-030-77238-3_58

Spink, T. (2020). Strategic geotechnical asset management. *Quarterly Journal of Engineering Geology and Hydrogeology*, 53(2), pp.304-320.

Stirling, R.A., Glendinning, S. and Davie, C.T. (2017). Modelling the deterioration of the near surface caused by drying induced cracking. *Applied Clay Science*, 146, pp.176-185.

Journal Pre-proofs

Stirling, R.A., Toll, D.G., Glendinning, S., Helm, P.R., Yildiz, A. and Hughes, P.N. (2020). Laboratory and field testing data - weather-driven deterioration processes on embankment slopes. Newcastle University. Dataset. https://doi.org/10.25405/data.ncl.12925673.v2

Stirling, R.A., Toll, D.G., Glendinning, S., Helm, P.R., Yildiz, A., Hughes, P.N. and Asquith, J.D. (2021). Weather-driven deterioration processes affecting the performance of embankment slopes. *Géotechnique*, 71(11), pp.957-969.

Svalova, A., Helm, P., Prangle, D., Rouainia, M., Glendinning, S. and Wilkinson, D.J. (2021). Emulating computer experiments of transport infrastructure slope stability using Gaussian processes and Bayesian inference. *Data-Centric Engineering*, 2, p.e12.

Take, W.A. (2003). The influence of seasonal moisture cycles on clay slopes. PhD Thesis. University of Cambridge. https://doi.org/https://doi.org/10.17863/CAM.19045

Take, W. A., & Bolton, M. D. (2011). Seasonal ratcheting and softening in clay slopes, leading to first-time failure. *Géotechnique*, *61*(9), 757-769.

Tang, C., Shi, B., Liu, C., Zhao, L. & Wang, B. (2008). Influencing factors of geometrical structure of surface shrinkage cracks in clayey soils. *Engineering Geology*. 101, No. 3–4, 204–217, https://doi.org/10.1016/j.enggeo.2008.05.005.

Tang, A.M., Hughes, P.N., Dijkstra, T.A., Askarinejad, A., Brenčič, M., Cui, Y.J., Diez, J.J., Firgi, T., Gajewska, B., Gentile, F., Grossi, G., Jommi, C., Kehagia, F., Koda, E., ter Matt, H.W., Lenart, S., Lourenco, S., Oliveira, M., Osinski, P., Springman, S.M., Stirling, R., Toll, D.G. and Van Beek, V. (2018). Atmosphere–vegetation–soil interactions in a climate change context; impact of changing conditions on engineered transport infrastructure slopes in Europe. *Quarterly Journal of Engineering Geology and Hydrogeology*, 51(2), pp.156-168.

Thurlby, R. (2013). Managing the asset time bomb: a system dynamics approach. *Proceedings of the Institution of Civil Engineers-Forensic Engineering*, 166(3), pp.134-142.

Toll, D.G., Mendes, J., Gallipoli, D., Glendinning, S. and Hughes, P.N. (2012). Investigating the impacts of climate change on slopes: field measurements. *Geological Society, London, Engineering Geology Special Publications*, 26(1), pp.151-161.

Trinidad González, Y., Briggs, K.M., Svalova, A. and Glendinning, S. (2023). Evaluating the likelihood of slope failure in ageing earthworks using Bayesian updating. *Infrastructure Asset Management*, pp.1-13. DOI: 10.1680/jinam.23.00005.

Tsiampousi, A., Zdravkovic, L. and Potts, D.M. (2017). Numerical study of the effect of soil–atmosphere interaction on the stability and serviceability of cut slopes in London clay. *Canadian Geotechnical Journal*, 54(3), pp.405-418.

Vardon, P.J. (2015). Climatic influence on geotechnical infrastructure: a review. *Environmental Geotechnics*, 2(3), pp.166-174.

Vaughan P.R, Walbancke H.J. (1973) Pore pressure changes and the delayed failure of cutting slopes in overconsolidated clay. *Geotechnique* 23:531– 539

Journal Pre-proofs

Vaughan, P.R., Hight, D.W., Sodha, V.G. and Walbancke, H.J. (1978). Factors controlling the stability of fills in Britain. In *Proceedings of the International Conference on Clay Fills*. Pg 205-217

Yu, Z., Stirling, R., Davie, C. and Eminue, O. (2020): *BIONICS Cracking Data*. Newcastle University. Dataset. https://doi.org/10.25405/data.ncl.12820802.v4

Yu, Z., Eminue, O.O., Stirling, R., Davie, C. and Glendinning, S. (2021). Desiccation cracking at field scale on a vegetated infrastructure embankment. *Géotechnique Letters*, 11(1), pp.88-95.

Kevin Briggs: Conceptualization, Investigation, Data Curation, Writing – Original Draft. **Peter Helm:** Resources, Data Curation, Writing - Review & Editing. **Joel A. Smethurst:** Resources, Data Curation, Writing - Review & Editing. **Alister Smith:** Writing - Review & Editing. **Ross Stirling:** Resources, Data Curation, Writing - Review & Editing. **Alex Svalova:** Writing - Review & Editing. **Yuderka Trinidad Gonzalez:** Writing - Review & Editing. **Fleur Loveridge:** Writing - Review & Editing. **Stephanie Glendinning:** Supervision.

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Declaration of 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.

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