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Wet winter pore pressures in railway embankments

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This paper demonstrates the influence of extreme wet winter weather on pore water pressures within clay fill railway embankments, using field-monitoring data and numerical modelling. Piezometer readings taken across the London Underground Ltd network following the wet winter of 2000–2001 were examined, and showed occurrences of hydrostatic pore water pressure within embankments, but also many readings below this. A correlation was found between the maximum pore water pressures and the permeability of the embankment foundation soil, with high-permeability foundation soils (of chalk or river terrace deposits) providing underdrainage and maintaining low pore water pressures within the overlying clay embankment fill. Numerical modelling of transient water flow in response to a climate boundary condition supports this conclusion, and has been used to demonstrate the influence of clay fill and underlying foundation permeability on transient pore water pressures during extreme (*c.* 1 in 100 years) and intermediate (*c.* 1 in 10 years) wet winter rainfall. For clay-founded embankments, extreme wet winter conditions increased pore water pressures significantly compared with an intermediate winter, whereas for embankments underlain by a permeable stratum pore water pressures were less sensitive to the extreme winter rainfall.

Notation

a	inflection point on SWRC; slightly greater than air-entry value
k_{sat}	saturated hydraulic conductivity
m, n	constants
θ_r	residual water content
θ_s	saturated water content

1. Introduction

Pore water pressures within railway embankments are influenced by seasonal weather patterns and the vegetation on the slope (Loveridge *et al.*, 2010; O'Brien *et al.*, 2004; Scott *et al.*, 2007). Negative pore water pressures (suctions) typically occur following dry periods, particularly during the summer in temperate climates, when evaporation and transpiration remove soil water (Smethurst *et al.*, 2006). Positive pore water pressures occur following wet periods as water infiltrates the soil, and are typically highest at the end of spring (between March and May in the northern hemisphere), as there is little evapotranspiration during the winter months. In the UK, rainfall is generally of low intensity and high frequency, and distributed fairly evenly throughout the year. Therefore periods of prolonged, higher than average intensity rainfall are considered extreme events. Increases in pore water pressure during extreme wet periods can lead to slope instability, and are of concern for infrastructure owners (AEAT, 2003).

During the winter of 2000–2001, the UK experienced the wettest weather since records began in 1766 (Birch and Dewar, 2002). Across England and Wales an average of 503 mm of precipitation was recorded from September to November 2000, which is 196% of the 1971–2000 long-term average (LTA). This wet autumn was preceded by wet winters in 1998–1999 and 1999–2000 (Ridley *et al.*, 2004), and a wetter than average summer in 2000, creating a wet initial condition at the start of autumn (Birch and Dewar, 2002). All these factors contributed to higher than average soil moisture contents and pore water pressures during the winter of 2000–2001. As a result, about 60 slope failures occurred on roads and more than 100 on railways across the UK (Turner, 2001).

Ridley *et al.* (2004) demonstrated a correlation between soil moisture content and slope instability by comparing the soil moisture deficit (SMD) for the London area with reported slope failures (Figure 1). The SMD is the volume of water per unit area that the soil can absorb before reaching 'field capacity', which is the equilibrium moisture content within a soil free to drain downwards under gravity. For many structured soils field capacity typically occurs a few days after rainfall, and is associated with small suctions in the soil. Further infiltration into a soil at field capacity may then rapidly generate positive pore water pressures. The SMD can be calculated by means of a soil water balance, taking into account rainfall infiltration and evapotranspiration of water from the soil (Smethurst *et al.*, 2006). Figure 1 shows that in the south-east of England between 1988 and 2001, periods of low SMD resulting from wet weather conditions correlate with earthworks failures. The SMD for tree-covered areas remained at zero for an exceptionally long period of 175 days during the winter of 2000–2001 (Ridley *et al.*, 2004), resulting in embankment pore water pressures at or close to their maximum during the lifetime of the earthwork. It is suggested by Loveridge *et al.* (2010) that the pore water pressures measured within embankments during this period could provide a design upper bound, corresponding to a rainfall return period of 1 in more than 100 years. Knowledge of this upper bound would be useful for infrastructure owners when carrying out risk assessment of their geotechnical assets.

In the early 1990s London Underground Ltd (LUL) identified a need to improve knowledge of pore water pressures within its clay earthworks, in order to better manage risk of slope failures. As part of a pore water pressure monitoring programme, over 150 piezometers were installed on a number of clay embankments and cuttings across the LUL network. Following the long period of zero SMD during the wet winter of 2000–2001, spot measurements of pore water pressure were taken by Ridley *et al.* (2004) at several of these sites, when pore water pressures would have been at their highest (Figure 2). Readings were from both open standpipes and GeO flushable piezometers that can measure suctions up to approximately 80 kPa (Ridley *et al.*, 2003).

Many LUL embankments and cuttings are constructed of or within the London Clay, a stiff overconsolidated clay of Palaeogene origin that underlies much of London. A small number of earthworks are constructed of glacial till. Many of the railway embankments were constructed from loosely tipped clay, with an ash capping at the embankment crest added later to compensate for settlements of the clay fill (Skempton, 1996). For the embankments monitored by Ridley *et al.* (2004), the thickness of the ash layer varied between 0 m and 3·8 m. When analysing the data, Ridley *et al.* (2004) plotted pressure head against the depth of measurement below the clay surface (the ash/clay interface). This allowed comparison with LUL Standard E3321 (London Underground Ltd, 2000), which provides guidance on the selection of critical pore water pressure profiles for embankment stability assessment, and assumes the ash to be free draining.

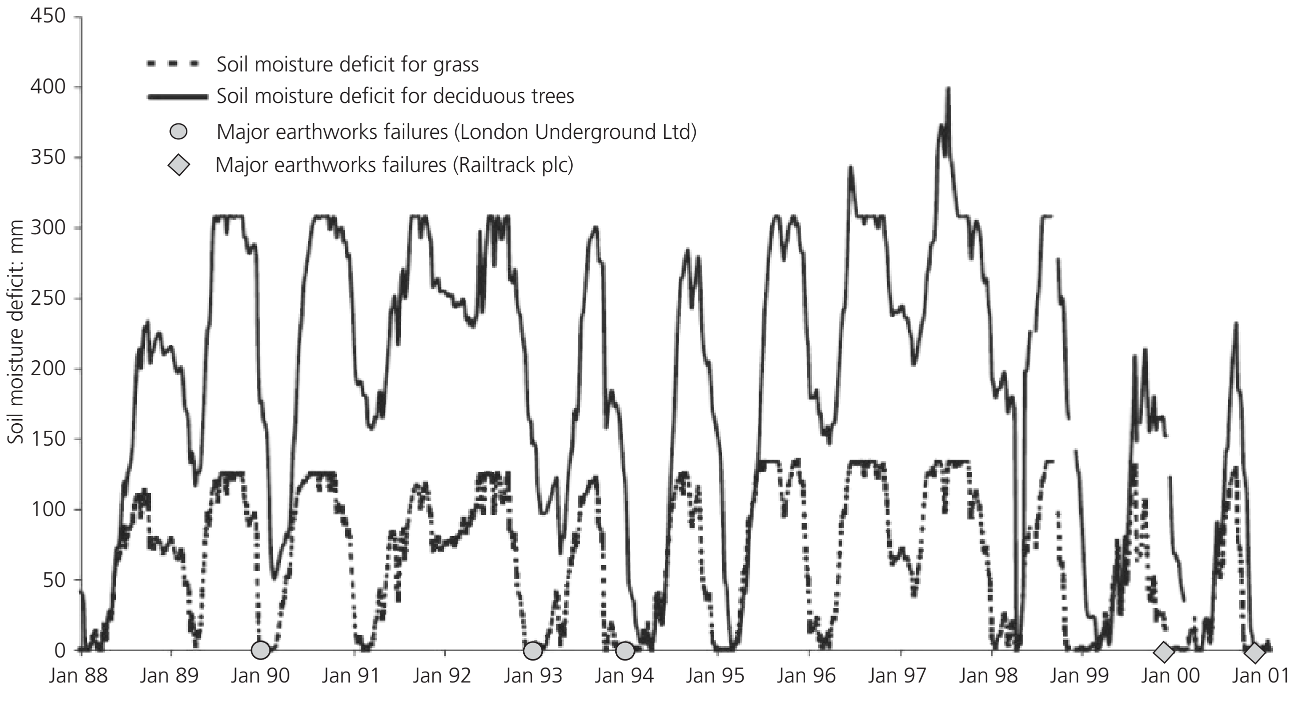

Figure 1. Variation of soil moisture deficit (1988–2001) from Meteorological Office Rainfall and Evaporation Calculation System, Morecs (Hough *et al.*, 1997), with timing of major earthworks failures indicated. Reproduced from Ridley *et al.* (2004)

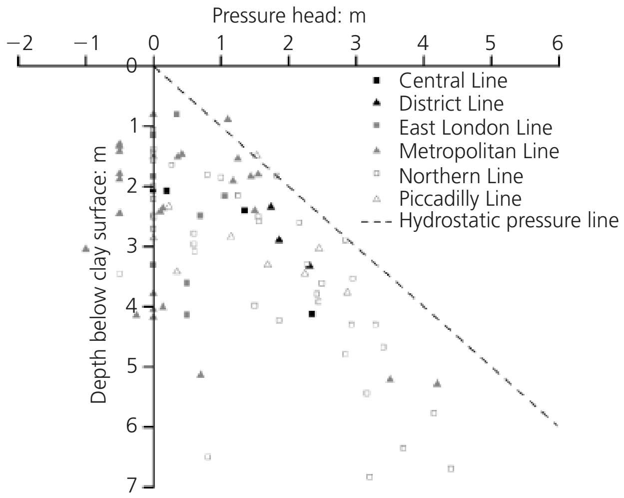

Figure 2. Peak pressure heads measured across London Underground Ltd network during spring 2001 by Ridley *et al.* (2004), categorised by underground line and plotted with depth of measurement below clay surface (ash/clay interface)

Figure 2, which is redrawn from Ridley *et al.* (2004), shows that the pressure head data lie almost entirely below a hydrostatic condition extending from zero pressure at the clay surface (ash/clay interface). A few readings exceed the hydrostatic condition, indicating water held or ponded in the ash layer, but most of the measurements show the ash layer to be free draining in comparison with the clay.

Ridley *et al.* (2004) showed that some pressure heads measured in the spring of 2001 reached hydrostatic below a zero pressure line located at the clay surface, suggesting that this could form an upper bound pressure head profile for design and assessment purposes. However, as an upper bound this is likely to be overly conservative for many embankments, as the data (measured in the spring of 2001) indicate a significant number of measurements below hydrostatic, and some negative values (Figure 2). The aims of this paper are to re-examine the Ridley *et al.* (2004) field measurements to understand the conditions contributing to the range of measured pore water pressures, and to identify the range of factors that should be considered when assessing appropriate pore water pressures for design and assessment.

2. Analysis of the LUL pore water pressure data

The raw data used by Ridley *et al.* (2004) were obtained and reassessed. These data included measurements made using a total of 75 flushable piezometers and 38 open standpipes during March and April 2001. Records from LUL including assessment, ground investigation, monitoring and interpretive reports, which were available in varying degrees of detail, were examined for 15 embankments. These provided supplementary information for 88 of the 113 piezometer locations, which was used to explore the factors influencing and responsible for the wide range of measured pore water pressures.

2.1 Method

The first stage of the data analysis was to identify each piezometer and confirm the reliability of its measurements to enable anomalous readings to be isolated (e.g. where there had been difficulties during measurement) and readings relating to perched water tables, unrepresentative of the whole embankment, to be removed. Anomalous readings, along with piezometers for which borehole location plans and geotechnical cross-sections could not be obtained, were not considered further.

Information was obtained from LUL records relating to

- embankment fill
- foundation soil (i.e. the underlying geology)
- remediation history (e.g. any history of widening and early repairs)
- embankment slope angle
- borehole slope orientation and slope location
- slope vegetation type.

Full details were obtained for 35 piezometers and limited information for the remaining 78, as categorised in Table 1. All 15 of the embankments were constructed predominantly from clay fill, with an average height of 5 m and slope gradient of 1 in 2·4 (slope angle of 23°).

2.2 Foundation soil

Figure 3 shows the piezometer measurements plotted against depth below the clay surface, categorised by the foundation soil underlying the clay fill (London Clay, chalk and river terrace deposits; Table 1). At sites with a London Clay foundation (Figure 3(a)), the majority of pressure heads are bounded by the hydrostatic pressure line to a depth of about 2 m below the clay surface. Beneath this, the bounding rate of increase in pore water pressure with depth reduces to about 60% of hydrostatic, creating a bilinear upper bound pressure head profile. Relatively low pore water pressures were recorded at many locations, with about 20% (8 out of 43) of the readings being zero, and more than half (24 out of 43) showing pressure heads of 2 m or less.

Embankments with a chalk or river terrace deposits foundation soil were underdrained, with pressure heads of less than 1 m measured at all depths for 29 of 34 piezometers (85% of cases). For 85% of the data points the pressure head profile can be described as hydrostatic to 1 m below the clay surface, before reducing to less than 1 m head throughout the soil profile below (Figure 3(b)).

2.3 Embankment vegetation cover

Limited information describing site vegetation was available for 80 piezometers, nine of which were on grass-covered embankments and 71 on tree-covered slopes (Table 1). Supplementary information describing the tree species and the spatial distribution

Category	Number of measurements in each category (from a total of 113 piezometers)			
	Type (number of measurements)			No data
Embankment fill	Clay (88)			Unknown (25)
Foundation soil	London Clay (54)	Chalk (20)	River terrace deposits (14)	Unknown (25)
History of widening	Yes (11)	No (24)		Unknown (78)
Slope angle	10–20° (2)	20–30° (32)	30–40° (8)	Unknown (71)
Slope orientation	North-east (13)	South-west (35)		Unknown (65)
Slope position	Upper slope (33)	Mid slope (7)	Lower slope (6)	Unknown (67)
Slope vegetation	Tree (71)	Grass (9)		Unknown (33)

Note: Tree type and density are not known.

Table 1. Categorisation of Ridley *et al.* (2004) measurements using London Underground Ltd data

of the trees was insufficient to be able to correlate tree species with the pore water pressures measured.

Measurements near trees on clay soils (Biddle, 1998; O'Brien, 2007; Scott *et al.*, 2007) indicate that the pattern and extent of seasonal soil moisture content and pressure head variation depends on a number of factors, such as the soil hydraulic conductivity, surface cracking of the clay fill, tree species, rooting depths and tree water demand. High water demand trees (e.g. oak and poplar) are often able to generate a moisture deficit and suctions in clays that can be sustained through UK winter periods (Biddle, 1998; O'Brien, 2007). In contrast, the generation of significant soil drying and suctions for grass and low water demand trees is typically limited to a shallow rooting zone of approximately 0·9 m depth (Biddle, 1998; Smethurst *et al.*, 2006), and is rarely sustained through an average winter (Figure 1; Clarke and Smethurst, 2010; Smethurst *et al.*, 2012).

Ridley *et al.* (2004) used data from two sites (N2 and N3) in which high (near hydrostatic) pressure heads occurred in tree-covered embankments to argue that, during periods of prolonged wet weather, the soil profile resaturates and the soil desiccation created by trees is reversed. However, Figure 4 shows that, while some pressure heads close to hydrostatic were measured at shallow depth, the majority of the readings, including some of those for sites N2 and N3, lie well below the hydrostatic line. The SMD for deciduous trees was consistently greater than 150 mm between March 1996 and January 1998 (Figure 1). This may have allowed high water demand trees to develop significant moisture deficits and pore water suctions, which were not completely eroded during the wetter period between the winter of 1998–1999 and the spring of 2001 (Figure 1).

2.4 Slope angle, construction history and borehole position

Information relating to the slope angle, history of widening or early repairs and borehole position on the embankment slope (upper slope, mid slope, lower slope) was available for 42 boreholes from seven embankments (Table 1). No correlation between the pressure head–depth relationship and the position of the piezometer on the slope was found. This is possibly due to the limited information describing the piezometer borehole slope positions in the LUL data set.

3. Finite-element modelling

The finite-element software Vadose/W (Geo-Slope, 2007) was used to examine the influence of different winter weather scenarios (Table 2) on embankment pore water pressures, and how the maximum pore water pressures achieved were influenced by the hydraulic conductivity of the foundation soil. Vadose/W has previously been used to examine the sensitivity of transient pore water pressure to seasonal climate, slope vegetation and soil permeability for a railway embankment at Charing, Kent (Briggs, 2010; Loveridge *et al.*, 2010). Vadose/W calculates saturated and unsaturated water and heat flow in response to applied boundary conditions. A notable feature of Vadose/W is that a transient climate boundary condition can be applied (this differs from most groundwater modelling reported in the literature, e.g. Zhang *et al.*, 2011). As described later, the climate boundary condition uses daily weather data (rainfall, air temperature, humidity, wind speed and solar radiation) to calculate water infiltration and water removal from the surface of the soil, and from a defined rooting zone. Variations in pore water pressure with time, in response to weather patterns of different duration and intensity, may then be investigated.

3.1 Mesh geometry

Models representing one-dimensional vertical flow through a column of soil were used to provide an insight into pressure head variation within soil profiles of different saturated hydraulic conductivity (Figure 5), in response to winter weather scenarios (Table 2). The models explore the extent to which a simple one-dimensional model can provide useful comparisons with limited field-monitoring data from different embankments, in assessing

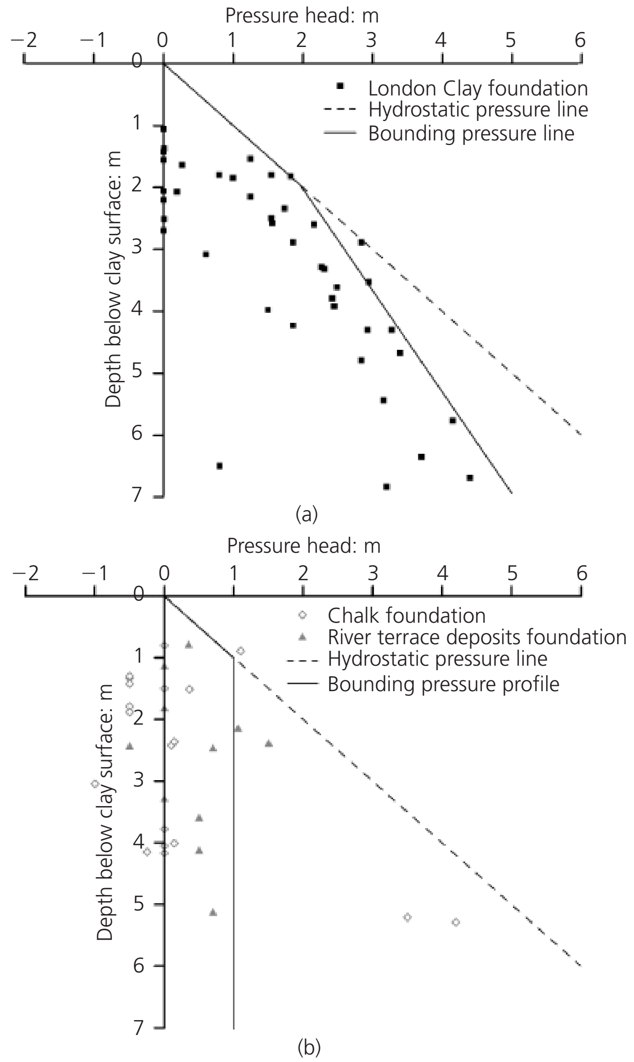

Figure 3. Peak pressure heads measured during spring 2001 by Ridley *et al.* (2004), categorised by foundation soil (underlying geology): (a) London Clay foundation; (b) chalk /river terrace deposits foundation

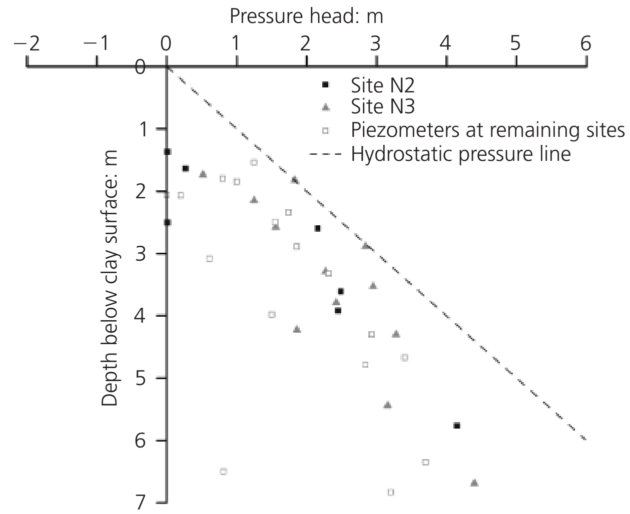

Figure 4. Open standpipe and GeO flushable piezometer measurements by Ridley *et al.* (2004) at tree-covered, London Clay founded embankments in spring 2001 (sites N2, N3 and N5-N8; tree species and water demand not known)

the pore water pressure response to long-term weather conditions, on the basis of short-term field-monitoring data.

The models neglect the influence of downslope flow, which field measurements have shown to increase soil water content at the toe of a slope relative to the crest (Rahardjo *et al.*, 2005). A two-dimensional finite-element model showed that pore water pressures with depth along an embankment slope can vary if changes in slope gradient, soil hydraulic conductivity or slope vegetation alter downslope flow (Briggs, 2010). Comparison between the one-dimensional column and a two-dimensional embankment model (see Appendix) shows that the one-dimensional soil column approximates the midslope condition in a uniform embankment slope, subject to uniform downslope flow.

Winter weather scenario[a,b]	Climate boundary	Dates	Applied time step	Approximate winter rainfall return period
—	Initial condition	Jan '98–Jan '00	Days 0–730	—
Extremely wet	2000–2001	Jan '00–Jan '02	Days 731–1462	1 in 100 years
Intermediate	2002–2003	Jan '02–Jan '04	Days 731–1462	1 in 10 years
Normal	2004–2005	Jan '04–Jan '06	Days 731–1462	1 in 1·2 years

[a]All scenarios use the 'initial condition' climate boundary for the first two years of the simulation.
[b]The terms 'extremely wet', 'intermediate' and 'normal' winter scenarios refer to climate boundaries for the years 2000–2001, 2002–2003 and 2004–2005 respectively within the main text.

Table 2. Summary of winter weather scenarios applied to finite-element model, climate boundary data used, time steps over which it was applied and approximate winter rainfall return period

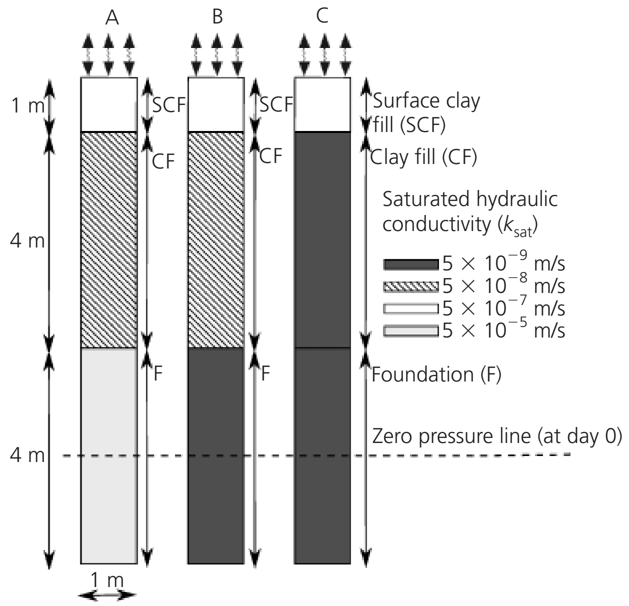

Figure 5. Finite-element model geometry for soil columns A–C. Unsaturated material properties for surface clay fill (SCF), clay fill (CF) and foundation (F) shown in Table 3

Different combinations of clay fill and foundation soil hydraulic conductivity were represented in three soil columns, A to C. Each 9 m deep soil column consisted of a higher-conductivity surface clay layer (to 1 m depth) and 4 m of clay fill, overlying 4 m of foundation soil (Figure 5). The top of the soil column corresponds to the clay surface (the clay/ash interface), with the ash layer assumed either not to be present, or to be free draining. A mesh of 0·1 m square elements was used in the surface zone to enable calculation of the response to high pressure gradients created by the boundary condition. In the remainder of the soil column, a mesh of 0·5 m square elements was used.

3.2 Material properties

As the soil becomes unsaturated, both its water content and its hydraulic conductivity decrease. This causes liquid and vapour flow rates, and rates of evaporation and transpiration, to reduce as the soil dries. Relationships between soil water content and soil suction, and soil water content and hydraulic conductivity, need to be obtained experimentally, but may for analytical convenience be represented by formulae such as those proposed by van Genuchten (1980) and Mualem (1976) respectively. The relationship between water content and suction for the in situ London Clay was based on the soil water retention curve (SWRC) measured for London Clay by Croney (1977), represented by the van Genuchten (1980) curve fit with the parameters given in Table 3. The clay fill was assigned a lower air-entry value and a curve of shallower gradient than in situ London Clay, reflecting its greater specific volume and wider range of pore sizes (Figure 6), consistent with those used by Loveridge *et al.* (2010) and Briggs (2010). In both cases, the reduction of soil hydraulic conductivity (below the saturated value, k_{sat}) with increasing soil suction was calculated from the SWRCs using the Mualem (1976) method with the van Genuchten (1980) parameters indicated in Table 3 (Figure 7).

Figure 5 shows the k_{sat} of the surface clay fill, clay fill and underlying foundation soil in each of the soil columns. Models A and B had a clay fill k_{sat} of 5×10^{-8} m/s, which is higher than the median value of 3×10^{-8} m/s measured for dumped clay fill embankments (O'Brien *et al.*, 2004), and model C had a reduced clay fill k_{sat} of 5×10^{-9} m/s, representing a likely lower limit (O'Brien *et al.*, 2004). Figure 5 shows that models B and C had a foundation soil k_{sat} of 5×10^{-9} m/s, consistent with in situ London Clay (Chandler *et al.*, 1990; O'Brien *et al.*, 2004). Table 3 shows that the same van Genuchten (1980) parameters were used for both the higher and lower k_{sat} clay fill soil types, to provide a comparison based on k_{sat}. Model A had a foundation soil k_{sat} of 5×10^{-5} m/s, consistent with measurements in chalk

Soil type	k_{sat}: m/s	van Genuchten constants				
		a[c]	θ_s	θ_r	m	n
Surface clay fill (A, B and C)	5×10^{-7}	30·3	0·47	0·1	0·13	1·15
Clay fill (A and B)	5×10^{-8}	30·3	0·47	0·1	0·13	1·15
Clay fill (C)	5×10^{-9}	30·3	0·47	0·1	0·13	1·15
London Clay foundation[a] (B and C)	5×10^{-9}	125	0·47	0·1	0·15	1·18
Chalk/river terrace deposit foundation[b] (A)	5×10^{-5}	2	0·45	0·1	0·5	2

[a]van Genuchten parameters were curve-fitted to data for drying London Clay (Croney, 1977).
[b]Estimated van Genuchten parameters for a sandy gravel.
[c]Fredlund (2000)

Table 3. Summary of soil properties used in finite-element model. Labels A–C indicate models to which relationships apply (see Figure 5)

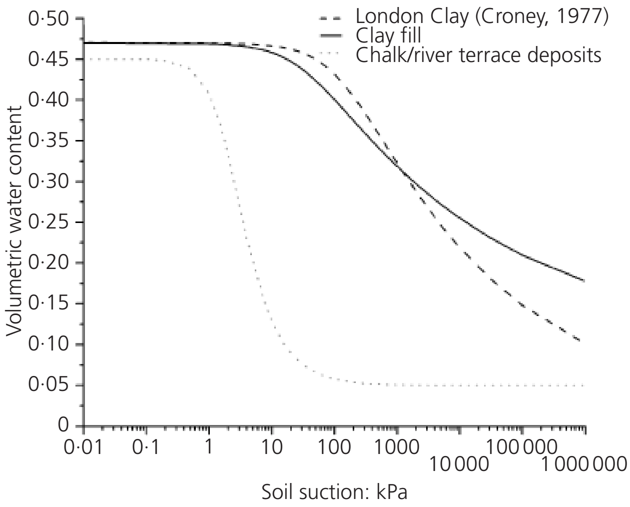

Figure 6. Soil water retention curves for London Clay (Croney, 1977), clay fill and chalk/river terrace deposits used in finite-element model

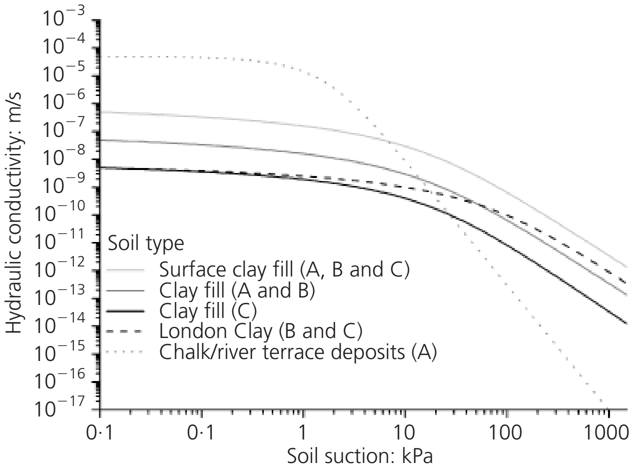

Figure 7. Curves showing reduction in hydraulic conductivity below k_{sat} with increasing soil suction for London Clay, clay fill and chalk/river terrace deposits. Labels A to C indicate finite-element models to which relationships apply

(Powrie and Roberts, 1995), and van Genuchten (1980) parameters for a sandy gravel, to represent full underdrainage by chalk or river terrace deposits.

The surface clay fill was assigned a value of k_{sat} 10 times greater in the vertical direction than the clay fill in the core of the embankment (Figure 5). This represents the effects of desiccation cracking in facilitating rainfall infiltration (Anderson *et al.*, 1982; Novak *et al.*, 2000). Li *et al.* (2011) showed that the vertical hydraulic conductivity of a compacted clay fill slope can vary by up to two orders of magnitude between 0·08 m and 1·08 m depth. Pore water pressures calculated in the two-dimensional slope model were insensitive to isotropy/anisotropy of the hydraulic conductivity applied to the surface clay fill (see Appendix).

3.3 Boundary and initial pore water pressure conditions

Vadose/W, with a climate boundary condition, calculates water removal due to evaporation from an unsaturated soil using the Penman–Wilson equation (Wilson *et al.*, 1994), and transpiration using a root water uptake model (Tratch *et al.*, 1995). Grass and shrub vegetation with a rooting zone of 0·9 m depth, from which soil water can be removed by the plant roots, was assumed in all of the models. Hence this model is intended to represent a slope with a cover of grass and low water demand trees, rather than the more deeply desiccating effects of high water demand trees. The leaf area index (LAI), defining the proportion of solar energy intercepted by the vegetation for transpiration (Ritchie, 1972), corresponded to full leaf cover during the summer period (1 April to 17 October) and zero during the winter, on the basis of UK plant leafing periods described by Biddle (1998). Reduction in root water uptake due to soil drying, as the plant becomes stressed and reduces transpiration, was modelled using the Feddes *et al.* (1978) relationship, with transpiration reducing linearly between 100 kPa and 1500 kPa suction. Effective rainfall (i.e. that not evaporated from the canopy or the soil surface) unable to infiltrate the soil is assumed to run off, and is removed from the model.

A climate boundary condition was applied at the soil surface to determine pore water pressure changes in response to winter weather scenarios. These are referred to as extremely wet, intermediate and normal winter weather scenarios (Table 2). The winter weather scenarios used daily values of temperature, relative humidity, wind speed and solar radiation obtained from a weather station at Shoeburyness in Essex, 60 km to the east of London. Winter rainfall in the south-east of England generally reduces from west to east (Figure 8) and the rainfall measured at Shoeburyness is likely to be lower than the Greater London area, where most of the study sites are located. Daily rainfall data measured near Heathrow Airport, which is to the west of the study sites, were therefore used in the weather data set (Table 4).

The extremely wet winter weather scenario (2000–2001) represents an extreme event, corresponding to a rainfall return period across much of England and Wales of 1 in at least 100 years. Weather data for 2002–2003 and 2004–2005 were used to create the intermediate and normal winter weather scenarios, corresponding to less extreme winter rainfall periods (Table 2). Monthly rainfall data recorded in the south-east of England (Meteorological Office, 2009) over 138 years (1873–2011) were used to calculate the return period for winter rainfall (1 October to 31 March) for the above climate scenarios. It was found that the intermediate (2002–2003) and normal (2004–2005) winter weather scenarios correspond to winter rainfall totals that are exceeded approximately 1 in 10 years and 1 in 1·2 years respectively (Table 2).

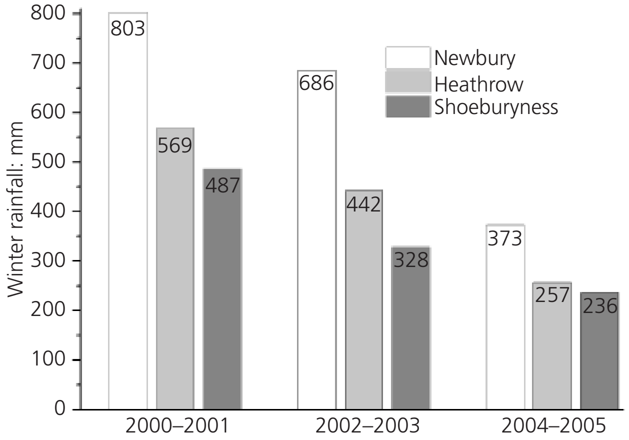

Figure 8. Comparison of winter rainfall totals (1 October to 31 March) measured at Shoeburyness (60 km to the east of London), at Heathrow Airport (Meteorological Office, 2009) and at Newbury (approximately 60 km to the west of Heathrow)

Dates	Annual potential evapotranspiration:[a] mm	Annual rainfall:[b] mm
Jan 1998–Jan 1999	759[c]	687
Jan 1999–Jan 2000	759	647
Jan 2000–Jan 2001	700	799
Jan 2001–Jan 2002	728	706
Jan 2002–Jan 2003	748	739
Jan 2003–Jan 2004	801	510
Jan 2004–Jan 2005	756	619
Jan 2005–Jan 2006	719	453

[a]Calculated using the Penman–Monteith equation (Allen *et al.*, 1994) and weather data measured at Shoeburyness (Weather Underground, 2010).
[b]Measured at Heathrow Airport.
[c]Data unavailable: therefore potential evapotranspiration for 1999 applied.

Table 4. Summary of weather data used in finite-element model

A sensitivity analysis using the finite-element model showed that, after two years of weather data had been applied to the model, the pore water pressure distribution in the soil column was independent of the starting condition. An initial condition appropriate to the saturated hydraulic conductivity of each column was therefore established by imposing 730 days of climate data (Table 2) onto a starting condition (day 0) of pore water pressures hydrostatic above and below a zero pressure line at 2 m below the foundation surface (Figure 5). Having established this initial (day 730) pore water pressure distribution, the climate boundary condition for the winter weather scenario being investigated was applied to the model surface boundary from days 731 to 1462 (Table 2).

The remaining mesh boundaries were assumed to be impermeable, with the water table allowed to fluctuate vertically. This represents a transient situation in which the water balance involves water storage within the soil column, groundwater recharge and discharge in the foundation, and surface infiltration and evapotranspiration (Freeze, 1969).

4. Modelling results

The cumulative volume of surface water infiltration, calculated for each soil column for the extremely wet winter weather scenario, is shown in Figure 9. This shows that the greatest volume of water was able to enter the fully underdrained model (A) during the wetting period (October to March), and that the cumulative water balance reached a maximum on different dates for each of the models. Water removal during dry periods (mainly April to September) occurred at a similar rate in all three models. Downwards flow in model A, promoted by underdrainage into the chalk/river terrace deposits foundation soil, allowed a higher rate of surface rainfall infiltration to occur. Runoff of excess rainfall occurred soonest in model C, as the rainfall infiltration rate was limited by the lower k_{sat} of the clay fill in this model.

Using model A as an example, Figure 10 shows daily pressure head profiles with depth below the clay surface varying significantly as wetting and drying fronts permeate the soil column in response to changes in the surface water balance (Figure 9). To allow comparison between the finite-element models over a longer period, maximum pressure head envelopes were calculated; these bound 92 individual daily pressure head profiles for the months of March, April and May (see later in Figures 11, 12, 14 and 17). For example, Figure 10 shows daily pressure head

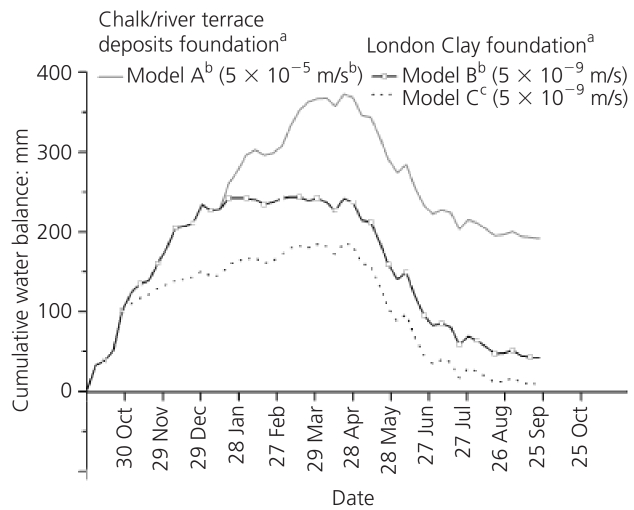

Figure 9. Cumulative surface water infiltration (= rainfall − evapotranspiration − runoff) calculated for finite-element models A–C between October 2000 and October 2001 for extremely wet winter weather scenario. A positive water balance indicates net flow into the model. [a]Foundation k_{sat} shown in brackets; [b]clay fill $k_{sat} = 5 \times 10^{-8}$ m/s; [c]clay fill $k_{sat} = 5 \times 10^{-9}$ m/s

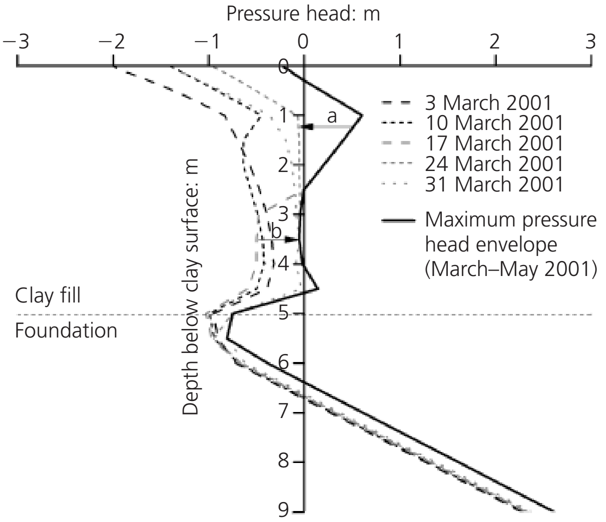

Figure 10. Finite-element calculation of daily pressure head profiles at weekly intervals in March 2001, bounded by maximum pressure head envelope for period March–May 2001. Profiles for finite-element model A shown. [a]Decrease in pressure head after 17 March 2001; [b]increase in pressure head after 17 March 2001

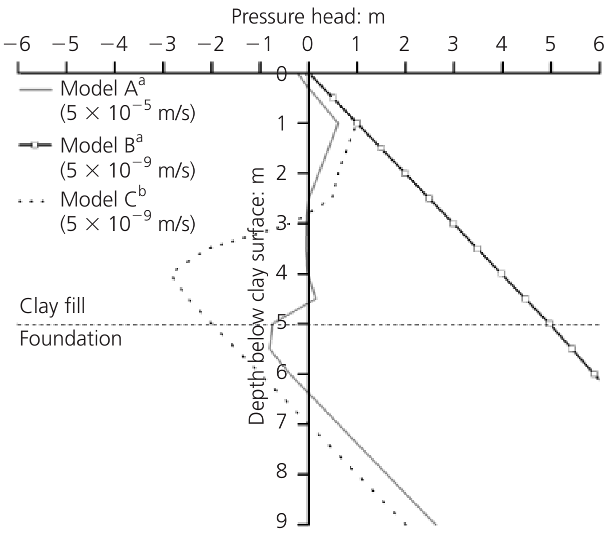

Figure 11. Comparison of maximum pressure head envelopes for March–May 2001, for extremely wet winter weather scenario, calculated using finite-element models A—C. Foundation k_{sat} shown in brackets; [a]clay fill $k_{sat} = 5 \times 10^{-8}$ m/s; [b]clay fill $k_{sat} = 5 \times 10^{-9}$ m/s

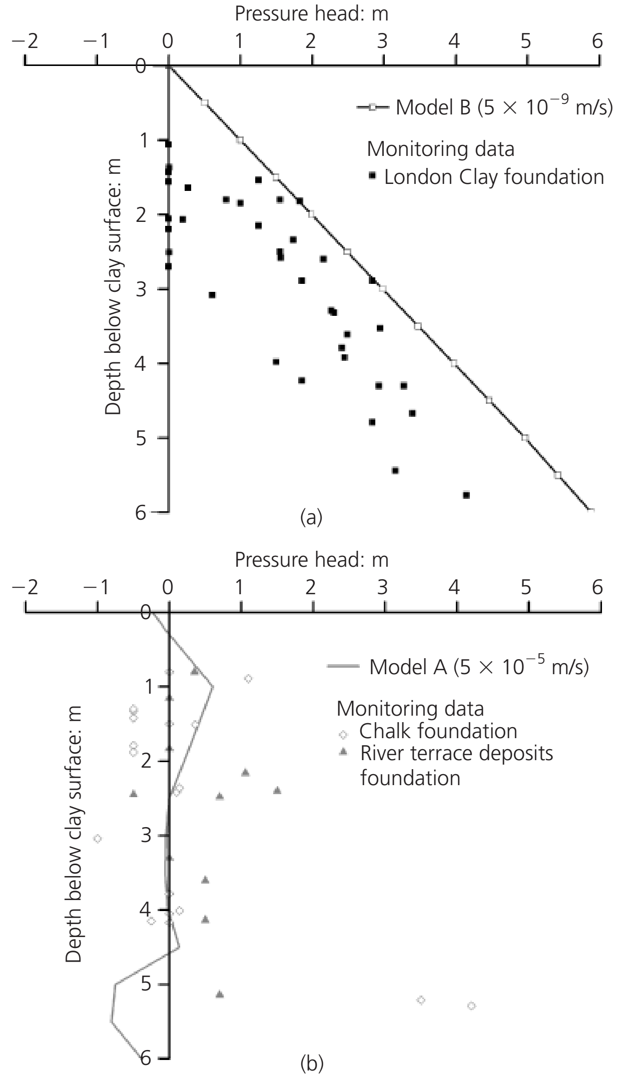

Figure 12. Field-monitoring data compared with finite-element model calculations of maximum pressure head envelopes for March–May 2001, for extremely wet winter weather scenario: (a) London Clay foundation; (b) chalk/river terrace deposits foundation. Foundation k_{sat} shown in brackets

profiles at weekly intervals for model A during March 2001, together with the maximum pressure head envelope over the period 1 March to 31 May 2001. The maximum pressure head up to 2·5 m depth is shown for 17 March, at which time suctions remained at greater depths. Below 2·5 m depth the pressure head continued to increase up to 31 March, as infiltrated water continued to flow downwards. During the same period, drying from the surface boundary (as shown in Figure 9) continued to reduce pressure heads at shallow depth. The maximum pressure head envelope reflects the maximum transient pressure head obtained at any depth over a longer period (in this case March to May 2001), and the actual pressure heads calculated on any specific day will lie on or below the maximum profile.

4.1 Foundation hydraulic conductivity

Figure 11 compares the March to May 2001 maximum pressure head envelopes for models A to C for the extremely wet winter weather scenario. Positive pressure heads are indicated at shallow depths in response to direct infiltration into the higher k_{sat} zone at the soil surface, while at greater depths the influence of the clay fill and foundation soil hydraulic conductivities (k_{sat}) become apparent, and significant differences between the profiles develop.

For a foundation soil k_{sat} of 5×10^{-9} m/s, one order of magnitude less than the overlying clay fill (model B), a maximum pressure head envelope close to hydrostatic pressure with zero pressure at the clay surface was calculated. For the fully underdrained soil column, with a foundation soil k_{sat} of 5×10^{-5} m/s (model A), pressure heads close to zero were calculated within the clay fill and at the top of the underlying foundation. Thus there is a distinct difference between the maximum pressure head envelope calculated for a soil column with a clay foundation soil (of lower hydraulic conductivity than the overlying fill) and that for a foundation soil with a higher hydraulic conductivity than the overlying fill, in the extremely wet winter weather scenario.

Comparison of the cumulative volume of surface water infiltration (Figure 9) with the pore water pressure profiles (Figure 11) shows that while the greatest volume of water entered model A, drainage and soil water storage provided by the foundation soil maintained low pore water pressures within the clay fill. Reference to the SWRC (Figure 6) shows that the small suction (7·5 kPa) in soil column A, between approximately 4·5 m and 6·5 m depth (Figure 11), is sufficient to desaturate the soil, maintaining soil water storage capacity for further water infiltration. Sensitivity analysis showed that both the saturated hydraulic conductivity (k_{sat}) and the soil water retention characteristics of the foundation soil influence the degree of underdrainage provided to the overlying clay fill.

4.2 Comparison of monitoring data and finite-element model

Figure 12 compares the finite-element model calculations for the extremely wet winter weather scenario with the monitoring data given in Figure 3. Figure 12(a) shows that the maximum pressure head envelope calculated using soil column B is close to hydrostatic, whereas the monitoring data from London Clay founded embankments indicate a bounding pressure head profile that reduces to 60% of hydrostatic below 2 m depth (Figure 3(a)). There are several possible explanations for these differences, including: the deep desiccation effects of high water demand trees (the model assumes grass cover); the in situ clay fill k_{sat} could be lower than assumed in the model; two-dimensional flow effects may influence pore water pressures in small embankments with steep slopes. However, Figure 12 demonstrates the value of the one-dimensional model for assessing different wet winter weather scenarios, and that the model will (on the basis of this study) tend to provide conservative estimates, provided the clay fill is underlain by a lower k_{sat} foundation soil.

Figure 12(b) compares the maximum pressure head envelope calculated using finite-element model A with field-monitoring data from embankments founded on chalk and river terrace deposits. The finite-element model shows a consistently low pressure head throughout the soil profile as rainfall infiltration (Figure 9) is drained from the clay fill into the foundation soil, preventing an increase in pressure head. This maximum pressure head envelope indicates underdrainage, as shown by the field-monitoring data, but does not represent an upper bound in this case. There may be several possible explanations for the differences between the monitoring data and the one-dimensional finite-element model. One factor of practical significance is that often there may be insufficient contrast between the hydraulic conductivity of the clay fill and the foundation soil to provide fully effective underdrainage in some embankments. Hence some care is required when modelling underdrainage, in order to avoid unsafe predictions. The Appendix outlines other issues that need to be considered when using either one- or two-dimensional models.

4.3 Clay fill hydraulic conductivity

Temporal pressure head variation at 2 m depth calculated using the finite-element model in a clay fill of a relatively high k_{sat} (model B, $k_{sat} = 5 \times 10^{-8}$ m/s) and a relatively low k_{sat} (model C, $k_{sat} = 5 \times 10^{-9}$ m/s) are compared in Figure 13. The rate and magnitude of pressure head increase for the extremely wet winter weather scenario between 1 October (at the end of summer) and 31 March are greater in model B than in model C. The lower k_{sat} clay fill of model C restricts both surface infiltration and drying of the soil, and the pressure heads are less affected by rainfall events than in higher k_{sat} clay fill (model B). The significant influence of clay fill k_{sat} is also shown in Figure 11 (model B and model C), with the pore water pressures in model C (lower k_{sat}) remaining relatively low (with suctions maintained below about 3 m depth) compared with near-hydrostatic conditions in model B (higher k_{sat}).

For both soil columns the maximum calculated pressure heads, at 2 m depth, occurred during late March 2001 (Figure 13). This is when Ridley *et al.* (2004) took many of their measurements, confirming that the field measurements should reflect the maximum or close to maximum pore water pressures.

4.4 Comparison of climate scenarios

Climate boundary conditions for the intermediate and normal winter weather scenarios were applied to model A (foundation soil $k_{sat} = 5 \times 10^{-5}$ m/s) and model B (foundation soil $k_{sat} = 5 \times 10^{-9}$ m/s). Maximum pressure head envelopes calculated using the one-dimensional finite-element model between March and May, following each winter period, are compared in Figure 14.

Comparison of the end of winter maximum pressure head envelopes for the soil column founded on London Clay (model B, Figure 14(a)) demonstrates the significant difference between maximum pressure heads during an extremely wet (1 in 100 years) winter and less extreme winters. During an extremely wet winter the soil water storage capacity of the clay fill is exceeded by infiltrating water. The profile is unable to drain, causing a rapid increase in pore water pressure (Figure 13).

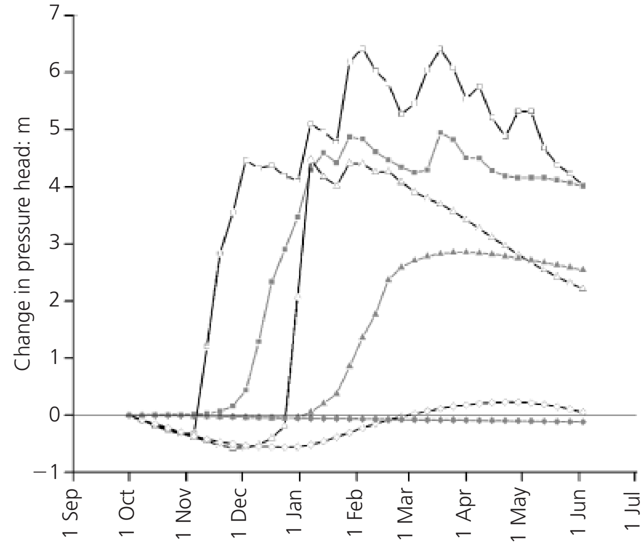

Figure 13. Finite-element calculations of pressure head variation at 2 m depth from models B and C between 1 October and 31 May for different winter weather scenarios (defined in Table 2). [a]Foundation $k_{sat} = 5 \times 10^{-9}$ m/s

Figure 14(b) shows that the maximum pressure head envelopes for a soil column founded on chalk/river terrace deposits (model A) converge to zero within the foundation layer for all winter scenarios, providing drainage to the clay fill and preventing a significant pressure head increase during an extremely wet winter.

For the intermediate and normal winter weather scenarios, both model A and model B show negative pressure heads near the soil surface (to 3·5 m depth), and there is less influence of the foundation soil on the maximum pressure head envelope than during the extremely wet winter weather scenario. This shows that field measurements are likely to be sensitive to weather conditions, and that measurements taken during less extreme (e.g. 1 in 10 years) winter weather will not reveal distinct differences in pressure head which may subsequently develop during an extremely wet winter (e.g. due to differing foundation soil k_{sat}).

5. Implications for earthworks assessment

Field data and numerical modelling have shown that the variation of saturated hydraulic conductivity with depth has a major effect on the end of winter pore water pressures following a period of extreme winter rainfall. Clay fill embankments founded on chalk and river terrace deposits are underdrained, with pore pressures remaining low in comparison with those in an embankment on a clay foundation soil. This should be considered when assessing the long-term stability of earthworks.

The field-monitoring data showed that even during an extremely wet winter, relatively low (0 kPa up to 2·5 m depth) pore water

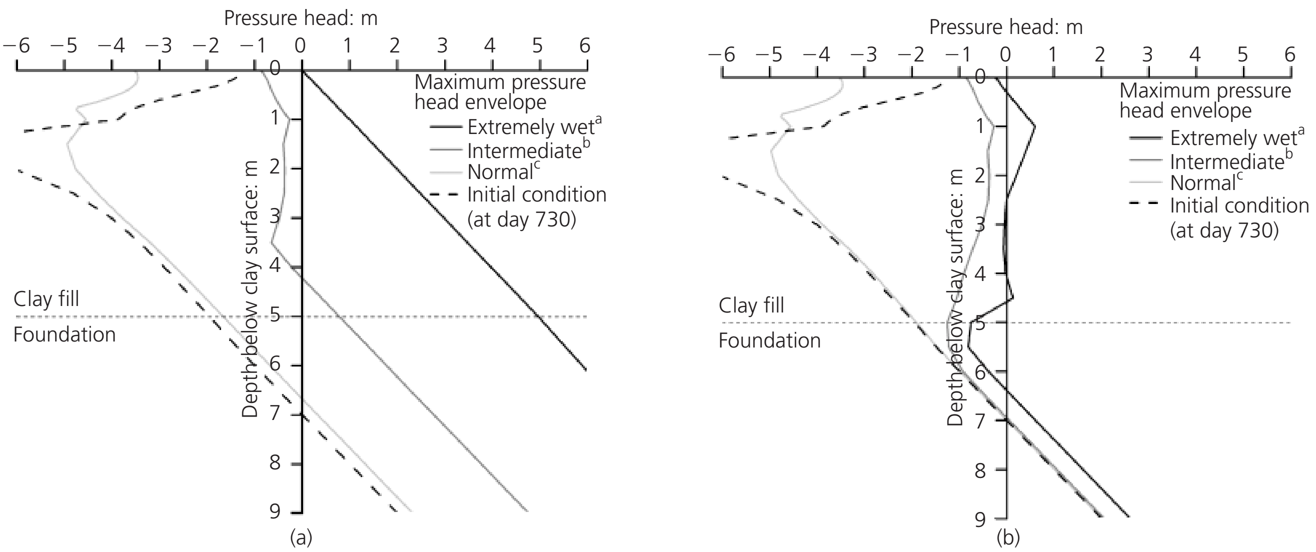

Figure 14. Finite-element calculations of maximum pressure head envelopes (March–May) for different weather scenarios shown in Table 4: (a) London Clay foundation (model B); (b) chalk/river terrace deposits foundation (model A). Approximate winter rainfall return periods: [a]1 in 100 years (2000–2001); [b]1 in 10 years (2002–2003); [c]1 in 1·2 years (2004–2005)

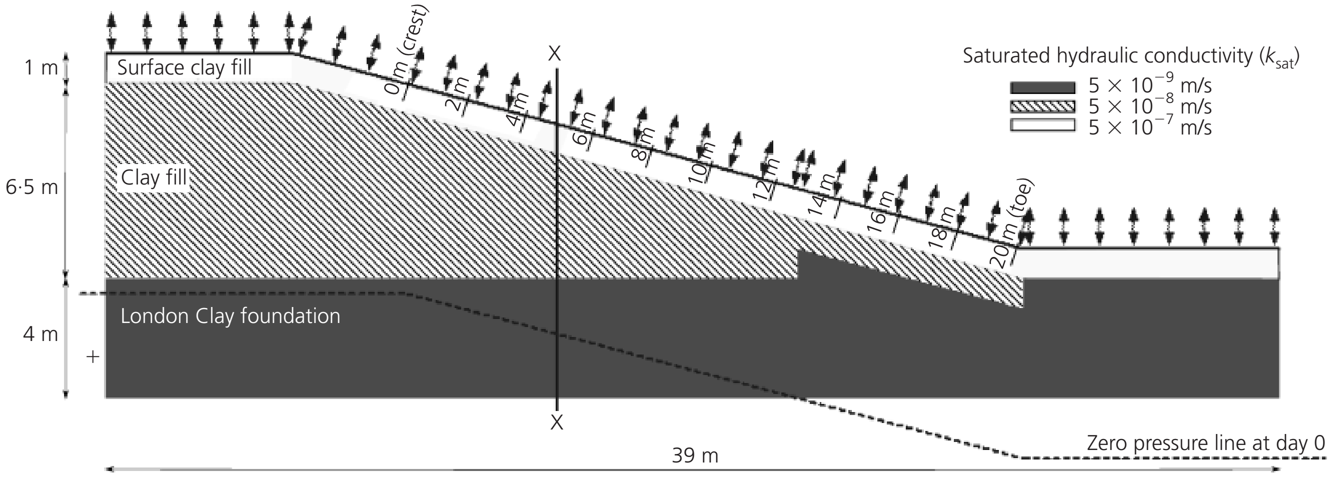

Figure 15. Two-dimensional embankment finite-element model geometry

pressures can be sustained throughout an embankment founded on London Clay. This may be due to the influence of high water demand (HWD) trees, which has been discussed elsewhere (O'Brien, 2007; Scott *et al.*, 2007; Briggs, 2010) but not included in the finite-element models in this paper. Low pore water pressures are also likely to remain at depth in embankments constructed of clay fill at the lower limit of saturated hydraulic conductivity (5×10^{-9} m/s).

The higher saturated hydraulic conductivity in a surface clay fill is clearly important, and full hydrostatic pore water pressures can rapidly become established in this zone. In the finite-element model this was assumed to be 1 m in depth, but it may be deeper in the field (Anderson *et al.*, 1982). Mechanisms potentially leading to deeper zones of cracking and higher mass hydraulic conductivity require further research.

6. Conclusion

The saturated hydraulic conductivity of the foundation soil has been shown to be a dominant influence on the maximum pore water pressures attained within railway embankments at the end of an extremely wet (1 in 100 years) winter.

Embankments underdrained by a more permeable layer, such as chalk or river terrace deposits, maintained pore water pressures of less than 10 kPa throughout the soil profile despite the wet winter and a high rate of water infiltration at the soil surface. Embankments founded on London Clay, and therefore not underdrained, showed higher pore water pressures. In this case, a bilinear profile of pore water pressures – hydrostatic near the surface (<2 m depth) and below hydrostatic at greater depth – forms a reasonable upper bound to the field data examined.

A finite-element model was used to investigate the influence of foundation soil and clay fill saturated hydraulic conductivity on embankment pore water pressures during winter weather. Comparison of soil columns founded on clay and on a more permeable soil demonstrated that during an extremely wet winter underdrainage reduces the pore water pressure throughout the soil profile. The seasonal change in pore water pressure in the soil columns founded on clay was shown to depend on the saturated hydraulic conductivity of the clay fill, with less water infiltration and a less rapid response to rainfall events being associated with a lower saturated hydraulic conductivity. Modelled pore water pressures peaked during March 2001, during the same period as the Ridley *et al.* (2004) field measurements, confirming that they should be representative of maximum or close to maximum pore water pressures.

The finite-element model showed that for embankments founded on London Clay an extremely wet (1 in 100 years) winter can cause significantly greater pore water pressures than a less extreme (1 in 10 year) winter. Pore water pressures in underdrained embankments are much less sensitive to weather extremes. During the less extreme winters investigated, pore water suctions were maintained throughout the clay fill, regardless of foundation soil hydraulic conductivity.

The data analysed in this paper were from LUL embankments. However, the general conclusions from this study are also relevant to other infrastructure embankments in temperate climates, where the variation of saturated hydraulic conductivity with depth in three key zones (surface clay fill, clay fill and foundation soil) will have a profound impact on the winter pore water pressures developed in the earthwork.

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Brian McGinnity of London Underground Ltd provided access to the monitoring data, and assessment, ground investigation and interpretative reports used in this study. The rainfall data for

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Appendix

A two-dimensional finite-element model of a 6·5 m high embankment, with a slope angle of approximately 15°, was created using Vadose/W (Figure 15). Results from this model were used to assess the adequacy of the one-dimensional model used to obtain the results presented in the main paper. At section X–X the soil profile comprises 1 m of isotropic surface clay fill overlying 4 m of clay fill and 4 m of London Clay foundation soil. This is equivalent to the profile of soil column B, shown in Figure 5. The soil properties are summarised in Table 3. In the two-dimensional slope all materials, including the surface clay fill, were isotropic in terms of k_{sat}. An initial condition of hydrostatic pore water pressures above and below a water table at 7 m depth was applied, together with the extremely wet winter weather climate boundary condition (Tables 2 and 4), identical to soil column B (Figure 5).

Figure 16 compares the pore water pressures calculated over time at 2 m depth, at the crest, midslope and toe of the two-dimensional slope model with those calculated for soil column B. The pore water pressures calculated in the soil column lie within the range of values calculated for the embankment slope. Comparison of pore water pressure profiles with depth for March, April and May 2001 shows close agreement between soil column B and section X–X of the two-dimensional slope model (Figure 17). In this case the effect of the sloped surface on the calculated pore water pressures is negligible. This is because elevation head gradients in the uniform slope, causing downslope flow, are small compared with the climate-induced pressure head variation.

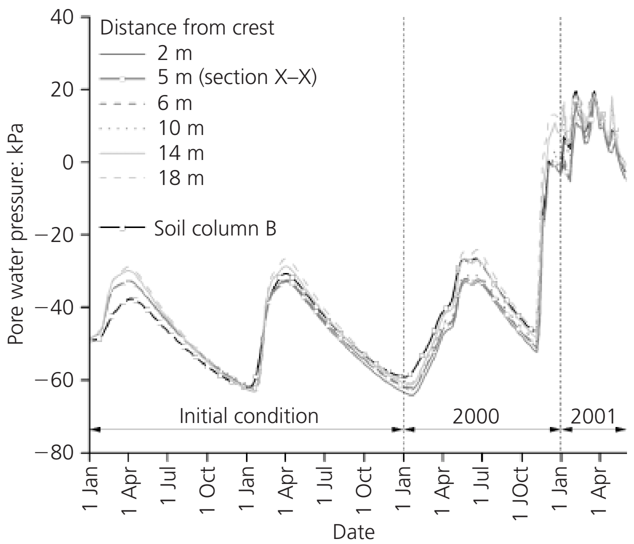

Figure 16. Comparison of pore water pressure at 2 m depth, calculated for soil column B (Figure 5) and section X–X (Figure 15) of two-dimensional embankment finite-element model for extremely wet winter weather scenario

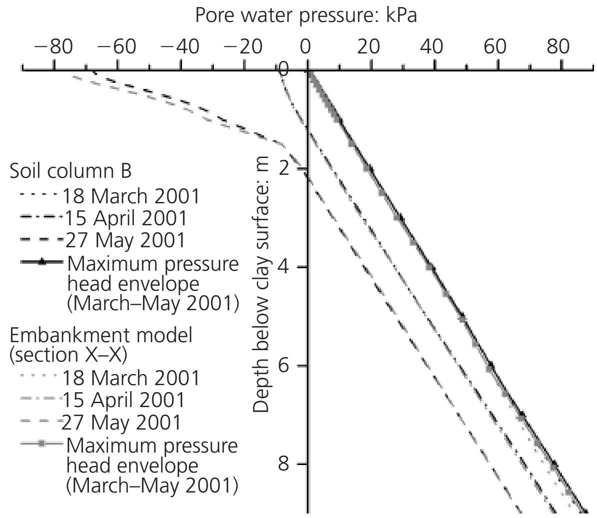

Figure 17. Comparison of pore water pressure profiles for March, April and May, calculated for soil column B (Figure 5) and two-dimensional embankment finite-element model (at section X–X, Figure 15) for the extremely wet winter weather scenario

It is well established that one-dimensional models can be used to calculate climate-induced pore water pressure variation in a uniform slope (Fourie *et al.*, 1999; Li *et al.*, 2005). However, where changes in slope gradient (e.g. at the toe and crest), and changes in soil saturated hydraulic conductivity or variation of slope vegetation cover, occur with distance down the slope, lateral downslope flow will vary, and site-specific conditions must be considered in a two-dimensional model.

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