Modelling the influence of tree removal on embankment slope hydrology

Kevin Briggs, Joel Smethurst and William Powrie

Abstract Trees cover the slopes of many railway earthworks supporting the UK's transport network. Root water uptake by trees can cause seasonal shrinkage and swelling of the embankment soil, affecting the line and level of the railway track. This requires continual maintenance to maintain the serviceability of the track and reduce train speed restrictions. However, the removal of trees from railway embankment slopes and the loss of soil suctions generated by root water uptake may negatively impact embankment stability, particularly during periods of wet weather. An improved understanding of the influence of tree removal on embankment hydrology is required so that infrastructure owners can develop a managed system of vegetation clearance.

Hydrological field monitoring data from an instrumented railway embankment are presented and compared with a finite element model of root water uptake incorporating daily weather data. It is shown that trees maintain persistent suctions within their root zone which are unaffected by seasonal wetting and drying at the soil surface. However, the removal of trees from the embankment slope causes wetting of the soil from the soil surface as persistent soil suctions within the root zone are lost.

Keywords tree removal, hydrological modelling, transport infrastructure

Introduction

Trees cover the slopes of many earthworks supporting the UK's railway network. Many of these trees are deciduous, transpiring and removing water from the soil during the summer months. Deciduous trees remain dormant in the winter and cease to remove water from the soil, during which time rainfall rehydrates the soil from the surface. This seasonal pattern of soil wetting and drying causes volume change in high plasticity clays. For tree-covered railway embankment slopes in areas of high plasticity clay, such as the London Clay basin, seasonal volume change of the soil can affect the line and level of the railway track. However, trees can provide a beneficial contribution to slope stability, through mechanical root reinforcement and the generation of soil suctions within the tree root zone. Railway infrastructure owners require a better understanding of tree influence on pore water pressure variation within slopes, to assess the impact of tree removal on railway embankment hydrology, deformation and hence stability.

Trees draw water from their root zone, which typically extends to about 2-3m depth (Biddle, 1998). In addition to seasonally wetting and drying the soil, mature trees have been shown to develop persistent suctions within their root zone that help to maintain the stability of railway embankment slopes (O'Brien, 2007; Glendinning et al., 2009). In some railway embankments constructed of low permeability clay fill, surface water is unable to infiltrate to greater than 1-2 m depth during the winter months. This allows zones of persistent suction to develop below 1-2m depth on tree-covered slopes. In over steep embankments, or where the clay fill has reduced strength due to strain softening of the clay, these persistent suctions may be crucial in preventing deep seated instability of the embankment slopes (Scott et al., 2006). Removal of mature trees from railway embankment slopes may negatively impact their stability, particularly during periods of wet winter weather.

Railway infrastructure owners, such as Network Rail, have been removing vegetation from the upper part of railway embankment slopes to reduce localised movements affecting the line and level of the railway track. Observations of changes in pore water pressure and soil moisture content in response to tree removal

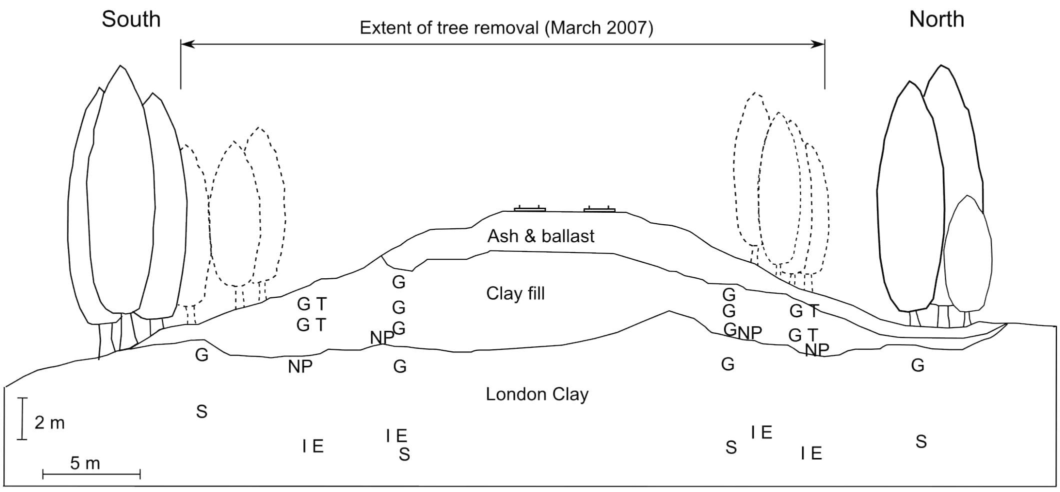

Figure 1. A cross section of the instrumented embankment showing the location of Geo-piezometers (G), Standpipe piezometers (S), Inclinometers (I), Extensometers (E), Neutron probe (NP) and TDR Theta probes (T).

are required. This will allow railway infrastructure owners to assess the impact of tree removal on railway embankment hydrology, so that a managed system of vegetation clearance may develop.

This paper presents monitoring data from an instrumented railway embankment with mature tree cover and a history of seasonal railway track movement. Trees were removed from the embankment slope after one year and the mechanical and hydrological response of the slope was measured for an additional two and a half years. A hydrological model incorporating a climate boundary condition is used to understand the influence of tree root water uptake on slope hydrology, for comparison with the field measurements from the embankment slope.

Field measurements

Site description and instrumentation

The instrumented embankment is situated on the Shenfield-Southend Victoria line in the south east of England. The embankment is 5.5 m high with typical slope angles of 23° on the north side and 20° on the south side. The embankment is constructed of intermediate to very high plasticity clay fill, excavated from a local cutting during construction in the 1800's. The embankment is founded on London clay and has a layer of granular ash covering the upper slope (Smethurst et al., in preparation). Prior to vegetation clearance the embankment was vegetated with mature and semi-mature trees covering the north and south slopes. In March 2007 trees were removed from the upper two-thirds of both slopes. The extent of the tree clearance is shown in Fig.1.

Instrumentation was installed at the site during March 2006 by Smethurst (2010). Fig.1 shows that instrumentation was installed on both the north and the south slopes of the embankment, with groups of instruments located at the crest, mid slope and the toe. A neutron probe with access tubes installed in the embankment slope and TDR ThetaProbes were used to measure soil moisture content. Pore water pressure was measured using Geo-flushable piezometers capable of measuring suctions of up to 90 kPa (Ridley, 2003) and conventional standpipe piezometers. Lateral and vertical movement of the embankment was measured using inclinometers and extensometers. Rainfall was measured using a tipping bucket rain gauge installed on the embankment slope. The instrumentation of the embankment is described by Smethurst et al., (in preparation).

Monitoring results

Removal of trees from the embankment slope caused the embankment soil to swell, pore water pressures within the embankment to increase and volumetric water content to increase from a persistently dry profile to a saturated condition.

Vertical displacement measured at the crest of the north slope of the embankment showed downward movement (settlement) of the embankment during the summer of the 2006 followed by upward movement (heave) during the winter of 2006/2007. Following tree removal in 2007 the seasonal movement of the slope ceased and the crest of the embankment continuously moved upward as the clay swelled. The swelling extended to approximately 3 m below the ground surface (Smethurst et al., in preparation).

Indicative piezometer data from the north crest of the embankment shows a condition of pore water suction (50-80 kPa), immediately prior to tree removal (Fig. 2). Pore water pressure increased towards 0 kPa following tree removal in March 2007. One year later, between March 2008 and September 2009, a pattern of seasonal pore water pressure variation close to 0 kPa was measured as light, shrub vegetation became established on the embankment slope. A pore water pressure increase was measured at 5.8 m depth, but negative pore water pressure was maintained.

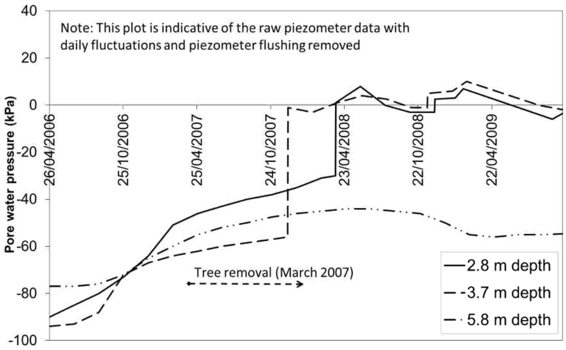

Figure 2. Indicative pore water pressures at 2.8 m, 3.7 m and 5.8 m depth, measured at the North crest by Smethurst et al., (in preparation).

Fig.3 shows profiles of volumetric water content with depth measured at the crest of the north embankment slope. Measurements of the wet, end of winter condition (March/April) are shown for 2007-2009. Fig.3 shows a dry profile within the clay fill below 2 m depth before tree removal. Following tree removal in March 2007 the soil progressively rewet towards saturation in April 2008 and the persistently dry profile was lost.

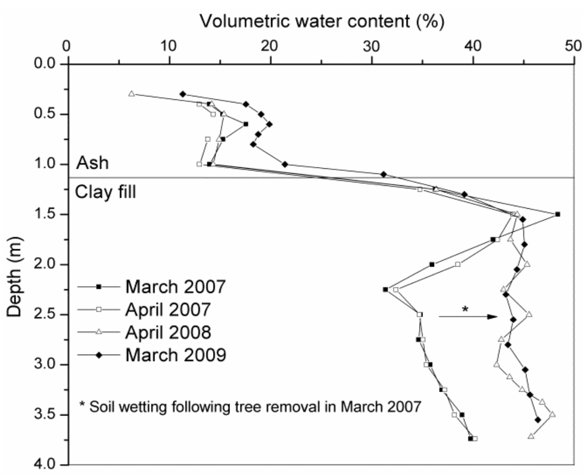

Figure 3. End of winter (March/April) volumetric water content at the crest of the north slope before and after tree removal in March 2007.

Finite element modelling

Finite element analysis using the software Vadose/w was used to examine the influence of tree root depth and tree removal on embankment hydrology, for comparison with the monitoring data.

Vadose/w calculates saturated and unsaturated water and heat flow in response to applied boundary conditions (Geo-Slope, 2007). Most notably, a climate boundary can be applied; this uses daily climate data to calculate water infiltration and water removal from the surface of the soil and from a defined rooting zone. This enables variations in pore water pressure and volumetric water content with time, in response to changes in weather conditions or changes in vegetation cover, to be investigated.

Mesh geometry

A one dimensional soil column was used to calculate vertical water flow in response to a climate boundary condition. This soil column represented a borehole at the crest of the north embankment slope.

The model explores the extent to which a one dimensional soil column with a climate boundary condition and root water uptake function can provide useful comparisons with the field measurements. The soil column considers changes in pore water pressure and volumetric water content in response to transient pressure gradients applied at the upper surface boundary and within the vegetation root zone of the column. A fine mesh of 0.1 m elements was used in the surface zone of the soil column, where high pressure gradients were likely to occur, while a mesh of 0.5 m elements was used in the remainder of the soil column.

Material properties

The soil column is representative of the borehole at the crest of the north embankment slope, which consists of 1.1 m of ash and ballast overlying 3 m of clay fill, with a London clay foundation extending for 13 m below.

The hydrological soil properties used in the one dimensional soil column are shown in Tab. 1. These are consistent with those used by Loveridge et al. (2010) and Briggs et al. (2013) to model railway embankment hydrology. The saturated permeability of the clay fill was based on the results of permeability testing by O'Brien et al. (2004) while the London clay underlying the embankment was assigned a saturated permeability consistent with the range measured by Chandler et al. (1990). The ash and the ballast soil layer was assigned a saturated permeability consistent with a sandy gravel, as in situ permeability data was unavailable.

As the soil becomes unsaturated, both its water content and its hydraulic conductivity decrease. Unsaturated soil properties describing the reduction in soil water content and hydraulic conductivity for the clay fill and the London clay were based on a modified version of the Croney (1977) soil water retention curve (SWRC) for London clay (Briggs et al., 2013). The soil water retention curve for the ash and ballast was based on the SWRC for a coarse granular material. The SWRCs were used to define the reduction of soil hydraulic conductivity and water content with increasing soil suction using the Mualem (1976) method with van Genuchten (1980) constants and the saturated permeability. Tab. 1 summarises the van Genuchten (1980) constants and soil properties used in the soil column. The lower limit of hydraulic conductivity for the ash and ballast layer was limited to 1×10^{-8} ms^{-1}, to facilitate rainfall infiltration into soil in the dry condition. The hysteretic wetting and drying of the granular soil with large voids was not well represented by the continuum assumed in the finite element model.

Table 1. Summary of soil properties used in the finite element model (From Briggs et al., 2013)

Soil type	Permeability (ms^{-1})	Van Genuchten constants AEV	θ_s	θ_r	m	n
Ash & ballast	4×10^{-5}	2	0.45	0.1	0.5	2
Clay fill	5×10^{-8}	30.3	0.47	0.1	0.13	1.15
London Clay	5×10^{-7}	125	0.47	0.1	0.15	1.18

Where AEV = Air entry value, θ_s = saturated water content, θ_r = residual water content, m and n = constants.

Boundary conditions

A climate boundary condition using daily weather data (solar radiation, relative humidity, temperature, rainfall and wind speed) was used to calculate the water flux at the soil surface. A root water uptake function was used to model water removal at depth due to transpiration. Three slope vegetation conditions were applied to the surface of the soil column, to represent the stages of tree removal at the instrumented embankment; mature tree cover, tree clearance (i.e. very light vegetation) and newly established shrubs (Tab. 2).

The Vadose/w climate boundary condition calculates evaporation from an unsaturated soil using the Penman-Wilson equation (Wilson et al., 1994). A proportion of the potential evaporative surface flux is removed as transpiration. This proportion is defined using a Leaf Area Index (LAI) (Ritchie, 1972). As soil dries and soil water is not readily available, plants close stomata on their leaves to reduce their transpiration rate and reduce water loss. The reduction of transpiration due to plant stress was modelled using the Feddes et al. (1978) relationship, with transpiration reducing linearly between 100 kPa soil suction and the plant wilting point at 1500 kPa soil suction.

Within Vadose/w, evaporated water is removed from the soil surface while transpired water is removed from the soil at depth using a root water uptake function (Tratch et al., 1995). The depth of root water uptake was used to differentiate between vegetation types on the instrumented embankment slope (Tab. 2).

A summary of the climate boundary condition applied to the soil column is shown in Tab. 2. The depth of root water uptake was varied to simulate the mature tree cover and tree clearance at the instrumented slope. Slope vegetation cover of mature tree cover (3 m root depth) was applied to the soil column prior to tree removal in March 2007. Very light vegetation cover (0.05 m root depth) was applied to the soil column for three months following tree removal (April 2007 to September 2007). Newly established shrub cover (0.2 m root depth) was applied to the soil column after September 2007, to model the growth of vegetation observed on the slopes of the instrumented embankment during this period.

Table 2. Summary of the climate boundary condition applied to the finite element model

Model stage	Vegetation cover	Weather data	Root depth
Initial condition	Mature tree cover	01/01/2001 to 31/12/2005	3 m
Before tree removal	Mature tree cover	01/01/2006 to 31/03/2007	3 m
Immediately after tree removal	Very light vegetation	01/04/2007 to 31/08/2007	0.05 m
After tree removal	Newly established shrubs	01/09/2007 to 01/09/2009	0.2 m

Daily weather data was obtained from a weather station at Shoeburyness, 11 km from the instrumented embankment and applied to the soil column. The weather data showed that the years preceding the monitoring period (2003 and 2005) were drier than the long term average for the south east of England, while the summers of 2007 and 2008 (immediately after tree felling) were wetter than average (Smethurst et al., in preparation). An initial condition of hydrostatic pressure above and below a zero pressure line at 8 m depth was applied to the soil column. Five years of weather data recorded prior to the monitoring period was then applied to the soil column to establish an initial distribution of pore water pressure. This was followed by nearly four years of weather data corresponding to the monitoring period (Tab. 2). Sensitivity analysis showed that after less than two years of applied climate data the pore water pressure distribution within the soil column was independent of the initial condition.

Modelling results

Altering the depth of root water uptake influenced pore water pressure and volumetric water content within the soil column. Fig. 4 shows pore water pressure calculated at locations between 2 m and 5.8 m depth below the surface of the soil column from January 2001 to October 2009. Pore water pressure calculated before tree removal shows seasonal pore water pressure variation, influenced by root water uptake. Before tree removal, soil suctions increased during the summer months due to water uptake within the tree root zone and evaporation from the soil surface. During the winter months soil suctions decreased as root water uptake and evaporation from the soil surface was reduced, allowing rainfall to infiltrate the soil. The highest pore water pressure (lowest suction) occured at the end of winter, in March of each year.

The model showed a pore water pressure increase from soil suction towards 0 kPa in the four months immediately after tree removal, when the depth of root water uptake was reduced (Tab. 2). During this period surface water was able to infiltrate below the plant root zone and rewet the soil. After September 2007 the model showed seasonal pore water pressure variation close to 0 kPa. This is in qualitative agreement with piezometer data from the north crest of the instrumented embankment (Fig. 2).

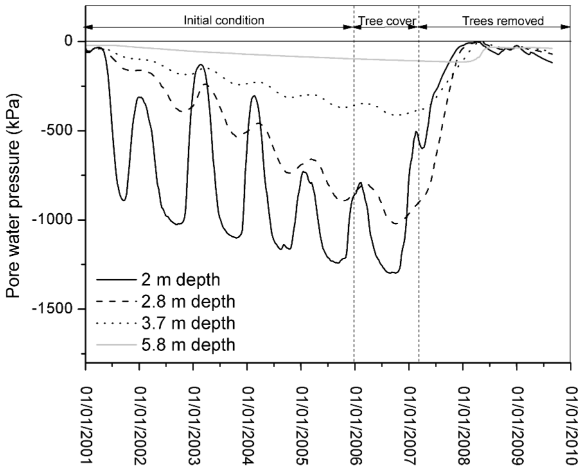

Figure 4. Finite element calculations of pore water pressure for the crest of the north embankment slope

Fig. 5 shows the volumetric water content with depth within the soil column for an end of winter (March) condition, before and after tree removal. This is compared with the field monitoring data for the same period (March 2007 and March 2009). The model shows that a persistently dry profile is maintained within the tree root zone, below 1.5 m depth, following the winter weather in 2007. During this period surface water was unable to infiltrate the soil and rewet the tree root zone before root water uptake commenced in the summer. However, after tree removal the persistently dry profile was lost and volumetric water content increased towards a saturated profile within the model. Fig. 5 shows that this is in agreement with the field measurements.

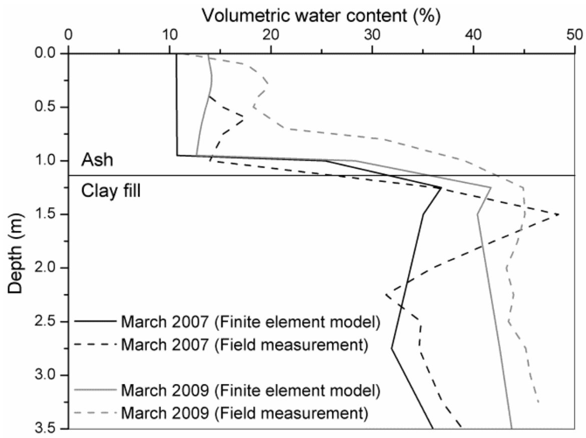

Figure 5. Comparison of finite element calculations and field measurements of volumetric water content before and after tree removal at the crest of the north embankment slope

Comment and conclusions

A finite element model incorporating a climate boundary condition and root water uptake was compared with hydrological measurements from an instrumented embankment following tree clearance from the embankment slopes.

The field measurements and model results showed that pore water pressure and soil displacement within an embankment are influenced by mature trees on the embankment slopes. The finite element model showed that the magnitude of pore water pressure variation within an embankment slope is influenced by the depth of the plant root zone.

The following conclusions can be drawn:

1) Mature trees are able to maintain a persistent water deficit within their root zone. Surface water is unable to infiltrate the soil and saturate the soil profile during the winter before root water uptake resumes in the summer months. This aids embankment slope stability during wet winter weather.

2) Root water uptake at depth ceases following tree removal and is not re-established by light, shallow rooted vegetation. This causes the embankment to rewet, pore water pressures to increase and the persistent soil water deficit and soil suctions to be lost. This reduces the resilience of the embankment to pore water pressure increases at depth during wet winter weather, potentially reducing the stability of the embankment slope.

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