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The influence of tree root water uptake on the long term hydrology of a clay fill railway embankment

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A B S T R A C T

This paper uses a numerical model to investigate the influence of tree root water uptake and tree removal on pore water pressures and the vertical movement of a clay fill railway embankment. Simulated results of soil wetting and drying are compared with field measurements from an instrumented railway embankment before and after tree removal. A parametric study compares the influence of vegetation on the seasonal movement of the embankment slope. The simulations and field measurements show that while trees cause significant seasonal variations in pore water pressure and water content near the soil surface, they can maintain persistent soil suctions at depth within the tree rooting zone. Demonstration of this result using a numerical model requires a root water uptake function that separates spatially the processes of water infiltration, evaporation and transpiration. When all of the trees are removed, the persistent soil suctions established by the trees are lost as water infiltrates from the soil surface. Leaving the trees in place over the bottom third of the slope can maintain persistent suctions at the slope toe, while potentially also reducing seasonal ground movements at the crest that may adversely affect railway track geometry.

Introduction

Trees cover many of the earthworks (embankments and cuttings) that support or flank a large part (>10,000 km) of the UK's railway infrastructure. Dense vegetation, including mature trees, often became established on earthwork slopes when aggressive lineside vegetation management ceased in the 1960s (Gellatley et al., 1995). Vegetation provides a natural habitat for wildlife, promoting biodiversity, and a visual and acoustic screen for adjacent residential areas (Glendinning et al., 2009). However, the seasonal and persistent influence of trees on water movement within embankment and cutting slopes can have both positive and negative impacts on the performance of earthworks as transport infrastructure assets (Glendinning et al., 2009).

Railway embankment slopes are typically less than 10 m high, with low total stresses on potential failure planes, while trees can generate soil suctions of 1500 kPa up to 2–3 m depth (Biddle, 1998). Therefore trees can have a significant influence on the effective stress state within a railway embankment and hence on slope stability (O'Brien et al., 2004; Greenwood et al., 2001; O'Brien, 2013). In over-steep embankments and embankments vulnerable to progressive failure, tree induced suctions may be crucial in preventing deep-seated instability (O'Brien, 2007; Glendinning et al., 2009; Loveridge et al., 2010).

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In temperate climates, the ability of a tree to transpire, remove water from the soil and generate soil suctions varies seasonally. Rainfall and soil water are evaporated from the surface or removed by tree roots during the summer months, when solar radiation is greatest. Transpiration and surface evaporation reduces or ceases during the winter months when solar radiation is reduced, allowing rainfall to infiltrate and wet the soil. This causes cycles of drying and wetting, and associated pore water pressure changes within the soil. In embankments constructed of clay having a high volume change potential, these are accompanied by corresponding seasonal cycles of soil shrinkage and swelling (Loveridge et al., 2010; Smethurst et al., 2015), which can result in train speed restrictions leading to delays for passengers, and require expensive re-levelling work (Scott et al., 2007; Glendinning et al., 2009).

Infrastructure owners must manage slope vegetation, including mature trees, so as to reduce the influence on track movement without compromising embankment stability. Approaches to vegetation management include removing trees from the upper two thirds of the slope (Smethurst et al., 2015), or from within a certain distance of the track depending on the tree species and height (Briggs et al., 2013b; London Underground Ltd, 2010). However these approaches are based empirically on datasets of less than two years; and the depth and extent of tree influence on the pore water pressures within embankments is poorly understood.

The influence of tree root water uptake on pore water pressures and ground behaviour has been investigated using finite element analyses incorporating root water uptake functions by Feddes et al. (1978), Wilkinson et al. (2002), Indraratna et al. (2006), Rees and Ali (2006), Nyambayo and Potts (2010), Fatahi et al. (2009, 2014), as distinct from the combined evapotranspiration models used to model grass vegetation cover by Allen et al. (1994) and Smethurst et al. (2006). Analyses incorporating root water uptake functions remove transpired water by means of a volumetric sink term in Richards (1931) equation, which governs moisture flow in an unsaturated soil (e.g. Eq. (A8)). The simpler of these approaches adopt a linear distribution of root water uptake within the soil, which decreases with both depth and radius from the tree (Rees and Ali, 2006), or with depth alone for one-dimensional conditions (Prasad, 1988; Briggs et al., 2014). Alternatively, where the root distribution, root growth rate and Leaf Area Index (LAI) of a tree is known, the root water uptake function can include the non-linear removal of potentially transpired water based on root length density and annual leaf growth and senescence rates (Fatahi et al., 2009, 2014).

This paper presents and uses an unsaturated numerical model incorporating tree root water uptake to investigate the influence of mature tree cover and tree removal on embankment hydrology. Simulation results are compared with field measurements from an extensively instrumented London Clay railway embankment at Hawkwell, Essex (Smethurst et al., 2010, 2015). A parametric analysis is used to explore the influence of vegetation cover on embankment movement, and the limitations of the numerical model are discussed.

Monitoring of tree removal at Hawkwell embankment

The instrumented site is at Hawkwell, on the Shenfield–Southend Victoria line north of Southend, Essex, UK (Fig. 1a; OS grid reference TQ856923). The 5.5 m tall embankment was constructed around 1887 from a fill consisting mainly of London Clay excavated from adjacent areas of cut. The clay embankment fill was of intermediate plasticity, containing occasional coarse to fine gravels, small pockets of ash and sand and fragments of brick. The underlying geology is the London Clay Formation, to about 5 m below the original ground surface comprising a stiff, brown-yellow clay of high plasticity (Smethurst et al., 2015). The embankment is capped with ash and ballast. The instrumented section of the embankment was densely vegetated with mature and semi-mature oak (*Quercus robur*) and ash (*Fraxinus excelsior*) trees until March 2007, when the trees were removed from the upper two-thirds of the slope (Fig. 1b). Further tree clearance occurred in March 2010, leaving just two semi-mature ash trees at the toe of the south facing slope.

Smethurst et al. (2015) reported measured pore water pressures, soil water contents and slope displacements over a five year period from March 2006. Rainfall was measured using a datalogged tipping bucket rain gauge installed on the north slope.

Field monitoring at Hawkwell showed that climate and vegetation effects influenced soil water content, pore water pressures and shrink-swell displacements within the embankment. The mature trees on the embankment slopes were able to generate large soil suctions and a substantial persistent soil moisture deficit, which was maintained below a depth of approximately 2 m during the winter months (Fig. 2a). Removal of the mature trees from the upper part of the embankment in March 2007 resulted in the earthwork gradually re-wetting and the loss of the persistent soil moisture deficit that had been created by the trees.

Small plants and saplings (scrub vegetation) became established on the embankment slopes in the years following tree removal. These caused seasonal cycles of wetting and drying at shallow depth, with the soil drying that occurred during the summer months being reversed during the winter (Fig. 2b). Smethurst et al. (2015) noted that while pore water pressure profiles within the embankment slopes remained sub-hydrostatic over the period of monitoring following tree removal, the pore water pressures could potentially increase in the future under different weather or vegetation cover scenarios. This could potentially affect the effective stress and hence the stability of the embankment slope.

Simulation of tree removal at Hawkwell embankment

The finite element software Vadose/w (Geo-Slope, 2007) was used to model Hawkwell embankment (Smethurst et al., 2015), and to explore the extent to which a simple root water uptake function and climate boundary condition can reproduce the near surface changes in water content measured. Vadose/w has previously been used to