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Managing the extent of tree removal from railway earthwork slopes

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Abstract

Trees cover the slopes of many earthworks (embankments and cuttings) supporting the UK's rail network. Trees provide ecological and slope stability benefits to earthwork slopes but they can also cause seasonal shrinking and swelling of the soil. Seasonal shrink-swell movement in earthworks can affect the level and alignment of the track, causing speed restrictions, associated delays for rail passengers and a substantial cost for infrastructure owners. Guidance is required to identify and manage the removal of problematic trees, while avoiding full tree clearance on earthworks slopes.

A study was undertaken on behalf of London Underground Ltd (LUL) to assess whether the National House Building Council (NHBC) guidance, considering tree species and the ratio of the distance of the tree from the track, D_t, to the mature tree height H_t, might be applicable to trees located on railway earthwork slopes. Excessive seasonal track movement was shown to correlate with the presence of high water demand (HWD) tree species located within a certain D_t/H_t ratio of the track, but not other tree species.

Soil heave was measured on the slope of an instrumented railway embankment following removal of trees from the embankment slope. The magnitude and rate of soil heave was also estimated from five years of pore water pressure data, using a one dimensional settlement/heave calculation based on a linear swelling index. It was found that while the removal of HWD trees reduced seasonal shrink-swell movement, soil heave and upward track movement continued for at least 4 years after tree felling.

Keywords

Infrastructure, vegetation management, trees, field monitoring

1. Introduction

Much of the UK's rail network is on or in earthworks (embankments and cuttings) constructed more than 100 years ago. Vegetation on earthwork slopes was managed until the 1960's, to reduce fire risk from steam locomotives. However, this ceased following the introduction of diesel and electric trains and dense vegetation, including large mature trees, gradually became established on the slopes of embankments and cuttings (Gellatley *et al.,* 1995).

Trees covering many of the UK's railway earthwork slopes provide a natural habitat for wildlife and biodiversity while creating a visual and acoustic screen for residential areas. From an engineering perspective, trees aid slope stability through mechanical root reinforcement and by the establishment of soil suctions (O'Brien *et al.,* 2004; Greenwood *et al.,* 2004; O'Brien, 2007). However, trees can also cause serviceability problems such as excessive track movement, resulting in delays for passengers and a substantial maintenance cost for infrastructure owners (Andrei, 2000; Scott *et al.,* 2007).

A tree's ability to transpire and remove water from the soil is at a maximum during the summer months, drying the soil within a 2-3 m deep root zone (Biddle, 1998). During the winter months or when a tree is felled, transpiration is reduced or ceases, allowing rainfall infiltration to rehydrate the soil. Seasonal wetting and drying can cause cycles of soil volume change, with shrinkage occurring during periods of dry weather and heave during wet periods or following tree felling. Seasonal shrink-swell movement of a clay railway embankment slope is an order of magnitude greater for a tree covered slope than for a grass covered slope (Scott *et al.,* 2007). If differential shrinkage or swelling occurs along an embankment, for example as a result of the localised influence of trees, the railway track will become uneven causing poor track quality, train speed restrictions and requiring constant maintenance. This is particularly prevalent in areas of clay with high volume change potential, such as the London basin in the south east of England.

A dichotomy exists for earthworks managers between keeping trees for their ecological and slope stability benefits, and removing trees to minimise seasonal track movements. This paper is based on a study undertaken on behalf of London Underground Ltd (LUL) to elucidate this, by investigating the influence of lineside trees on poor track quality. The aims are 1) to use simple parameters to correlate the presence of trees with incidences of seasonal track movement; 2) to use the parameters to evaluate the likelihood of poor track quality at embankments with vegetated slopes; 3) to present pore water pressure and displacement data adjacent to felled trees, by means of a case study of tree removal from an instrumented embankment; 4) to provide a simplified method for estimating the magnitude of track heave when trees are removed from an embankment slope.

2. The London Underground Ltd study

The relationship between seasonal track movement and lineside trees was investigated using data for 16 earthworks across the London Underground Ltd network (Table 1). The study sites included thirteen railway embankments, one cutting and two sections of railway 'at grade' (i.e. at the surrounding ground level), all of which had historically poor track quality or a risk of slope instability.

Tree influence on ground and track movement was considered in the context of the National House Building Council guidance ‘Building near trees’ (NHBC, 2007). The National House Building Council (NHBC) guidance leads to the calculation of a minimum foundation depth by considering the depth, extent and intensity of soil drying due to nearby trees. Although patterns of soil drying close to trees are highly variable and difficult to predict (Biddle, 1998), a simplified ‘zone of influence’ is defined within the guidance using simple, measureable parameters. The zone of influence considers the soil volume change potential, tree species and tree height. Tree species are categorised into low, moderate and high water demand species, referred to as LWD, MWD and HWD respectively (Table 2). High water demand trees have the greatest zone of influence while low water demand trees have a limited zone of influence (Table 3). This reflects the lateral extent and depth of seasonal wetting and drying measured adjacent to trees (Biddle, 1998) and the potential for building damage ranked by tree species (Driscoll *et al.,* 1996).

The essence of the NHBC guidance is the definition of a distance of influence D_{t0} from the tree, expressed as a threshold ratio of the tree height H_t (Figure 1), within which mature trees are likely to cause shrink-swell ground movements and ground heave. The threshold ratio $(D_t/H_t)_0$ varies with tree species and soil type. The NHBC guidance assumes the mature tree height as a precautionary measure when assessing potential building damage. A building or other structure that is located a distance (D_t) from a tree of mature height (H_t) with a ratio (D_t/H_t) less than the threshold ratio $(D_t/H_t)_0$ will be susceptible to damage as a result of cycles of shrinkage and swelling. The current tree height is used to asses heave precautions due to tree removal, or when assessing current ground movement.

2.1 Materials and methods

Information on each of the LUL study sites was obtained from assessment reports, track maintenance reports and ground investigations from London Underground Ltd records. Track monitoring data were available for eight of the study sites, having been undertaken for the assessment of earthwork stability or to confirm the performance of remedial works. The most useful track monitoring data were obtained for sections of earthwork beyond the extent of the remedial works, which were unaffected by slope stabilisation measures. Tree data were obtained from a GIS database held by London Underground Ltd, detailing the location, height and species of mature trees on assets across the LUL network. From this it was possible to compare measured track movements with the tree influence parameters given in the NHBC guidance.

Trees were considered to contribute equally to track movement when closely spaced along the track, but only the tree nearest to the line, at the crest or midslope, was compared with track movement at locations with trees spaced down the embankment slope. A potential limitation of the LUL database is that it only includes trees on LUL land; this resulted in a maximum D_t/H_t ratio of 1 for the majority of the trees, because trees beyond this ratio were generally located outside the LUL boundary and were not recorded in the LUL tree database.

For each study site, the seasonal track movement or records of poor track quality measured closest to the tree were assessed in relation to the D_t/H_t ratio (Figure 1) for each tree. The data points were categorised by tree water demand type (Table 2) and compared with the NHBC threshold ratio $(D_t/H_t)_0$, defining the distance of influence, D_{t0} (Table 3). Where data were available, the actual tree height rather than the mature tree height was used to calculate $(D_t/H_t)_0$ and D_{t0}, to consider current rather than future ground movement.

The study sites considered were located in the London basin, in or on London Clay of high volume change potential. Therefore the influence of soil volume change potential and regional climate parameters, which form part of the NHBC guidance and were similar for all of the current study sites, were not considered explicitly.

2.2 Results

The threshold $(D_t/H_t)_0$ ratios given in the NHBC guidance (2007; Table 3) were compared with the data from individual study sites. A correlation was found between incidences of poor track quality and lineside trees located within the threshold $(D_t/H_t)_0$ ratio. Three examples are presented, illustrating an extreme of behaviour at a site influenced by trees; a site unaffected by trees; and a site where lineside trees were removed. The seasonal movement of the track measured closest to line adjacent trees was compared for each of the study sites where monitoring data was available.

Figure 2 compares the D_t/H_t ratio for trees at study site 1 (Table 1) with the threshold ratio $(D_t/H_t)_0$, categorised by tree water demand type (Table 2). Comparison of the data with the NHBC guidance shows that many of the HWD trees at this embankment are located within the threshold $(D_t/H_t)_0$ ratio, and hence within the distance of influence. LUL records show that Site 1 has a history of poor track quality, regular track maintenance and track replacement.

Figure 3 compares the D_t/H_t ratio for trees at study site 15 with the threshold ratio $(D_t/H_t)_0$, categorised by water demand type (Table 2). This site was heavily vegetated, with a large number of trees. However, Figure 3 shows that most of the trees are located beyond the distance of influence. Reference to LUL records shows that there is no history of poor track quality at this embankment (Table 1).

Figure 4 compares the D_t/H_t ratio for trees at study site 4 with the threshold ratio $(D_t/H_t)_0$, categorised by water demand type (Table 2). At this study site there were few trees, but Willow and Poplar trees were located within the threshold $(D_t/H_t)_0$ ratio. Most of the HWD tress were felled after 3 months of track monitoring in November 2005. The track displacement measured at study site 4, closest to HWD Poplar trees and a felled HWD Willow tree, is shown in Figure 5. Seasonal movement of the track (defined as the difference between the maximum winter heave and the minimum summer shrinkage in a one year period) occurred close to the trees, with downward movement during the summer months due to soil drying and shrinkage. The track moved upward during the winter months as the soil re-wetted and swelled. After the Willow was felled, continuous upward movement of the track occurred closest to the tree and summer shrinkage ceased. Rainfall data measured at Newbury, 100 km to the west of London, indicate that the winter of 2005/2006 and the summer of 2006 were drier than average (Smethurst *et al.,* 2012). Therefore, during an average or wetter than average summer, greater heave may occur closest to the felled Willow tree than that shown (Figure 5).

Figure 6 plots the seasonal track movement measured closest to the trees against the D_t/H_t ratio for trees from eight of the sixteen study sites. The data are categorised by tree species and water demand (High, Moderate or Low). Seasonal track movements measured closest to Moderate Water

Demand (MWD) and Low Water Demand (LWD) trees were less than 10 mm, irrespective of the distance of the tree from the track. Seasonal track movements greater than 10 mm were measured closest to Oak, Poplar and felled Willow trees. These tree species are classified in the NHBC guidance as High Water Demand (HWD; Table 2). Figure 6 also shows the threshold ratio $(D_t/H_t)_0$ and the distance of influence given in the NHBC guidance (Table 3). Most seasonal track movements greater than 10 mm occur adjacent to HWD trees located within the threshold $(D_t/H_t)_0$ ratio.

2.3 Discussion and implications for practice

The results show that the threshold $(D_t/H_t)_0$ ratio, as defined in the NHBC guidance, can also be used to assess the influence of trees on seasonal track movement. Sites with HWD trees located within the distance of influence from the track were shown to be associated with poor track quality. This also applied to sites where HWD trees had been recently felled. In contrast, poor track quality was not apparent where HWD trees were located outside the distance of influence, even at heavily vegetated sites. Poor track quality was not recorded at sites only vegetated with MWD and LWD trees located within the distance of influence. However, trees of these species were less likely to be located within the distance of influence than HWD trees due to the reduced threshold $(D_t/H_t)_0$ ratio of MWD and LWD trees (Figure 1, Table 3). Trees located within this proximity to the track are likely to be managed (felled or coppiced) by LUL, to maintain train sighting distance and to prevent tree or leaf fall hazards.

Monitoring data showed that seasonal track movements in excess of 10 mm were measured adjacent to tree species in the HWD tree category, but not adjacent to tree species in the MWD and LWD tree categories. This suggests that seasonal track movement may be reduced by the managed removal of HWD tree species located within the distance of influence from heavily vegetated embankments, while allowing LWD and MWD species to remain. However, the data show that if HWD trees are felled, for example to improve track quality, upward movement of the track will occur due to swelling and heave of the underlying soil. Therefore track maintenance should be anticipated in the years after such trees have been removed from an embankment slope.

3. Heave case study

Biddle (1998) showed that some trees are able to maintain persistent soil suctions beneath a seasonally affected zone near the soil surface. When a tree is felled, the dissipation of these persistent soil suctions and the associated soil heave may take many years, depending on the extent of the suction and the permeability of the soil (Driscoll *et al.,* 1996; Biddle, 1998; Driscoll, 2000). For example, 160 mm of soil heave was measured over a 4 year period adjacent to felled Lombardy Poplar trees at a site on London Clay (Driscoll, 2000). Other measurements have shown soil heave to continue for much longer periods, up to 20 years (Driscoll, 2000). The NHBC guidance suggests that, where a foundation is located within the zone of influence of a felled tree, 50-150 mm of potential ground movement (heave) should be allowed for, depending on the soil volume change potential.

An embankment in Southend, UK was monitored over a 5 year period, close to the start of which trees were removed from the embankment slopes to improve track quality. Vegetation was removed from the upper part of the slopes only, to reduce seasonal track movement while maintaining the beneficial influence on stability of trees close to the slope toe. A simple, routine geotechnical calculation was used to estimate the vertical movement of the soil based on pore water pressure measurements, for comparison with the measured displacements. This was to assess its potential usefulness in estimating the magnitude and rate of soil heave when planning medium and long term track maintenance at locations where trees have been removed from an embankment slope.

The instrumented section of the embankment is approximately 17 m long and 5.5 m high, with typical slope angles of 23° on the north facing slope and 20° on the south facing slope. The embankment was constructed of locally excavated London Clay, of high volume change potential. Ash and ballast overlies the clay fill at the crest of the embankment and on the north facing slope (Figure 7). Before vegetation clearance in March 2007, a number of mature and semi mature trees were growing on both sides of the instrumented section of the embankment. Figure 8 shows that the felled trees were HWD species located within the threshold $(D_t/H_t)_0$ ratio of the railway track. This suggests that heave of the track closest to the trees would occur following tree removal.

Rainfall totals measured at London Heathrow Airport, 100 km to the west of the instrumented embankment, show that the years preceding the monitoring period were drier than the Greenwich 1971-2000 long term average (Met Office, 2012), causing greater than average soil drying and soil suction. The summers following tree felling (2007 and 2008) were wetter than average, causing lower than average soil drying.

3.1 Materials and methods

The layout of the instrumentation and the location of trees on the embankment is shown in Figure 7. The instrumentation included deep standpipe piezometers, flushable piezometers, neutron probe access tubes, time-domain reflectometry sensors, inclinometer tubes and magnet extensometers. Five flushable piezometers and two open standpipes were installed on the south facing embankment slope in three groups, located at the embankment crest, midslope and the toe of the slope. A magnet extensometer was installed at the midslope, located within 2-4 m of felled Oak trees (a HWD species) and 5-10 m of mature trees remaining at the toe of the slope. Flushable piezometer and magnet extensometer data were recorded continuously throughout the monitoring period (April 2006 to April 2011), while water levels in the open standpipes were measured at monthly intervals during visits to the site.

Classical soil mechanics, based on a linear swelling index $C_s = -\Delta e/\Delta log_{10}(\sigma'_v)$, gives the following equation for calculating one dimensional soil heave (Δh) due to changes in vertical stress (σ'_v) within a saturated soil layer of void ratio e (e.g. Fredlund and Rahardjo,1993):

$$\Delta h = h \times C_s/(1+e_0) \times log(\sigma'_{vf} / \sigma'_{v0}) \qquad \text{Equation (1)}$$

where h is the depth of the soil layer, C_s is the swelling index, and e_0 is the initial void ratio. σ'_{v0} and σ'_{vf} are the initial and final effective stress states in the soil layer respectively.

The pore water pressures measured within the embankment at between 0.8 m and 5.8 m depth (Figure 9) were used to calculate the change in effective stress at monthly intervals for soil layers 0.8

m to 2 m thick, between 1 m and 5.8 m depth (Table 4). A swelling index (C_s) of 0.045 and an initial void ratio (e_0) of 0.52 were used in the analysis, based on oedometer testing of 50 mm diameter intact London Clay fill samples at vertical stresses <300 kPa (O'Brien, 2004; Mott MacDonald, 1999). These represent mid range values of measured swelling indices of 0.029-0.075 and initial void ratios of 0.6-0.7. Upper and lower bound heave estimates were calculated using the full range of the measured swelling index and void ratio for the intact London Clay fill samples (Table 4).

3.2 Results and discussion

The magnet extensometer measurements for the south facing midslope of the embankment, at 1.08 m depth, are shown in Figure 10. Up to 28 mm of soil settlement was measured during the summer months prior to tree removal as the trees abstracted water from the soil, causing shrinkage. Movements of this order were sufficient to require temporary train speed restrictions at this site on several occasions prior to tree removal in March 2007. In the four years following tree removal, between March 2007 and March 2011, 53mm of soil heave was measured at 1.08 m depth. This measured displacement lies at the lower end of the 50 -150 mm potential soil heave range given in the NHBC guidelines. However, magnet extensometer measurements were not taken within the surface 1 m of soil and it is likely that swelling of the soil closer to the embankment surface would have resulted in upward track movements greater than that measured at 1 m depth. Some seasonal shrink-swell movement is shown at the midslope following tree removal, influenced by the mature trees remaining at the toe of the slope. However at the crest of the embankment, shrink-swell track movement was reduced following tree removal (Butcher, pers. comm.).

The open standpipes remained dry (indicating pore water pressures less than 0 kPa) throughout the monitoring period, suggesting that a severely desiccated soil profile had been established. Figure 9 shows that when trees were removed from the embankment slope, soil suctions decreased towards 0 kPa throughout the soil profile. Tree felling altered the surface water balance in two ways, with the loss of canopy increasing the volume of water infiltration from the soil surface and the loss of root water uptake reducing water removal due to evapotranspiration. The data indicate a summer suction of up to 80-90 kPa prior to tree removal, gradually reducing to 0 kPa over the following 4 years with some seasonal variation. Modelling data show that the rate of pore water pressure increase due to rainfall infiltration is related to the soil permeability (Loveridge *et al.,* 2010; Briggs *et al.,* in press). This increase is likely to occur at a higher rate in clay fill, used to construct railway embankments, than in situ London Clay of lower bulk permeability.

The extensometer and piezometer measurements show that following tree removal the soil rehydrated, removing the suctions that had been established by the trees and causing the soil to heave. The soil displacement calculated using the simple one dimensional swelling equation and the mid-range soil parameters measured in oedometer tests is compared with the extensometer measurements in Figure 10. This shows reasonable consistency between the calculated soil displacement and the extensometer measurements, with the measured soil heave between April 2006 and April 2011 lying at the lower range of the calculated displacement. The pattern of shrink and swell displacement shown in the extensometer measurements was not reproduced by the settlement/heave calculation using the piezometer data. A closer correlation might be achieved by measuring pore water pressure at closer depth intervals and including the surface metre depth of soil, which would have been a major influencing factor in this respect (Biddle, 1998; Smethurst *et al.*, 2006).

The results show that the simple equation (equation 1) can be used to estimate the magnitude and rate of potential soil heave following tree removal from the slope of a railway embankment, if the magnitude and rate of pore water pressure change can be assessed. This could be achieved empirically, for example, by measuring the depth and magnitude of soil suction using piezometers prior to tree removal.

4. Conclusions

Data from sixteen sites across the LUL network and from an instrumented railway embankment have provided an insight into the general influence of trees on track movement. The methods presented can be used as an assessment tool to identify where trees may be a primary cause of poor track quality, requiring track maintenance or train speed restrictions.

The National House Building Council guidance 'Building near trees' can be used to determine whether a tree of a particular species, tree height (H_t) and distance from the track (D_t) is likely to influence track movement, as follows. High water demand species (e.g. Oak, Poplar, Willow), located within the threshold ratio $(D_t/H_t)_0$ of the track, as defined in the NHBC guidance, were shown to cause seasonal track movement greater than 10 mm and to correlate with incidences of poor track quality. Moderate and low water demand tree species (e.g. Ash, Sycamore, Birch) were not associated with seasonal track movements greater than 10 mm, even when a large number of lineside trees were located on an embankment slope. Managed removal of HWD tree species located within the threshold $(D_t/H_t)_0$ ratio, while maintaining MWD and LWD tree species on an embankment slope, may minimise seasonal track movement while retaining the beneficial ecological and slope stability effects of a tree covered slope.

Removal of lineside trees may reduce seasonal shrink-swell cycles but does not immediately eliminate ground and track movements, which may continue for at least four years. Removal of HWD trees from an instrumented railway embankment showed continued swelling of the soil surface over a period of four years, as soil suctions established by the trees gradually reduced to zero. The magnitude of soil swelling due to tree removal was reasonably well estimated from pore water pressure measurements and a simple one dimensional settlement/heave calculation based on a linear swelling index, and a saturated soil, with the measured movement close to the low end of the calculated range.

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Table captions

Table 1. Summary of London Underground Ltd (LUL) study sites

Table 2. Classification of water demand for various tree species (adapted from NHBC (2007))

Table 3. Tree zone of influence (from NHBC (2007))

Table 4. Summary of soil parameters for the heave calculation

Table 5. Soil layers used for the heave calculation

Figure captions

Figure 1. Definition of the D_t/H_t ratio, where D_t is the distance of the tree from the track (the nearest running rail) and H_t is the tree height (note: the mature tree height is used in the NHBC guidance (2007))

Figure 2. Study site 1- Most trees are located within the distance of influence (as defined by the water demand type, NHBC (2007))

Figure 3. Study site 15 – Most trees are located beyond the distance of influence (as defined by the water demand type, NHBC (2007))

Figure 4. Study site 4 – Felled high water demand (HWD) trees are located within the distance of influence (as defined by the water demand type, NHBC (2007))

Figure 5. Comparison of seasonal vertical track movement measured adjacent to 2 no. Poplar trees and upwards vertical track movement measured adjacent to a felled Willow tree, at study site 4

Figure 6. Comparison of seasonal track movement with distance of the tree from the track, normalised by the NHBC threshold $(D_t/H_t)_0$, categorised by tree species

Figure 7. Cross section of the instrumented railway embankment with instrumentation shown

Figure 8. Felled high water demand trees are located within the distance of influence (NHBC, 2007) at the instrumented railway embankment (mature tree height assumed)

Figure 9. Increasing pore water pressure measured at the crest and midslope on the south facing slope of the instrumented embankment

Figure 10. Upward vertical displacement due to soil heave measured at the midslope on the south facing slope of the instrumented embankment, compared with the calculated displacement

Table 1. Summary of London Underground Ltd (LUL) study sites

Study site	Asset type	LUL line	Mature tree cover	Poor track performance
1	Embankment	Jubilee	Yes	Yes
2	Grade*	Jubilee	Yes	No
3	Embankment	Metropolitan	Yes	Yes
4	Grade*	Metropolitan	Yes (majority felled)	Yes (including soil heave)
5	Embankment	Metropolitan	Yes	Yes
6	Embankment	Metropolitan	Yes	Yes
7	Embankment	Metropolitan	Yes	No
8	Embankment	Central	Yes	No
9	Embankment	Central	Yes	Yes
10	Embankment	Central	Yes	No data
11	Embankment	Central	Yes	No
12	Cutting	Central	Yes	No
13	Embankment	District	Yes	Yes
14	Embankment	District	Yes	No
15	Embankment	District	Yes	No
16	Embankment	Northern	Yes	Yes

*Grade refers to track at ground level

Table 2. Classification of water demand for various tree species (adapted from NHBC (2007))

Water demand*	Broad leafed tree species	Coniferous tree species
High (HWD)	Oak Poplar Willow Hawthorn	Cypress (Leyland)
Moderate (MWD)	Ash Beech Cherry Sycamore	Cedar Spruce Yew Douglas Fir
Low (LWD)	Birch Holly	

*Note: Water demand is a category name rather than actual water use (Biddle, 1998)

Table 3. Tree distance of influence (from NHBC (2007))

Water demand	Distance of influence (D_{t0})	Threshold $(D_t/H_t)_0$ ratio
High (HWD)	1.25 × tree height*	1.25
Moderate (MWD)	0.75 × tree height*	0.75
Low (LWD)	0.50 × tree height*	0.50

*Note: Mature tree height is assumed in the NHBC guidance to assess potential distance of influence. In this study the current tree height is used to assess the current distance of influence.

Table 4. Summary of soil parameters for the heave calculation (Figure 10)

Heave calculation parameters	**Swelling index (C_s)***	**Initial void ratio***
Upper bound	0.075	0.6
Lower bound	0.029	0.7
Mid range	0.052	0.65

* Measured by O'Brien *et al.,* 2004

Table 5. Soil layers used for the heave calculation (Figure 10)

Soil layer	Layer thickness, h (m)	Layer depth (m)
1	0.8	1 – 1.8
2	0.8	1.8 – 2.6
3	1.2	2.6 – 3.8
4	2	3.8 – 5.8

The total heave, $\Delta H_s = \sum \Delta h_i$, where Δh_i is the heave of an individual soil layer

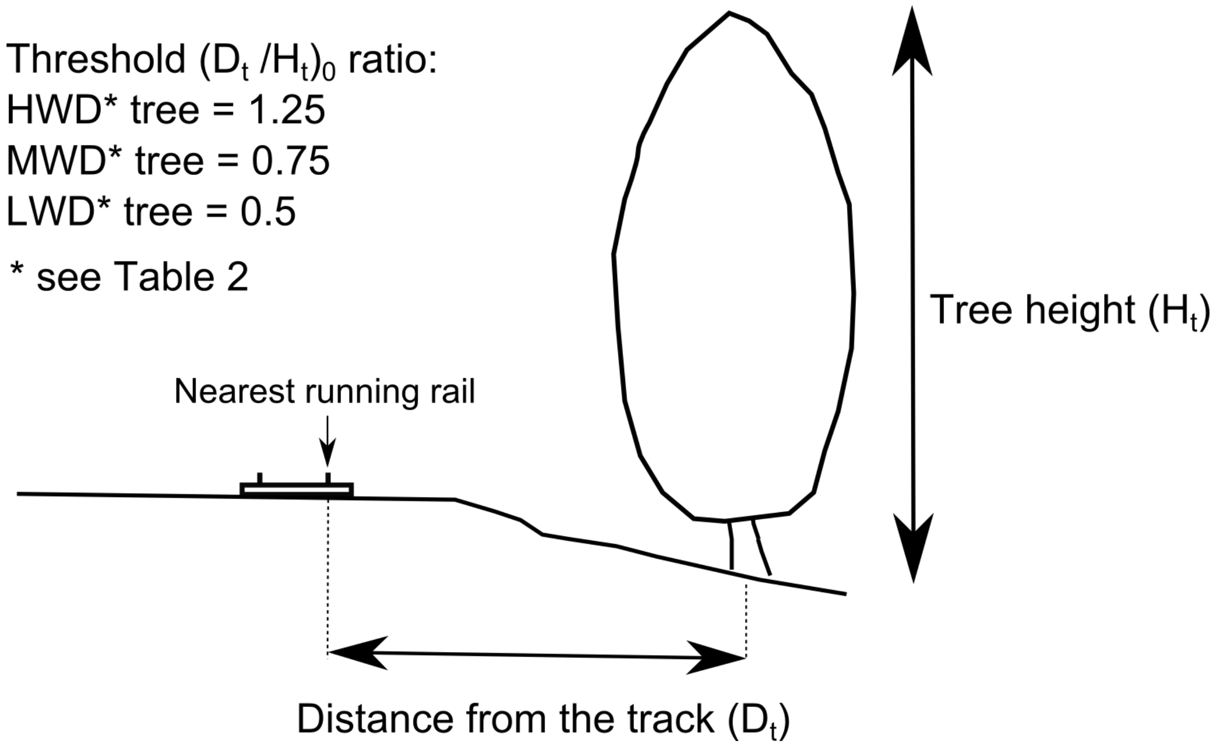

Figure 1. Definition of the D_t/H_t ratio, where D_t is the distance of the tree from the track (the nearest running rail) and H_t is the actual tree height (note: the mature tree height is used in the NHBC guidance (2007))

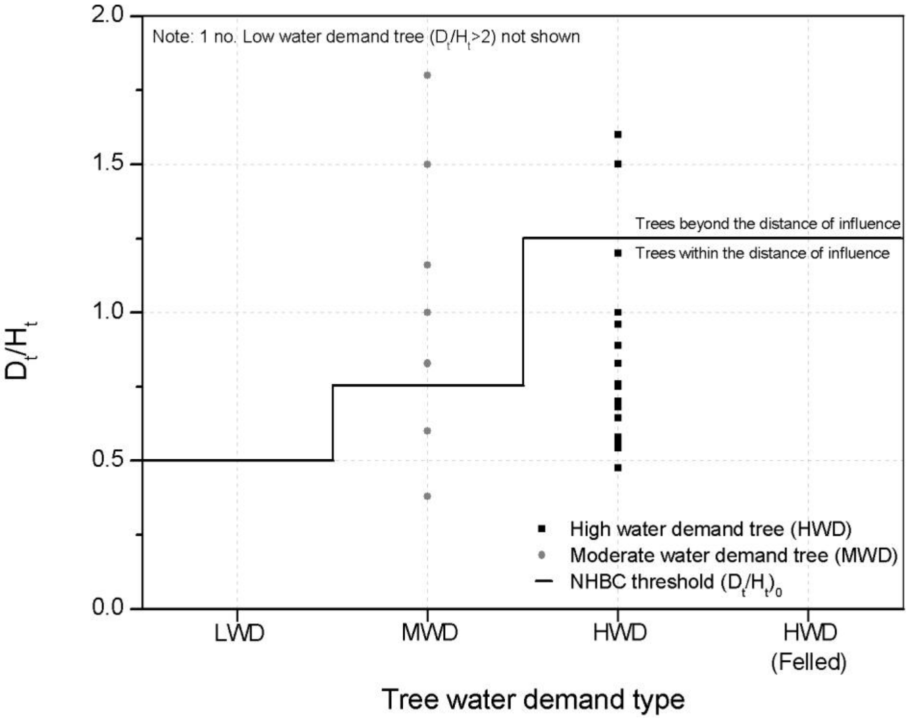

Figure 2. Study site 1- Most of the trees are located within the distance of influence (as defined by the water demand type, NHBC (2007))

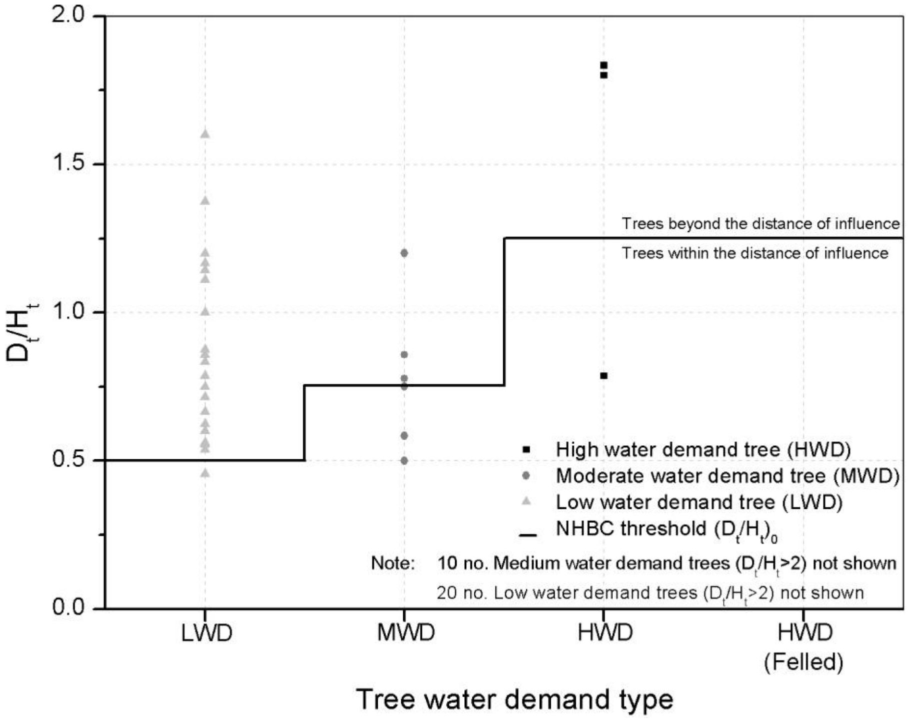

Figure 3. Study site 15 – Most of the trees are located beyond the distance of influence (as defined by the water demand type, NHBC (2007))

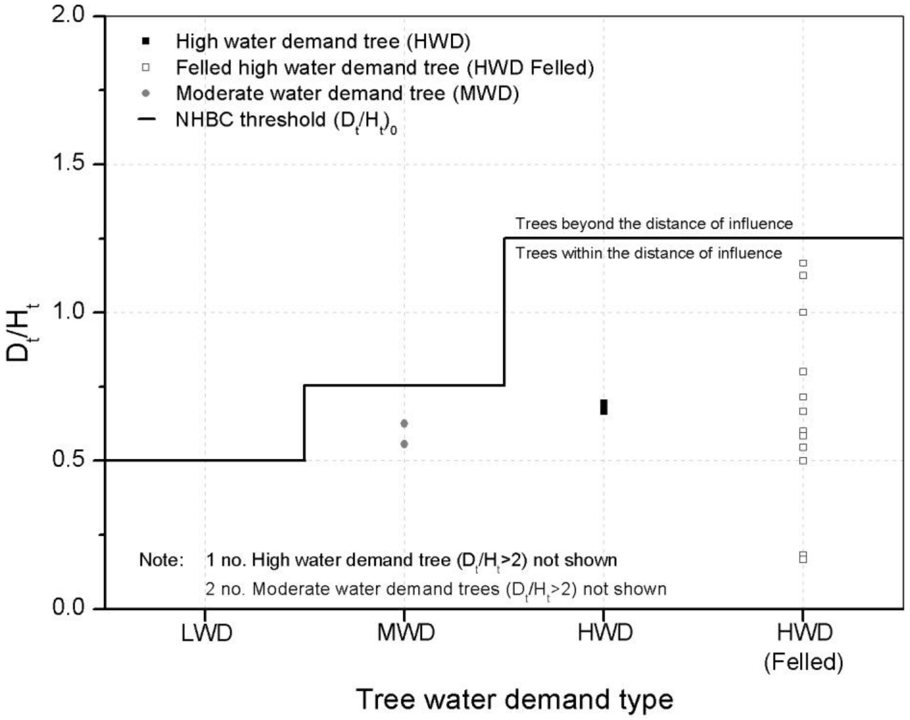

Figure 4. Study site 4 – Felled high water demand (HWD) trees are located within the distance of influence (as defined by the water demand type, NHBC (2007))

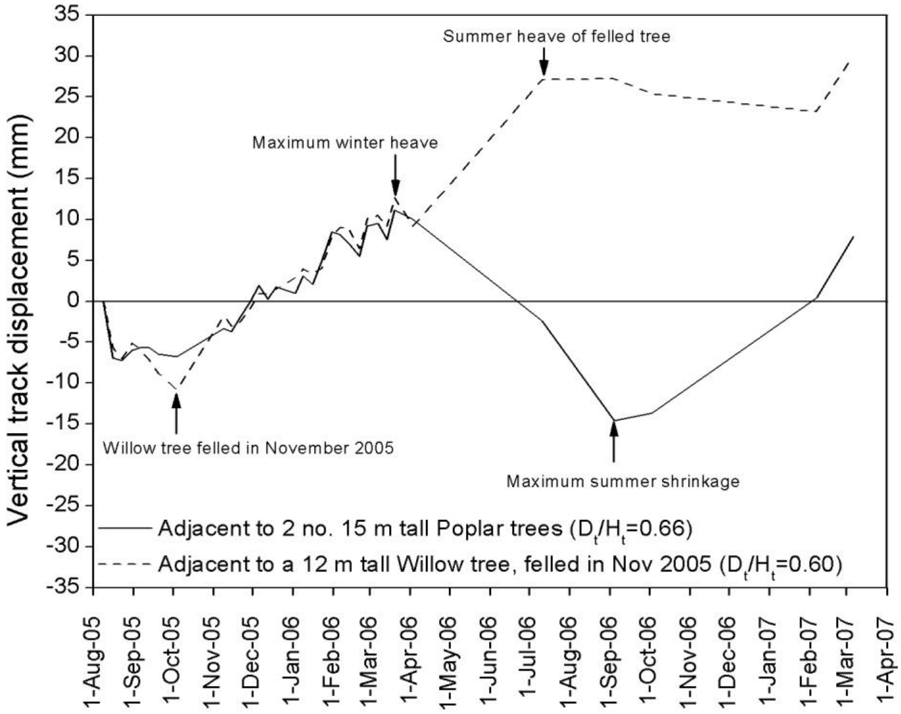

Figure 5. Comparison of seasonal vertical track movement measured adjacent to 2 no. Poplar trees and upwards vertical track movement measured adjacent to a felled Willow tree, at study site 4

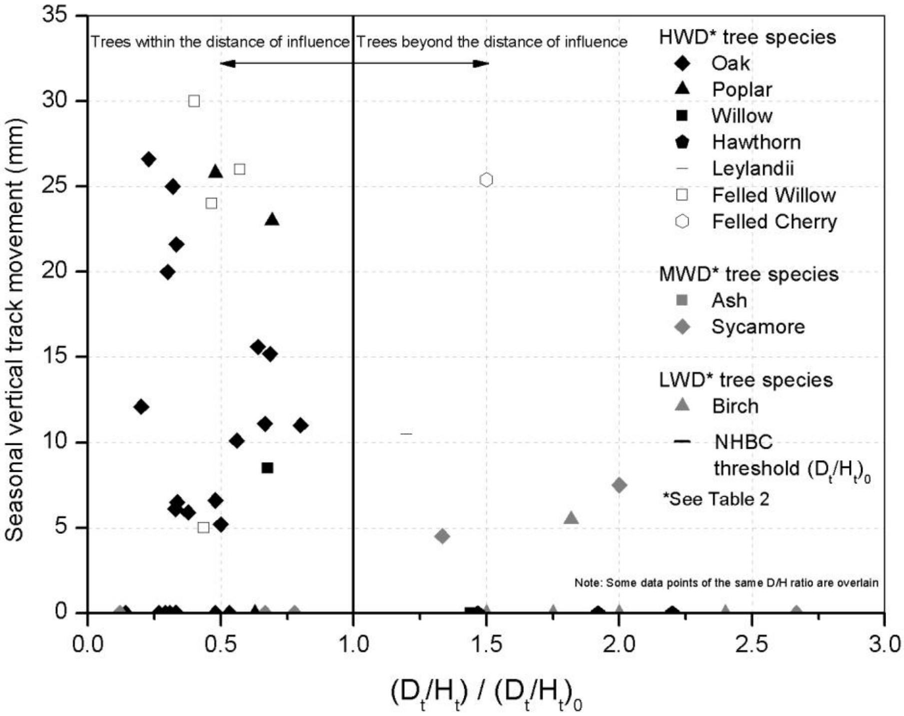

Figure 6. Comparison of seasonal track movement with distance of the tree from the track, normalised by the NHBC threshold $(D_t/H_t)_0$, categorised by tree species

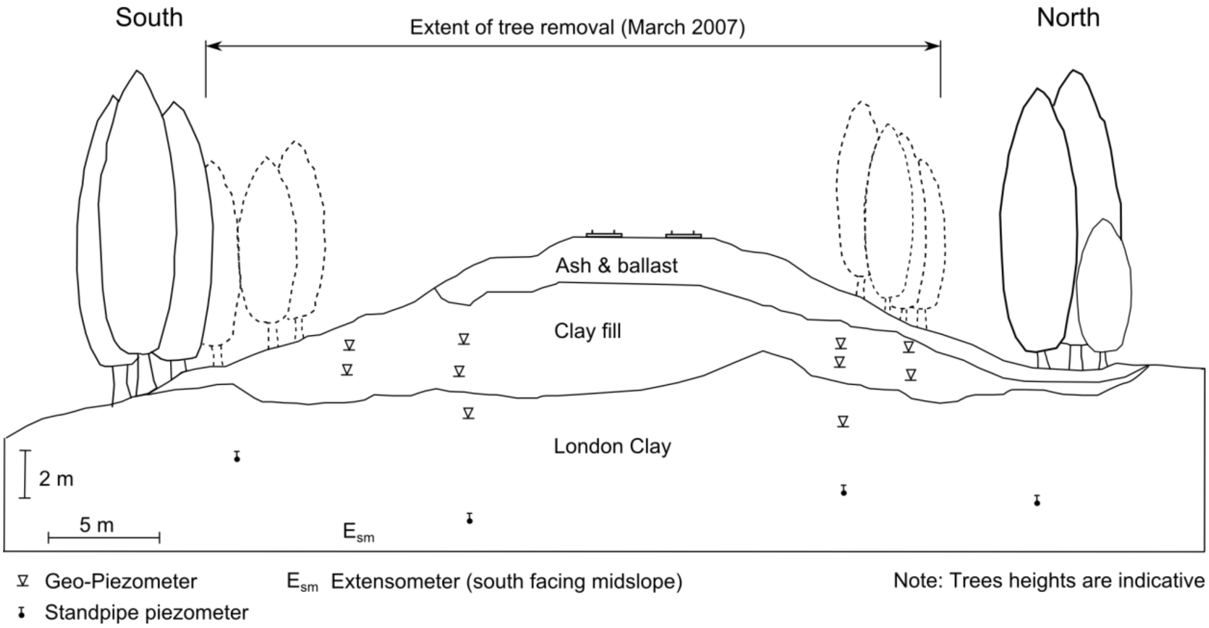

Figure 7. Cross section of the instrumented railway embankment with instrumentation shown

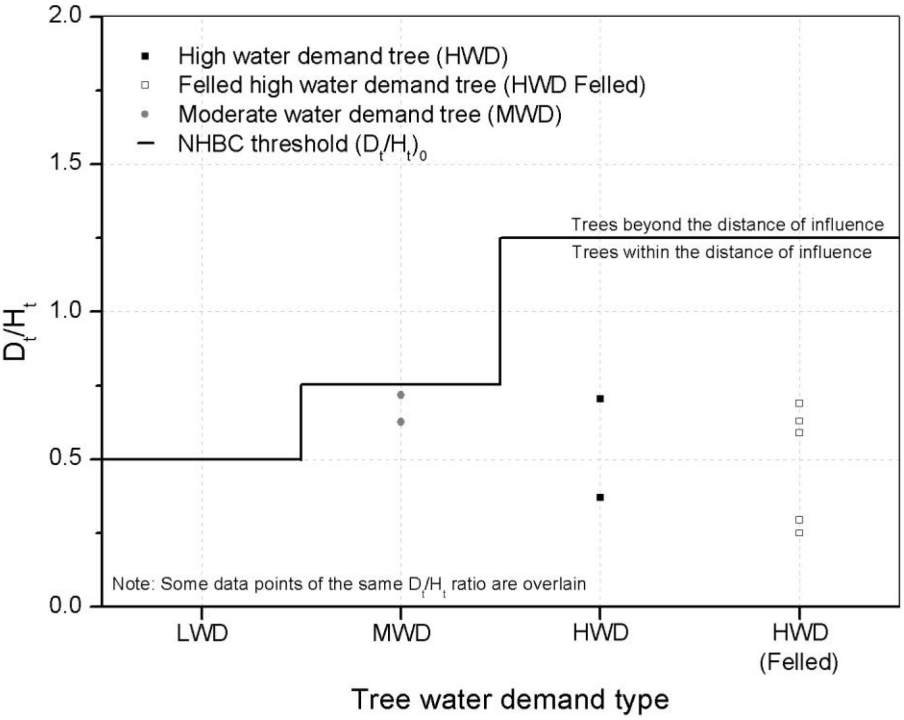

Figure 8. Felled high water demand trees are located within the distance of influence (NHBC, 2007) at the instrumented railway embankment (mature tree height assumed)

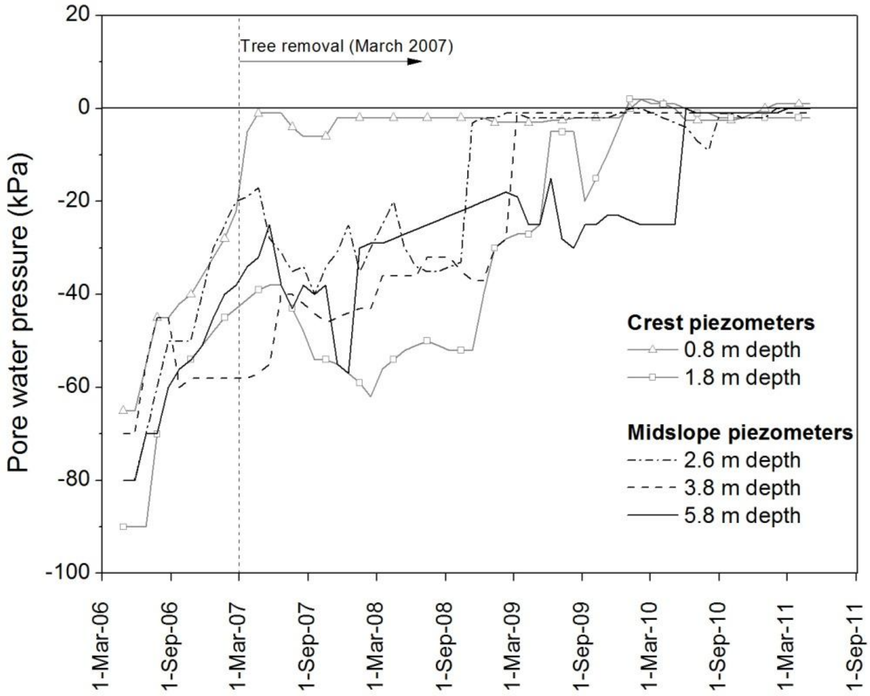

Figure 9. Increasing pore water pressure measured at the crest and midslope on the south facing slope of the instrumented embankment

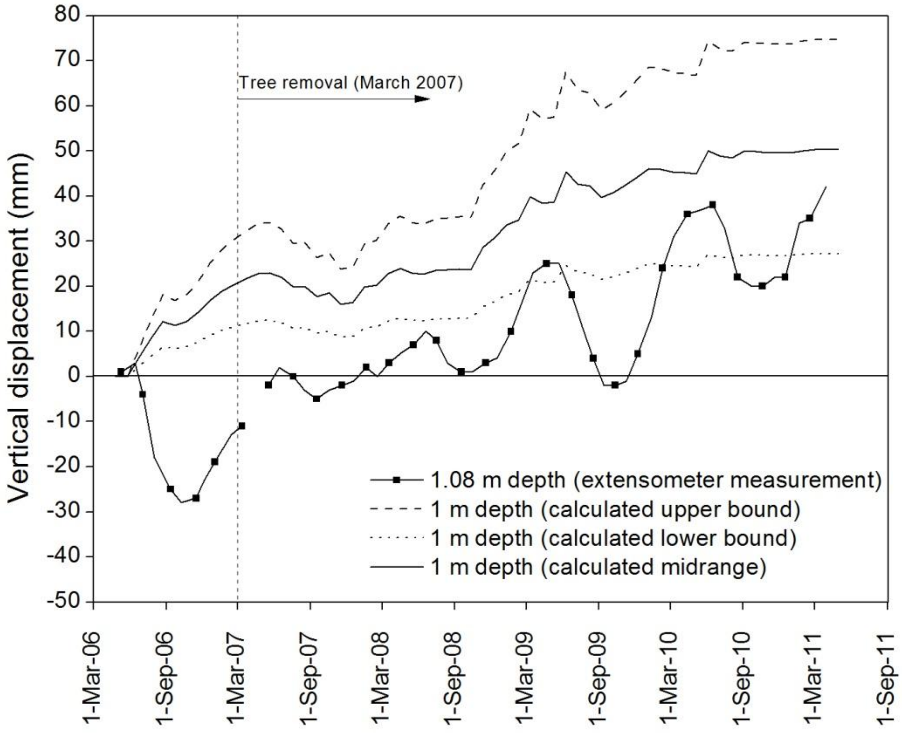

Figure 10. Upward vertical displacement due to soil heave measured at the midslope on the south facing slope of the instrumented embankment, compared with the calculated displacement