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Lifecycle and Resilience Assessment of Earth Embankments in a Changing Climate

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Abstract

Anthropogenic climate change is increasingly causing higher incidences of extreme weather events such as storms and droughts. This affects the stability and resilience of earth embankments, as it disturbs their water balance by dual action of rainfall infiltration into the soil and evapotranspiration through vegetation roots. With the development of advanced coupled numerical tools to model soil-atmosphere interaction in saturated and saturated soil conditions, it is possible to simulate the complete lifecycle of an earth embankment, from its construction in the past to the present, and into the future, taking into consideration historic, present and projected future rainfall and atmospheric conditions. This paper outlines a lifecycle and resilience assessment framework, taking into consideration antecedent conditions in a changing climate and its influence on the stability of earth embankments.

Keywords: Lifecycle assessment, numerical analysis, soil atmosphere interaction, embankments

1. Introduction

The effects of seasonal rainfall and evapotranspiration on the serviceability and ultimate limit states of infrastructure embankments in the UK are well documented (O'Brien, 2013). Growth of high water demand vegetation tends to result in serviceability problems, while heavy rain or uncontrolled vegetation removal may lead to stability problems due to the changes in the water balance of the embankment.

With the development of soil constitutive models that can capture seasonal drying and wetting and changes from saturated to potentially unsaturated conditions and vice versa (Alonso et al., 1990; Georgiadis et al., 2005), as well as the development of evapotranspiration and precipitation boundary conditions (Nyambayo and Potts, 2010; Smith et al., 2008) to capture rainfall infiltration and runoff, both serviceability and ultimate limit states of soil-atmosphere interaction problems may now be modelled with reasonable accuracy. While most soil-atmosphere interaction problems are generally modelled to the present time using historic rainfall data, human induced changes to the climate are expected to impact earthfill infrastructure such as embankments and cut slopes, with heavier storms and / or more severe droughts. There is, therefore, a need to quantify the impacts of the future climate change on the exposed infrastructure.

In this work a numerical methodology for lifecycle assessment of earthfill embankments is presented, utilising a coupled hydro-mechanical finite element formulation for unsaturated soil behaviour, together with the methodology for projecting rainfall patterns in the long-term. The presented numerical analyses are applied to a rail embankment in Essex, UK, as an example boundary value problem, using the finite element software ICFEP (Imperial College Finite Element Program), Potts and Zdravkovic (1999), which employs a modified Newton-Raphson approach with a sub-stepping stress-point algorithm as its nonlinear solver.

2. Rainfall prediction approach

The approach for predicting future rainfall patterns, as a consequence of the effects of future climate change, utilises the existing rainfall data measured by the network of raingauges. The measured rainfall series are often problematic due to a limited length of the record, its discontinuity (missing data), or its coarse resolution (daily or monthly rather than sub-daily). The objective of the rainfall modelling process is to firstly develop a synthetic rainfall series that is continuous and is characterised by summary statistics similar to those characterising the measured rainfall series. Such a rainfall series is then combined with relevant climate change variables for the purpose of predictive rainfall modelling, generating projected future rainfall that accounts for a changing climate. Finally, a downscaling methodology may be applied to generate sub-daily records of future rainfall.

2.1. Rainfall statistics at Rayleigh

The rain station local to the rail embankment in Essex was that at the town of Rayleigh, with the available rainfall series spanning from January 2002 to July 2017. The applied rainfall characterisation comprised calculation of monthly summary statistics which included an arithmetic mean, standard deviation, skewness, auto-correlation and the percentage of wet days for each month. The process first calculated these summary statistics for each month of each year, before the average of the statistics for a calendar month from all the years could be determined. Due to the presence of missing data, the averaging process was weighted with a percentage of data availability, achieving that months with higher percentage of missing data would affect less the final averaged summary statistics. Further details can be found in Guo (2021).

The next step in the process was the application of stochastic models to create a synthetic rainfall series with summary statistics similar to those corresponding to the measured series at Rayleigh. In the current work the Bartlett-Lewis rectangular pulse (BLRP) family of models was adopted as most flexible (see Kaczmarska et al., 2014; Cross, 2019; Guo, 2021; for the discussion about this selection) and producing a representative set of statistical measures which agreed reasonably well with the measured. As an example, Figure 1 compares a 1-hour mean, in mm/h, calculated from the measured rainfall (red) and from 100 BLRP simulations (blue), for each month in a year.

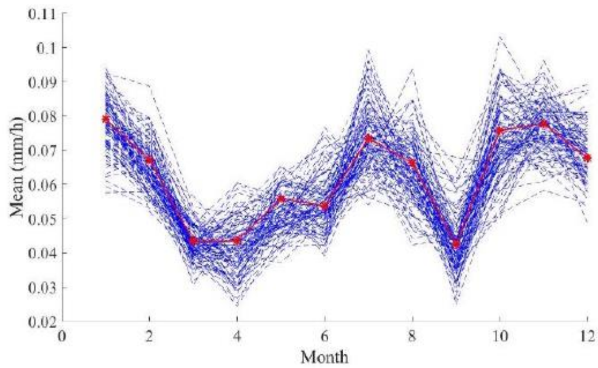

Figure 1: Example comparison of measured (red) and simulated (blue) 1-hour mean rainfall.

2.2 Rainfall projection

To predict future rainfall series that also takes account of future climate change, the generalised linear modelling (GLM) was utilised, taking into consideration the evolution of climate variables predicted in the UK Climate Projection 2018 (UKCP18). This work considered temperature, surface pressure, relative humidity, cloud cover, 10m easterly and 10m northerly wind speeds, concluding that temperature and pressure demonstrated the strongest correlations between the occurrence and amount of rainfall. The modelling adopted a Representative Concentration Pathway (RCP) scenario of 8.5, which represents a high emissions scenario, predicted to deliver the temperature increase of 4.3^oC by year 2100 relative to pre-industrial temperatures. This weather generator produced projected rainfall at the Rayleigh site up to the year 2080, shown as monthly rainfall in Figure 2. The general predicted trend was that of gradual reduction in rainfall volumes at the site, with increasing temperature, although the occasional months would still see significant storms and rainfall. Further details can be found in Guo (2021). The record in Figure 2 was then used as precipitation boundary condition in the geotechnical finite element analysis, to predict its impact on the stability and serviceability of the rail embankment up to year 2080.

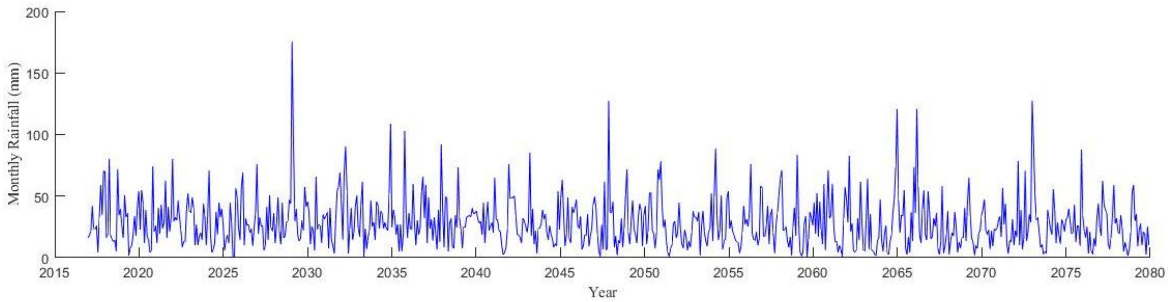

Figure 2: Predicted future monthly rainfall at Essex that takes into account the impact of climate change.

3. Methodology for lifecycle geotechnical analysis

3.1 Problem description and material modelling

A satellite view in Figure 3, of the embankment site in Essex, shows a highly vegetated environment which, together with rainfall precipitation, affects the water balance in the embankment and, in turn, its stability and serviceability.

Figure 3: Satellite view of the rail embankment, next to Magnolia Road (Google, 2021).

The site consists of a London Clay foundation (see the cross-section in Figure 4), with a chalk bedrock at around 70m below the ground surface (Arup Geotechnics, 2007) and the ground water level at 3m below the ground surface. To take into consideration the natural weathering of London Clay before embankment construction, the top 3m was assumed to be weathered (WLC), with a higher permeability compared to the unweathered London clay (UWLC). Clods of London Clay were used as the main embankment fill material (LCF), dumped on site without much compaction during embankment construction and subsequently topped up with industrial ash and ballast to maintain track level as the clay fill compressed over time (Smethurst et al., 2015).

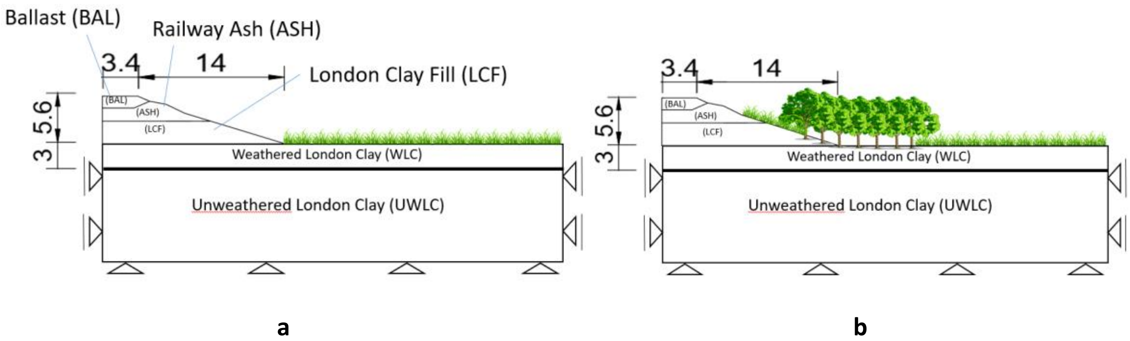

Figure 4: Geometry and evapotranspiration boundary conditions during a) embankment construction and b) after vegetation removal.

Table 1 summarises the constitutive modelling adopted for each soil layer. The mechanical behaviour of WLC and LCF was represented with the unsaturated Imperial College Single Structure Model (ICSSM; Georgiadis et al., 2005), complemented with the hysteretic soil water retention (SWR) model (Tsiampousi et al., 2013) to represent their hydraulic behaviour. The ICSSM was calibrated with confined wetting and free swelling experimental data of compacted London Clay from Monroy et al. (2010), while the SWR model was calibrated with experimental data on clay fill specimens from Melgarejo-Corredor (2004). The industrial ash was modelled with an unsaturated Mohr-Coulomb model and with a monotonic SWR model calibrated with drying and wetting tests form Melgarejo-Corredor (2004). In addition, a dual permeability model (Potts and Zdravkovic, 1999; Nyambayo and Potts, 2010) was employed for LCF and UWLC, allowing a reduction of saturated permeability with increasing suction and / or an increase of saturated permeability with increasing tensile principle stresses (simulating desiccation cracking). Details of model calibrations and summary of derived parameters can be found in Guo (2021).

The ballast was assumed to be drained and a simple linear-elastic perfectly-plastic Mohr Coulomb model was adopted for it, while a nonlinear Mohr-Coulomb model, adopting the Imperial College Generalised Small Strain Stiffness (ICG3S; Taborda and Zdravkovic, 2012) model was employed for the UWLC at the base. The parameters for the latter modelling were adopted from Tsiampousi et al. (2016).

3.2 Lifecycle modelling sequence

The embankment lifecycle was modelled in 5 key stages; initialisation, embankment construction, vegetation growth and maturity, vegetation removal, and future prediction to 2080. During the initialisation phase, the ground surface was assumed covered by grass. Hence the hydraulic boundary condition on the surface of the foundation soil comprised evapotranspiration from grass, together with average monthly rainfall from 1971 to 2000 for Greenwich, London (in the form of precipitation; Met Office, 2012), applied over 5 years. This duration was sufficient to establish the steady-state pore water pressure profile in the ground that combined soil-atmosphere interaction with the initial hydrostatic pore water pressure in the ground (Tsiampousi et al., 2016). Subsequently, the embankment was constructed over 1 year, with the grass removed over the embankment footprint (Figure 2a). Over the next 25 years, average precipitation was applied onto the surface of the model, with the vegetation around and on the embankment slopes slowly growing and maturing, first from grass to shrubs and finally to fully matured trees.

At the end of the 25 years of applied average monthly rainfall, the trees on the embankment slope were partially removed, as part of vegetation management performed in 2007. Figure 4b shows the remaining vegetation, where grass on the slope indicates the extent of tree removal on the slope. For the next 14 years of the analysis (from 2007 to 2020), actual monthly rainfall in Rayleigh obtained from the Environment Agency was applied onto the surface, instead of the average monthly rainfall, as the former record was used for the projection of future rainfall.

Table 1: Summary of constitutive model and basic soil parameters adopted for the numerical analysis.

Soil	Mechanical constitutive model	Saturated permeability (m/s)	Bulk unit weight (kN/m³)	Angle of shearing resistance (°)	Soil water retention model (SWR)
Ballast	Mohr Coulomb	drained	18.0	40.0	N/A
Ash	Unsaturated Mohr Coulomb	4×10^{-5}	11.0	35.0	Monotonic
London Clay fill	ICSSM	3.7×10^{-8}	18.1	22.0	Hysteretic
Weathered London Clay	ICSSM	4.3×10^{-9}	19.1	22.0	Hysteretic
Unweathered London Clay	Mohr Coulomb with ICG3S	3.7×10^{-10}	19.1	23.0	N/A

2.2 Embankment resilience assessment due to storm

While the lifecycle analysis is able to capture the general long-term behaviour of the rail embankment with monthly rainfall, a further refinement to the main analysis is required to study the resilience of the embankment to storms at various stages of its lifecycle. This involved first identifying critical moments in the embankment's lifecycle, then performing secondary analyses in which a storm scenario was applied to the embankment at those periods, but with a much finer resolution and timestep at the level of hours. The resilience to storm was assessed by the factor of safety (F_S) in the embankment before and after the storm, calculated with the numerical approach developed by Potts and Zdravkovic (2012) that applies a partial material factor to soil strength.

The applied storm scenario involved a total rainfall of 95mm over a period of 5 days (15mm of rain per day for 4 days, and a final 35mm rainfall on day 5). Several other storms scenarios were investigated with varying durations and volumes in Guo (2021). The storms were applied at the end of August 2014 and September 2069, corresponding to the wettest and driest embankment state, respectively, during its lifecycle.

3. Discussion of results

This section presents a brief discussion of the numerical results, showing validation of the numerical model against field measurements, followed by predictions of the long-term embankment response and resilience to storm.

3.1 Seasonal variations of movements and pore pressures in a typical year

The vertical displacements at various depths in the mid-slope of the modelled embankment during a typical year before vegetation removal are plotted in Figure 5. The displacements are compared with field monitoring measurements obtained from 2006-2007 by Geotechnical Observations (2013). In addition, contours of pore water pressures (with suction as positive) developed in the model at the end of summer (September) and end of winter (March) are plotted in Figure 6.

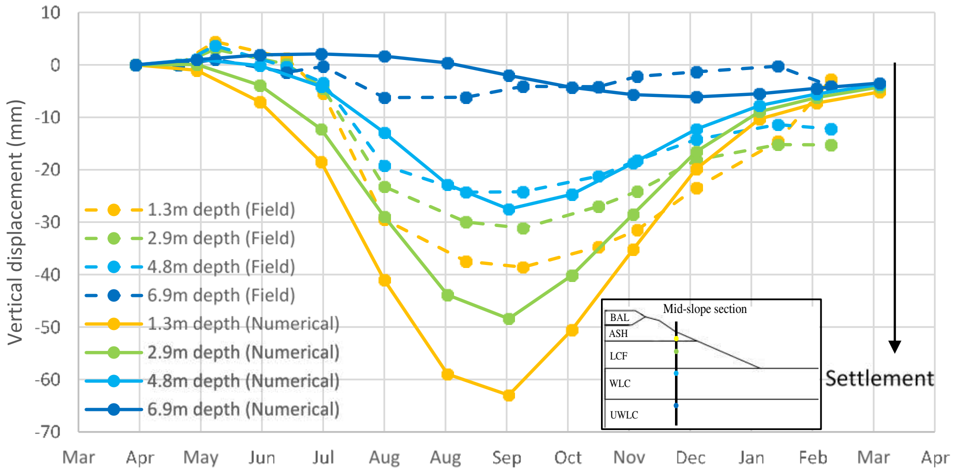

Figure 5: Comparison of vertical displacements in the mid-slope section between field measurements by Geotechnical Observations (2013), and the numerical analysis for a typical year.

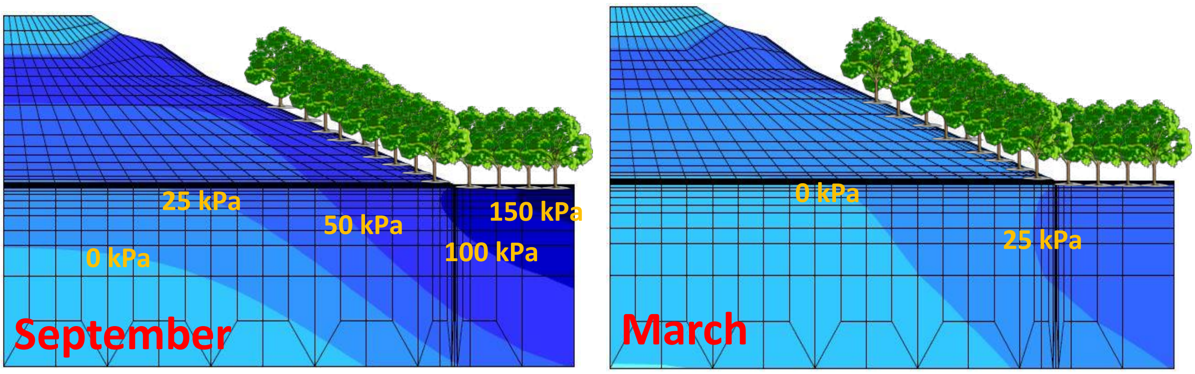

Figure 6: Pore water pressures contours at the end of summer (September) and end of winter (March) in a typical year before the removal of trees.

During the summer, evapotranspiration from the trees exceeded precipitation in the same period, resulting in mobilisation of suctions of up to 100kPa within the embankment, as shown in Figure 6. As a result, the soil within the embankment and in the superficial part of the weathered London Clay shrank, causing settlements, as depicted in Figure 5. This process reversed during the winter months, with suctions largely dissipating as precipitation exceeded evapotranspiration and the mid-slope vertical displacement showing heave. Figure 5 shows that while the numerical model slightly overpredicts settlement in the embankment, the general seasonal shrink-swell behaviour was well captured.

3.2 Prediction of long-term movements to 2080

Figure 7a plots the pore water pressures at the mid-slope section at the end of summer for every year from 2007 to 2080. Each colour presents a decade and 10 profiles within that decade, apart from the initial range from 2007 to 2009. Due to the predicted overall drier climate in Essex as a result of climate change (reducing rainfall in Section 2.2) and trees remaining at the foot of the embankment, suctions at the end of summer were predicted to consistently increases, reaching close to 100kPa within the ash layer. Although a reduction of suctions was predicted over winter months, the predicted overall reduction in rainfall resulted in some suctions being maintained in the foundation soil at the end of winter, in particular from the 2060s onward.

While the high suctions predicted in the future due to drier climate would result in a higher factor of safety, the serviceability of the embankment would be impacted, as a slip surface at the ash - London Clay fill interface was predicted to develop over the years (Figure 7b). A smaller slip was also indicated to develop between the embankment and the foundation soil, however it may not be as severe as the ash-fill slip. The implication from these results is a potential necessity for remedial measures to mitigate the slip surface formation.

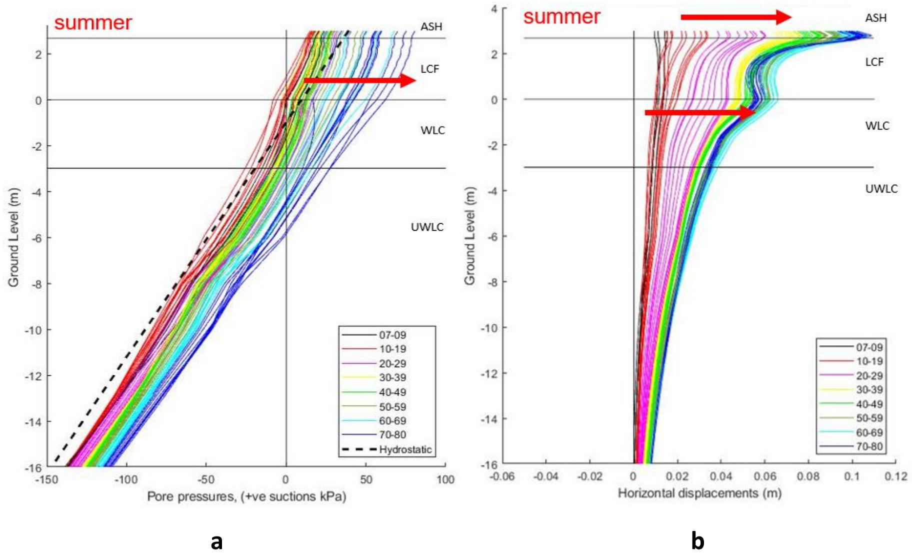

Figure 7: Mid-slope profiles of (a) pore water pressure and (b) horizontal displacements at the end of summer, for each year from 2007 to 2080.

3.3 Embankment resilience to storm

Figure 8 summarises the contours of pore water pressure and the corresponding factor of safety, F_S, before and after the storm event for the 2 periods in the embankment's lifecycle. In the case of the wettest summer in August 2014, a nearly fully saturated antecedent situation in the embankment resulted in practically no change in F_S, due to the storm water runoff as it could not infiltrate the embankment. On the contrary, in the case of the predicted driest summer in September 2069, the very high suctions in the embankment were depleted by the storm rainfall, reducing the safety by 40%, although the embankment still predicted to remain stable, with $F_S = 1.66$.

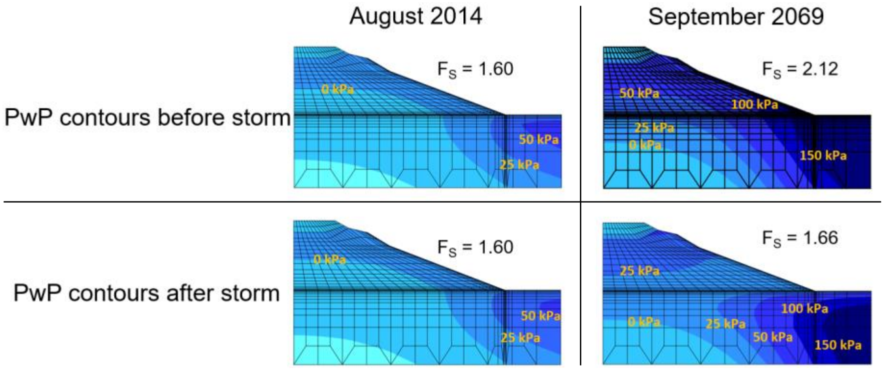

Figure 8: Contours of pore water pressure and the corresponding F_S before and after the storm event at critical periods of the embankment's lifecycle.

4. Conclusions

The paper presents a consistent and validated numerical approach for lifecycle assessment of geotechnical infrastructure. The finite element analyses of a rail embankment case study have shown that both serviceability and stability of the embankment are sensitive to the climate and vegetation on the embankment. Within a typical year, seasonal variations of pore water pressures and displacements are significant and generally should be monitored for an efficient maintenance.

A drier future climate due to predicted climate change was shown to impact on the serviceability of the embankment, with a need for potential mitigation measures. This was driven by increased shrinkage of the embankment at higher suctions, the latter in turn generally improving embankment stability.

The examined resilience to storm examined indicated that the embankment could experience significant loss of stability with drier antecedent conditions, reducing dramatically the factor of safety.

This study highlights the importance of performing a complete lifecycle and storm resilience assessment of earth infrastructure, that is able to accurately reproduce the current conditions and has the capability to predict future changes, taking into account also the effects of future climate change.

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