Study of the Impact of Wetting Processes on Transport Infrastructure Performance

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Abstract

Extreme weather events attributed to climate change have been gradually causing engineered soils to experience larger and more frequent variations between unsaturated and saturated states by periodically changing their moisture and suction due to wetting (rainfall) and drying (evaporation). Geotechnical assets critical to the transport network are particularly vulnerable to the influence of these climatic conditions due to its impact on their performance including swelling, shrinkage and collapse. However, the implementation of unsaturated soil behaviour into practice is not commonplace despite its importance for increasing resilience of the transport network. This paper addresses the impact of wetting processes, mimicking periods of intense rainfall, on the performance of a typical Victorian rail embankment asset using the Barcelona Basic Model (BBM) implemented in a finite element platform (PLAXIS 2D). The embankment was subject to the simulation of increasing degrees of saturation followed by the application of rail traffic to investigate their effect on performance and serviceability. The transition between unsaturated and saturated conditions during the wetting process was shown to produce significant swelling and strength changes which were exacerbated by increased wetting owing to climate change. Settlement due the application of train loads similarly increased in future scenarios. The results not only demonstrate the importance of considering unsaturated modelling conditions when managing geotechnical assets but also its role in better accounting for the effects of climate change.

Keywords: Unsaturated soils, Transport infrastructure, Geostructures, Climate change

1. Introduction

The impact of climate change, and in particular the wetting process, on rail assets have gained some attention recently due to performance shortfalls and localised failures on the UK rail network. In fact, between 2017/2018, £111 million was spent on routine maintenance of earthworks, with emergency repairs costing ten times that of planned works (Stirling et al., 2020). Furthermore, the recent 2020 Stonehaven train derailment has highlighted the importance of asset management and the need to better understand the impacts of intensifying soil-atmosphere interactions associated with climate change (BBC News, 2020b; BBC News, 2020a).

Consideration of the effects of climate change in the UK have become critical in the last decade, as many locations are now prone to long periods of drought and rapid flooding (Tang et al., 2018). Predicted climatic trends suggest that for both Representative Concentration Pathway (RCP) 2.6 and 8.5, there is an incidence of increasingly high temperatures and likelihood of widespread drought due to decreased summer rainfall, in conjunction with increasingly wetter winters due to a growth in winter precipitation and its intensity (Lowe et al., 2019).

These developing climatic changes can have a dramatic influence on the performance of built infrastructure. This is of particular significance for transport assets (e.g. rail) located where there is a greater prevalence of soils with high susceptibility for volume change upon variation in moisture (Loveridge et al., 2010). Past research has shown these impacts hinge upon the consideration of the shear strength behaviour when subgrade soils and compacted fills experience changes in their stress state post compaction, i.e. transition from unsaturated to saturated states (Take and Bolton, 2011; Glendinning et al., 2014; Heitor et al., 2015b; Heitor et al., 2015a; Briggs et al., 2017; Stirling et al., 2020). Advancing the use of numerical analysis to simulate the influence of this transition on shear strength of compacted soils and fills will become paramount to the future design of transport infrastructure. It will also be intrinsic for the determination of the impact of climate change, particularly the effect of wetting processes, on current transport geo-structures.

In this paper, this is investigated by simulating the wetting process for a railway embankment and modelling the behaviour of the Jossigny silt using the well-established Barcelona Basic Model (BBM).

2. Modelling of unsaturated soil behaviour in PLAXIS 2D

The implementation of the Barcelona Basic Model into PLAXIS 2D has allowed for the numerical analysis of unsaturated soils in geotechnical problems. For instance, it has been successfully applied in the calibration and modelling of soil behaviour based on laboratory test data and foundation design (Abed and Pieter, 2006; Gonzalez and Gens, 2008). However, the application of this well-established model to transport infrastructure has been more limited. This particularly important as stability and serviceability problems for structures such as embankments are dependent upon the consideration of unsaturated soil conditions, as their behaviour both in terms of shear strength and volumetric changes are sensitive to moisture change.

The Barcelona Basic Model or BBM, was used to simulate unsaturated soils behaviour in PLAXIS 2D (Sloot, 2020). The BBM is an elastoplastic model that builds upon the Modified Cam Clay model (Alonso et al., 1990), while incorporating the influence of suction on soil behaviour. For brevity only the parameters of the model are described in this section. Further detail can be found in the original publication by Alonso et al. (1990).

To accurately simulate a representative soil response to hydraulic stress changes, the BBM parameters reported by Gonzalez and Gens (2008) were adopted (Table 1 and Table 2). The calibration was undertaken for the Jossigny silt, a compacted clayey silt, whose unsaturated mechanical behaviour was reported by Casini (2008). The compaction state used for calibration was at dry of optimum moisture content at 13% and producing a dry unit weight of 14.5kN/m3 (Proctor compaction) and allowed for adequate volume change during wetting.

	Description	Units	Value
ν	Poisson's ratio		0.3
k	Gradient of the saturated unload and reload line		0.005
λ_o	Gradient of the saturated normal compression line		0.12
k_s	Effect of suction on gradient on unload reload line		0
K_s	Constant which describes the effect on suction on cohesion, therefore tensile capacity		0.14
M	Gradient of the critical state line		1.45
e_o	The initial void ratio		0.81
P_o	Saturated pre-consolidation stress	kPa	55
P_r	The reference mean stress (1 kPa)	kPa	1
r	Constant used to control the maximum stiffness of soil due to suction		0.5
β	The rate of increase in soil stiffness due to suction	kPa^{-1}	0.005
α	The non-associated flow rule for plasticity		1

Table 1: BBM parameters for the Jossigny silt used in calibration adopted after (Gonzalez and Gens, 2008).

Parameter	Units	Description
$S_{r\ \mathrm{res}}$		0.39
$S_{r\ \mathrm{sat}}$		1
g_a	m^{-1}	0.7
g_n		2.083
g_c		-0.52
g_l		0
k_y, k_x	$m/day/day$	0.0864

Table 2: Hydraulic parameters for the Jossigny silt used in calibration adopted after (Gonzalez and Gens, 2008).

3. Numerical Analysis

3.1 Model Parameters

The unsaturated numerical model was implemented in a 2D model adopting the geometry of a typical Victorian railway embankment to investigate the effect of saturation. The geometry of the model was inspired by a numerical analysis conducted by Loveridge et al. (2003) and is presented in Figure 1. The embankment is 5m in height and consists of 2.5m of ballast above clay core and secondary fill flanking the embankment used for widening comprising gravel material, underlain by a subgrade clay foundation.

A 2D plain strain model type was developed to simulate a typical cross section perpendicular to the central axis of the embankment. Four point loads were set for the stresses applied by passing trains; beneath which wooden sleepers, 2.5m wide and 0.2m thick, were simulated using the linear elastic model. A static load of 50 kN was estimated as representative of the wheel load of a high-speed train. It was applied to both tracks simultaneously simulating a worst-case scenario where four trains are present concurrently.

The ballast, subgrade and gravel fill were modelled using Mohr Coulomb, while the clay core was substituted with the BBM calibrated Jossigny silt parameters. Cohesion, friction angle and unit weight for the gravel fill and clay subgrade were taken from Loveridge et al. (2003) and Young's modulus and Poisson's ratio estimated using Look (2014). The ballast and sleeper properties were taken from an FE sleeper and ballast analysis by Namura et al. (2005). The groundwater flow properties were modelled using the standard PLAXIS data set; the hydraulic conductivity for the ballast, subgrade and ash/chalk fill was estimated using Look (2014). The soil properties and groundwater flow properties used in the model are presented in Table 3 and Table 4.

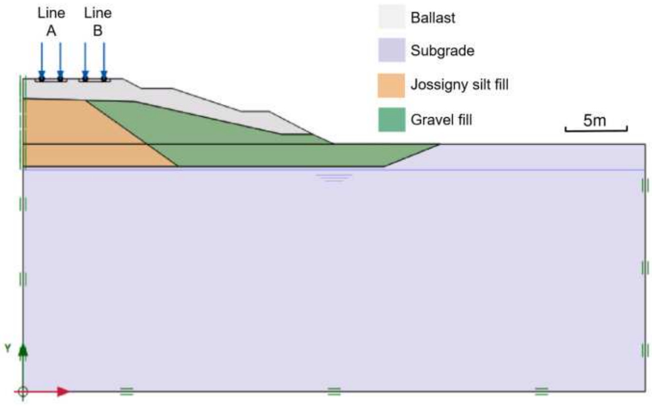

Figure 1: Geometry of the model used for embankment analysis.

Parameter	Ballast	Subgrade	Jossigny silt	Gravel
k_y, k_x	86.4	0.0013	0.0864	0.864
Model	Standard	Standard	Van Genuchten	Standard
Coarseness	Coarse	Very Fine	N/A	Medium

Table 3: Mohr Coulomb parameters used for embankment analysis.

Parameter	Ballast	Subgrade	Gravel	Sleeper
γ_{sat} (kN/m³)	21	19	18	20
γ_{unsat} (kN/m³)	19	18	17	20
E' (MPa)	30	90	90	20
ν	0.4	0.4	0.35	0.15
Friction angle	35	30	30	N/A
Cohesion (kPa)	30	2	1	N/A

Table 4: Ground water flow parameters used for embankment analysis.

3.2 Transient Flow Analysis

Limitations in PLAXIS regarding simulation of sub-surface infiltration during deformation means suction was altered by raising the water table. Therefore, the initial water level was assumed to sit at ground level.

It should be noted that the method selected does not incorporate the role of factors such as surface runoff, vegetation, surface permeability and desiccation, which are all important components in the soil-atmosphere interaction. The analysis is therefore an investigation dedicated to the effect of dissipation of suction pore pressures. Prior to this an infiltration exercise was undertaken to determine the degree of saturation of the embankment due to changes in water content caused by infiltration associated with climate change.

Infiltration was replicated using a transient flow only calculation where rainfall was simulated at surface over 90 days. Rainfall data was taken from Sheffield, UK during autumn 2019/2020 where 427mm of precipitation was measured over 3 months (Muchan, 2019). This was subdivided to estimate an average daily rainfall of 4.7mm. A 44% addition was also included for the predicted 2050 precipitation rate and a 75% increase was added for the 2080 precipitation rate to account for the predicted increase in the UK's daily winter average rainfall due to climate change, used by the Environment Agency (2019). These predictions are consistent with a 4°C rise in global mean temperature by the end of the century taken from UKCP09 and represent a precautionary scenario using Representative Concentration Pathway 8.5 (RCP 8.5).

The results of the predicted rainfall and associated change in suction are presented in Figure 2. The results show the expected increase in the speed of saturation with increasing rainfall associated with climate change.

The analysis allowed for an approximation of a representative water table height for the embankment during the deformation analysis, which was taken at approximately 47 days for each scenario (as full saturation of the embankment was achieved for all scenario by day 90) and summarised below:

- 2020 – 4.5m below embankment formation level
- 2050 – 3.5m below embankment formation level
- 2080 – 2.5m below embankment formation level

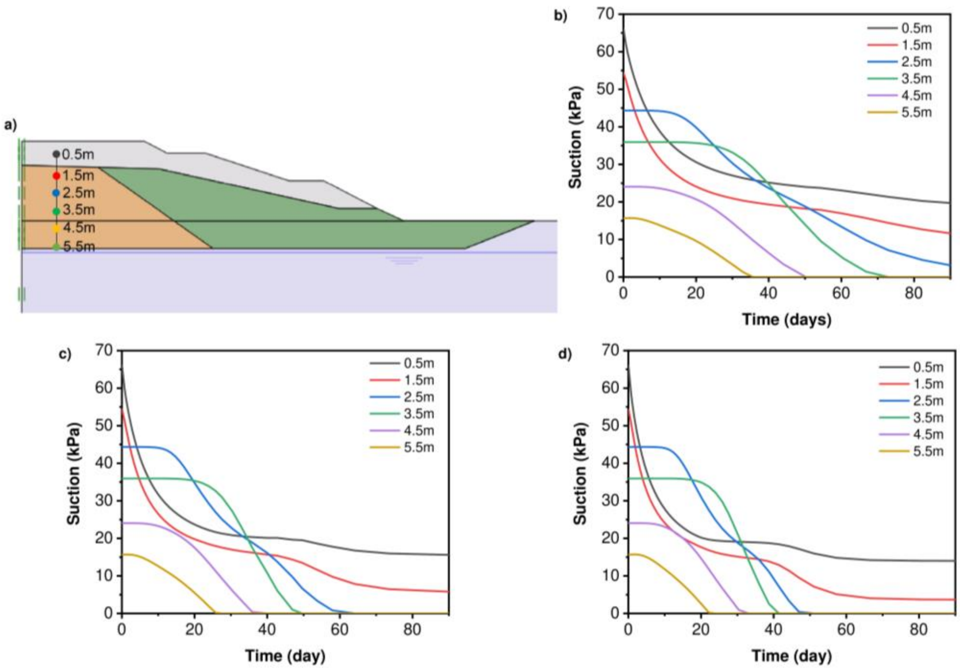

Figure 2: a) Depth below formation level and position of nodes selected for analyses b) Change in suction at each node during present day infiltration c) Change in suction at each node during predicted 2050 infiltration d) Change in suction at each node during predicted 2080 infiltration.

3.3 Deformation Analysis

The deformation analysis was undertaken in a similar manner to dam stability modelling. Firstly, a K_o initial phase followed by a plastic nil-phase was used to produce equilibrium within the model. The water table was then raised over a period of 47 days to simulate change in saturation of the embankment. This means that the increase in the height of the water table simulates an increase in the speed within which saturation of the embankment occurs. Finally, points loads were applied to both tracks to simulate train loads.

3.4 Deformation Results

The results from deformation analyses are presented in Figure 3 and show swelling was induced after initial water table rise in all three scenarios. Laboratory testing in which swelling was measured was not undertaken and therefore could not be incorporated into the calibration exercise. However, this behaviour is confirmed by simulations presented by Gonzalez and Gens (2008) which demonstrate that during saturation under vertical stresses below 100 kPa, the parameters for the Jossigny silt produces significant swelling. The reduced stress state within the embankment prior to loading, and the reduction in effective stress during water table rise, is consistent with this finding.

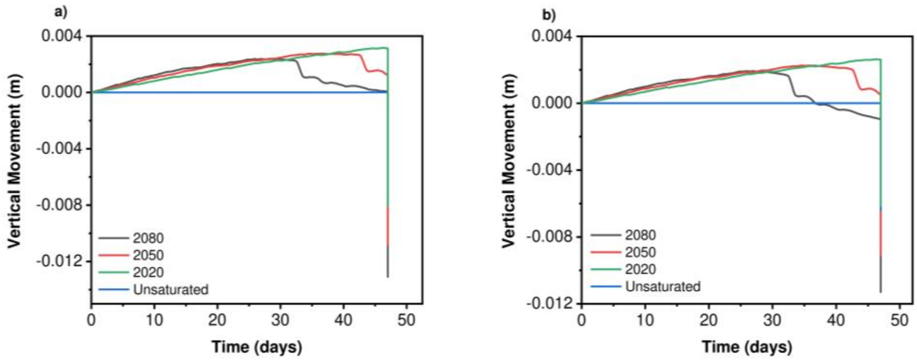

Figure 3: Vertical movement against time on a) Line A and b) Line B.

This swelling phenomenon resulted in an increase in formation level on both the up and down fast lines. The maximum vertical movement on each line after the 47 day period was approximately 3mm. Consequently, it is probable that this volumetric response would significantly contribute to the propagation of progressive failure. These results also agree with data recorded by Standing et al. (2020) which showed 2mm of heave from between mid-December to February in electrolevel data at the crest of Roding Valley historic railway embankment constructed in London clay.

The increase in saturation for 2050 and 2080 did not produce a corresponding escalated volume increase. Vertical movement on both lines showed that initially the future predicted hydraulic conditions produced swelling greater than the 2020 scenario, however, a significant decrease was experienced after 30 days, especially in the 2080 simulation. It seems that when the water level exceeded approximately 2.9m below embankment formation an imbalance was reached; at this point formation level began to decrease due to change in properties predicted by the BBM. Consequently, instability was created during the transition from the initial unsaturated equilibrium phase and the saturated re-equilibrium of the embankment. This would therefore indicate high embankment sensitivity which correlates well with modelling undertaken by Loveridge et al. (2003) where the fully saturated factor of safety for a similar historic embankment was found to be between 0.9 and 1.1.

The application of line loads representing passing trains successfully simulated the interaction between swelling and application of vertical stresses. The decrease in stiffness and shear strength of the embankment due to increasing saturation for the estimated climatic conditions is evident. The difference between unsaturated conditions and the 2080 scenario for both lines was approximately 5mm. Due to the geometry of the Jossigny silt Line B, which lies in proximity to the crest of the embankment, is also underlain by both ash/chalk fill. As a result it showed an overall reduced settlement of 2mm in all scenarios with comparison to Line A. This is within the permissible differential settlement between running rails which is usually set to <5mm (Nowak, 2012). Furthermore, the 2020 simulation showed an overall formation level which equalled that of the unsaturated state. This means that there was a net reduction in the final vertical movement when compared to the 2080 scenario, due to initial swelling resulting in a reduced formation change. These findings are corroborated by data collected by Standing et al. (2020). Elevation measurements made at the crest of the High Barnet historic railway embankment constructed in London clay, showed approximately 5mm settlement between mid-March and June which corresponds moderately well with the unsaturated application of train loads; although it seems the Jossigny silt exaggerates settlements during all scenarios which is likely due to the reduced dry density used during calibration.

Several limitations restrain the accuracy of the model for embankment analysis. During the initial 47 day water table rise multiple train passes would be experienced concurrently, however, cyclic loading is incompatible with this iteration of the BBM (Pedroso and Farias, 2011). This means that this complex interaction is oversimplified. Furthermore, the inability for a fully coupled hydro-mechanical analysis to be performed means boundary conditions for the simulation of infiltration could not be applied. The impact of infiltration within the near surface is important and can lead to shallow instability but also its absence simplifies the spatial stress changes which occur during wetting propagating from the embankment surface (Briggs et al., 2017). Furthermore, the simplification and assumption made by use of the critical state model are also pertinent for a slope stability problem where peak and residual strength play a long-term role in progression of failures. In this regard, the behaviour and properties of the Jossigny silt does not represent the response of compacted clay used in practice. Although, its compaction dry of optimum water content is somewhat comparable to historic compaction techniques during embankment construction where end tipping was likely used during placement of material (Skempton, 1996; Walker et al., 2022). Moreover, the behaviour of ash fill in historic embankments has been shown to be complex. Standing et al. (2020) surmised that due to its free draining nature, drying of this ash in summer caused it to become more mobile due to the loss of suction and therefore contributes to settlement, particularly under cyclic loading.

4. Conclusion

The BBM has been used to model the volumetric and strength changes caused by the wetting process during the transition of compacted soils from unsaturated to saturated conditions. This has been undertaken using the Jossigny silt whose parameters were taken from existing literature.

Subsequent implementation in an embankment model illustrated that unsaturated conditions were hugely important to it serviceability. The transition between unsaturated and saturated conditions during the wetting process was shown to produce significant swelling and strength changes which were exacerbated by increased wetting owing to climate change. Settlement due the application of train loads was modelled on both lines which correlated moderately well with field data. However, the inability for the BBM to model cyclic loading conditions and simulate hydro-mechanical coupling somewhat limits it applicability for use in PLAXIS.

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