The British Dam Society

Numerical simulation and assessment of a clay embankment dam experiencing climate-induced deformation

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SYNOPSIS Thames Water's Reservoir Safety Group noted movement in the south-eastern slope of the Stoke Newington (East) Reservoir embankment, deemed to be excessive for the relative size of the embankment and showing a marginal increase in settlement rate over time. By modelling the climatic conditions as a boundary condition within a Finite Element and Finite Difference Analysis model and simulating the periods for which measurement is available, the mechanism of deformation within the embankment could be identified. PLAXIS was found to be useful for setting up boundary conditions to simulate the fluid-mechanical conditions within the embankment, but the software does not accurately translate this behaviour into representative stress and strains. FLAC was used as an alternative to model these conditions using the saturation profile from PLAXIS as a starting point. The deformation predicted by FLAC shows a good correlation with the monitoring results available, allowing the asset owner to forecast the strains to be developed in the embankment in the future and to set up inclinometer trigger levels for monitoring the asset. With this information in hand, together with the knowledge that climatic boundary conditions are due to worsen with global warming, a solution was later developed to mitigate the risk of embankment instability.

INTRODUCTION

The influence of climate on clay earthfill embankments has been well documented since Walbancke and Vaughn (1976), in their seminal study, illustrated how climate has a more significant effect on pore pressure changes within the downstream slope than the reservoir itself. Furthermore, seasonal ratcheting in active clays has been documented, particularly in railway cuttings in stiff London Clay, e.g. Skempton (1977), and many studies have investigated strain softening behaviour in this material e.g. Potts et al (1997).

This behaviour and resulting deformation can only be adequately captured using Finite Element or Finite Difference Analyses (FEA or FDA). The use of FEA/FDA to analyse deformations in earth embankments is often undertaken using complex constitutive models. These complex constitutive models are typically outside the realm of routine analysis due to time and budgetary constraints of asset owners. In these circumstances, a simple constitutive model undertaken using ubiquitous FEA/FDA software such as PLAXIS or FLAC is a useful tool for dam engineers. Once the mode of deformation is understood, an effective construction solution can be developed.

BACKGROUND

Stoke Newington (East) Reservoir

Stoke Newington (East) Reservoir was constructed in 1833 as a non-impounding reservoir that draws water from the adjacent New River, which was constructed in the 17th century. The reservoir comprises an approximately 7.5m high homogenous clay embankment. The site, shown in Figure 1, is in north London on former agricultural land comprising London Clay.

Figure 1. Stoke East Newington Reservoir with area of highest settlement circled © Google (2024).

The asset owner noted movement in the south-eastern embankment of the reservoir and as per Figure 2, seasonal behaviour has been noted, with shrinkage and swelling behaviour observed in summer and winter respectively. These movements, recorded through surveys of surface-level monitoring pins, installed in 1999, have been deemed to be excessive for the relative size of the embankment and have shown a marginal increase in settlement rate over time. Settlements within the area of interest highlighted in Figure 1 averaged between 4mm/year and 15mm/year between 2004, when a new temporary benchmark was set up, and 2021 at the time of the investigation.

After a critical review of the monitoring results, it was suspected that the frequency readings, and ultimately phreatic surface output, of the Heavy-Duty Vibrating Wire Piezometers (HDVWP) were being affected by a mechanism separate from, or perhaps in addition to, seepage from the reservoir. As such, Thames Water’s Reservoir Safety Group, on the advice of the Panel Engineer, requested that further analysis be undertaken to ascertain the mechanism causing movements within the embankment and to assess global stability.

Figure 2. North-eastern portion of the embankment with shrinkage of clay in summer creating cracks in the crest path, looking north-east.

METHODOLOGY

A phased approach to the problem was undertaken, starting with limit equilibrium and one-dimensional consolidation approaches followed by a more complex FEA/FDA analysis of deformation. The same philosophy was applied to the ground investigation (GI), initially obtaining GI related to total strength and thereafter obtaining a greater density of data providing deformation, permeability and effective strength parameters required to formulate a constitutive model.

Model geometry

The south-eastern embankment, with a maximum height of 7.5m, was divided into five distinct materials for the analysis, as shown in Figure 3. High-strength reworked London Clay (HSMG) recorded between 2.5m and 3.5m depth is typically described as firm to stiff and friable. Desiccation cracks, decreasing in prevalence with depth, were noted in this material during the ground investigation. Although the overconsolidated London Clay was remoulded during construction, the construction method and subsequent desiccation have resulted in high effective stresses (from negative pore water pressures) causing overconsolidation.

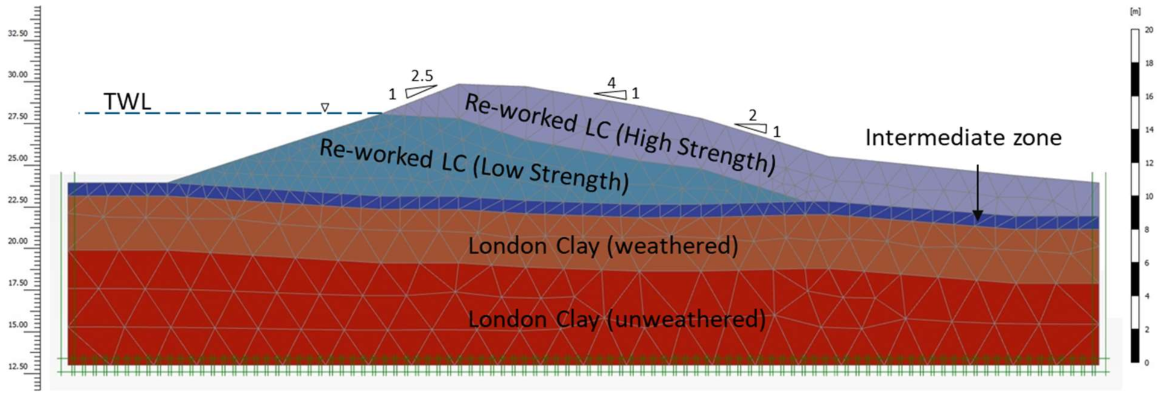

Figure 3. Cross section at CH 273 analysed in PLAXIS and FLAC.

Below this material, soft, low to medium strength reworked London Clay (LSMG) was recorded to the base of the embankment at depths between 6.0m and 7.5m. The softened material corresponds with the material beneath the steady-state phreatic surface and overlying capillary zone. The high swelling pressures recorded in laboratory swelling tests indicate that the soft material could swell beneath the phreatic surface under the prevailing overburden pressures.

An intermediate layer of London Clay between 0.1m and 1.0m thick (based on CPTu records) is located directly beneath the embankment. This material has a similar composition to in-situ London Clay, although it is suspected that it has become less stiff by reworking or swelling due to past site activities such as agriculture (tilling) and climate, respectively.

Weathered London Clay, typically comprising overconsolidated silty clay, forms the foundation material to a depth of between 10m and 11m where unweathered material of similar composition was encountered.

Model Conditions

The ability of FEA and FDA to simulate the behaviour and deformation of geotechnical structures is helpful in such an assessment, where moisture changes within the embankment, influenced by seepage from the reservoir as well as from climatic controls, have significant influence on the behaviour of plastic clays. The first step in such an analysis is to develop a constitutive model which can represent the behaviour of the soil in a mathematical framework.

The FEA software PLAXIS 2D version 2023.2 was used for the analysis of this project, whilst the FDA program FLAC version 8.1 was used together with PLAXIS to check and improve upon deformation results. Two-dimensional analysis is considered to be appropriate in this context, as plane strain conditions can be assumed when analysing linear structures such as embankments.

Constitutive model

Because the stress-strain behaviour of soils is highly non-linear and stress-dependent, a single stiffness modulus is not sufficient to accurately reflect the deformation changes that take place prior to shear failure, the normalised stress-independent stiffness formulation presented as part of the Hardening Soil constitutive model, first presented by Schanz, Vermeer, & Bonnier (1999), was adopted for the methodology used to estimate the stiffness properties of the materials used in analysis in both PLAXIS and FLAC.

The input parameters for this model for a reference stress of 100kPa were obtained from a combination of laboratory data, empirical correlations, and CPT records. A summary of the key parameters defining the constitutive model is provided in Table 1.

Table 1. Summary of input parameters for the constitutive model

Material type	Bottom Depth*	p_{ref} (kPa)	E_{50}^{ref} (kPa)	E_{oed}^{ref} (kPa)	E_{ur}^{ref} (kPa)	Power (m)	v_u	k_0^{nc}
High Strength Made Ground (HSMG)	2.5	100	31.0 x 10^{-3}	30.8 x 10^{-3}	93.0 x 10^{-3}	0.80	0.495	0.65
Low Strength Made Ground (LSMG)	6.9	100	38.0 x 10^{-3}	31.0 x 10^{-3}	114.0 x 10^{-3}	0.90	0.495	0.65
Intermediate layer (reworked London Clay)	7.7	100	39.0 x 10^{-3}	32.0 x 10^{-3}	117.0 x 10^{-3}	0.90	0.495	0.64
Upper (weathered) London Clay	10.9	100	41.0 x 10^{-3}	34.0 x 10^{-3}	123.0 x 10^{-3}	0.80	0.495	0.66
Lower (unweathered) London Clay	17.0 **	100	46.0 x 10^{-3}	38.0 x 10^{-3}	138.0 x 10^{-3}	0.80	0.495	0.66
Source	Explora-tory holes		Correlation with CPTu results (Lunne, et al., 1997) checked against laboratory tests					

* (mbgl) from crest road ** not proven

Analysis

Boundary restraints are no different from a typical deformation analysis with Y_{max} set as a free boundary, Y_{min} fully fixed and the X_{max} and X_{min} boundaries normally fixed; these are shown graphically in Figure 3. To correctly model movements associated with seasonal swelling and shrinkage, a discharge boundary condition is the most appropriate approach to drive seasonal transient pore water pressure cycles, and therefore stress cycles, to produce the most realistic displacements associated with seasonal wetting and drying. The built-in *Climate* function in PLAXIS, called *Precipitation*, is a useful discharge boundary tool, as runoff is automatically activated on the relevant boundary once the soil becomes fully saturated.

The boundary conditions are modelled separately for winter and summer, with winter conditions assumed to occur over five months and summer over seven months in line with findings by Posthill (2018). The model was run for ten annual cycles, simulating the period between 2010 and 2020. Winter conditions are modelled by a uniform discharge function representing the mean rainfall over the relevant season with parameters constrained to a maximum 0.1m head on the boundary and a minimum -1.0m head associated with the maximum height of water on the slope before runoff and 10kPa suction, respectively.

The measured rainfall was obtained from the closest weather station to the site i.e., Hampstead weather station (http://nw3weather.co.uk/wxdataday.php).

The summer boundary condition, i.e. net evapotranspiration, is represented by a negative discharge which has been calculated as a daily incremental function of the total soil moisture deficit (90mm at the end of summer) of a published study in similar conditions (Smethurst et al, 2012). The constraints on this function correspond with a 40kPa suction at the end of summer (min head of -4.0m) and runoff as with winter, i.e. maximum head of 0.1m. These boundary conditions are informed by previous studies on active clays in London (Posthill, 2018). A relaxation phase is created after each evaporation to view the stresses and deformations developed each year before the next cycles are modelled.

A fully coupled fluid-mechanical analysis is run for each phase; each winter season is run for 150 days, whilst each summer season is run for 215 or 216 days, where applicable. After the flow net and suctions are set up in the embankment, the pore pressures defining each phase are progressively taken from the previous phase.

RESULTS

The initial results of the transient pore water changes within PLAXIS showed positive results; the saturation profile shown in Figure 4 indicates a good interplay between boundary conditions and internal fluid-mechanical conditions within the model.

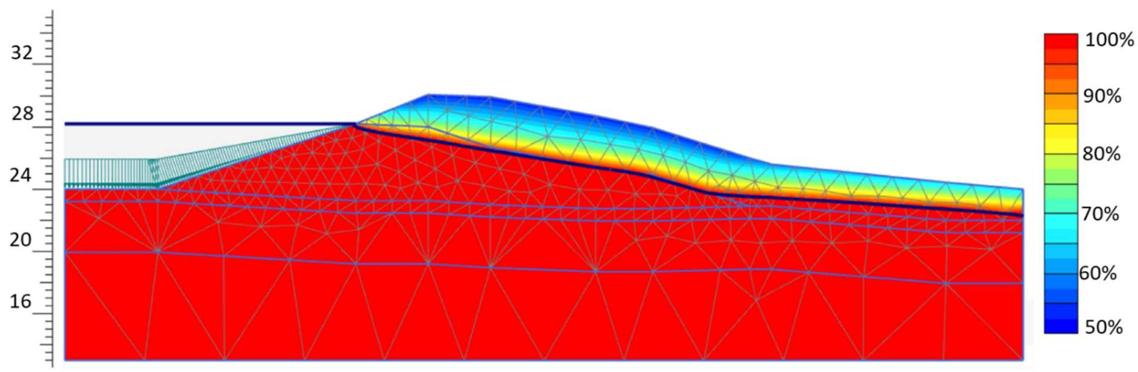

Figure 4. Typical saturation profile at the end of summer.

However, the way in which these (pore water) changes influence stress and deformation cycles in PLAXIS was immediately picked up as a potential shortcoming for this mechanism of cumulative deformation. A decision was made to undertake a check of the results in FLAC. To ensure parity between the two software codes, the saturation profile from PLAXIS was replicated in FLAC. The results of the deviatoric strain and displacements are provided in Figures 5 to 8.

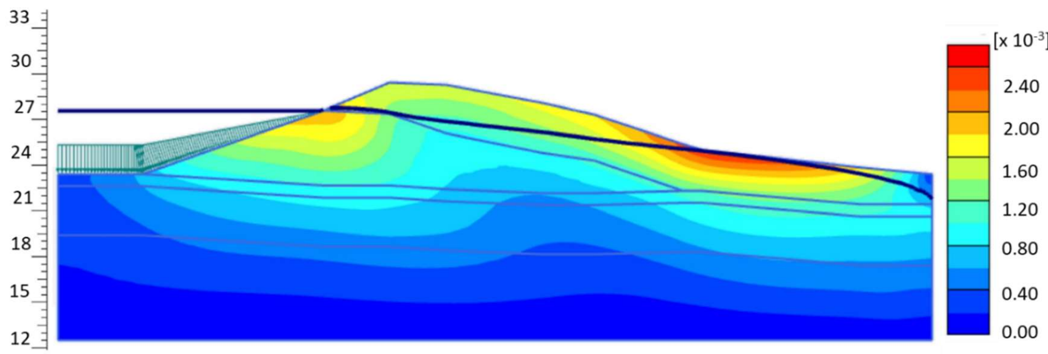

Figure 5. PLAXIS output showing total displacements (metres) after 10 years.

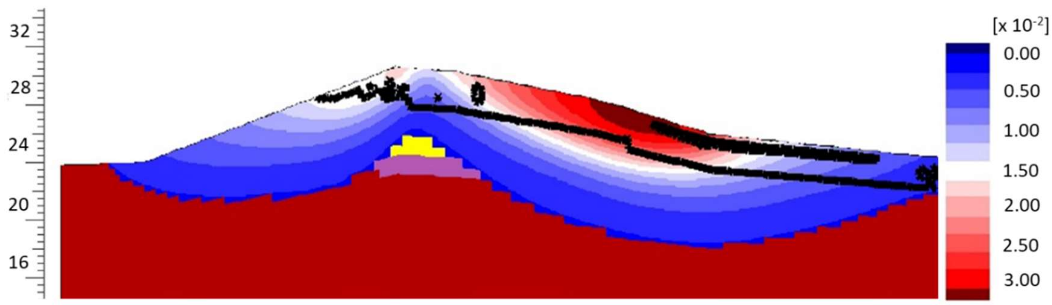

Figure 6. FLAC output showing total displacements (metres) after 10 years with material boundaries in background as per Figure 3 and phreatic surface shown in black.

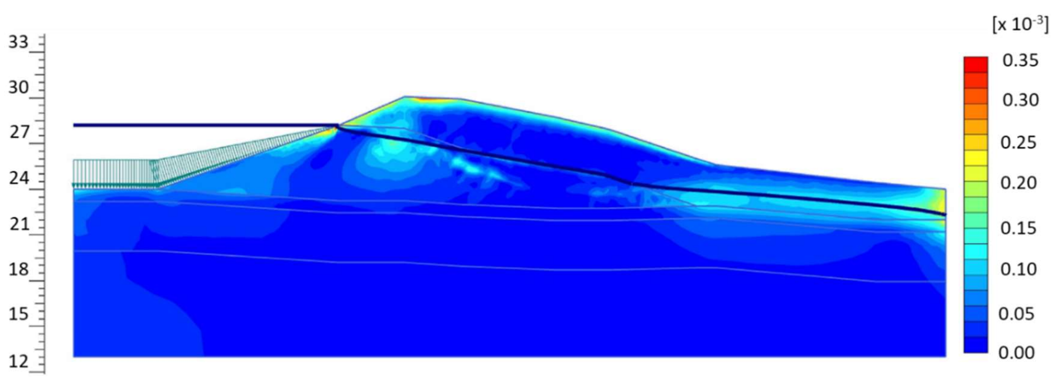

Figure 7. PLAXIS output showing shear strain after 10 years (end of Summer).

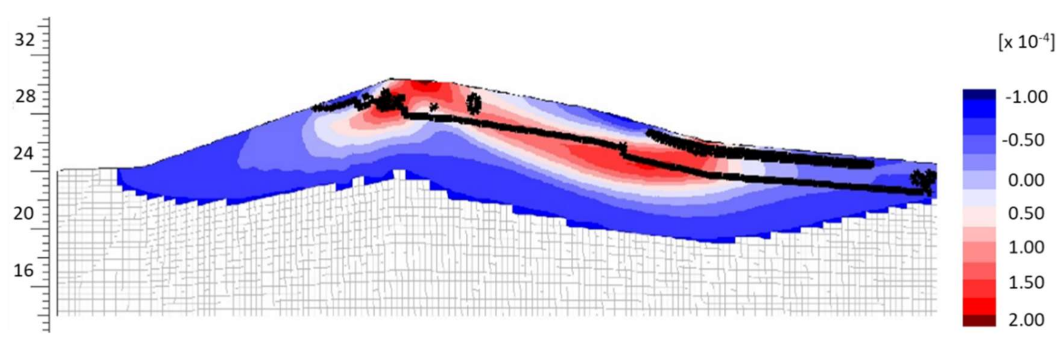

Figure 8. FLAC output showing shear strain after 10 years and phreatic surface shown in black.

DISCUSSION

Both the deviatoric strain and deformation results in FLAC immediately appear more realistic for a ratcheting profile when compared with the PLAXIS results. PLAXIS results showed no progressive stress or strain propagation over time with the formulation seemingly limiting the progression of these even where strain reset functions are disabled. Settings in the FLAC formulation tend to allow the progression of stress and strain over time without hindrance and allow the constitutive model to be influenced by stress levels in a more realistic manner for this mode of deformation.

The two most significant influences in this contrast in results are speculated upon. Firstly, within PLAXIS, the stiffness regains its maximum value for a stress level when the direction of loading changes. FLAC's formulation appears better at accounting for both stress and direction changes, allowing more nuanced stiffness degradation behaviour to be captured. Secondly, the finite difference method by default recalculates the stress-strain and strength conditions per node in a large strain environment whilst PLAXIS is formulated to be more efficient with small strain.

Any further discussion on the back-end formulation differences between the two software codes will be left for a different forum, as the purpose of this paper is to present a working solution for dam engineers and guidance on the appropriate software to use. It should also be noted that the software support team from PLAXIS was consulted about the limitations described and provided helpful support, but no working solution was found at the time. Future versions of PLAXIS, or the current version with a user defined model and manual alteration at each phase, may well solve the limitations noted here but this too is beyond the scope of this paper.

A comparison of Figures 5 to 8 with inclinometer results shown in Figure 9 shows the formulation procedure in PLAXIS is limited in practically representing the strain and deformation elements of this embankment's behaviour. The base of the shear zones downslope of the crest at approximately 3m depth noted in Figure 8 align well with the zone of general downward movement recorded in Figure 9. As the FLAC displacements and strains better match the inclinometer displacement the FLAC model was selected for interrogation to provide further insight for the project.

Displacements

Total displacements at the end of the end of the 10-year cycle are shown in Figure 6. FLAC predicts a displacement towards both faces of the embankment. Although observations on site tend to agree with the findings of the FLAC analysis, i.e. hummocky ground indicative of shallow movements mid-slope on the downslope face and a wave wall which has rotated at the top of the upstream face, it is considered likely that only regions above the phreatic surface on the upstream slope are to be significantly affected by seasonal ratcheting.

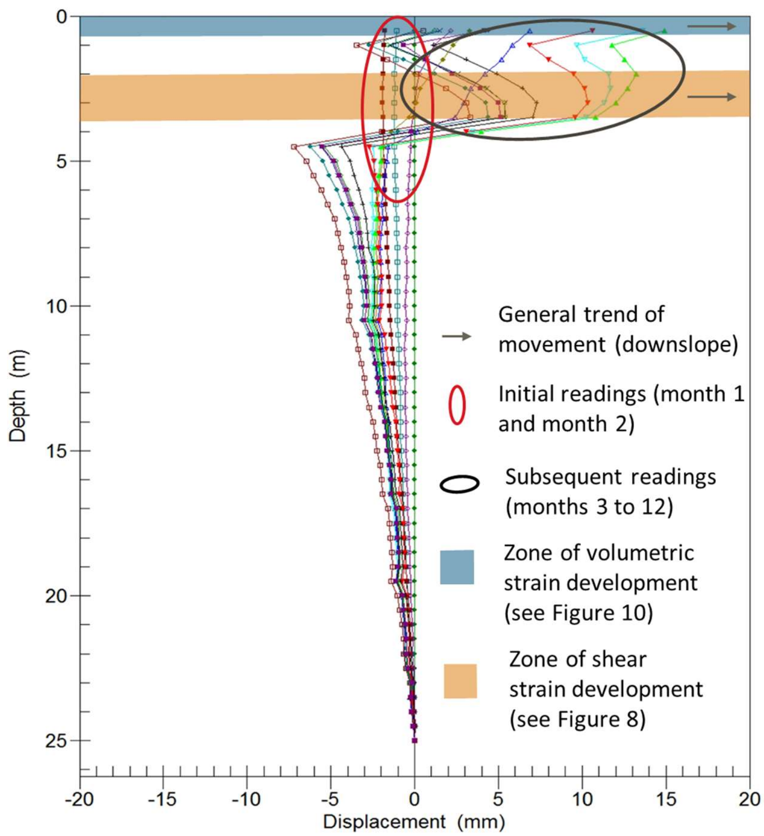

Figure 9. Cumulative inclinometer results between initial installation on 2nd July 2020 and 23rd June 2021 for the embankment section under investigation.

Volumetric strains

Volumetric strains resulting from 10 cycles (10 years) are presented in Figure 10. FLAC predicts volumetric strains concentrated just above the phreatic surface under the downstream face. The volumetric strains calculated in the FLAC analysis are the results of effective stress changes due to changes in pore pressures. The pore pressure response is not fully recoverable at the end of each season but is rather 'stored' within the embankment with pore pressures close to the surface boundary recovering quicker. A general downslope movement is initiated at shallow depths, resulting from seasonal movement along the free boundary and aligns with the inclinometer movement noted in Figure 9. This behaviour illustrated by the FLAC analysis is considered to be in close agreement with previous studies, e.g. Potts et al. (1997).

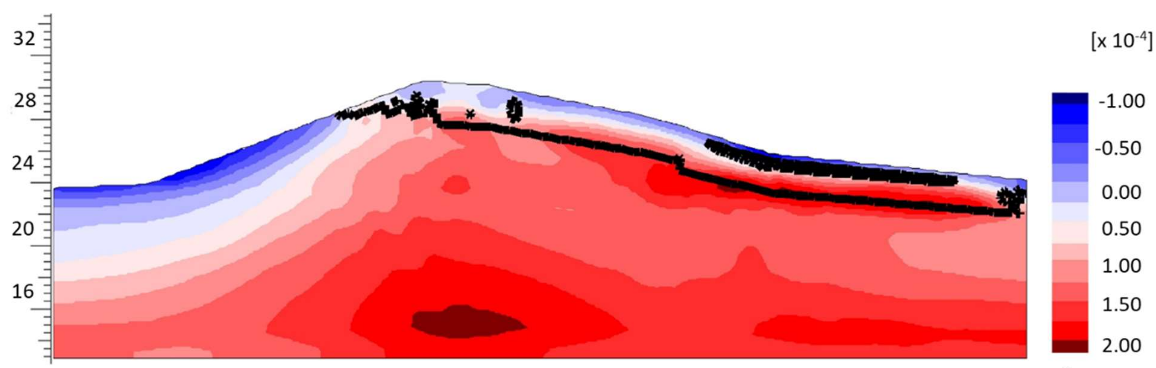

Figure 10. Volumetric strains resulting from 10 cycles.

Potential shear plane development

The magnitude of strains shown in Figure 8 is important as previous studies have shown that at strains of approximately 20%, residual strengths in London Clay typically begin dictating shear resistance (Skempton, 1977; Potts et al, 1997). Reworked London Clay typically requires higher shear strain to engage residual strength. However, as the mechanism is progressive, these strains will likely accumulate and propagate through the slope until a slip surface dictated by residual strengths is developed.

Based on the results of nineteen cycles, representing ten years of seasonal fluctuations, it is predicted that the amount of shear strain developed within the slope amounts to 8% in the downstream slope, developing from the toe then upslope. Although strain is also generated in the upstream slope, here the model differs from reality as the reservoir level and capillary zone restricts pore water fluctuations significantly. This was not considered an issue for the purposes of the study, but further controls on the spatial distribution of materials experiencing two-phase flows or pore pressure changes can be introduced in scenarios where upslope deformation is being assessed.

The strain values could be used in conjunction with a limit equilibrium safety map to assess the implication of residual conditions on the stability of various slip surfaces, in some cases with factors of safety below unity, typically at shallower depths. The progressive nature of strain development in active clays together with these results informed the All Reservoirs Panel Engineer (ARPE) that a measure in the interest of safety (MITIOS) was required to reduce the risk of embankment instability and works are being progressed.

Whilst these works are being progressed, the results have also been used by the ARPE to establish trigger levels for inclinometer readings which correspond with various increments of strain. These provide the Supervising Engineer with a practical means of monitoring the asset.

Settlement prediction

The end-of-cycle settlements for each annual simulation are provided in Table 2. It is apparent that the FLAC estimations follow a progressively increasing magnitude which aligns with the observations made by the asset owner.

Table 2. End-of-cycle yearly crest settlement estimations predicted by FLAC

Year	1	2	3	4	5	6	7	8	9	10
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Settlement (mm)	1.5	2.6	3.9	5.1	6.4	7.8	9.3	10.8	12.4	14.1

The best-fit trend lines for the set of estimations from FLAC were then calculated based on 200 years' worth of winter and summer cycles and are presented in Figure 11 below.

Actual settlement records obtained from surface monitoring pins (CH300 and CH200 in Figure 11) were also provided by the asset owner.

The settlement records between 2010 and 2020 are plotted on the FLAC predicted settlement line using 2010 as the benchmark for the first reading. This time range corresponds to a period of 177 – 187 years after the completion of the embankment (in 1833).

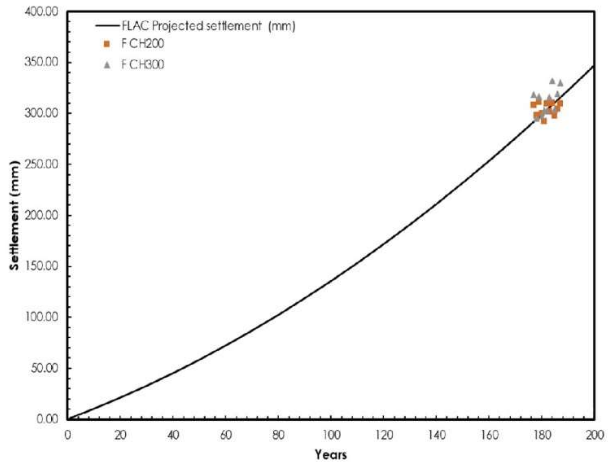

Figure 11. Retroactive projected settlement of FE analysis vs normalized predictions from settlement monitoring at CH200 and CH300 (normalised to 2010).

It is evident that the trend and magnitude from actual records fits quite closely to the FLAC predictions from 200 simulations. The FLAC curve implies that since 1833 approximately 330 to 340 mm of settlement took place that was induced by seasonal boundary effects. It is also clear that the amount of settlement is increasing over time.

The FLAC 200-year simulation in Figure 11 is a close approximation when compared with settlement data over the last 10 years i.e. 35mm simulated compared with 36mm and 150mm for both nearby settlement monitoring points.

We do not have measurement data from the last 183 years available and the current measurement shows clear spatial variability. This is not unexpected considering the age of the asset with different loading histories across the length, the period in which it was constructed and the variability of vegetation and surface cover across the embankment.

In light of this uncertainty, the level of correlation between simulated and measured results is considered acceptable for verification of the accuracy of deformation simulation.

Other possible mechanisms

The study has confirmed that consolidation resulting from fluctuating reservoir water levels as provided by TWUL is unlikely to contribute significantly to the current deformation of the embankment. Consolidation occurring after embankment construction would be considered to be of a similar order of magnitude to those currently experienced i.e. in the order of 300mm, depending on the initial compaction achieved and associated void ratios. However, displacements resulting from consolidation decrease with time and are expected to be largely complete 187 years post-construction, based on CPTu interpretation of consolidation parameters. Current displacements resulting from consolidation are likely to be negligible in comparison with total settlements currently recorded and those associated with seasonal deformation.

CONCLUSION

The results of this study have shed light on the mechanism causing the significant settlement recorded at Stoke Newington (East) Reservoir over the last 20 years and experienced by the embankment since construction in 1833. PLAXIS has been useful in creating a link between climatic boundary conditions and pore water response but is limited in modelling the cumulative stress and strain response to these changes. It is suggested for future works in embankments made up of active clays and potentially experiencing climate-induced deformation, that FLAC is used as the simulation tool to understand behaviour. This would ensure continuity from start to finish in the modelling process.

The FLAC analysis has shown the development of shear strains at locations in line with observed inclinometer records. The level of correlation between modelled and recorded crest settlement is considered acceptable for verification that the FLAC model accurately represents the observed deformation behaviour.

The FDA (FLAC) software, through its inbuilt computational process, has captured the progressive nature of deformation and strain propagation within the embankment. This has provided insight into the reasons for significant settlements which in places have been observed to increase over time. This occurrence is likely to result in residual strength conditions in areas where significant shear strain has developed.

The results have also been used to establish trigger levels to provide the Supervising Engineer a practical means of monitoring the asset.

Through an understanding of the amount of deformation and strains which have and are likely to continue developing within the embankment, a general timeframe for the generation of residual conditions along shear planes can be understood. It should also be noted that a study by Posthill (2018) has found that the phenomenon of seasonal ratcheting is being expedited by climate change.

This information on the mechanism, potential timing and further changes to the climate-induced deformation allows the asset owner to make informed decisions on possible remedial measures.

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