ACHILLES

An EPSRC Programme Grant

READING GUIDE 5:

Design considerations for clay earthworks

ADDRESSING INFRASTRUCTURE'S ACHILLES HEEL

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Introduction

Steeper slope angles mean less land take, reduced earthworks volumes, reduced embodied carbon, and cost savings. However, they may also come with increased future maintenance. Considering long-term slope conditions in design enables decisions about whole-life cost and carbon trade-offs between initial slope angles, asset-life, and future maintenance.

The importance of asset-life in design

Slope stability analysis in routine earthworks (cuttings and embankments) design has typically been based on static Mohr-Coulomb shear strength parameters, assumed worst-case pore-water pressures, and limit equilibrium-derived critical failure surfaces.

ACHILLES outputs include new understanding of, and guidance for, shear strength design parameters (c' and ϕ'), critical slip surface geometry, and pore pressure regimes for use in limit equilibrium stability analyses that account for seasonal weather and pore pressure cycles, long-term deterioration, and climate change. The importance of accurately capturing the time varying nature of the design properties is illustrated in Figure 1.

While these processes are summarised in isolation in this guide, they should be viewed as an interacting system, where each process / mechanism influences the others [1].

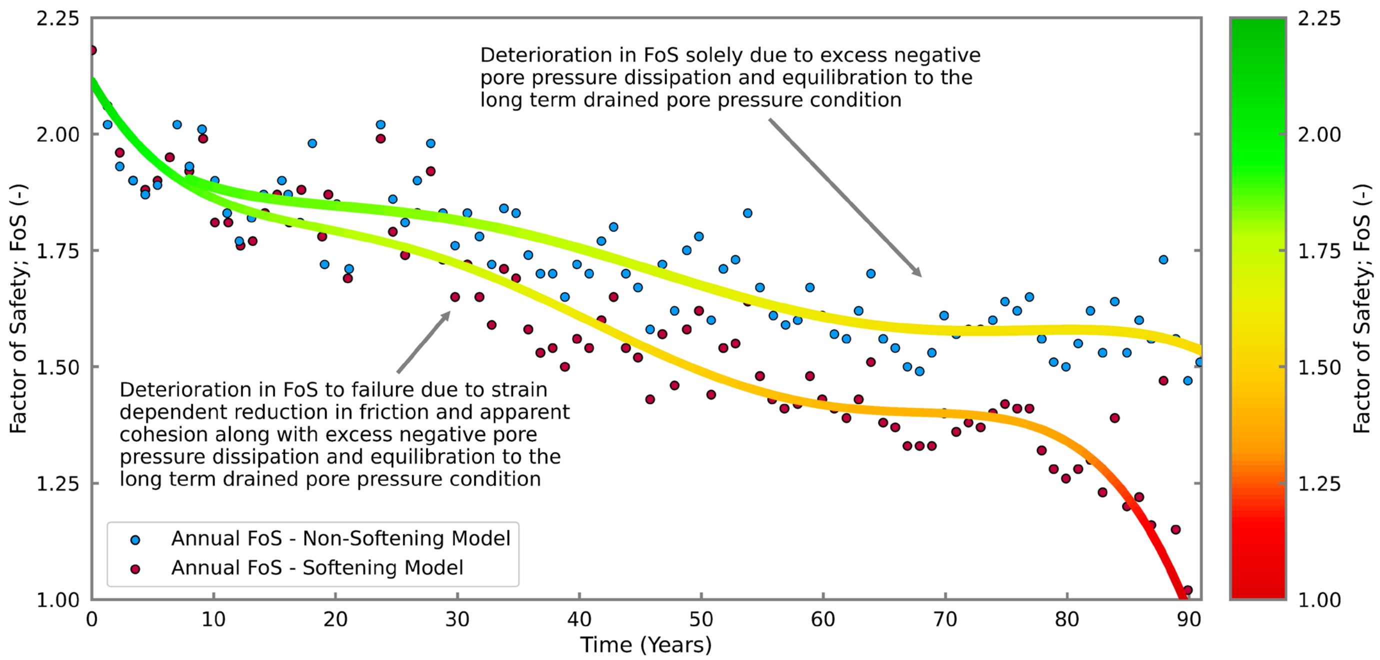

Figure 1: Factor of safety deterioration curves for a cut slope in high plasticity clay illustrating the importance of accounting for both transient pore pressure and time varying shear strength design parameters (c' and ϕ') for stability assessment to avoid overestimating stability.

Key considerations for asset-life in design

Selection of shear strength parameters for design should reflect the long-term slope conditions following multiple years of weather-driven deterioration

Traditional assumptions about critical state strength being appropriate for designs considering deep-seated mechanisms and first-time slides may not always be appropriate in the case of long term near surface deterioration or in the presence of climate change:

- Shallow seasonal ratcheting can mobilise frictional strengths which are lower than the fully softened / critical state strength values that may normally be adopted [1].
- This mechanism is of greatest significance in high-plasticity materials where the residual frictional strength can be significantly lower than the fully softened / critical state strength [1].
- This behaviour is exacerbated by near surface permeability changes that develop rapidly after slope construction and lead to reductions in design life [1, 2, 3].
- In intermediate plasticity materials, subjected to a present climate, there is significantly lower deterioration in strength, however when subjected to a future climate the rates of deterioration increase significantly.
- Choice of mobilised strength parameters for design therefore need to be made with full consideration of the desired design life. For new slopes this should include climate change; for assessment of existing assets, it should include accounting for exposure to seasonal cycles during life to date as well as future expected asset life and future climate.

The overall design pore-water pressures for clay earthworks do not need to increase due to climate change

Seepage analyses for a typical London Clay embankment/cutting in the London area with a wide range of climate projection scenarios from UKCP18 [4] has shown that:

- In future, summers are projected to be hotter and drier, resulting in a higher moisture deficit (i.e., water storage capacity) in earthworks.
- Increased winter rainfall is expected to cause greater net infiltration into the soil and/or runoff, depending on soil permeability and vegetation conditions.
- Because of the summer drying, there will be greater soil pore space that needs to be refilled with water in winter. Since it will take longer to saturate the soil pores, this indicates that worse-case hydrostatic pore-water pressures will occur less frequently.
- Therefore, suggesting that despite the forecast increase in winter rainfall, greater design water pressures will not be required. However, the larger magnitude of seasonal cycle size and increase in extreme events may cause more rapid deterioration in strength.

The critical failure surface will change over time due to deterioration

Analysis of cut slopes shows that the critical failure surface may become shallower with time due to weather driven near surface deterioration [3]. This process occurs from construction but becomes significant on the order of 50 to 80 years after construction. The timings and significance of this change depends on the slope permeability, with lower permeability slopes being less effected. This behaviour has several implications:

- Cut slopes at angles lower than critical state may appear stable when considering shallow failures if this near surface deterioration in strength is not accounted for.
- Long duration wet periods (e.g. wet summers, preceded or followed by wet winters) exacerbate this behaviour [3].
- The larger seasonal magnitudes of pore pressure variation due to future climate change also increase the near surface deterioration.
- The increasing near surface deterioration can lead to progressively shallower critical surfaces over time. See for example Figure 2.
- This process involves complex interactions between slope geometry, deformation, pore pressure, surface-vegetation-atmosphere interaction and material properties and so may not occur in all slopes.

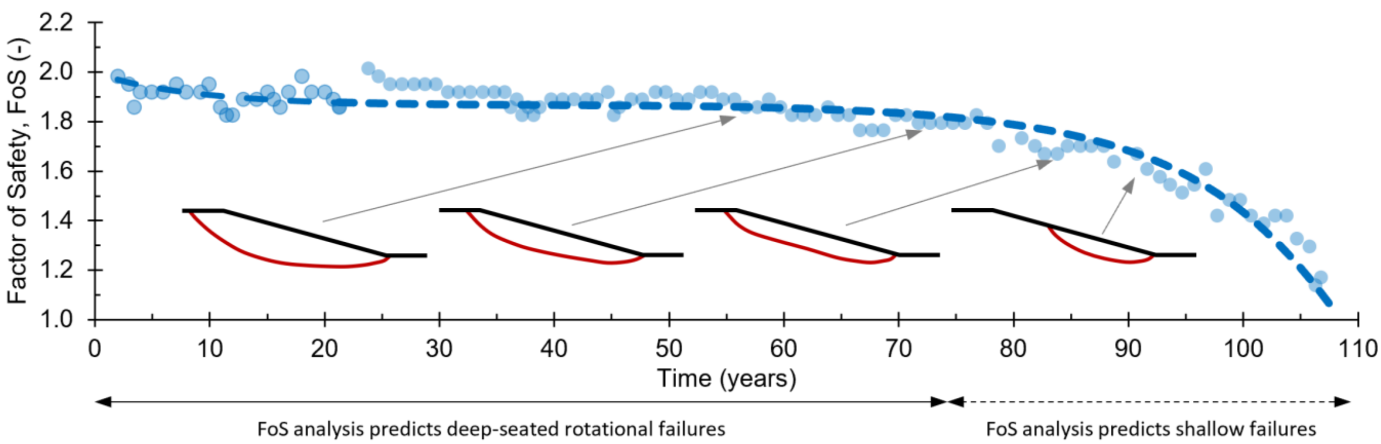

Figure 2: Progressively shallower critical shear surface mechanisms with time as near surface deterioration progresses. Ultimate failure is relatively shallow compared to the critical surfaces predicted earlier in slope life [1].

The ACHILLES methodology accounts for long-term climate-driven deterioration of slopes for better design-life based asset management strategies.

Slope geometry influences long-term behaviour

Cut slopes steeper than the critical state strength are more likely to undergo deep seated rotational failure mechanisms driven by excavation induced pore pressure dissipation and strain-softening / progressive failure.

This is likely to occur earlier in the life of the slope, during excess negative pore pressure dissipation.

Cut slopes less steep than the critical state strength are more likely to undergo shallow ratchetting deformations and near surface weather driven deterioration.

This can lead to failures tens of years after the majority of pore pressure dissipation is completed [3].

The extent of softening is controlled by plasticity and the potential for post peak reduction in strength towards residual.

Time dependent behaviour can be captured in routine analysis

It is clear from the above discussion, that the time dependency of input parameters is critical for future design / assessment of earthworks. This can be achieved by applying a design life based approach to static parameters [1,6] which are applied in analytical [7,8] or limit equilibrium techniques. Alternatively a dynamic approach can be taken where the parameters evolve over time as driven by weather and climate [2,3,9]. In addition, the ACHILLES emulator [10,11] can be used to bring design life and time to failure into slope design and stability assessment in a number of ways, including:

- Rapidly characterising time to failure for varying material properties and slope geometries subjected to present climate in the form of design charts (e.g. Figure 3).
- Rapidly undertaking probabilistic stability assessments for a given geometry, assuming a range of other soil properties to derive the probability of failure for a specified design life.

Conclusions

Together these approaches allow asset owners to make quantified assessments of the relative risk of failure of slopes of varying geometries and for a range of strengths.

Ultimately, weather / climate change has the following effects on deterioration:

- Weather driven deterioration can be accelerated by wet years, more specifically low or zero soil moisture deficit due to some combination of abnormally high rainfall and low rates of evapotranspiration [3].
- Deterioration can be significantly accelerated by future climate change.
- These factors should be considered when selecting appropriate design parameters and in interpreting Figure 3.

More information about the emulator can be found in ref [11] and *Reading Guide* 6 [12].

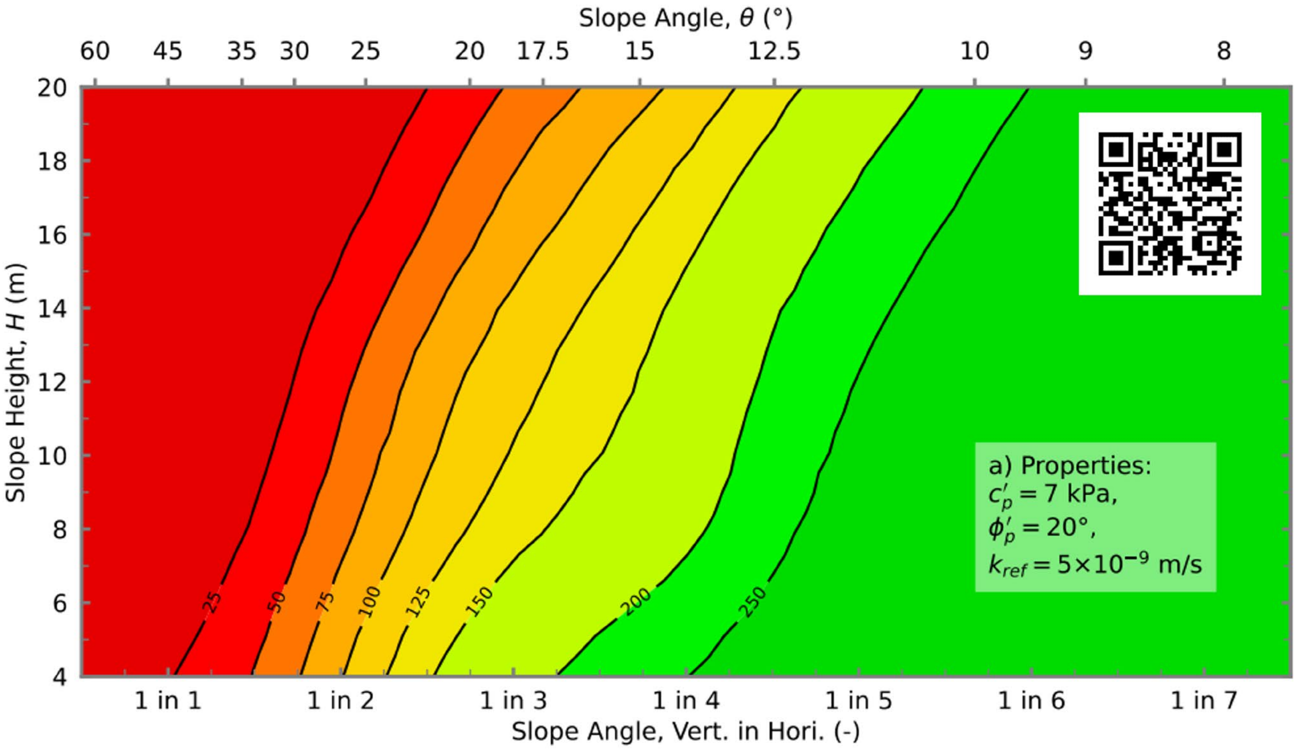

Figure 3: Exemplar contour plot showing times to failure of cut slopes with varying geometries, and a prescribed set of input parameters representative of the peak strength and permeability of an overconsolidated high plasticity clay. The QR code links to the emulator app used to produce the figure data: ***https://asvalova.shinyapps.io/ACHIMULATOR/***

Further reading

Please also refer to the other ACHILLES reading guides where you can find out more about what we have achieved. *Reading Guide 1* explains the context of the ACHILLES Programme Grant. *Reading Guide 2* describes how we have achieved a deeper understanding of deterioration affecting the clay materials that we focused on. *Reading Guide 3* extends our understanding of deterioration to the long linear geotechnical asset scale. *Reading Guide 4* outlines the ways in which we can assess the condition of our long linear geotechnical assets. *Reading Guide 6* explains how ACHILLES sees data analytics playing a role in addressing deterioration of long-linear geotechnical assets. *Reading Guide 7* discusses the complexities of the business case of timely intervention and mitigation.

Key references

[1] Postill, H., Helm, P.R., Dixon, N., El-Hamalawi, A., Glendinning, S., Take, W.A. (2023). **Strength parameter selection framework for evaluating the design life of clay cut slopes.** Proceedings of the Institution of Civil Engineers - *Geotechnical Engineering*. 176(3):254–73. DOI.org/10.1680/jgeen.21.00125

[2] Rouainia, M., Helm, P., Davies, O., Glendinning, S. (2020). **Deterioration of an infrastructure cutting subjected to climate change.** *Acta Geotechnica*. 15(10):2997–3016. DOI.org/10.1007/s11440-020-00965-1

[3] Postill, H., Helm, P.R., Dixon, N., Glendinning, S., Smethurst, J.A., Rouainia, M., Briggs, K.M., El-Hamalawi, A., Blake, A.P. (2021). **Forecasting the long-term deterioration of a cut slope in high-plasticity clay using a numerical model.** *Engineering Geology*. 280(1):105912. DOI.org/10.1016/j.enggeo.2020.105912

[4] Huang, W., Loveridge, F.A., Briggs, K.M., Smethurst, J.A. (2024). **Forecast climate change impact on porewater pressure regimes for the design and assessment of clay earthworks.** *Quarterly Journal of Engineering Geology and Hydrogeology*. 57(1): qjegh2023-015. DOI.org/10.1144/qjegh2023-015

[5] Huang, W, Dijkstra, T, Loveridge, F, Hughes, P, Blake, AP, Dobbs, M, Trinidad González, Y. (2022). **Spatial variability of London Clay using CPT and SPT data.** In: Huang, J, Griffiths, DV, Jiang, S-H, Giacomini, A, Kelly, R, editors. Proceedings of 8th International Symposium on Geotechnical Safety and Risk (ISGSR 2022) [Internet]. Newcastle, Australia, Research Publishing, p. 228–34. Available from: https://rpsonline.com.sg/proceedings/isgsr2022/html/03-015.html

[6] Huang, W., Loveridge, F., Johnston, I., Helm, P., Dixon, N. (2023). **Design-life based approach for the design of cutting slopes in stiff clay.** In: Proceedings of the 3rd Biennial BGA Conference Geo-Resilience 2023 [Internet]. Cardiff, UK, . Available from: https://research.tees.ac.uk/files/60543627/2023._Design_Life_based_Approach_for_the_design_of_cutting_slopes_in_stiff_clay.pdf

[7] Huang, W. (2023). **Efficient analytical approach for stability analysis of infrastructure slopes.** Proceedings of the Institution of Civil Engineers - *Geotechnical Engineering*. 176(2):194–207. DOI.org/10.1680/jgeen.21.00106

[8] Huang, W., Loveridge, F., Satyanaga, A. (2022). **Translational upper bound limit analysis of shallow landslides accounting for pore pressure effects.** *Computers and Geotechnics*. 148:104841. DOI.org/10.1016/j.compgeo.2022.104841

[9] Morsy, A.M., Helm, P.R., El-Hamalawi, A., Smith, A., Hughes, P.N., Stirling, R.A., Dijkstra, T.A., Dixon, N., Glendinning, S. (2023). **Development of a Multiphase Numerical Modeling Approach for Hydromechanical Behavior of Clay Embankments Subject to Weather-Driven Deterioration.** *Journal of Geotechnical and Geoenvironmental Engineering*. 149(8):04023062. DOI.org/10.1061/JGGEFK.GTENG-11213

[10] Helm, P.R., Svalova, A., Morsy, A.M., Rouainia, M., Smith, A., El-Hamalawi, A., Wilkinson, D.J., Postill, H., Glendinning, S. (2023). **Emulating long-term weather-driven transportation earthworks deterioration models to support asset management.** *Transportation Geotechnics*.

[11] Svalova, A., Helm, P., Prangle, D., Rouainia, M., Glendinning, S., Wilkinson, D.J. (2021). **Emulating computer experiments of transport infrastructure slope stability using Gaussian processes and Bayesian inference.** *Data-Centric Engineering*. 2:e12. DOI.org/10.1017/dce.2021.14

[12] Loveridge, F., Svalova, A., Helm, P.R., Armstrong, J., Oakley, J. (2023). **ACHILLES Reading Guide 6: The role of data analytics in decision-making.** The ACHILLES Programme Grant Consortium, Newcastle University, UK, 8p

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1. The ACHILLES concept
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3. Asset scale deterioration
4. Asset condition assessment
5. **Design considerations for clay earthworks**
6. The role of data analytics in decision-making
7. Intervention strategies and business case

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