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Design-life Based Approach for the Design of Cutting Slopes in Stiff Clay

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Abstract

Progressive failure of cutting slopes in stiff clay can be analysed by coupled hydro-mechanical analyses. But such analyses are computationally expensive and reserved for research or large-scale projects. In routine practice, limit equilibrium method (LEM) is still commonly used. However, it is beyond LEM's capability to replicate the mechanisms of progressive failure, or subsequent deterioration under current and future climate scenarios. Analysis is often carried out with conservative assumptions (e.g., using critical state strength) for long-term soil and groundwater conditions, when these vary temporally. In this study, an alternative method that considers soil strength to be a transient parameter allows for a design-life based approach to be developed. Mobilised strength parameters as a function of time and slope geometry have been derived from the outputs of a series of coupled hydro-mechanical analyses, for cuttings in London Clay, using a regression model. It is demonstrated that peak strength parameters should be used to search for the critical slip surface (CSS) during LEM analysis. The CSS is then fixed, and in subsequent analyses mobilised strength parameters are suggested according to the design-life. The design-life based approach permits generation of design charts. A case example is used to demonstrate the application and potential benefits of the proposed approach.

Keywords: Slope Stability, design-life, limit equilibrium method, cuttings, stiff clay

1. Introduction

Overconsolidated clay is common in Southeast and Central England, and many railway and highway cuttings are situated in deposits such as London Clay, Gault Clay and Oxford Clay (e.g., Clarke and Smethurst, 2010). The shear strength characteristics of overconsolidated clays and normally consolidated clays are shown in Figure 1. The peak strength of overconsolidated clay is higher than normally consolidated clay, as the water content is lower and diagenetic bonding may be created after the overconsolidation process (Bjerum, 1967). However, at large shear displacements the residual strength of overconsolidated and normally consolidated clays of equivelent plasticity would be the same due to strong reorientation of the clay particles during shearing (Skempton, 1970).

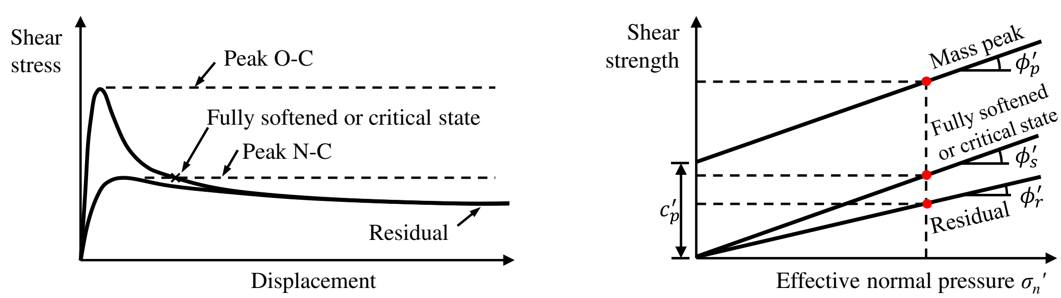

Figure 1: Strength of overconsolidated (OC) and normal consolidated (NC) clay (after Skempton, 1970).

The mechanism of progressive failure in overconsolidated clay is known to be the reduction of strength with displacement or strain, as shown in Figure 1. In the back analysis of failures in clay cuttings, De Lory (1957) and James (1970) modelled the loss of strength as a reduction in cohesion with time. Through field monitoring of pore-water pressure response and back calculation of pore-water pressure ratio for failure cases, Vaughan and Walbancke (1973) proposed that the delayed failure of cuttings could be explained by pore-water pressure equilibration after excavation. With the advancement of numerical techniques, strain-softening behaviour of stiff clays and staged construction processes can be realistically modelled. The observation by Vaughan and Walbancke (1973) is replicated by finite element analyses carried out by Potts et al. (1997). Further numerical analyses have been carried out to investigate the influence of permeability (Rouainia et al. 2020), slope height (Ellis et al. 2007), vegetation (e.g., Tsiampousi, et al., 2017), and long-term climate and climate change (Rouainia et al. 2020; Postill et al. 2021) on progressive failure development. Though progressive failure of cutting slopes in overconsolidated clay slopes can be analysed by coupled hydro-mechanical analyses, such analyses are computationally expensive and reserved for research or large-scale projects.

In routine practice, the limit equilibrium method (LEM) is still commonly used. However, it is beyond LEM's capability to replicate the mechanisms of progressive failure, or subsequent deterioration under current and future climate scenarios. Back analysis of failures has shown that the fully softened strength, as indicated in Figure 1, can be used to design cutting slopes in stiff clays against first-time slides (Skempton, 1964, 1970; Chandler and Skempton, 1974; Castellanos et al., 2016). Fully softened strength is regarded as being identical to the critical state strength (Skempton, 1970; Nowak and Gilbert, 2015). The term "critical state strength" is more commonly used in the recent UK design guidelines (BS 6031:2009; Nowak and Gilbert, 2015) and used hereafter.

However, use of critical state strength regardless of design-life, cutting height and slope angle does not fully consider the transient nature of mobilised strength. For example, it is known that the height of a cutting can significantly affect the time required for pore-water pressure equilibration in clay cuttings (Chandler and Skempton, 1974). The slope angle and height of cuttings are also expected to affect the shear stress level that stiff clays are subjected to, and therefore affect the strain softening rate. A design-life based approach to slope design that fully considers the transient nature of mobilised strength allows for: differing slope designs for different asset target design lives; balancing of capital expense and operational expense through long term knowledge of expected material degradation; building resilience to climate change, known to accelerate strength deterioration, into slope design.

This study aims to develop a practical design-life based approach in the LEM framework for the design of cutting slopes in overconsolidated clays, in which mobilised soil strength is considered a transient parameter. Mobilised soil strength as a function of time and slope geometry is developed through regression analysis, based on the outputs of a series of coupled hydro-mechanical analyses for cutting slopes in London Clay. Since the value of strength parameters adopted can influence the location of critical slip surface (CSS) in LEM analysis, a procedure that enables correct determination of CSS for stiff clay slopes is suggested. Application and potential benefit of the design-life based approach is demonstrated through a design example.

2. Transient parameters: a design life approach

2.1 Residual factor

It is known that strength decreases during the process of progressive failure, which can be quantified by the residual factor (Eq. 1) proposed by Skempton (1964),

$$R_f = \frac{\tau_p - \tau}{\tau_p - \tau_r} \quad \text{(equation 1)}$$

where R_f is the residual factor, τ_p is the peak strength, τ_r is the residual strength, and τ is the shear strength at current state. If R_f, τ_p and τ_r are known, by rearranging Eq. (1) the current shear strength τ can be back calculated by Eq. (2)

$$\tau = \tau_p - R_f(\tau_p - \tau_r) \quad \text{(equation 2)}$$

The shear strength in the Mohr-Coulomb model consists of cohesive and frictional components. If it is assumed that cohesion c' and friction angle ϕ' are reduced by the same proportion as current strength τ, the current cohesion c' and friction angle ϕ' can be calculated as

$$c' = c'_p - R_f(c'_p - c'_r) \quad \text{(equation 3)} \qquad \phi' = \phi'_p - R_f(\phi'_p - \phi'_r) \quad \text{(equation 4)}$$

where the subscripts "p" and "r" denote that the parameters at peak and residual states, respectively.

The residual factor, R_f, is the key parameter to characterize deterioration. There are various factors which may affect R_f which include slope geometry, soil mechanical properties and hydrological properties, weather patterns, and failure modes. The selection of appropriate R_f for limit equilibrium analysis is a challenging task (Bishop, 1971). In the ACHILLES research program (supported by Engineering and Physical Science Research Council), advanced numerical modelling with FLAC has been carried out, which can rigorously capture the deterioration of strength with time and other factors (Rouainia et al. 2020; Postill et al. 2021). R_f can be output from the FLAC analyses. By collecting data on the variation of R_f with time in different conditions, it is possible to establish a relationship between R_f and other factors. The relationship is useful for estimating the strength parameters used during limit equilibrium analysis.

2.2 Numerical simulation

Values of residual factor for use in the design-life based approach were output from numerical simulations which partially coupled FLAC and SHETRAN. SHETRAN (Ewen, 2001) is a hydrological model capable of simulating a wide range of meteorological processes including evapotranspiration and precipitation, and was used to derive the surface boundary condition. Slope modelling was then carried out with the fully coupled hydro-mechanical finite difference code FLAC Two-Phase Flow (Itasca, 2016) using the boundary condition derived in SHETRAN. The strain softening behaviour of London Clay is illustrated in Figure 2. Analyses were carried out for London Clay cuttings of various heights and slope angles, as shown in Figure 3. The UKCP09 weather generator (Kilsby et al. 2007) was used to provide the future climate data, with extreme events (dry or wet years of less than 10% probability) removed. Analyses were carried out up to 200 years or stopped when slope failures occurred. Full details on the SHETRAN-FLAC modelling can be found in Rouainia et al. (2020).

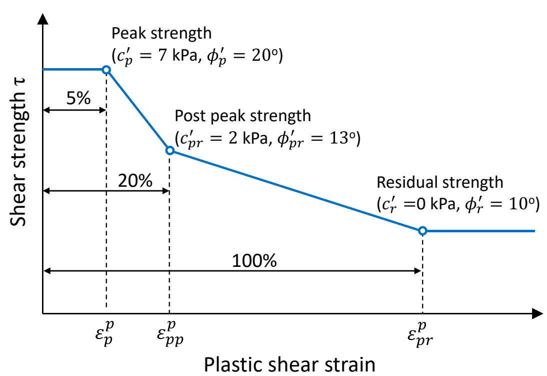

Figure 2: London Clay strain-softening behaviour.

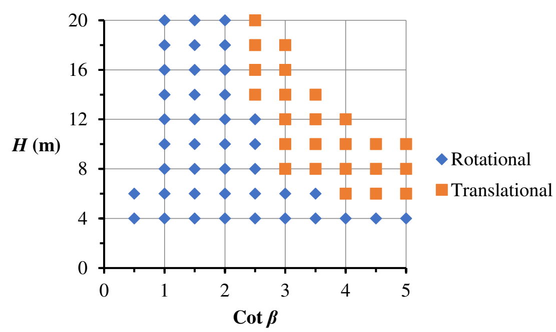

Figure 3: Slope heights (H) and angles (β) used in the SHETRAN-FLAC modelling and the critical failure mechanisms.

2.3 Slip surface classification

Based on the depth/length ratio, the failure modes obtained in FLAC modelling can be classified as deep rotational or shallow translational. Skempton (1953) studied landslides in the field and reported that the depth/length ratio for rotational failure ranged from 0.15 to 0.28, and for shallow translational failure from 0.03 to 0.06. In this analysis, a failure was considered to be translational if the depth/length ratio was <0.1, otherwise the failure was considered rotational (Huang et al. 2015). The failure mode for models which did not reach failure during the 200-year analysis is based on the critical failure surface derived from the last strength reduction stability analysis conducted in the 200th year. As shown in Figure 3, translational failures tend to occur in gentle slopes (e.g. $\cot\beta = 5$), and rotational failure tends to occur in steep slopes (e.g. $\cot\beta = 1$). The possible explanations could be that the gentler the slope, the less surface runoff during a rainfall event. Consequently, gentler slopes may be susceptible to more cyclic seasonal drying and wetting than steeper slopes, causing more strength deterioration at shallow depths - leading to translational failure development.

2.4 Mobilised strength

The variations of residual factors with time for various slope angles and heights are shown in Figure 4. It can generally be seen that the gentler the slope angle or/and the lower the slope height, the smaller the residual factor is for a given time. Steeper slopes fail sooner at lower values of residual factor. Shallower slopes may, at the end of simulation, go onto achieve higher residual factor without failing.

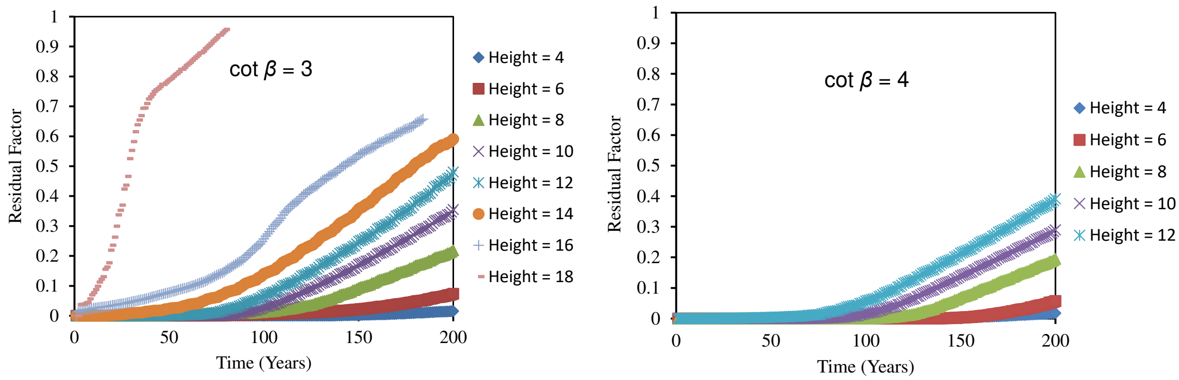

Figure 4: Residual factor with time.

The residual factor curves in Figure 4 can generally be fitted by bilinear curves (Figure 5). Through the bilinear fitting, R_f can be approximated as

$$R_f = \begin{cases} 0 & , \ t \leq start\_time \qquad \text{(equation 5a)} \\ (t - start\_time) \times Fitting\_slope\,, & t > start\_time \qquad \text{(equation 5b)} \end{cases}$$

where *start_time* is the horizontal intercept which indicates the time for R_f starts to deviate from zero and *Fitting_slope* is the slope of the straight-line which indicates the increment rate of R_f with time.

The regression models for **rotational** failure mechanisms are:

$Start\_time\ (\mathrm{yr}) = 154.6 + 7.5\cot\beta - 8.8H$ Adj. R^2 = 0.85 Eq. 6a

$Fitting\_slope\ (\mathrm{yr}^{-1}) = \frac{0.44 - 5.2\cot\beta + 5H}{10{,}000}$ Adj. R^2 = 0.76 Eq. 6b

where β denotes the slope angle, and H slope height.

The regression models for **translational** failure mechanisms are:

$Start\_time\ (\mathrm{yr}) = 171.0 + 6.0\cot\beta - 8.7H$, Adj. R^2 = 0.94 Eq. 7a

$Fitting\_slope\ (\mathrm{yr}^{-1}) = \frac{2.1 - 2.9\cot\beta + 4H}{10{,}000}$, Adj R^2 = 0.93 Eq. 7b

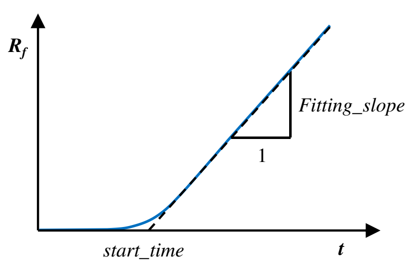

Figure 5: Fitting of residual factor with bilinear curves.

The parameters *start_time* and *Fitting_slope* were found to have linear relationships with slope height and angle (not shown). With the increase in height and angle, *start_time* decreases and *Fitting_slope* increases, which reveals earlier and increasing deterioration rates. Therefore, multivariate linear regression analyses were carried out to determine the relationship between slope height and slope angle variation with *start_time* and *Fitting_slope*.

The adjusted R^2 of the multivariate linear regression is greater than 0.7 for rotational failure mechanisms, and greater than 0.9 for translational failure mechanisms. By substituting Eq. (6) or (7) into Eq. (5), the residual factor (R_f) for any design-life (t) can be calculated. The residual factor R_f can be further substituted into Eqs. (3) and (4) to calculate the mobilised shear strength corresponding to the design-life t. Therefore, a design-life based approach is established in the framework of LEM for the design of cutting slopes in stiff clay.

3. Example

3.1 Critical slip surface determination

Limit equilibrium analysis involves searching for the critical slip surface. The location of the critical slip surface is directly related to the strength parameters used in the search. For a homogeneous slope, the location of critical slip surface is determined by the parameter group $c'/\gamma H \tan\phi'$ (Spencer, 1967; Jiang and Yamagami, 2006; Huang et al., 2022). The smaller $c'/\gamma H \tan\phi'$ is, the closer the critical slip surface is to the slope surface. If LEM is used in conjunction with the critical state strength ($c' = 0$, as shown in Figure 1), the critical slip surface is coincident with the slope surface. Chandler and Skempton (1974) identified this and noted "the $c' = 0$ assumption leads to the conclusion that the limiting slope of a cut in any particular clay is, contrary to practical experience, independent of depth." Therefore, Chandler and Skempton recommended $c' = 1.5$ kPa for LEM with the circular arc analysis in brown London Clay cuttings.

Figure 6 shows the slip surfaces in London Clay cuttings from field observations (James, 1970), back analysed by finite element method (FEM) (Potts et al. 1997) and LEM with $\phi' = 20°$ and c' ranging from 0 (for illustration purpose, 0.01 kPa was used) to 20 kPa. The critical slip surface corresponding to $c' = 1.5$ kPa recommended by Chandler and Skempton is still shallower than field observations. The critical slip surfaces corresponding to $c' = 7$ kPa (mass peak strength) and 20 kPa (intact peak strength) agree better with the field observations and those obtained by FEM.

In the period immediately following cutting excavation, it was likely that the operational strength along the critical slip surface would be at pre-peak or peak values. With progressive failure, the superfluous load shifts and softening propagates to adjacent soils along the predefined critical slip surface. This model, though highly conceptual, logically explains why the ultimate slip surface can be predetermined by the initial (mass) peak strength. Therefore, initial (mass) peak strength is recommended for the critical slip surface searching if LEM is used. This approach has previously been suggested (Mesri and Abdel-Ghaffar, 1993; Castellanos et al., 2016) and confirmed in this study. The critical slip surface is then fixed for the subsequent LEM analyses with reduced strength parameters. It should be noted that critical slip surfaces may be controlled by bedding features if they are present (Bromhead, 2013). The location of critical slip surface is an important piece of information if slope stabilisation (e.g., by soil nailing) is needed.

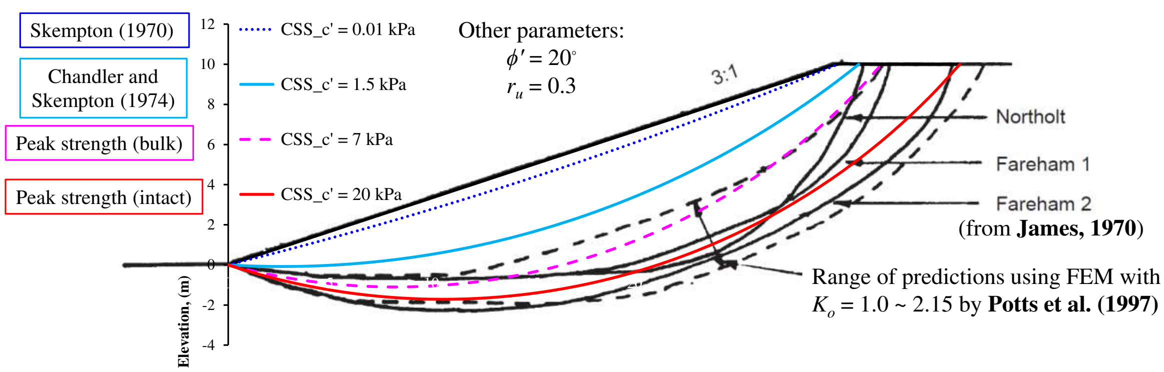

Figure 6: Slip surfaces in London Clay cuttings from Field observations (James, 1970), back analysed by FEM (Potts et al. 1997), and by LEM with various soil cohesions.

3.2 Design charts

An example is given for the design of London clay cuttings. The soil unit weight was $\gamma = 18.8$ kN/m^3; peak strength: $c'_p = 7$ kPa, $\phi'_p = 20°$; critical state strength: $c'_{cs} = 0$ kPa, $\phi'_{cs} = 20°$; residual strength: $c'_r = 0$ kPa, $\phi'_r = 13°$. Two cutting heights were considered, $H = 6$ m or 10 m. In this example, only deep rotational failure is considered, and a pore-water pressure ratio, $r_u = 0.3$ was adopted. The overall slope stability was determined using LEM applying Design Approach 1 Combination 2 (BS 6031:2009). Partial factors of 1.25 were applied on the peak strength and 1.1 on residual and critical state strength (BS EN 1997-1:2004; BS 6031:2009). The maximum slope angles that fullfill the Eurocode 7 design requirement can be calculated using LEM with critical state strength (the conventional approach) or the design-life based approach proposed in this study. The results are summarised in Figure 7.

The target design slope angle was 14.5° ($\cot\beta = 3.87$) for $H = 10$ m and 15° ($\cot\beta = 3.73$) for $H = 6$ m regardless of design-life using the critical state strength. Using the proposed design-life based apprach with $H = 10$ m, the slope angle can be 17.3° ($\cot\beta = 3.22$) for a design-life of 120 years, and 14.8° ($\cot\beta = 3.80$) for a design-life of 200 years. If the cutting height $H = 6$ m, the slope angle for design-life of 120 years and 200 years would be 24.3°

$(\cot\beta = 2.22)$ and $21.5°$ $(\cot\beta = 2.54)$, respectively. In this case for the strength and porewater pressure parameters selected it is shown that a less conservative approach can be adopted for shorter design life choices.

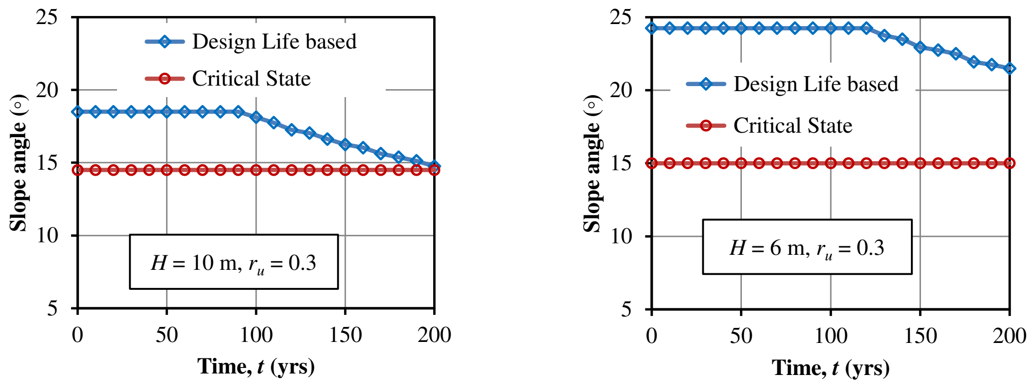

Figure 7: A design example using the conventional and proposed design-life based approaches.

4. Discussion

Steeper cut angles mean less land take and excavation, less environmental impact and significant cost savings. The benefit of using the proposed design-life based approach is the potential to make quantifiable evidence based decisions about whole life cost trade offs between initial slope angles and future maintenance. The proposed approach will also allow resilience to deterioration to be quantified aiding prioritisation decisions.

It should be noted that the current model is a test of concept, for one set of soil parameters (London Clay) and considers slope geometry only. Further development of the underlying numerical simulations have also been carried out since that will allow preparation of more robust recommendations for transient parameters and development of a wider range of design charts. Further development will also allow consideration of the effects of different mechanical and hydrological properties and extreme weather events.

5. Conclusion

A design-life based approach in the LEM framework for the design of cutting slopes in stiff clay is proposed. The outputs of a series of coupled hydro-mechanical analyses for cutting slopes in London Clay were used to derive regression models which can calculate the mobilised soil strength as a function of time and slope geometry. Therefore, aged strength parameters can be chosen for different design lives. Application of the proposed design-life based approach is demonstrated through a design example, which shows that steeper slopes can be adopted for a shorter design life, or shallow slopes for a longer design life. This will permit quantification of whole life costs and choices to be made about approaches to resilience.

Acknowledgements

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References

Bishop, A. W. (1971). The influence of progressive failure on the choice of the method of stability analysis. *Géotechnique*, 21(2), 168-172.

Bjerrum, L. (1967). Progressive failure in slopes of overconsolidated plastic clay and clay shales. *Journal of Soil Mechanics & Foundations Division*, 93(5), 3-49.

British Standards Institution (2004). *BS EN 1997-1:2004, Eurocode 7: Geotechnical design – Part 1: General rules*

British Standards Institution (2009). *BS 6031. Code of Practice for Earthworks*. London: BSI.

Bromhead, E. N. (2013). Reflections on the residual strength of clay soils, with special reference to bedding-controlled landslides. *Quarterly Journal of Engineering Geology and Hydrogeology*, Vol. 46, 2013, pp. 132–155

Castellanos, B. A., Brandon, T. L., & VandenBerge, D. R. (2016). *Use of fully softened shear strength in slope stability analysis. Landslides*, 13(4), 697-709.

Chandler, R. J., & Skempton, A. W. (1974). The design of permanent cutting slopes in stiff fissured clays. *Géotechnique*, 24(4), 457-466.

Clarke, D., & Smethurst, J. A. (2010). Effects of climate change on cycles of wetting and drying in engineered clay slopes in England. *Quarterly Journal of Engineering Geology and Hydrogeology*, 43(4), 473-486.

De Lory, F. A. (1957). *Long term stability of slopes in over-consolidated clays*. PhD thesis, Imperial College, London.

Ellis, E. A., & O'Brien, A. S. (2007). Effect of height on delayed collapse of cuttings in stiff clay. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*, 160(2), 73-84.

Ewen, J. (2001). *SHETRAN: Physically-based spatially-distributed river catchment modelling system*. USER MANUAL for Version 5.1. Water Resources Systems Research Laboratory, Newcastle University.

Huang, W., Leong, E. C., & Rahardjo, H. (2015). Translational slip failures on slope incorporating unsaturated soil mechanics. *Proc. 6th Asia-Pacific Conf. on Unsaturated Soils*, 23rd – 26th October 2015, Guilin, China, pp. 771-775.

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.

Itasca (2016). *FLAC: fast Lagrangian analysis of Continua – Version 8 users guide*. Itasca Consulting Group, Minneapolis.

James, P.M. (1970). *Time effects and progressive failure in clay slopes*. PhD thesis, Imperial College, London.

Jiang, J. C., & Yamagami, T. (2006). Charts for estimating strength parameters from slips in homogeneous slopes. *Computers and Geotechnics*, 33(6-7), 294-304.

Kilsby CG, Jones PD, Burton A, Ford AC, Fowler HJ, Harpham C, James P, Smith A, Wilby RL (2007). A daily weather generator for use in climate change studies. *Environmental Modelling & Software*. 22(12):1705–1719

Mesri, G., & Abdel-Ghaffar, M. E. M. (1993). Cohesion intercept in effective stress-stability analysis. *Journal of Geotechnical Engineering*, 119(8), 1229-1249.

Nowak, P., and Gilbert, P. (2015). *Earthworks: a guide (second edition)*. ICE Publishing.

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, 105912.

Potts, D.M., Kovacevic, N. & Vaughan, P.R. (1997). Delayed collapse of cut slopes in stiff clay. *Géotechnique*, 47(5):953-982.

Rouainia, M., Helm, P., Davies, O., Glendinning, S. (2020). Deterioration of an infrastructure cutting subjected to climate change. *Acta Geotechnica*, 15(10):2997–3016.

Skempton, A. W. (1953). Discussion. In: R. Glossop and G.C. Wilson (Editors), Soil Stability Problems in Road Engineering. *Proc. Inst. Civil Eng. Road Eng. Div. Meeting*, 2: 219–280.

Skempton, A. W. (1964). Long-term stability of clay slopes. *Géotechnique*, 14(2), 77-102.

Skempton, A. W. (1970). First-time slides in over-consolidated clays. *Géotechnique*, 20(3), 320-324.

Spencer, E. (1967). A method of analysis of the stability of embankments assuming parallel inter-slice forces. *Géotechnique*, 17(1), 11-26.

Tsiampousi, A., Zdravkovic, L., & Potts, D. M. (2017). Numerical study of the effect of soil–atmosphere interaction on the stability and serviceability of cut slopes in London clay. *Canadian Geotechnical Journal*, 54(3), 405-418.

Vaughan, P. R. & Walbancke, H. J. (1973). Pore pressure changes and the delayed failure of cutting slopes in over-consolidated clay. *Géotechnique*, 23(4), 531-539.

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