Moving towards a performance-based design approach for cutting slopes in high PI clays

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Abstract

The design of new, or the remediation of existing, cutting slopes in high-plasticity clay geologies is of considerable economic interest in the UK because they comprise a significant percentage of the UK's existing and proposed linear transportation infrastructure.

The key metrics which asset owners need to understand to make informed decisions about these designs are capital cost and whole life cost (including the operational impact of future interventions or absence of interventions). Design is undertaken in a framework of code compliance which incorrectly gives the impression that different solutions either pass or fail, but it does address the question of comparative capital cost. It doesn't, however, allow the designer to express the relative merits of different design options, because it is very difficult to quantify the functional design life of different designs, and therefore their whole-life cost. Some designs 'pass' more easily than others, but there is no tangible way of defining what this means in terms of those key asset management metrics.

This paper reviews the latest science on the performance of cutting slopes in high plasticity clays from the perspective of design. It shows that the potential impacts of long-term weather conditions add significant uncertainty to established, simplified, design approaches. It then proposes that there is an emerging opportunity to refocus design on performance, quantified through the concept of effective design life, rather than purely on compliance with calibrated partial factor models. The benefit of this is that design could be presented in terms of key asset management metrics and would become immediately more tangible to all stakeholders, with a consequence of facilitating more informed, and therefore, better decision-making.

Keywords: Earthmoving, Slopes, Design life, Performance-based design

1. Introduction

The design of new, or for the remediation of existing, cutting slopes in high-plasticity clay geologies is of considerable economic interest in the UK because they comprise a significant percentage of the UK's existing and proposed linear infrastructure.

The key metrics which asset owners need to understand to make informed decisions about these designs are capital cost, whole life cost (including the operational impact of future interventions or absence of interventions), and reliability. Whole life cost and reliability require knowledge of design life, a fundamental parameter in much of engineering design, defined as the "assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary" (BSI, 2002). Designers or asset managers can use a clear understanding of design life to manage and balance capital cost, operational cost, durability and expected obsolescence. It enables informed decisions about value for money and sustainability to be made.

For assets for which the deterioration mechanisms are well established empirically or can be calculated, these metrics, and the relationships between them, are comparatively straightforward to establish. An example would be pump components whose performance can be established through rigorous testing and observed performance. An asset-owner can readily establish the merits and drawbacks in investing in more robust componentry with a longer design life, as opposed to cheaper products which may need earlier replacement.

For earthworks assets the situation is significantly complicated by two factors. First, the idea of design life is notional, with BS6031 suggesting that while serviceability conditions should be considered, that the focus should be on using materials that do not deteriorate, or on preventing deterioration by maintenance (BSI, 2009). However, recent research shows clay earthworks do deteriorate (Briggs *et al.*, 2023), but deterioration models on a single-asset scale are in their infancy compared with other structural materials or components. Therefore, although the design life of an earthwork is notional, the operational life is real and finite, as evidenced by the ultimate failure of older assets.

This paper reviews the question of design life for cutting slopes to investigate if it could be used, in combination with emerging science from the ACHILLES research programme (Briggs *et al.*, 2023), to support performance-based design that would enable earthwork-infrastructure owners to address these questions.

2. Cutting slope design

Civil engineers have been constructing cutting slopes for centuries, mostly using empiricism, but with support from soil mechanics as it emerged in the 20th century (Skempton, 1996). Cutting slopes are complex structures because they are engineered from soils whose behaviour is complex and in geology which is often complex (especially in superficial deposits in which cuttings are often formed). The cutting itself adds to this complexity by creating an environment where moisture content and pore pressures are transient, and weather and vegetation change the chemistry and structure of the soils over time (Glendinning *et al.*, 2018).

Engineering design does not (routinely) explicitly account for this complexity, but uses simplified models of the expected behaviour, calibrated through experience, to design cuttings which are deemed to meet society's needs. The calibration is made through the design approach which is either using a 'factor of safety' (FoS), or a set of calibrated partial factors supplemented by empirical evidence of the performance of previous cuttings in similar ground conditions. This experience is invaluable, for example, for understanding the effects of weathering and time-dependent behaviour (Perry, 1989).

Slopes may be analysed using limit equilibrium methods (e.g. Morgenstern & Price, 1965) or numerical analyses, with the latter being potentially significantly more complex. Routine design work using numerical analyses is often used to allow for complex geometry or engineering reinforcement, but normally with relatively straightforward constitutive models (i.e. Mohr-Coulomb). They do not typically try to account for the full complexity of cutting behaviour, ignoring for example the effects of post-peak strain softening, seasonally transient pore pressures, or wetting and drying.

This commentary is not to criticise. There is merit in keeping analyses straightforward in respect of the quality of data available to input into models, computing efficiency, the ability to evaluate sensitivities using parametric models and ease of checking, and good designers are able to use the available tools to effectively design safe and economic slopes. But because of this, necessarily, reductionist approach to design, designs are not performance-based and rely on notionally pass/fail criteria of 'factor of safety is acceptable', or 'utilisation is acceptable' (in the case of partial factor methods). These criteria give no insight to nuances such as the different consequences of failure of shallow and deep-seated slope failures, how to allow for progressive failure mechanisms or the impact of climate change. They do not even allow straightforward comparison of different slopes because, in practice, the actual reliability of the design is conditioned not only by the choice of partial factor, but by the experience of the designer and their selection of appropriate strength and pore-pressure parameters to use in these models.

In particular, they give no indication about the implications for the operational life of the asset (which is why the idea of design life for earthworks is notional) or whole-life cost of options which may have lower utilisation. It is therefore very difficult for engineers to make a quantitative cost-benefit assessment (CBA) of different designs, or, by extension, to communicate the potential real benefits of a more cautious design than the minimum code-compliant option.

3. Cost-benefit assessment

CBA methods for new infrastructure are well established, but are usually applied when deciding whether to construct earthworks, rather than how to design earthworks. For example, CBA may evaluate benefits in terms of safety and journey time improvements against capital cost. Shallower earthworks slopes would increase those costs, but because the understanding of design life is absent, the benefits cannot be quantified meaningfully. Furthermore, costs have different value at different times in the future due to the method of discounting. This means that money saved later is less valuable than that saved now. So even if different capital versus operational costs were evaluated, this approach is likely to arrive at a sweet spot of intermediate design life since benefits beyond 60 years are not typically accounted for. Therefore, while CBA is conducted for new infrastructure schemes, current thinking does not allow comprehensive decision making even though we are starting to have the tools to do so. This means that we cannot give value to existence of infrastructure that we know will be a benefit to society for 100s of years to come.

Of course, financial constraints may mean a shorter design life is preferred, but at least the consequences of this decision can be fully understood if a performance-based approach is taken. Armstrong *et al.* (2024) illustrate how when an earthworks deterioration model is available, these trade-offs can be at least assessed. They show how early interventions for existing cuttings can give the greatest design life extensions, but that optimising for change in annualised present value suggests much later intervention. However, getting too close to failure brings unacceptable risks and consequences, and this approach does not account for the severity of failure and therefore remediation costs increasing, nor the fact that allowing further deterioration is in itself damaging. The fact that climate change will increase the future rate of that deterioration also needs to be accounted for (Huang *et al*. 2024). None of this analysis accounts for full societal impacts of failure, e.g. unreliability of rail journeys influencing decisions to take the car and not the train, with safety and emissions implications.

4. How might we want to design slopes?

To address these issues it would be better, but undeniably more complex, to adopt performance-based design with an explicit consideration of design life. A design method predicated on an expected time to failure (TTF), as opposed to a notional FoS, would be much more transparent in respect of the relationship between capital and operation expenditure (i.e. whole-life cost), and the relative benefits of more or less cautious designs, such as operational availability, would be readily understandable by all stakeholders.

It would allow designs to be modified to suit changing climates or the circular economy agenda, or the risk appetite of particular clients or situations through more meaningful consideration of parameters such as reliability, resilience, robustness and risk.

To do this, it is necessary to explicitly include in design models the deterioration in the performance of cutting slopes over time. Emerging science from the ACHILLES research programme potentially presents an opportunity to start to rethink design in this context.

5. Key findings from ACHILLES

Outputs from the ACHILLES Programme showed that the performance of transport infrastructure earthworks changes over their lifetime, from a state of reliable performance to a deteriorated state of unreliable performance below an acceptable threshold, Figure 1. This is in response to ageing, physical loading and environmental loading over long periods of time. A critical process that reduces the stability and serviceability of cut slopes is weather-driven deterioration due to seasonal weather cycles. A conceptual model for weather-driven deterioration in clay earthworks (Briggs *et al*. 2023) showed that seasonal wetting, drying and changes in pore water pressure reduced the strength, stiffness, hydraulic properties and fabric of in situ clays and clay fills. This reduces the stability and serviceability of earthworks as they age and makes them more vulnerable to weather-induced failures such as rainfall-induced slope failures or drying-induced settlement.

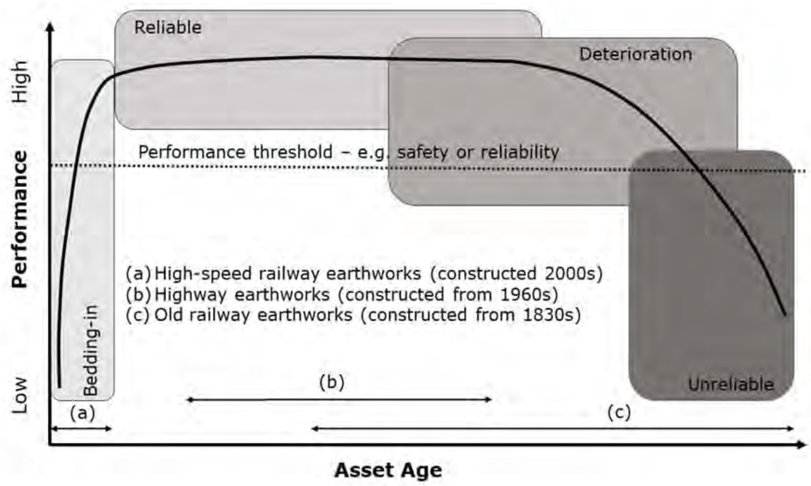

Figure 1: Transportation earthworks in the UK at various ages and stages of performance (Briggs *et al*. 2023).

Measurements from instrumented cuttings (O'Brien, 2013; Ridley, 2012; Saffari & Ridley, 2022; Blake *et al*. 2022) and forecasting using numerical analyses (Rouainia *et al*. 2020; Postill *et al*. 2021; Postill *et al*. 2023; Huang *et al*. 2024) showed that seasonal pore water pressure cycles can induce irreversible, downslope, ratcheting displacements and strain-softening in high-plasticity clay slopes. This continued beyond the post-construction equilibration of pore water pressures that have been associated with delayed failures in cut slopes (Vaughan & Walbancke, 1973; Chandler & Skempton, 1974). The analyses showed that in high-plasticity clay cuttings (i) the deterioration of the cutting strength and stiffness reduced the trigger threshold for failure, making such slopes more vulnerable to failure than they were in less onerous weather conditions during the earlier, more reliable stage of their life, (ii) climate-change projections of wetter winters and drier summers in the UK will not make maximum pore water pressures in cuttings more onerous, but greater pore water pressure cycles will enhance the rate of deterioration, and (iii) the critical failure surface in cut slopes will change over time from a deep-seated to a shallow failure mechanism. As a result, the changing performance of the cuttings with age is related to both changes in loading and changes (i.e. a reduction) in resistance.

The time dependency of input parameters is therefore critical for the future design or the assessment of existing cuttings. This can be achieved by applying a design life based approach to static parameters (Postill *et al*. 2023; Huang *et al*. 2023a) which are applied in analytical or limit equilibrium techniques (Huang *et al*. 2022; Huang 2023b). Alternatively, a dynamic approach can be taken where the parameters evolve over time as driven by weather and climate (Rouainia *et al*. 2020; Postill *et al*. 2021).

6. Relationship between ACHILLES findings and performance-based design

One part of the ACHILLES research was to develop analytical tools which could model this complexity, for which numerical simulations were undertaken using coupled hydro-mechanical finite element and finite difference analyses that captured different aspects of the deterioration processes. The simulations were validated against the field and laboratory data, and used simulated climate models to assess future behaviour in response to long-term seasonal weather cycles.

The numerical simulations (Postill *et al*. 2023) were used to produce a framework for the number of annual pore water pressure cycles required to trigger the failure of high-plasticity clay cuttings. The framework (Figure 2) relates the slope angle and slope height to the failure time in four categories ranging from 60 to 120 cycles. Figure 2 shows that short (< 3m) and relatively shallow (37.5^{o}) slopes did not fail after 120 seasonal cycles. This reduced for steeper and/or taller slopes. While the framework does not provide forecasts, it can be used to compare the relative performance or resilience of different slope geometries.

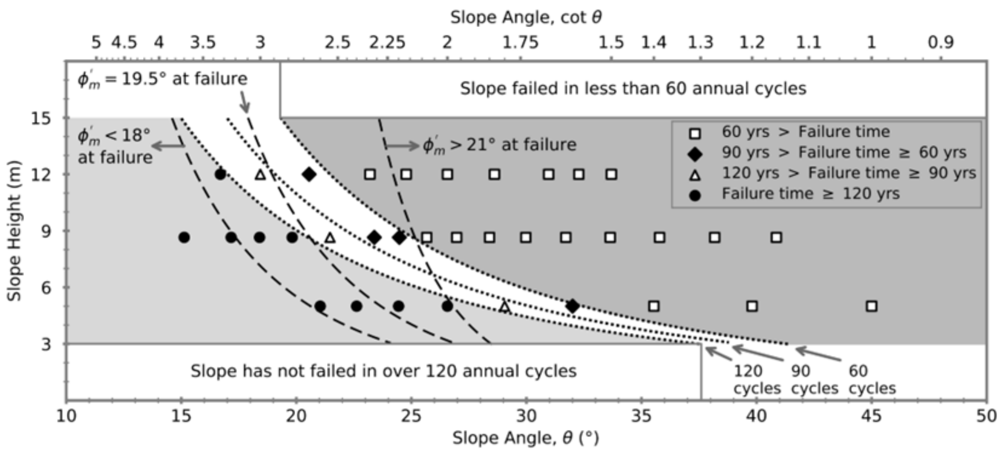

Figure 2: A framework for the number of cycles to failure in high-plasticity, strain-softening, clay cut slopes for varied slope geometries (Postill *et al*. 2023; Helm *et al*. 2021). Note that ϕ'_m is the mobilised friction angle. (Courtesy of 4.0 International (CC BY 4.0)).

In principle these simulations could analyse any combination of input parameter such as slope height, angle, initial soil strength or phreatic surface, but this was not practical for wider dissemination because they were computationally expensive and time-consuming to run.

To resolve this difficulty, statistical tools were developed to rapidly consider slope stability for a large number of possible slope geometries and material properties. These were trained using the results of 76 numerical simulations (Svalova *et al*. 2021; Helm *et al*. 2024) and earthwork failure records (Trinidad González *et al*. 2023) to produce outputs for the changing TTF, FoS or probability of slope failure. The TTF outputs were validated by comparing to failure potential contours used by Network Rail, as reported in the Global Stability and Resilience Appraisal (Mellor *et al*. 2017).

The *ACHIMULATOR* (ACHILLES emulator) tool (Svalova *et al*. 2021; Helm *et al*. 2024) requires input of five variables that relate to slope deterioration. These are slope height, slope angle, soil strength (c' and φ'), and permeability. The slope geometry ranges were based on those measured in LiDAR scans of cuttings on the Great Western Railway and surveys of the M4 motorway (height range 4 to 20m, slope angles of 1V in 0.5H to 1V in 7.5H). The soil shear strength and permeability values were derived from the literature (c' values of 3 to 10 kPa, φ' of 18.5° to 25° and permeability from 1.5×10^{-9} to 2.5×10^{-8} m/s).

Numerical simulations of the type undertaken in the ACHILLES programme, or statistical tools such as the *ACHIMULATOR* could be used to bring design life and TTF into slope design and stability assessment. As with all simulations, it is essential that users understand the models to ensure that a correct choice of input parameters to suit their situation is made.

7. Case study

As an example of the approach, consider a 12m deep new cutting in high plasticity clay with a base width of 20m. Assume that the cutting is symmetrical, and no further engineering interventions are applied to the slopes to enhance their stability. Figure 3 presents the output from the *ACHIMULATOR*. The input parameters (slope height, slope angle, soil peak cohesion, soil peak friction angle, soil permeability) were held constant except for the cutting slope angle. This is presented on the x-axis of Figure 3a as the excavated volume per metre length of the cutting (the slope and base width combining to define the cross-section of the cutting), which is a reasonable proxy for relative capital cost in rural environments without physical constraints to the overall cutting width (even accounting for the cost of land). The y-axis shows estimated TTF for the different slope angles considered (the modelling underpinning the *ACHIMULATOR* is not yet sufficiently well calibrated to give an absolute value of TTF, but is considered acceptable for comparisons between different options).

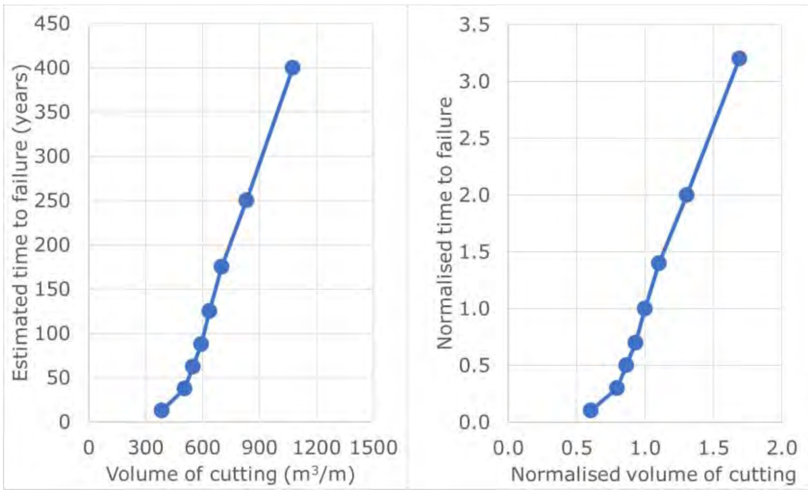

Figure 3: Estimated time to failure of an example 12m deep plasticity cutting with a 20m wide base for different slope angles using the *ACHIMULATOR*, shown as a) as time to failure against cutting volume, b) the same data normalised to 125 years

Figure 3 can be used to understand how the capital expenditure on the cutting influences its expected TTF, from which can be inferred operational costs for maintenance and renewal. The data is re-plotted in Figure 3b by normalising the TTF of 125 years (120 years being the notional design life for a design to BS EN 1997-1, but 125 years being the closest point from the *ACHIMULATOR*) and normalising the volume to the volume needed for a TTF of 125 years. For this example, the cost of additional TTF (and therefore lower maintenance, higher safety) is modest for designs beyond the notional BS EN 1997 design life. A 50% increase in excavation volume brings a 250% increase in design life, with a consequent reduction in maintenance cost and increase in reliability.

8. Conclusions

Even though engineers have been designing and constructing cutting slopes in high plasticity clays for centuries, the complexities of their behaviour are still being understood, and consequently analytical engineering models which fully capture their complexity are not readily available.

There have been a number of paradigm shifts in design approaches and understanding, for example progressing from purely empirical approaches to using the science of soil mechanics, and most recently progressing from lumped FoS approaches to partial factor models. Potentially the use of TTF, supported by the science from the ACHILLES programme, and the approach to numerical simulation and statistical modelling trialled therein, will contribute to the next one.

This paper explored the concept of design life for infrastructure slopes, and the idea that engineering design could move from codified partial factor design methods to genuine performance-based approaches. This move potentially has the following significant advantages, for both the maintenance of existing earthworks and the design of new ones:

- It could be used to communicate to stakeholders beyond engineering teams, such as asset owners the benefits and drawbacks of design options using metrics such as relative time-to-failure, which is much more transparent, and therefore understandable, than Factor of Safety (FoS) or degree of utilisation;
- It would therefore enable informed capital expenditure decisions because it would be possible to quantify the impact of these decisions on operational expenditure. In this way designs could more explicitly consider sustainability because they wouldn't simply be 'over' or 'under' designed, they would have differently quantified outcomes for different investment in materials;
- They could be used to explicitly design for different climate scenarios, including concepts of reliability, resilience, robustness and risk.

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