# The seasonal ratcheting of clay cut slopes in response to seasonal weather cycles

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**Abstract**

Many cut slopes in the UK are in the later stages of their operational life but continue to support road and rail transportation networks. Some of these slopes experienced delayed, deep-seated, first-time failures between 10 and 50 years after construction. However, some continue to seasonally deform and then fail at shallow depth due to the process of seasonal, downslope ratcheting. This paper reviews the evidence for seasonally-induced, downslope ratcheting movements in clay cut slopes, gathered from physical model tests, in-situ monitoring and numerical simulations. The evidence shows that seasonal ratcheting is an increasingly dominant mechanism of slope deformation and ultimate failure for some high-plasticity clay cut slopes as they are exposed to many seasonal weather cycles. The rate of downslope ratcheting depends on the slope age (*i.e.*, number of seasonal weather cycles since construction), the slope geometry (*i.e.*, slope height and angle) and the strain-softening behaviour of the slope material (*e.g.*, as observed in stiff, high-plasticity clays). This rate, when measured, can be used to inform monitoring and management strategies for old, clay cut slopes (*e.g.*, ageing railway and highway cuttings) by identifying the slopes that are prone to seasonally-induced, downslope ratcheting towards the end of their operational life.

Keywords: Cut slopes, Slope stability, Strain-softening, Downslope ratcheting

## 1. Introduction

Cut slopes in high-plasticity clays form a critical part of road and rail transportation infrastructure. This includes many UK railway cuttings that were constructed during the Victorian period and are some of the oldest in the world (c.1830s). They are at various stages of deterioration and require proactive inspection, maintenance and/or repair to extend their serviceable condition into the 21st Century. Infrastructure owners must understand the key deformation and failure mechanisms in cut slopes if the early signs of deterioration are to be detected and monitored prior to failure.

During construction of the early railways, shallow slope failures commonly occurred following periods of wet weather (Squire, 1880). These were followed by deeper-seated failures in subsequent years, that were attributed to stress relief and later confirmed as delayed failures due to long-term pore water pressure equilibration, irreversible swelling, strain-softening and progressive failure (Skempton, 1964; James, 1970; Potts *et al.*, 1997). Most of these delayed, first-time failures were observed between 10 and 50 years after construction, with some more than 100 years after construction (Chandler & Skempton, 1974; Castellanos *et al*., 2016).

However, some cut slopes in high-plasticity clays continue to experience irreversible, downslope, plastic deformation at shallow depths. The process known as seasonal ratcheting describes how shrink-swell cycles and accumulated displacements occur in response to annual wetting and drying of clays, driven by seasonal weather changes (Take & Bolton, 2011). This disrupts the serviceability of railway track and rail services. It also reduces the resilience of cut slopes to ultimate limit failures triggered by an increase in surface loading or pore water pressure.

This paper reviews evidence of downslope ratcheting in response to wetting and drying cycles that was first observed in centrifuge model experiments and later measured in-situ on high-plasticity clay, cut slopes. It also includes results from calibrated numerical simulations that have been used to forecast the longer-term role that

seasonal ratcheting plays in the deterioration of cut slope stability. Finally, the implications of seasonal ratcheting on the resilience of cut slopes are considered for design and new construction.

## 2. Evidence for near-surface seasonal movement and ratcheting in cut slopes

### 2.1 Centrifuge experiments

Take & Bolton (2011) showed that cyclical variation in soil water content can drive effective stress changes in a clay slope and temporarily mobilise the post-peak strength of the soil (*i.e.*, towards fully softened strength). The repeated mobilisation of dilatancy in wet periods induced strain accumulation, slope ratcheting and localised strain softening. They hypothesised that such slopes can be brought to failure in response to long-term, seasonal pore pressure cycles and that a post-peak strength, such as Skempton's fully-softened shear strength, is appropriate for limit-equilibrium stability analyses in design.

The measurements were carried out using a physical centrifuge model with controlled material properties, stress conditions and boundary conditions. A 140mm high, 1/60th scale, Speswhite Kaolin slope was subjected to surface wetting and drying using a climate chamber developed by Take (2003). Displacements within the slope were measured using particle image velocimetry and pore pressures were measured using high capacity tensiometers. The results showed that dilation and softening of the slope was accompanied by downslope ratcheting and a localised failure at the toe of the slope. The cyclic slope displacements were predominately vertical at the crest of the slope and horizontal at the slope toe.

Postill *et al.* (2020) simulated seasonal ratcheting movements and progressive slope failure due to stress changes induced by wetting and drying cycles. A coupled hydro-mechanical model of unsaturated soil behaviour was validated against the physical measurements of Take & Bolton (2011). The model was able to replicate the seasonal ratcheting deformations measured by Take & Bolton (2011) for different initial stress conditions (Figure 1). Additional sensitivity analyses showed that the material stiffness controlled the rate of strength deterioration in the slope simulations, with stiffer materials showing a more gradual accumulation of irrecoverable strains and softening than less-stiff materials.
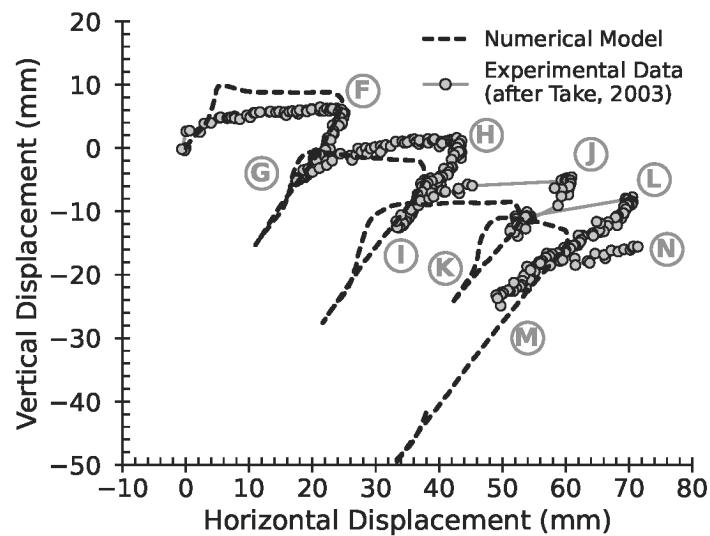


**Figure 1**: Vertical and horizontal displacements at the toe of a physical model (grey circles) and numerical model (black dashed line) showing ratcheting deformations in response to wetting and drying cycles (E-N). Redrawn from Postill *et al.*, 2020.

### 2.2 In-situ monitoring of cut slopes

In-situ measurements obtained from high-plasticity cut slopes show seasonal displacements and irreversible, downslope ratcheting in response to cyclic wetting and drying of the near-surface soil.

Saffari & Ridley (2022) showed measurements of cyclic, seasonal deformations and pore water pressures from a cut slope in high-plasticity London Clay on the London Underground network (Figure 2). The cut slope had a covering of large mature trees that were subsequently removed during remedial works to improve the slope condition, following a history of instability. The mature trees induced seasonal pore water pressure cycles (up to 60 kPa variation) within the slope and prior to their removal there was a clear pattern of cyclic, downslope movements extending to approximately 2.6 m below ground level. The inclinometers showed upslope

movement in the winter months (wet season), followed by downslope movement toward the track in the summer months (dry season), with a long-term, downslope trend. The trees did not induce failure of the cut slope. But they did reactivate an existing shear surface that was identified prior to the subsequent remedial works. Following removal of the trees, the downslope movements became less cyclic but markedly increased.
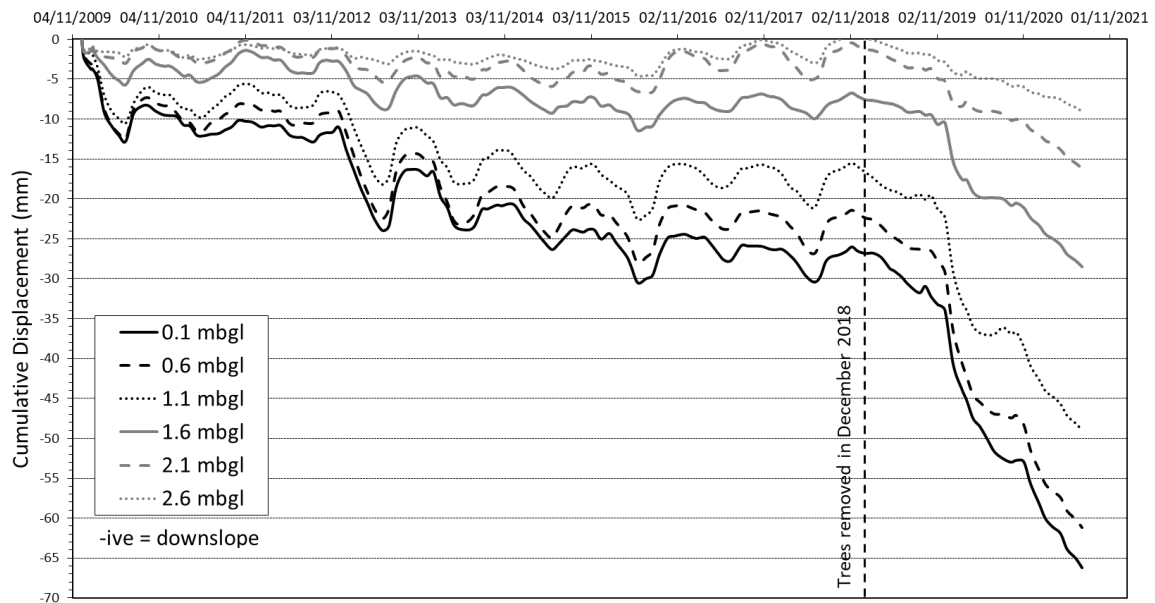


**Figure 2**: Inclinometer measurements at shallow depth in a high-plasticity cut slope on the London Underground network (redrawn from Saffari & Ridley, (2022), with data courtesy of Geotechnical Observations Limited).

Ridley (2012) showed in-situ monitoring data linking climate, vegetation, pore water pressures and slope displacements. Inclinometer measurements from a heavily vegetated, cut slope in London Clay showed shallow (up to 3 m below ground level), shrink-swell movement in response to seasonal changes in pore water pressure. Winter swelling of the cut slope occurred upward and outward in response to increased pore water pressure. Pore water pressure reduced in the summer, causing shrinkage that was downward and slightly inward. The shrink-swell movements showed net downslope displacement over successive annual cycles, leading to shallow instability. In another 5 m high cut slope, inclinometer and extensometer measurements also showed summer settlement and winter heave displacements (Ridley, 2017). These compared with reducing pore water pressures at shallow depth (1.5 m below ground level) in the summer months and increasing pore water pressures in the winter months. This led to a net downward and outward slope displacement of more than 15 mm and 25 mm, respectively, over three annual shrink-swell cycles.

**2.3 Hydro-mechanical simulations of cut slopes**

Postill *et al.* (2021a) used a coupled, saturated and unsaturated, hydro-mechanical model to simulate seasonal displacements in a high-plasticity cut slope, in response to seasonal pore pressure cycles. The model was validated using 16 years of monitoring data from a cut slope in London Clay (Smethurst *et al.,* 2012). Long-term projections of slope behaviour were undertaken using 90 years of synthetic weather data that were calibrated to the baseline regional weather for 1961 to 1990.

The simulations showed seasonal shrink-swell displacements at the mid-slope and toe; with a net cumulative upward and outward swelling at shallow depth during first 15-20 years after construction and at greater depth (5 to 10 m below ground level) until approximately 50 to 80 years after construction. This can be associated with post-construction stress relief and the dissipation of excess pore pressure generated during construction in low permeability clay slopes (Vaughan & Walbancke, 1973). However, after 15 years of seasonal pore water pressure cycles, the simulations showed downslope ratcheting deformation and a reduction in slope stability. The simulations showed upward and outward mid-slope displacements in periods of wet winter weather, followed by downward, inward displacements in the drier summer months (Figure 3). The displacements were greatest during periods of prolonged wet weather, such as 2007-2009 and 2015-2018. The annual downslope displacement increments increased with successive seasonal wetting and drying cycles. Accumulated plastic shear strains led to localised strain-softening, the redistribution of stresses and progressive failure. A calculation

of the slope factor of safety (FoS) at annual increments showed that it gradually reduced towards slope failure (FoS < 1) approximately 90 years after construction.

A comparison of simulations with a strain-softening material model against simulations with a non-softening material model confirmed that the initial reduction of the slope FoS was solely due to post-construction pore pressure dissipation, as described by Vaughan & Walbancke (1973). However, the simulations showed that beyond the initial 10- to 15-year period, the reduction of the slope FoS was increasingly driven by material strain-softening in response to seasonal pore water pressure cycles (Figure 4). This shows that the long-term reduction in slope stability was due to a permanent reduction in shear strength and not only in response to reversible pore water pressure changes. This reduction in the long-term slope FoS helps to explain field observations that suggest cut slope failures can be triggered by wet winter weather conditions (and a subsequent pore water pressure increase) that are less onerous than past conditions.

By pausing the numerical analysis and applying a classical strength reduction technique, the simulations showed that the initial (less than 25 years after construction) critical failure surface was a deep seated, rotational failure mechanism. Later, the critical failure surface changed to a shallow translational failure mechanism (Figure 5). This was driven by strain softening due to downslope ratcheting in the near surface of the cut slope, where seasonal pore water pressure and stress cycles were greatest.
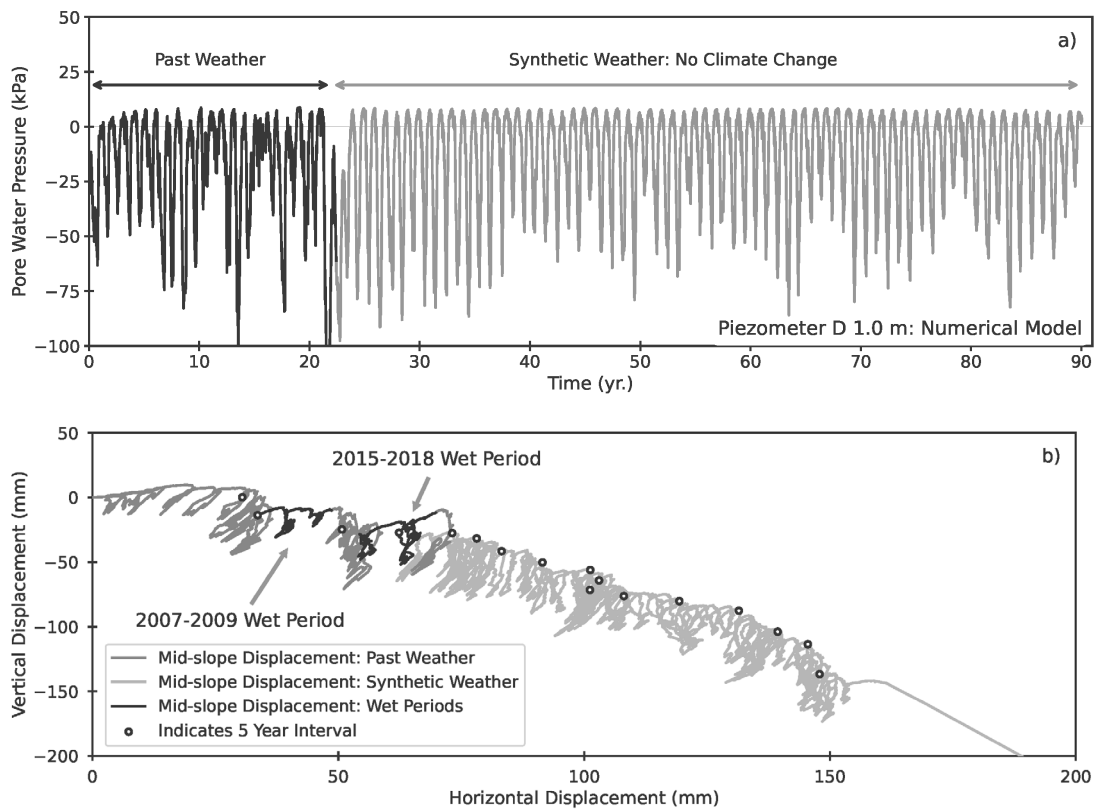
**Figure 3:** (a) Pore water pressures, and (b) mid-slope displacements simulated in a hydro-mechanical model of a high-plasticity clay cut slope, in response to measured weather data and synthetic weather data (from Postill *et al.*, 2021a). (Courtesy of 4.0 International (CC BY 4.0))
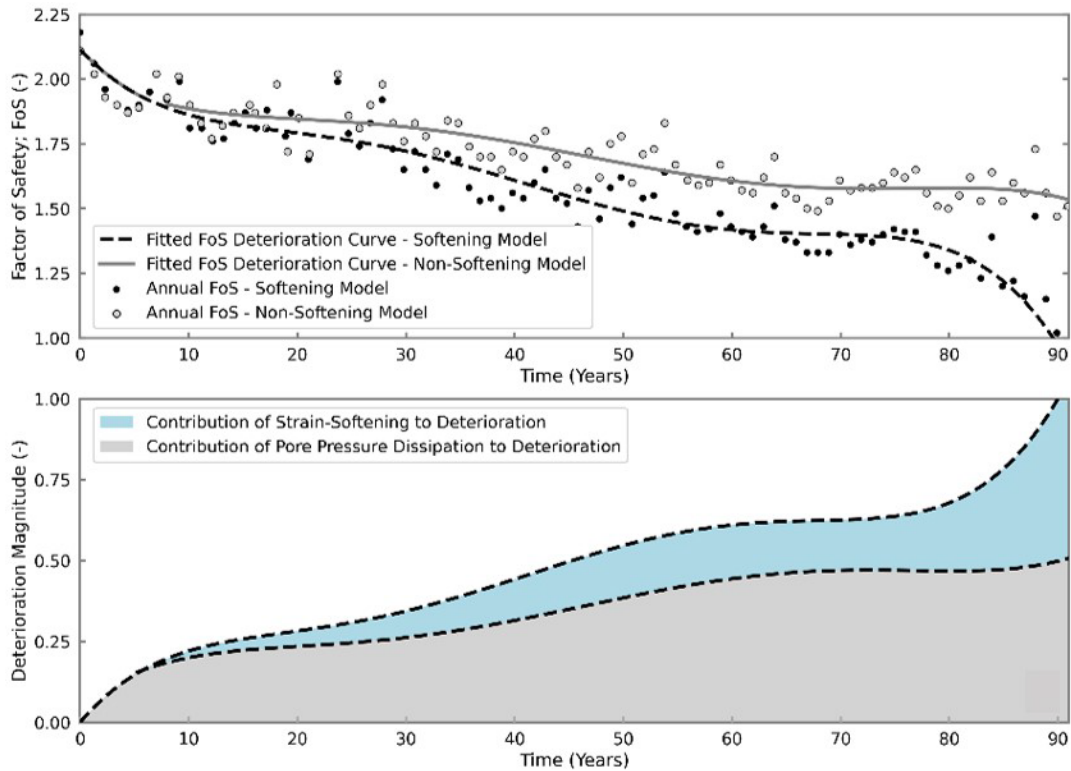
**Figure 4**: The change in cut slope (a) factor of safety and (b) deterioration magnitude for a softening and non-softening material model (from Postill *et al.*, 2021a). (Courtesy of 4.0 International (CC BY 4.0))
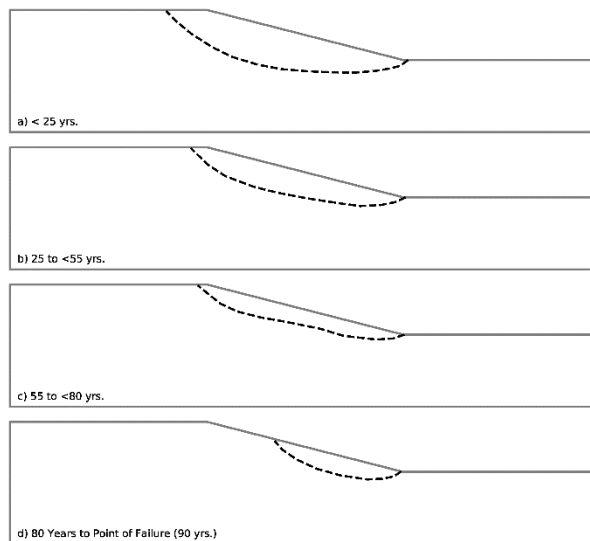


**Figure 5:** Critical failure surfaces in simulations of cut slopes after a) <25 years; b) 25 to < 50 years; c) 55 to <80 years and d) ≥ 80 years (from Postill *et al.*, 2021a). (Courtesy of 4.0 International (CC BY 4.0))

### 3. Implications for the design and assessment of cut slopes

Understanding of seasonal, downslope ratcheting has implications for the stability assessment of ageing slopes and the design of new slopes. Assessment of slope stability is conventionally undertaken using limit equilibrium analyses, with a consideration of critical failure mechanisms. For cut slopes, this assessment requires fully softened shear strength parameters for the analysis of deep-seated failures driven by pore water pressure dissipation (Skempton, 1984). The use of fully softened shear strength parameters was informed by the back-analyses of first-time failures in overconsolidated, high-plasticity clay, cut slopes by Chandler & Skempton (1974). However, Postill *et al.* (2021b) showed that the fully softened strength criteria used to assess deep-seated failures may be inappropriate for the assessment of slopes with post-peak shear strength (between the material's peak friction angle and residual friction angle).

Postill *et al.* (2021b) used hydro-mechanical simulations and limit equilibrium analyses to study shallow first-time failures in cut slopes for a range of slope geometries and for three material property scenarios. These scenarios considered idealised strength and stiffness properties for a high-plasticity clay (Sivakumar *et al.*, 2009) with low swelling potential. They were assigned different strain-softening curves (SSCs) for: (i) a low to intermediate-plasticity, overconsolidated clay (SSC A); (ii) a high-plasticity, overconsolidated clay with strength reduction from fully softened to residual (SSC B); and (iii) a more rapid strength reduction from fully softened to residual (SCC C). The operational failure of the slope was defined as the time (number of annual shrink-swell cycles) when uncontrolled displacements occurred. The average mobilised shear strength for the critical failure surface was calculated using Skempton's (1964) residual factor.

Postill *et al.*, (2021b showed that the number of cycles required to cause operational slope failure increased as the slope angle reduced towards the minimum friction angle of the clay. For a given slope angle, a steeper reduction in strength from fully softened to residual strength (*i.e.*, a steeper SSC) resulted in a shorter time to failure and a deeper failure surface. Postill *et al.*, (2021b) used the simulation results to produce an idealised framework for permissible slope geometries in strain-softening, high-plasticity, overconsolidated clays (Figure 6). This shows how a given slope geometry (slope height and angle) can be altered at the design stage to increase the operational life of a slope. For example, the slope angle of a 6 m high slope should be reduced from approximately 31° to 25° in order to double its design life from 60 years to 120 years.
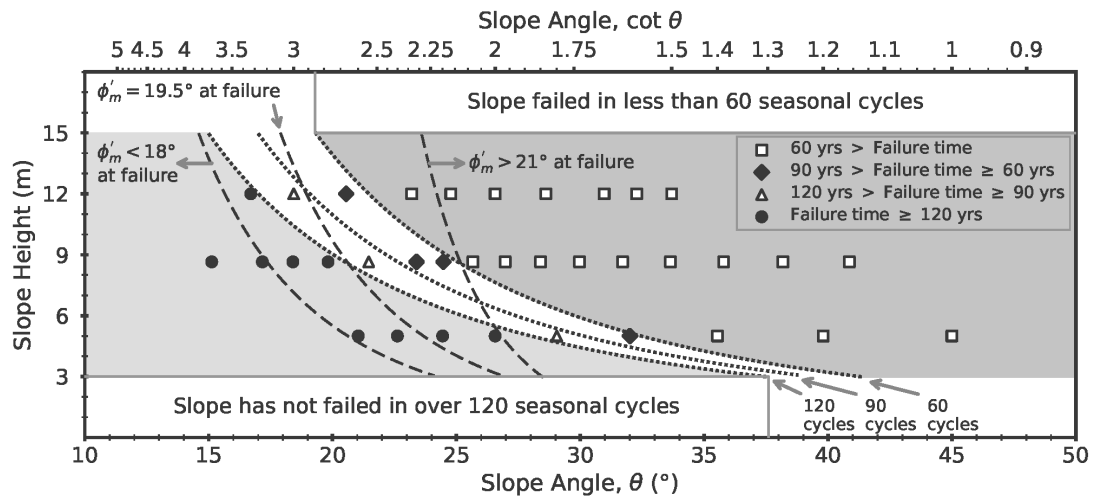


**Figure 6:** A framework for the number of cycles to failure in high-plasticity, strain-softening, clay cut slopes for varied slope geometries (from Postill *et al.*, 2021b). (Courtesy of 4.0 International (CC BY 4.0))

## 4. Conclusions

There is evidence of seasonal ratcheting, downslope displacements in monitoring data from high-plasticity cut slopes. They show upward and outward swelling of the slopes in response to increased pore water pressure during the winter months, followed by downward and slightly inward shrinkage during the drier summer months. The monitoring data do not show failure, but shallow downslope displacements have been described in failure records for cut slope failures that occurred more than 80 years after construction, when the likelihood of deep-seated failures in response to excess pore water pressure will have reduced.

A calibrated, hydro-mechanical model of a high-plasticity cut slope showed that a shallow translational failure mechanism, driven by seasonal ratcheting, became the dominant failure mechanism after construction induced swelling of the slope had ceased (at approximately 80 years). Over the operational life of similar cut slopes, this will result in a gradual transition from deep seated failures in their early life (up to 25 years) towards shallow translational failures in later years (>25 years). The simulations showed that irreversible, downslope, ratcheting displacements increased incrementally with each annual wetting and drying cycle, with particularly large displacement increments during periods of prolonged wet weather.

Seasonal, downslope ratcheting and strain-softening can be considered within traditional limit equilibrium slope stability analyses, that consider the number of annual pore water pressure cycles and the strain-softening behaviour of the slope material. For example, slopes with a shallow slope angle and material strength that

reduces rapidly from fully softened to residual (*i.e.*, typical of high-plasticity clay) have a high likelihood of ratcheting induced, shallow failure within their operational design life (*i.e.*, 120 years).

Seasonal ratcheting will become an increasingly dominant driver of shallow failures in high-plasticity cut slopes as their operational life extends beyond the initial period of excess pore water pressure dissipation. Therefore, the management of cut slopes that form geotechnical assets (*e.g.*, for highways and railways) should include assessment and monitoring regimes to detect seasonal slope displacements that may be precursors to failure.

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