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Deterioration models for geotechnical slopes: A systematic review on the long-term behaviour of earthwork assets

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Abstract

Deteriorating infrastructure slopes have significant implications for infrastructure management, as their performance and long-term behaviour can impact travel, costs, safety, and operational efficiency. Understanding the long-term behaviour and performance of geotechnical assets is crucial for effective asset management and proactive maintenance. This systematic review examines existing research on deterioration models to identify methodologies, monitoring techniques, and data collection approaches employed to analyse the behaviour of geotechnical assets over time. The review emphasizes the importance of understanding asset deterioration mechanisms, particularly those influenced by weathering, and their impact on the overall performance and long-term behaviour of geotechnical assets. By consolidating knowledge from the scientific literature, this study highlights the limited availability of comprehensive deterioration models for earthwork slopes but identifies a growing interest in studying factors and mechanisms that contribute to understanding long-term asset behaviour. The review underscores the significance of monitoring, instrumentation, and data collection to enhance our understanding of geotechnical asset deterioration and improve predictive capabilities. Additionally, a proposed framework is introduced for long-term analysis of geotechnical assets, advocating combining lab and field tests for precise soil characterization and developing deterioration models. This systematic review deepens the understanding of asset deterioration mechanisms and aids in decision-making for infrastructure resilience.

Keywords: Deterioration mechanisms; Geotechnical Asset; Performance; Long-term behaviour; Earthwork Slope; Deterioration Model; Embankment; Cut slope

1. Introduction

Deteriorating infrastructure slopes disrupt travel, increase costs, pose safety risks, and hinder operational efficiency. These consequences can lead to inconveniences for commuters, financial burdens for infrastructure budgets, and potential hazards to public safety and surrounding structures. To improve asset management, it is essential to comprehend the deterioration processes that cause failure and damage (Stirling et al., 2021). Insufficient understanding of the long-term behaviour, performance, and deterioration of geotechnical slopes can result in uncontrolled deformations, reduced service performance, negative economic impacts, and, in extreme cases, fatalities (Svalova et al., 2021). Infrastructure asset management involves predicting the performance and remaining service life of assets under different operating conditions. This necessitates deterioration modelling, which focuses on geotechnical assets like embankments and cut slopes in the present investigation. However, accurately modelling the effectiveness of maintenance for these assets, as well as other earthwork slopes, is challenging due to the often-unknown conditions before and after maintenance activities (Lin et al., 2019).

The engineering community normally has well-established methods for managing geotechnical hazards to transportation infrastructure. Geotechnical asset management goes beyond these processes by including constructed geotechnical assets in addition to natural hazards in the inventory, developing deterioration models specifically for geotechnical assets, using these models in conjunction with unit cost estimates to forecast future risk levels and funding requirements, and determining the best timing and cost-benefit ratio of interventions (Tappenden & Skirrow, 2020). The ageing infrastructure is an issue for rail network owners, operators, and asset managers (Power et al., 2016).

The objective of managing geotechnical assets is to minimize life-cycle costs associated with the construction and maintenance of these assets on a system-wide level. Highway embankments and cut slopes often experience recurring slope failures, which present substantial risks such as pavement damage, compromised safety features like guardrails, blockage of drainage channels, and potential structural damage to bridges and other infrastructure due to ground support loss or increased loads resulting from soil and rock sliding (Sanford Bernhardt et al., 2003).

The deterioration of slope stability, particularly the degradation of slope performance over extended periods, is predominantly influenced by weathering. This includes the cumulative impact of long-term physical, chemical, and biological weathering cycles (Xiong & Huang, 2022). The primary meteorological mechanism affecting slopes is the changes in effective stress caused by water infiltration and extraction. Seasonal and cyclic variations in pore water pressures can result in volumetric changes, such as swelling during saturation and shrinking during drying. These cycles can lead to irreversible deformations, strain softening, and ultimately slope failure (Rouainia et al., 2020). While the scientific literature on the topic may be limited, significant attention has been given by deterioration models to the mechanisms and relevant factors that impact the long-term performance and serviceability of geotechnical assets (Hu et al., 2020; Postill et al., 2021b; She et al., 2019; Stirling et al., 2017a).

Deterioration models play a crucial role in asset management by providing valuable insights into the long-term behaviour and performance of earthwork slopes (Postill et al., 2021b). These models are essential for identifying risks, prioritizing maintenance tasks, and ensuring the safety and stability of infrastructure networks. Accurate deterioration models enable proactive planning and timely interventions, resulting in cost savings, reduced disruptions, and enhanced overall infrastructure resilience (Bai et al., 2022). While there is existing knowledge and a growing body of literature in this field, there are still limitations and gaps that need attention (Stirling et al., 2017a). A comprehensive review of the available literature was considered necessary to consolidate knowledge and effectively address these research gaps. The present investigation focuses on studying these mechanisms and conducting a comprehensive review of the available deterioration models described in the scientific literature to analyse the long-term behaviour of geotechnical assets.

2. Methods

2.1 Research questions

The purpose of this systematic review was to identify research on the development of deterioration models for geotechnical assets used in predicting the long-term behaviour of cut slopes and embankments. This study aims to enhance understanding by identifying various models, instruments, monitored variables and collected data relevant to the deterioration modelling of earthwork slopes worldwide. The study followed the PRISMA protocol (Moher et al., 2009) with some flexibility. The research questions addressed in this study are:

- What deterioration models of geotechnical slopes have been published?
- How was the long-term behaviour of geotechnical assets studied?
- How were cut slopes and embankments monitored and instrumented?
- What data was collected to calibrate the models or describe the deterioration mechanisms?
- Which variables and deterioration mechanisms were studied?

2.2 Search strategy

In this study, the collected articles were reviewed to determine their suitability for inclusion in the literature review. Every research paper was analysed based on the research questions defined, and a quality appraisal was conducted to analyse the methods or approaches used for modelling the deterioration of geotechnical assets, the variables employed, and their overall relevance to this systematic research.

This systematic review compiles data from the well-known research database Scopus. Several publishers were utilized to gather information, such as Springer, Elsevier, John Wiley and Sons Ltd, ICE Publishing, MDPI, and Cambridge University Press. The search was performed using a combination of specific key terms (search document) within the article title, abstract, and keywords.

The systematic review included research articles that met specific inclusion criteria: original research studying and/or modelling the deterioration of earthwork slopes, or research related to the development of deterioration models for other slope types to gain insights and learn from their methods. Exclusion criteria comprised non-English papers and subjects unrelated to engineering, earth and planetary sciences, or environmental science. Additionally, documents that did not focus on the deterioration of earthwork slopes were excluded.

2.3 Data collection and extraction

The execution of the query in the Scopus database yielded 277 documents. The articles were initially classified based on their applicability (considering the title and abstract), using the following categories: "Applicable," "Not applicable," "Unknown," "Possibly applicable," "Repeated," and "Unknown, but possibly applicable." Based on this classification, articles applicable were selected for inclusion in the study, while the others were excluded. Articles that were initially categorized as "Unknown" or "Possibly applicable" during the first review could be reconsidered for inclusion in the analysis after a more detailed examination only when a decision was made to change their category to "Applicable." A total of 41 papers advanced to the next stage, in which the full article was analysed.

The data extracted from each research paper was based on a form that was designed considering the research questions. After studying the full research articles a decision to exclude 4 additional documents was made because of their lack of relevance related to the research questions (not studying deterioration models for earthwork slopes).

The present research considered additional research papers cited within the same documents found and those obtained in different databases (e.g., Google Scholar, Swedish Geotechnical Institute - SGI), but their content was used uniquely to improve the discussion and not for the scientific mapping, scientometric analysis and statistical representation, of the selected documents, and the research questions addressed in the form that was filled. In general, those citations or additional documents (from other databases) were not new deterioration models for earthwork slopes, but related reports or papers studying a specific variable, instrumentation, procedures, or field/laboratory test with supporting information.

3. Data analysis

Figure 1 shows the distribution of the articles according to the document type. The final 37 documents selected included twenty-six articles, one book chapter and ten conference papers. A relatively low number of literature contributions was expected, given that the development of deterioration models for earthwork slopes is not extensively researched worldwide. Figure 2 displays the countries where the research studies were carried out. Documents related to deterioration models for embankments or cut slopes were found in only eight different countries. The top three nations with the greater number of documents are the United Kingdom (UK), with almost half of the papers (18 documents), China (6 documents) and Japan (4 documents). The rest of the countries (Croatia, Hong Kong, Sweden, and Spain) have less than three documents, except for India (with 3 documents).

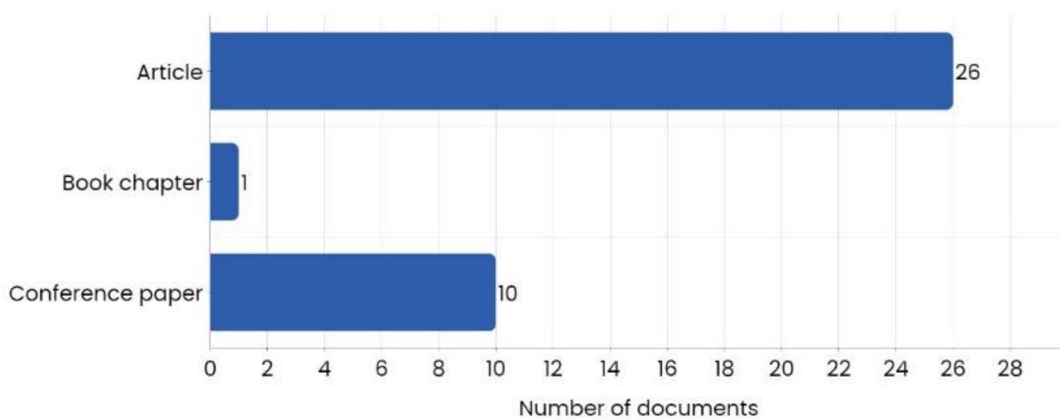

Figure 1. Number of documents for each document type.

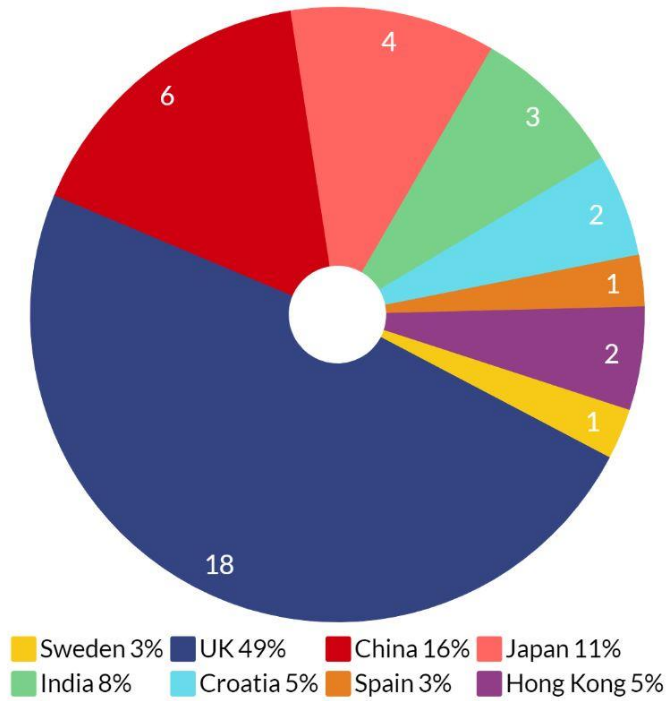

Figure 2. Number of documents for each country.

Figure 3 illustrates the number of documents published within a particular time frame. The first document was published in 1995, and between those 7- or 8-year periods, there is an increase in the number of published documents. There is also a broad difference between the last range of years (2017-2023), with 24 documents (65%), and the rest of the range of years. Between 2015 and 2023, 30 documents (81%) were published (search on March 23, 2023). Figure 4 depicts the graphical illustration (mapping network) of keywords co-occurrence. It represents the frequency of these keywords in the literature selected (37 documents) and the average number of citations of each keyword. It was elaborated with VOSviewer 1.6.19, using the full counting method (it means that each co-occurrence has the same weight), showing keywords with at least two occurrences.

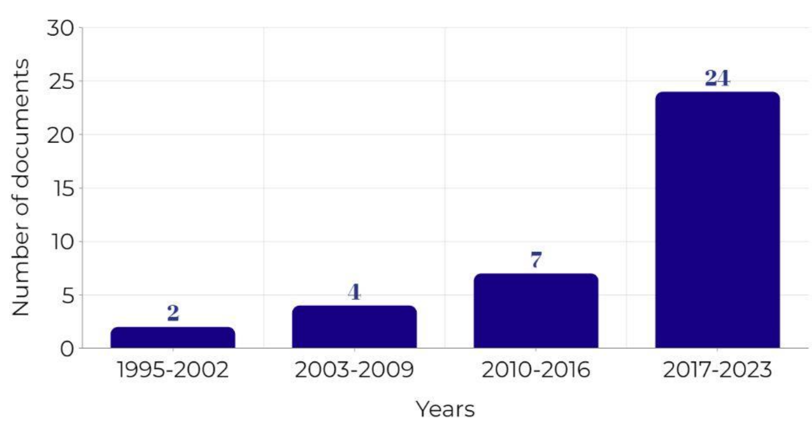

Figure 3. Distribution of documents by year of publication.

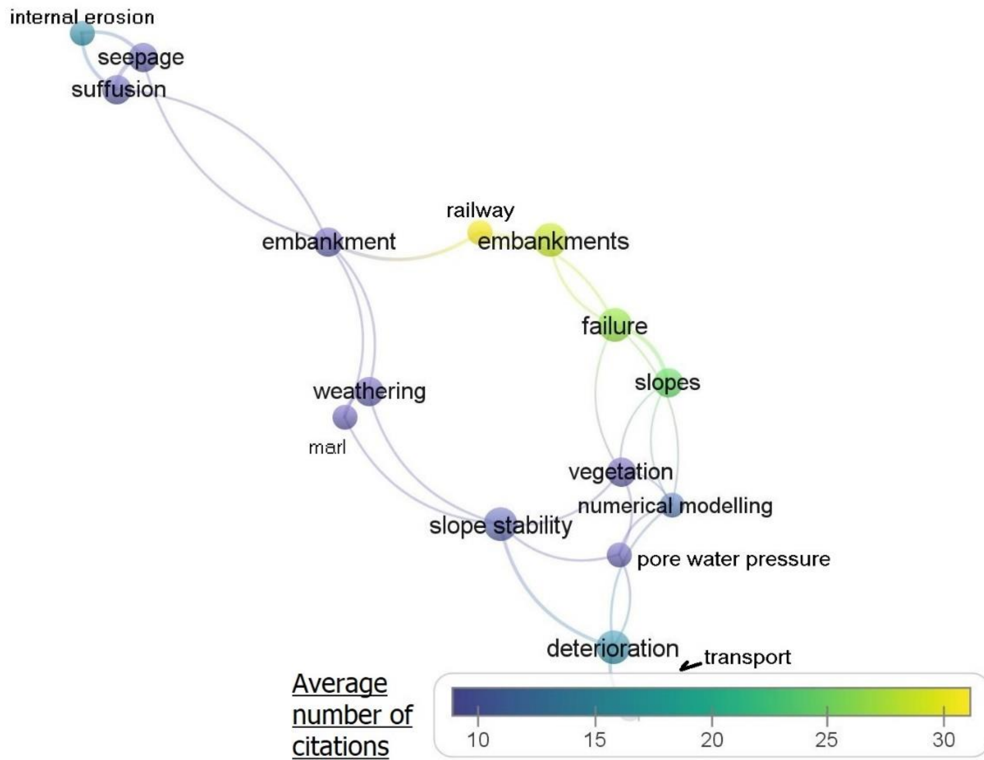

Figure 4. Co-occurrence keywords represented using a mapping network.

The keyword "Deterioration" appeared only four times with four associated links. The preferred keyword related to "model" was "Numerical modelling" with two occurrences. However, the specific keyword "Deterioration model" was not used in any of the 37 documents, except for one instance where it appeared as part of the keyword "Time-dependency deterioration model." Among the selected documents, ten included the term "model" in keywords such as "Physical modelling," "Physical model tests," and "Finite element model." Three of these occurrences also included the term "deterioration" as part of another keyword. This suggests that the research papers found generally do not focus explicitly on presenting deterioration models for earthwork slope, indicating a scarcity of research in this specific area.

4. Modelling deterioration of earthwork slopes

4.1 National and regional projects

Figure 5 shows a summary of the information extracted (and filled in a form) from studying the 37 documents selected. Among them, seventeen (45.9%) were identified as part of a national (or regional) project. There is a well-documented national project in the United Kingdom named iSMART (infrastructure Slopes: Sustainable Management And Resilience Assessment, 2013-2017), which was continued later with the project Achilles, and 13 of these documents are from these projects. The primary objective of the iSMART project was to enhance comprehension regarding the alterations in the state of geotechnical assets. Glendinning et al. (2015) presented the progress of the first 2 years of the iSMART project.

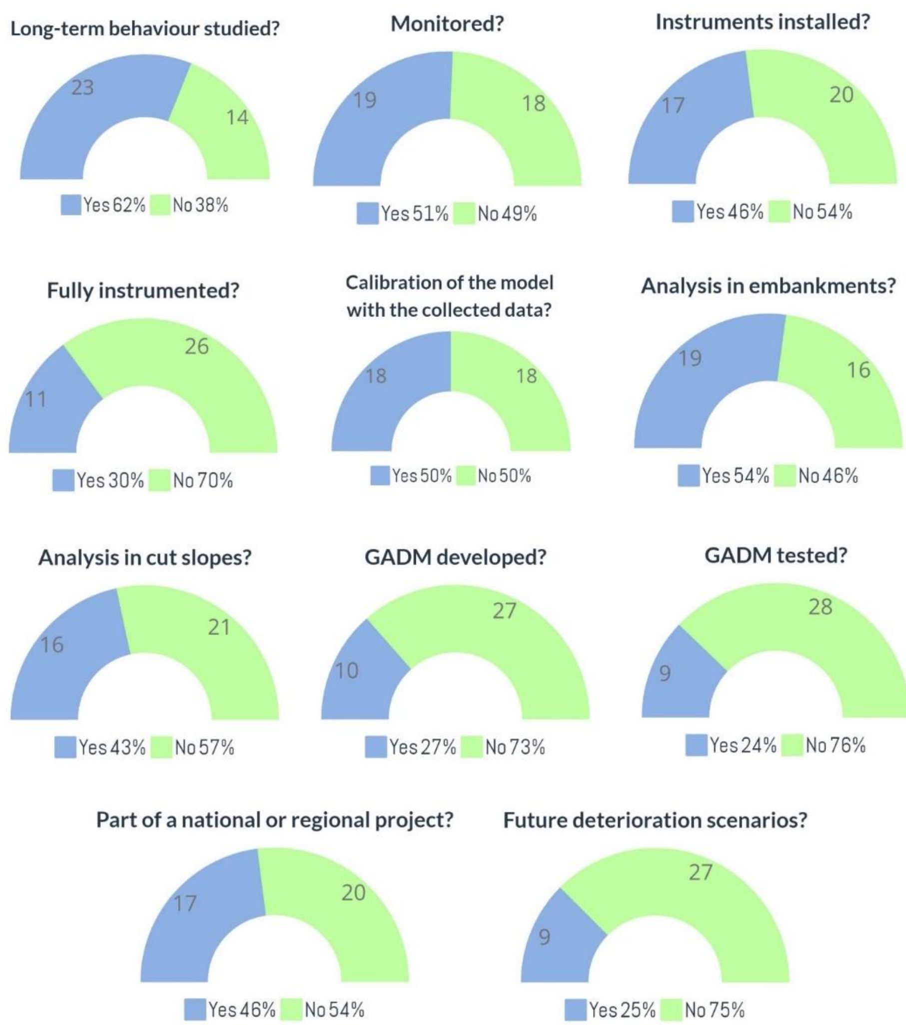

Figure 5. Summary of the Yes/No answers from the form filled when studying the selected documents.

ACHILLES (Assessment, Costing and enHancement of long lIfe, Long Linear assEtS) is a project that concentrates on geotechnical elements related to long linear assets (e.g. road/railway embankments and cut slopes, and flood defence structures). They aim to ensure that the UK's infrastructure provides reliable, cost-effective, and secure services, aided by intelligent planning, control, and maintenance. The project's key research objectives include examining deterioration processes, the performance of geotechnical assets, and developing predictive models (forecast) and decision-making tools. Powrie & Smethurst (2019) described ACHILLES, which was initiated in July 2018, as a continuation of iSMART to improve the deterioration models, failure, and climate change effects on geotechnical assets, earthworks, and other long linear infrastructure.

In 2018, a research study was conducted by AECOM in the UK, commissioned by Network Rail. It was described by Kite et al. (2020). The study investigated the use of track geometry data in identifying instabilities in embankments. In Hong Kong, Cheung & Tang (2005a, 2005b) presented a reliability model to enhance the precision of predicting the number of slope failures in Hong Kong based on rainfall forecasts, along with a procedure developed to create a probabilistic model of slope deterioration. It considers factors that are challenging to analyse in current slope reliability assessments, such as age, maintenance frequency and quality, and other relevant factors.

Finally, Hansson et al., (2005) published research conducted as part of the Swedish National Road Administration's goal to create a numerical model of the deterioration of roads that can be used to improve the construction and maintenance of their road network (Sweden). The rest (20) of the documents reviewed (54%) were not identified as part of a national project.

4.2 Long-term geotechnical behaviour of earthwork slopes

Twenty-three (62%) of the documents studied the long-term behaviour of geotechnical assets. The monitoring of geotechnical earthworks was reported in 51% of the documents, while 46% utilized on-site instruments (Fig. 5). An earthwork was deemed fully instrumented when multiple variables were measured using distinct sensors/instruments installed at the site (at least three). In instances where documents provided information (or references within) indicating that the site was fully instrumented, they were counted as such, even if the document primarily focused on a specific variable.

Specifically, among the documents in which the long-term behaviour of earthwork slopes was studied, less than 40% of them presented fully instrumented geotechnical assets. This is considered a very low quantity due to the relevance in safety and economic impact on road and railway networks worldwide. It shows again that the long-term behaviour of earthwork slopes is still a research topic with scarce global knowledge that deserves deep study.

Justo & Durand (2000) identified creep settlements as the primary factor behind road pavement deterioration, also studying the impervious components of dams. They put forth viscoelastic rheological models for both dams and road embankments, examining the time-dependent settlement behaviour of (granular) embankments. These models enable the estimation of the waiting period necessary before paving a road embankment so that the remaining settlement conforms to acceptable limits.

Cheung & Tang (2005a) used rainfall measurements from 1984 to 2002 to study the reliability of slopes under different rainfall characteristics. They divided Hong Kong into a grid of 1600 cells (1.5 km x 1.2 km). To model the impact of deterioration on the likelihood of slope failure with time, probabilistic models were employed, using around 20,000 aged cut slopes dispersed across the region as a representative population. The analysis was extended to predict the probability of slope failure over diverse future service periods. Cheung & Tang (2005b) systematically examined the performance of comparable geotechnical slopes in Hong Kong, by assessing the likelihood (probability) of cut slope failure for varying age groups and expected service periods.

Glendinning et al. (2015), Spink (2020) and Briggs et al. (2019) illustrated the long-term behaviour of geotechnical assets with a dependence on the performance on time (age of the asset), as presented in Figure 6 (following Thurlby, 2013). This performance curve offers a valuable means of estimating the effectiveness of geotechnical assets across their lifespan, while also providing insights into the mechanisms driving asset deterioration. By utilizing this curve, it is possible to predict the timing and pace of future deterioration, and plan appropriate interventions aimed at mitigating such deterioration and preserving or enhancing asset performance (Briggs et al., 2019). The performance curve is comprised of four major stages, starting with a bedding-in period marked by significant improvements in performance, followed by a phase of stable and reliable performance throughout the asset's lifespan. The third phase (degenerating) is characterized by deterioration and/or maintenance work aimed at improving performance, culminating in a final stage (unreliable) where the geotechnical asset fails, becomes unreliable, or reaches the end of its useful life (Briggs et al., 2019).

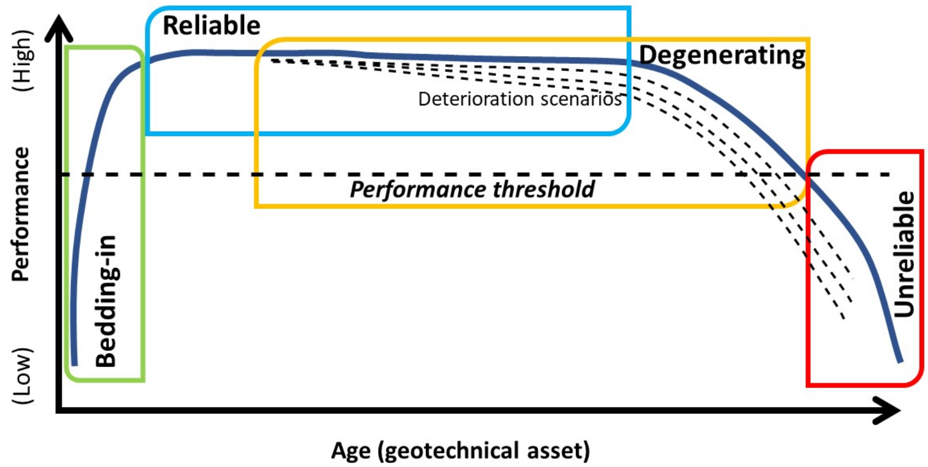

Figure 6. Performance curve of geotechnical assets (following Thurlby, 2013).

Research articles derived from the projects iSMART and Achilles were based on this framework. For example, Stirling et al. (2017b) examined how weather-induced deterioration processes affect the long-term performance of infrastructure earthworks. A fully monitored embankment was constructed as part of a project (BIONICS, 2004-2009) in which this full-scale geotechnical asset was intended to represent the UK's infrastructure, leading to the creation of a very helpful database of performance. Stirling et al. (2017b) used that data (monitored data and experiments conducted in the laboratory and field) and showed that seasonal processes, such as desiccation, can cause significant changes in soil-water retention behaviour. Stirling et al. (2017a) used collected data on the same embankment to investigate the desiccation mechanisms and the subsequent initiation and propagation of cracks. A more detailed analysis (same embankment) was presented by Stirling et al. (2021), using data monitored from 2009-2015 for suctions and from 2015-2016 for crack displacements.

Dixon et al. (2019) conducted a study on six fully instrumented geotechnical assets (including the BIONICS embankment mentioned above), comprising three embankments and three cut slopes, in the UK (iSMART project). They analysed the spatial and temporal variability factors affecting hydraulic conductivity, using in situ measurements (143 different measurements on the 6 geotechnical assets).

Gunn et al. (2015, 2016) provided three examples (three embankments in the UK) to illustrate how continuous surface wave (CSW) and multichannel analysis of surface wave (MASW) methods can be applied to evaluate the internal condition of ageing embankments, highlighting both the advantages and drawbacks of these techniques. Gunn et al. (2018) described a study that used a combination of rapid cone penetration and non-invasive geophysical methods (CSW, MASW and electrical resistivity tomography, ERT) to investigate the three-dimensional and temporal changes occurring in an end-tipped embankment.

Smethurst et al. (2022) presented and characterized significant findings obtained from long-term field measurements (soil moisture and pore water pressure) at a cut slope in Newbury, UK (iSMART and Achilles projects). The observations from the site have been utilized to calibrate suitable models of seasonal cycles of pore water pressure and slope deterioration. A period of 17 years (2002-2020) of monitoring data was essential to comprehend the long-term deterioration and performance of clay cut slopes, as well as to assess the impact of various factors such as weather, climate change, and vegetation. Postill et al. (2021b) utilized the same monitoring data to verify the simulation outcomes of a model developed by them. They showed that the model can reproduce the field-measured response, specifically of soil moisture and pore water pressure, during both short and long wet and dry seasons.

Miščević & Vlastelica (2019) presented research in which the settlement of an embankment constructed using compacted marl aggregates in Split (Croatia) was measured 5 years after the construction phase, during which it was monitored. They argued that soft rock materials used in embankment construction can undergo grain deterioration leading to additional settlement, particularly in the case of marl grains which primarily experience weathering due to wetting and drying. This can pose a risk to the stability and integrity of the embankment due to the breakage and decomposition of the grains.

Bao et al. (2022) quantified the erosion deterioration of three cut slopes using a method based on LiDAR data (Li et al., 2020). Two of them were protected by ecological materials: polypropylene fibre and guar gum. By incorporating the deterioration of the material mechanical properties due to rainfall, a model was developed to evaluate the long-term performance of protection materials that are prone to time-dependent deterioration. Erosion of the blank test slope (without protection material) was also measured. The study period, which included 7 scans of the slope surfaces, was from August 2018 to September 2019, during which measurements of rainfall and LiDAR data were taken.

4.3 Measured variables and instrumentation

As part of the study, a form was filled out to gather information on the deterioration models and research advancements presented in the selected documents. One of the questions included in the form concerned the number and type of variables studied in each document. Although it was not possible to determine the exact number of variables considered in each research paper, the most relevant and clear variables were annotated. The answers related to variables were not included in Figure 5 due to the difficulty to determine the number of variables or to extract an exact list of the variables studied. Additionally, the form did not inquire about the specific instruments used to measure variables but rather asked if instruments were installed or used in the research, and whether the geotechnical assets were fully instrumented with at least three variables measured.

This section will present information on the main variables considered in the deterioration models for earthwork slopes, as well as the relevant instruments used to measure these variables. It will also include information from additional research articles that were not part of the selected documents for this systematic review.

Different authors have grouped or listed the factors and variables influencing the deterioration of earthwork slopes (Apriyono et al., 2022; Briggs et al., 2019; Corker-Knott, 2021). Briggs et al. (2019) summarized the factors influencing the deterioration of embankments as loading factors (e.g., pore water pressure cycles), intrinsic features (e.g., geometry, material, and age), and soil factors (e.g., crack initiation, disaggregation, or strain-softening after changes in soil moisture and pore water pressures).

Corker-Knott (2021) considered that the main causes of slope failure are erosion, weathering, and settlement caused by variations in loading or fluctuations in groundwater. Failure may also result from exceptional events like earthquakes, poorly prepared excavations, or even vandalism. Typically, the decline of a geotechnical asset from good to poor condition is a gradual process, as depicted in Figure 6 (the performance curve), and the rate of deterioration is influenced by various factors. To develop a risk assessment tool, they conducted a literature review on the impact factors that can influence the performance, serviceability, stability, or safety of an asset. The literature review focused on identifying the key elements associated with each factor and ultimately identified 11 critical impact factors that were selected (included) in the risk assessment tool. Figure 7 shows the critical impact factors defined by Corker-Knott (2021).

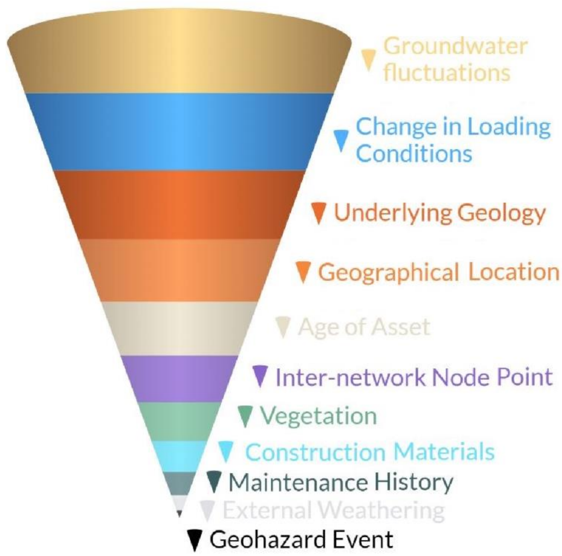

Figure 7. Critical impact factors for risk assessment tool of geotechnical assets (Corker-Knott, 2021).

Argyroudis et al. (2019) proposed a methodological framework for creating fragility functions that consider multiple hazards for assets. They described the impacts of geotechnical hazards and other hydraulic conditions on infrastructure assets such as embankments and cuttings (Figure 8). Apriyono et al. (2022) published a comprehensive review analysing the serviceability of embankments and cut slopes subjected to seasonal climate fluctuations. Their findings indicated that prolonged exposure to wet and dry cycles can significantly impact the long-term performance of these slopes, leading to deformation that can compromise their safety and overall serviceability, posing significant challenges for the associated infrastructure.

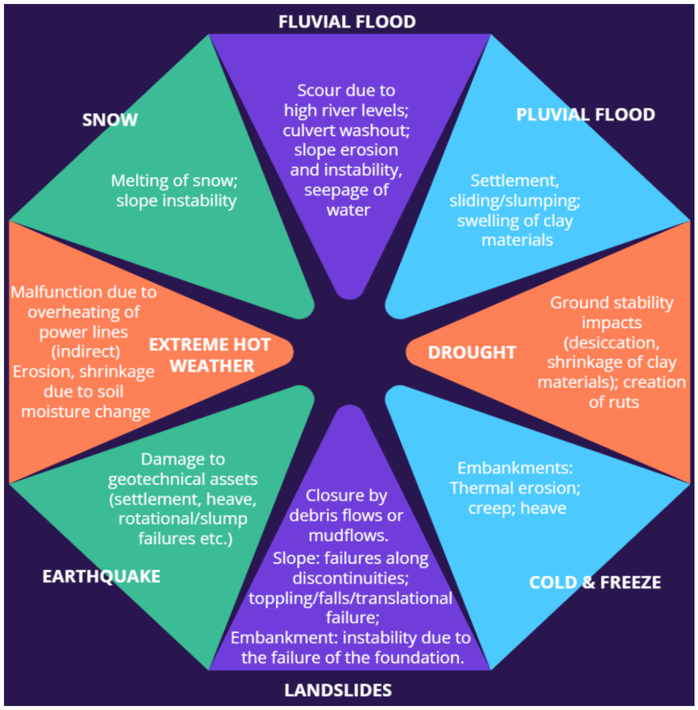

Figure 8. Effects of geotechnical hazards and critical hydraulic conditions on cut slopes and embankments (Argyroudis et al., 2019).

Apriyono et al. (2022) found that embankments and cut slopes exhibit varying responses to seasonal influences. The cut slope displays a greater capacity for retaining pore water pressure during a wet season, owing to its lower permeability compared to the embankment, as dictated by its construction history. Nevertheless, the consolidation process following excavation tends to raise pore water pressure and displacement in the cut slope, requiring more time to reach equilibrium. Additionally, an increased displacement in the cut slope could potentially increase the chances of a delayed failure occurring in the future.

It is also well known that different types of soil deteriorate in distinct manners when subjected to cycles of wetting and drying (Briggs et al., 2019; Stirling et al., 2017a). Permeability and vegetation also play a significant role in the pore water pressure response (Loveridge et al., 2010; Walker et al., 2022). Smethurst et al. (2017) investigated the use of instrumentation and monitoring techniques for infrastructure slopes. They explored the motivations behind slope monitoring, the standard instruments used, the parameters measured, and advances in technology. They suggested parameters that could be measured and monitored for different applications such as monitoring: slope conditions, design of corrective schemes, early warning systems, risk management of long linear assets, research, and development of new instruments. The most measured variables, instruments and their importance are illustrated in Figure 9.

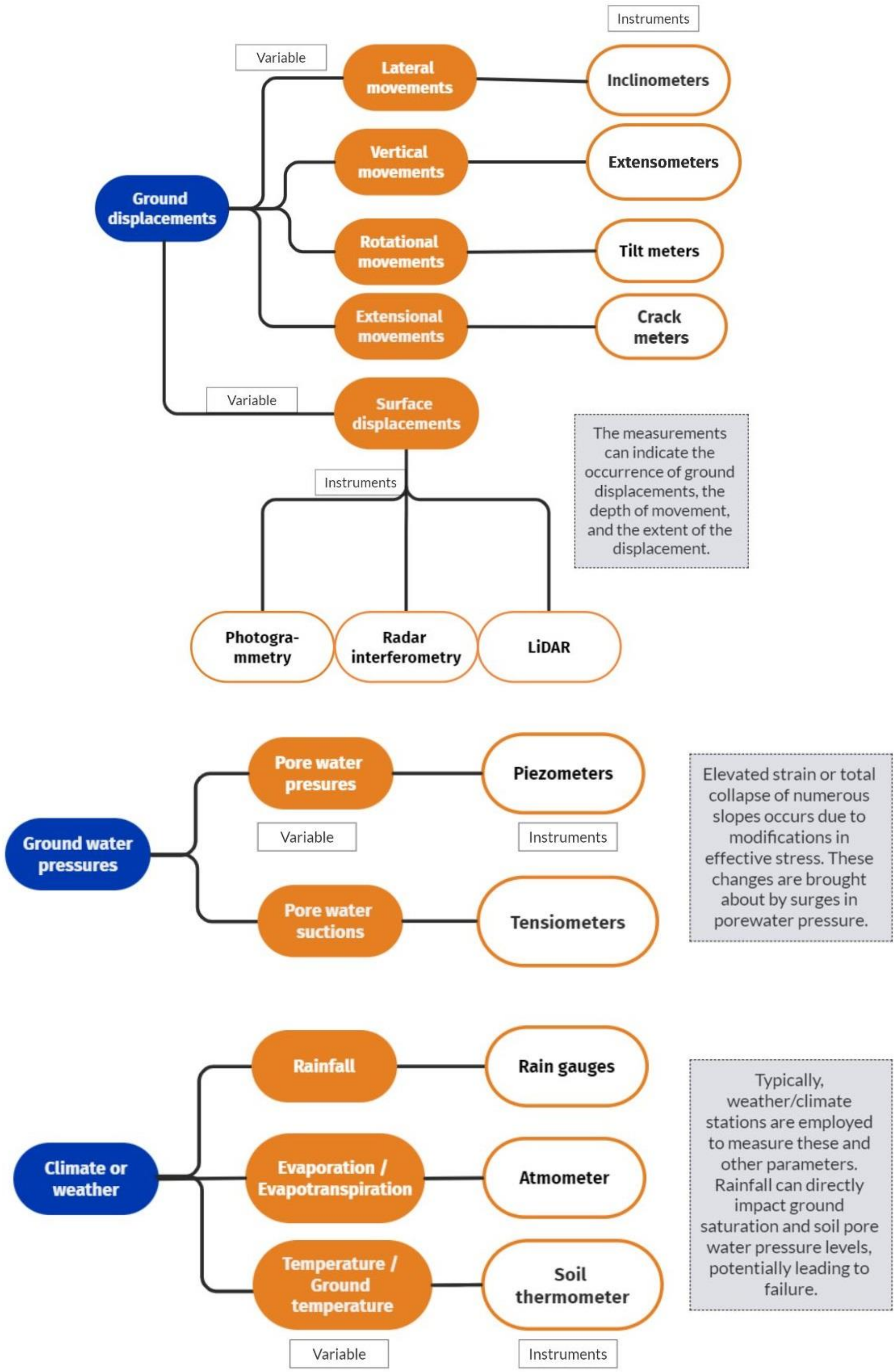

Figure 9. Variables commonly measured in geotechnical slope, according to Smethurst et al. (2017).

Glendinning et al. (2015) described the long-term monitoring program used in the iSMART project. Due to the exceptionally long lifetimes of earthworks assets, comprehensive knowledge of their behaviour can only be acquired through prolonged monitoring programs. To calibrate numerical models that capture the behaviour of entire slopes, long-term datasets from 3 embankments and 3 cut slopes were utilized. Field experiments and laboratory tests were carried out to obtain parameters for the numerical models and validate them. They reported measurements of the following factors and variables in their sites (Figure 10).

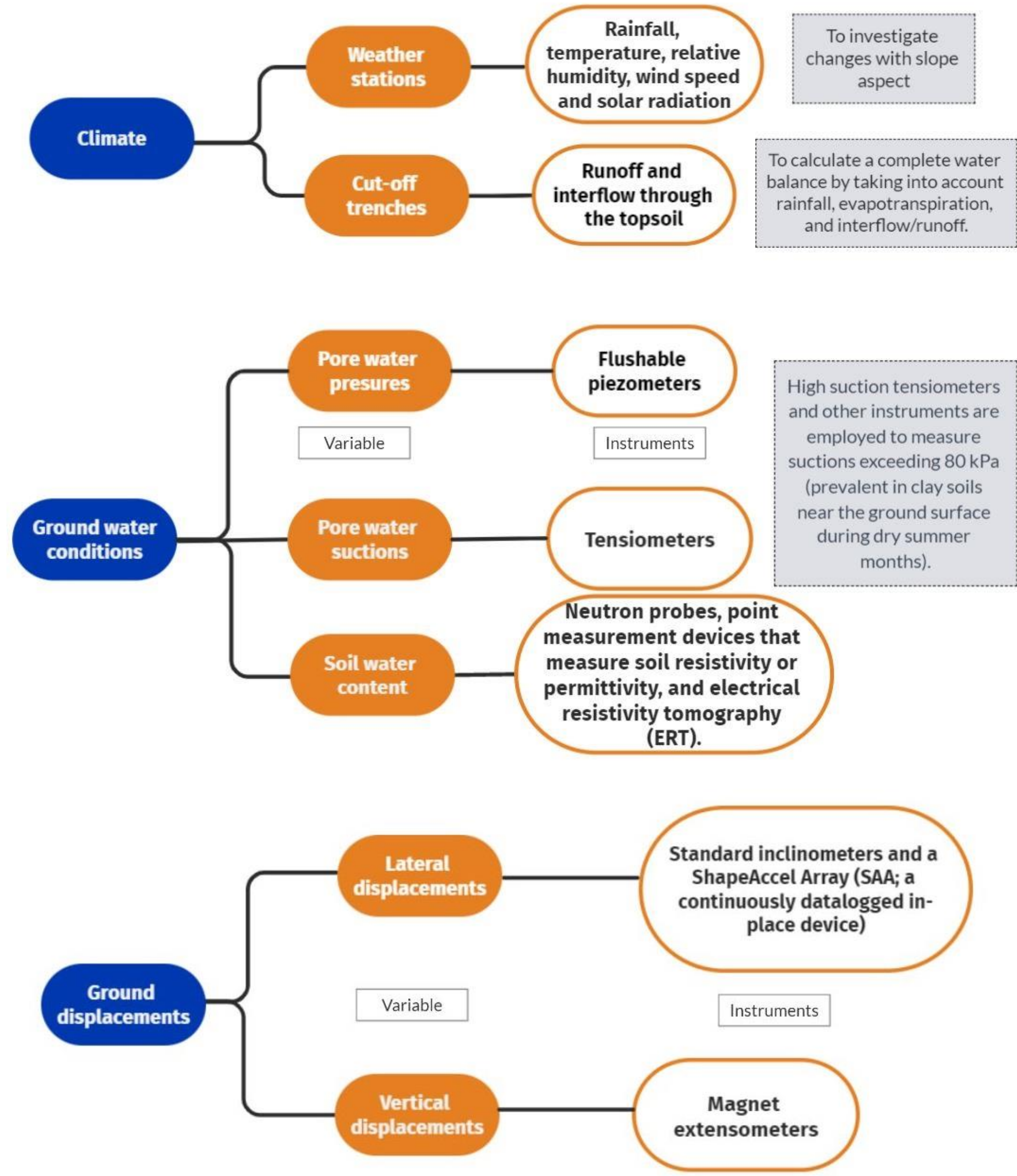

Figure 10. Variables measured in the sites studied in the iSMART project, reported by Glendinning et al. (2015).

4.4 Deterioration models to predict the long-term behaviour of earthwork slopes

It was found that only in ten (27%) of the selected documents (Figure 5) a geotechnical asset deterioration model was developed. Of them, 8 were part of the projects iSMART or Achilles. Glendinning et al. (2015) provided a clear outline of the main objectives of numerical modelling within the iSMART framework. These objectives involve improving and validating numerical models of slopes, gaining insights into climate-related factors that lead to slope failure, and devising adaptation strategies and monitoring protocols to effectively prevent slope failure and ensure the safety of geotechnical assets. In the final report of the project, Glendinning et al. (2018) described the goal of modelling the strain-softening behaviour of soil and capturing progressive failure, influenced by both weather conditions and the effects of vegetation on the surface boundary. Four modelling approaches investigated the geotechnical earthwork behaviour using a two-phase flow. Three coupled hydromechanical models and a hydrological (VADOSE/SEEP) model were used (boundaries used in parentheses):

- SHETRAN/FLAC (Weather-vegetation-soil).
- FLAC (Discharge boundary-soil).
- Water balance/FLAC (Discharge boundary).
- VADOSE/SEEP (Weather-vegetation-soil, no stress).

Postill et al. (2020) developed a numerical model to study seasonal ratcheting in high-plasticity clay slopes under wetting and drying stress cycles. The model incorporated unsaturated behaviour and a non-local strain-softening regulatory approach, and its accuracy was validated against physical experiments. It considered mechanical behaviour using Bishop's generalized effective stress and hydrogeological behaviour through descriptors like matric suction and saturation. A Mohr-Coulomb strain-softening constitutive model was used to capture post-peak strain softening and progressive failure. Material parameters (Kaolin) were derived from literature and calibrated with triaxial tests. Kaolin is commonly used in soil behaviour studies and physical model tests, although it does not fully replicate natural soil properties. Its classification as a high-plasticity clay (CH) makes it suitable for studying cohesive soils (Chian & Bi, 2021; Knodel et al., 1992). The model successfully replicated seasonal ratcheting and progressive failure observed in physical behaviour, representing a significant advancement in understanding, and validating these phenomena.

This research was extended by Postill et al. (2021b) by presenting an innovative approach to model the long-term deterioration of high-plasticity clay cut slopes subjected to seasonal stress cycles. The hydrogeological behaviour was validated using field measurements, and laboratory tests were conducted to assess the mechanical behaviour. While the slope modelling approach presented by Postill et al. (2020) was validated for replicating displacements caused by surface water flux, this research specifically focuses on strain softening as the main mechanism of deterioration, considering the dissipation of negative excess water pressures and stress cycles driven by annual weather conditions.

To simulate the deterioration, a two-phase flow numerical procedure was employed by Postill et al., (2021b), allowing for the simultaneous modelling of saturated and unsaturated processes. The FLAC-TP (Fast Lagrangian Analysis of Continua with Two-Phase Flow) software was utilized and modified to incorporate user-specified algorithms. The modelling approach included the Mohr-Coulomb strength envelope to represent soil strength, considering peak, post-peak, and large displacement residual strength properties. The non-local strain softening model was adopted, incorporating an internal length parameter controlling the distance at which neighbouring strains impact strain calculations, influencing the softening rate after plastic strains occur. The research provides valuable insights into the long-term behaviour of high-plasticity clay slopes and contributes to the understanding of their progressive failure under seasonal stress cycles.

Postill et al. (2021a) also used the numerical modelling approach published previously (Postill et al., 2020) to explore how the mechanism of seasonal ratcheting and progressive failure affects engineered clay cut slopes. They examined the impact of slope geometry and strain-softening behaviour on seasonal ratcheting, using numerical analyses with different geometries and strain-softening relationships. They found that cut slopes made of high-plasticity clays with shrink-swell potential, at angles greater than the residual friction angle of the material, can experience seasonal ratcheting caused by weather-driven pore pressure cycles, which can lead to shallow first-time progressive failure.

Rouainia et al. (2020) modelled the failure of a cut slope by accounting for changes in pore water pressure caused by weather fluctuations. The study examined a high-plasticity clay slope and found that the annual magnitude of pore pressure fluctuations played a significant role in determining the rate of progressive failure. Additionally, future climate scenarios were found to result in higher rates of softening compared to control scenarios. The hydrological model used in the study could simulate a wide range of processes affecting slope pore water pressures, and it allowed for the simulation of temporal deformations of a slope over extended periods in response to weather and climate. To generate rainfall and potential evapotranspiration time series data representative of control and future climates, the UK Climate Projections 2009 (UKCP09) weather generator (Defra, 2009) was used. The SHETRAN slope model (Ewen et al., 2000) was then employed to apply these data as boundary conditions. The study confirmed the model's capacity to capture meteorologically driven changes in pore pressure in a slope.

Svalova et al. (2021) developed a geotechnical model for simulating deterioration in cut slopes using FLAC-TP software, which considers the effect of weather and climate using a coupled fluid-mechanical approach. The model represents soil as a porous medium with variable saturation and depth-dependent permeability. To predict the time to failure, the authors employed a Gaussian processes emulator (GPE) and designed an optimally space-filling experiment using Latin hypercube sampling. The Bayesian Gaussian process emulation was then used to produce time-to-failure maps that show the correlation between slope geometry and failure probability. Compared to the geotechnical model, the emulator significantly reduces computational expense, making it a more attractive tool for real-time assessment of slope stability and deterioration.

Stirling et al. (2017b) investigated the impact of seasonal processes on the soil-water retention characteristics and its effect on infrastructure stability. As previously mentioned, they used a combination of full-scale testing, at the BIONICS embankment, and laboratory testing to identify key factors, such as desiccation cracking, vegetation, and cycles of evapotranspiration-recharge, that contribute to changes in soil-water retention behaviour. They used a coupled hydrological-mechanical model to evaluate the sensitivity of suction generation and demonstrate the implications of cyclic variability on slope stability. Within this model, they utilized the van Genuchten-Mualem constitutive model (van Genuchten, 1980) implemented in PLAXIS to simulate the suction-water content-unsaturated conductivity behaviour. They highlighted the importance of accurately modelling these deterioration processes to fully understand the impact of changing climate on infrastructure stability.

Stirling et al. (2021) extended this work and proposed a new mechanism for soil deterioration caused by cyclic wetting and drying, using the laboratory and field experiments data collected on the BIONICS embankment. The deterioration is attributed to micro-structural changes in the soil fabric that lead to a loss of suction generation capacity and cracking, resulting in changes in hydraulic conductivity and significant reductions in shear and tensile strength. This process has implications for the stability of engineered clay slopes, and the study suggests the need for new constitutive soil models that can properly account for weather and climate change impacts on long-term slope stability. The authors hope that their findings will enable the development of such models and improve our understanding of soil deterioration due to wetting and drying. Figure 11 summarizes the conceptual model presented by Stirling et al. (2021) illustrating the weather-induced deterioration of compacted clay fills.

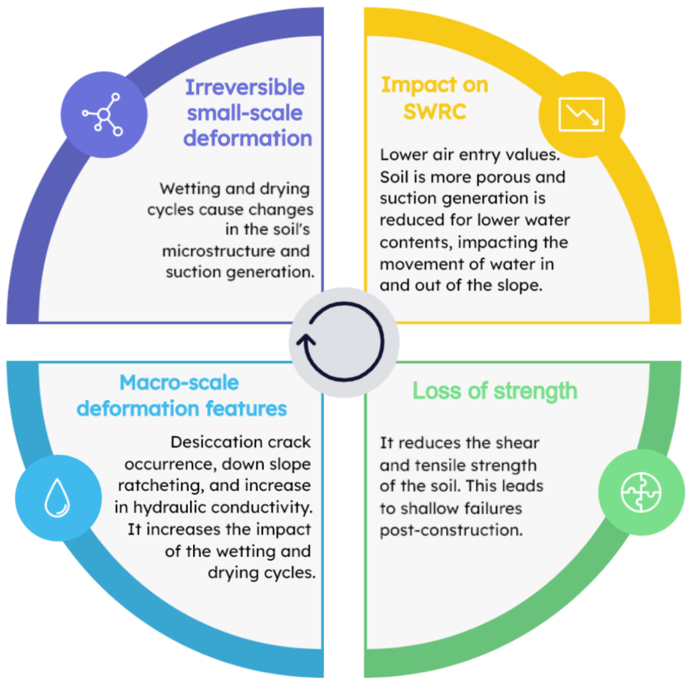

Figure 11. Weather-induced deterioration of compacted clay embankments (Stirling et al., 2021).

Kite et al. (2020) investigated the use of track geometry data in detecting embankment instabilities. Over 1800 embankments were analysed using track geometry data to identify parameters that correlate with embankment movements, which were then used to generate an embankment instability metric (an indication of the worsening of track geometry that is likely due to embankment instability). The study found that railway embankment instability is visible in track geometry data. They conducted a numerical simulation to better understand the relationship between sampling frequency and the apparent rate of deterioration for a given actual rate of deterioration. The simulation determined that a minimum of two track geometry recordings per year are required to calculate an embankment instability metric value for that year in that section, but a higher frequency of recording is recommended for more accurate metric values. The study concludes that track geometry data can be a reliable source for detecting railway embankment instability and assigning an embankment instability metric can provide a measure of asset vulnerability to failure.

Bao et al. (2022) developed a time-dependency deterioration model for two ecological materials, guar gum mixed soil (GGS) and polypropylene fibre-reinforced soil (PFS), to evaluate their long-term performance. The model integrates rainfall characteristics with the deterioration law for the mechanical properties of materials. A power function was used to establish the deterioration model between erosion mass and rainfall intensity (I). They found that the time-dependency deterioration model for the slope protective effect involves internal (mechanical parameters of slope protection material) and external (average rainfall intensity) factors that affect slope surface erosion. The model, although relatively simple, is valuable for portraying the deterioration process of materials, especially in environments characterized by intense dry-wet cycles. The study provides empirical reference and theoretical support for the evaluation and improvement of slope ecological protection materials, helping to promote the ecological protective effects for the loess areas.

Briggs et al. (2023) explored weather-induced deterioration in ageing clay-based transportation earthwork slopes, primarily within temperate climates, such as the UK. Their research revealed how seasonal shifts in soil moisture and pore pressures influence the material properties, deformation, and stability of such earthworks. They presented a novel conceptual model, drawing from a wide range of sources, including laboratory experiments and real-world observations. This model identified four key types of deterioration processes in ageing clay earthworks:

- Irreversible micro-scale deformations within the clay structure.
- Macro-scale deformations across the entire earthwork.
- Permanent changes in hydraulic and water-retention properties.
- Irreversible loss of clay strength, leading to reduced slope stability.

These processes result from the recurring wetting and drying cycles triggered by seasonal weather changes. While the model is tailored to temperate climates, it offers valuable insights applicable to various settings and newly constructed earthworks experiencing the onset of deterioration.

5. Discussion

The systematic literature review aimed to enhance the understanding of the long-term behaviour of geotechnical assets, with a specific focus on embankments and cut slopes, by examining existing research on deterioration models. It focused on aspects such as monitoring, instrumentation, and the collection of data related to these geotechnical assets. The review also emphasized the numerical models developed to predict or forecast future scenarios of embankment and cut slope deterioration. Furthermore, it provided a summary of the experimental techniques and test conditions used to model the deterioration of these geotechnical assets. Its goal was to compile and present relevant information on how asset deterioration is studied and simulated in experimental settings.

As expected, not many deterioration models for earthwork slopes were found in the scientific literature review. Figure 4 (mapping network of the co-occurrence keywords, Data Analysis section) demonstrates that a comprehensive geotechnical asset deterioration model, which fully describes the behaviour of geotechnical assets, is uncommon in the scientific literature. However, in recent years, there has been a significant increase in the number of research papers addressing this topic. Furthermore, the current review's search strategy did not identify studies that were not specifically focused on deterioration models for earthwork slopes. However, there is a growing body of literature dedicated to studying factors and mechanisms that enhance our understanding of the long-term behaviour of earthwork slopes.

Although these studies do not directly address deterioration models, they have the potential to contribute to the development or improvement of such models for earthwork slopes. A significant number of these studies were discussed or referenced in the present review, despite not being included in the systematic process (Data Analysis section).

The parameters commonly measured in geotechnical slopes (Figure 9) and those summarized from the iSMART project (Figure 10) are not an exhaustive list of all the intrinsic variables, factors, or mechanisms involved in the long-term deterioration of earthwork slopes. The present literature review identified a greater number of variables, including those mentioned in research articles cited in the selected documents, as well as others identified through targeted searches for relevant parameters and variables related to the deterioration of geotechnical assets. They included those related to groundwater conditions: soil water retention curve (Liu et al., 2020; Lynch et al., 2019; Toll et al., 2015, 2019) and water contents (Smethurst et al., 2022; Sophocleous et al., 2020); suctions (Huat et al., 2006; Liu et al., 2020) and pore water pressures (Glendinning et al., 2014; Smethurst et al., 2012). Permeability, which has been extensively studied concerning slope deterioration, is included as a relevant factor in deterioration models (Rouainia et al., 2020; Svalova et al., 2021; Woodman et al., 2020). It was investigated through both laboratory tests (Muddle & Briggs, 2019) and in-situ investigations (Dixon et al., 2019). Soil strength (Briggs, Blackmore, et al., 2022; Han, 2019; Postill et al., 2021a; Stark & Fernandez, 2020), stiffness (Gunn et al., 2018; Hughes et al., 2019; Tamang et al., 2022), and other material properties (Glendinning et al., 2018; Hughes et al., 2019) were also considered relevant factors in the study of slope deterioration.

Modelling seasonal ratcheting has been challenging (Glendinning et al., 2018) due to the complex nature of the cyclic process, which entails soil shrinkage and swelling caused by annual wetting and drying cycles. This process leads to the gradual accumulation of displacements over time. Seasonal ratcheting has been a crucial mechanism that has captured the attention of numerous researchers (Postill et al., 2020; Postill et al., 2021a; Postill et al., 2021b; Rouainia et al., 2020; Stirling et al., 2021; Take & Bolton, 2011), who have made significant advancements in understanding it and achieving promising outcomes.

For example, Ng et al. (2023) used centrifuge modelling to study unsaturated slopes in cold regions subjected to freeze-thaw cycles using a novel in-flight freeze-thaw system. This system allowed for controlled freezing and thawing of a typical unsaturated slope. The study used loess soil from Shanxi Province, China, which is characterized as silty clay, commonly found in seasonally frozen regions. The soil was carefully prepared and shaped into a steep, wet, and loose slope to induce deformation, cracks, and landforms during freeze-thaw cycles. Various sensors and instruments were employed to monitor temperature, pore water pressure, and deformation. The study observed that the freeze-thaw cycles caused soil deformation, with swelling during freezing and downslope movement during thawing. Additionally, these cycles generated issues such as surface fractures and deep cracks, resembling ice lenses, and these were influenced by water migration and suction-induced changes. The development of deep cracks, which can threaten slope stability, was attributed to tensile rupture during freeze-thaw cycles. Freezing increased soil suction significantly, emphasizing the need to consider water transport in modelling. Thawing reduced suction, causing distinctive soil movement and surface fractures.

Electrical Resistivity Tomography (ERT) has proven to be a valuable tool for monitoring earthwork structures (Ball et al., 2023; Gunn et al., 2018; Holmes et al., 2020, 2022; Neyamadpour, 2018). By detecting spatial variations in lithology, ERT allows for the assessment of complex subsurface structures in heterogeneous earthwork slopes. Moreover, the electrical resistivity measurements are influenced by moisture content, which is closely related to soil suction (an important factor in slope stability assessment), as well as the resistivity of pore fluid and temperature. Therefore, ERT enables the assessment of changes in these parameters over time and across different locations.

ERT was also used to detect subsurface cracking (Neyamadpour, 2018). Cracking (desiccation cracks) has been widely recognized as a significant factor in modelling the deterioration of the near-surface (Cordero et al., 2021; Stirling et al., 2015a; Stirling et al., 2017a; Wang et al., 2023; Yu et al., 2021). It has been extensively studied both in situ and in laboratory settings. Vegetation is a factor that influences asset deterioration through various mechanisms, including interception, transpiration, plant water uptake, and runoff-crack desiccation (Glendinning et al., 2018; Smethurst et al., 2022; Spink, 2020; Tang et al., 2018; Yu et al., 2021). The significance of tree removal has also been extensively studied concerning asset deterioration (Smethurst et al., 2015).

Other characteristics that have been investigated or taken into consideration for the deterioration modelling of geotechnical assets include slope geometry (Argyroudis et al., 2019; Postill et al., 2021a; Svalova et al., 2021; Tang et al., 2020), age of the asset (Briggs et al., 2017, 2019; Corker-Knott, 2021), construction method and other characteristics (Armstrong et al., 2021; Postill et al., 2021b), as well the history of vegetation (Powrie & Smethurst, 2019; Spink, 2020), such as tree removal, and slope history (Briggs et al., 2017, 2019; Corker-Knott, 2021), including maintenance activities. Many other factors can contribute to the deterioration of geotechnical assets, including soil temperature, rainfall, runoff, conductance, deformations, atmospheric pressure, evapotranspiration, wind speed, air temperature, relative humidity, solar radiation, drainage type, peak ground acceleration, peak ground velocity, corrosion, erosion, fatigue, and chemical characteristics (Argyroudis et al., 2019; Blake et al., 2022; Briggs et al., 2017; Glendinning et al., 2018; Grebby et al., 2021; Jiang et al., 2014; Mingolarra-Garaizara et al., 2020; Postill et al., 2020; Postill et al., 2021a; Postill et al., 2021b; Powrie & Smethurst, 2019; Smethurst et al., 2017, 2022; Sophocleous et al., 2020; Stirling et al., 2021; Stirling et al., 2015b; White et al., 2003; Wu et al., 2019).

This highlights the evolution of geotechnical asset deterioration models, which have expanded beyond the usual focus on analysing slope stability, where failure is determined based on the factor of safety against failure (Srivastava, 2012; Wang et al., 2013). New models now offer a more intricate and comprehensive examination of the long-term behaviour of geotechnical slopes, emphasizing the underlying processes and mechanisms. Nevertheless, the concept of slope failure still receives substantial emphasis in some cases. For example, Trinidad González et al., 2023) focused on the evaluation of earthwork assets (cut slopes and embankments), developing a Bayesian logistic regression model to predict the probability of slope failure based on published case histories of slope failures. Using this model, the researchers assessed the probability of failure for clay-cut slopes within a railway earthwork asset portfolio. Key findings include a higher probability of failure for steeper slopes and a 20% higher probability of failure for poorly drained slopes with shallower angles.

5.1 Performance and deterioration curves

Currently, the performance curve (Figure 6) proposed by Thurlby (2013) to represent the behaviour of assets has been adopted for relevant projects (Briggs et al., 2019; Glendinning et al., 2018; Walker et al., 2022), especially in the UK. Thurlby (2013) suggested that the bathtub curve behaviour pattern applies to different assets. He attributed the vertical axis to typically representing the number of failures per asset, although it is generally understood as a hazard function. The horizontal axis represents time. Based on this understanding, he supported the idea that modelling a population of assets with homogeneous usage, rather than focusing on a single asset, improves the predictability and usability of the curve. Briggs, Dijkstra, et al. (2022) utilized it to illustrate the deterioration in safety and serviceability of geotechnical earthwork slopes throughout their lifespan. The performance, measured in terms of slope movement, slope stability, or maintenance cost, is considered for either an individual geotechnical asset or a set of assets forming a transportation network.

Briggs et al. (2019) presented the performance curves as a valuable tool for comparing and predicting the performance of infrastructure assets as they undergo physical deterioration, with an appropriate understanding of the physical mechanisms affecting the assets and the availability of accurate data. They enable the evaluation of asset performance over time, facilitate comparisons between different asset types, and aid in prioritizing maintenance and renewal activities. Walker et al. (2022) employed these curves to compare the performance of embankments under various climatic and construction conditions. They analysed the performance of assets based on construction methods, both before and after the implementation of regulatory techniques. Walker et al. (2022) used "deterioration curves" as synonyms for "performance curves."

Armstrong et al. (2021) described the generation of "performance deterioration curves" through modelling and simulation techniques in terms of the factor of safety. Postill et al. (2021b) also utilize this approach, defining the performance of slopes based on the factor of safety (FoS) against ultimate limit state failure, in addition to considering horizontal and vertical displacement and velocity vectors indicating movements. It is considered unacceptable when a failure occurs (FoS<1). Calculating the annual factor of safety (FoS) over a long-term period of 90 years, a deterioration curve for FoS was fitted for both a softening and non-softening model in a cutting formed within London Clay (Newbury, UK).

Hu et al. (2020) depicted deterioration curves of cohesion and friction angle variations after drying–wetting cycles, using soil samples from an embankment in Yan'an City (Shaanxi, China). They represented the deterioration of cohesion and friction angle calculating a deterioration rate, as a relative variation of the variable after drying–wetting cycles. Hyperbolic functions were used to fit the cohesion and friction angle deterioration rates after different drying-wetting cycles. Additionally, the safety factor for a typical Yan'an City embankment was calculated using the different strength parameter values after drying-wetting cycles. The calculation was performed using the finite element strength reduction method, and a curve illustrating the relationship between the factor of safety and the number of drying-wetting cycles was plotted.

5.2 A basic framework for deterioration models for earthwork slopes

Considering the deterioration models identified in this comprehensive systematic review of earthwork slopes, a framework aimed at facilitating long-term analysis of geotechnical asset behaviour is proposed. Special attention was directed towards research articles featuring validated models for geotechnical asset deterioration. Within Table 1, research literature encompassing validated deterioration models for earthwork slopes is presented. The ten most relevant contributions featuring deterioration models for earthwork slopes are presented including a critical evaluation of their respective strengths and limitations. Table 1 includes details about the asset type, instrumentation status, and project scale, along with an assessment of the strengths and weaknesses of each approach.

A framework for in-depth investigations into the behaviour of geotechnical assets, aimed at fostering further advancements in the field, is described as follows, with the objective of providing insights to guide new research for advancing the understanding in this field. This framework includes initial laboratory and field testing, as well as preliminary simulations that inform strategic site sampling and instrumentation placement. It supports a comprehensive understanding of geotechnical asset behaviour and the development of reliable deterioration models specific to the studied soil.

Some studies have focused on examining soil strength parameters and related properties through laboratory analyses to assess long-term changes in soil. While these analyses provide valuable insights into soil behaviour, this approach can be supported including evaluations of the effect of small-scale soil property variations for short- and long-term conditions.

To facilitate a more holistic understanding of geotechnical assets, it is strongly recommended to integrate both laboratory and field-testing approaches, even in the early stages of slope deterioration analysis. Such integration is crucial for comprehending the underlying mechanisms that govern material behaviour and failure. Accurate constitutive models, representing long-term material responses to external changes, hinge on this thorough understanding. Moreover, external factors that significantly influence earthwork slope deterioration present ample opportunities for further exploration.

Preliminary simulation analyses (e.g., slope stability analysis using assumed soil typical values) provide valuable guidance for designing laboratory tests strategically, ensuring that they address the most relevant soil properties aligning with the analysis objective, especially when focused on understanding the long-term behaviour of a specific material. It helps to design a precise selection of sampling locations on slopes and depths for acquiring property measurements. Consequently, laboratory tests substantially enhance the accuracy of input parameters, leading to improved characterization of soil properties and reducing uncertainty in subsequent slope stability analyses.

For a comprehensive understanding of geotechnical asset behaviour, it is imperative to employ a suitable constitutive soil model capable of accounting for the deterioration resulting from wetting, drying, and other factors impacting long-term behaviour, specific to the soil under study (refer to Table 1). This model plays a pivotal role in assessing the impact of weather and climate change on engineered slope stability over time. While preliminary assessments represent the initial stage, more robust analyses are necessary to develop and validate models that accurately describe geotechnical slope deterioration. Such research paves the way for identifying underlying mechanisms, selecting appropriate constitutive models, and establishing tailored measurement strategies, all of which are vital for creating reliable deterioration models based on valuable datasets of measured soil parameters. This approach serves as a valuable starting point for comprehending the intricacies of material behaviour and advancing knowledge in this crucial field.

Table 1. Comparative analysis of validated deterioration models for earthwork slopes: Asset characteristics and assessment of approaches.

Reference	Asset instrumented and monitored?	Asset type	Part of a national or regional project?	Country	Strengths	Limitations
Glendinning et al. (2015)	Yes	Both	Yes	UK	Integrates field site monitoring, laboratory testing, and unsaturated finite element analysis. Considers historical and future weather events.	Limited information on specific findings or case studies. Partial results presented for iSMART project. Primarily focuses on UK context, which may limit generalizability to other regions.
Stirling et al. (2017b)	Yes	Embankment	Yes	UK	Integrates field monitoring, lab testing, and analysis to understand seasonal soil-water processes. Utilization of a coupled hydrological-mechanical model enhances understanding of long-term infrastructure stability.	Sensor limitations result in incomplete data, and the study's technical complexities restrict its broader applicability.
Rouainia et al. (2020)	Yes	Cut slope	Yes	UK	Advanced climate change analysis, detailed numerical modelling, comprehensive process consideration, and verification through field data.	Complex data requirements. Desiccation cracking and near-surface behaviour require further investigation and validation. Potential field variability.
Kite et al. (2020)	No	Embankment	Yes	UK	Innovative use of track geometry data. Successful development of embankment instability metric (EIM). Sensitivity analysis confirms metric's independence from other variables. Potential for automation and machine learning.	Limited data coverage. Calibration needed for risk level thresholds. Focus on assets requiring remedial work. Automation implementation pending.
Svalova et al. (2021)	No	Cut slope	Yes	UK	Innovative approach using Bayesian Gaussian process emulation (GPE) for geotechnical asset deterioration modelling, reducing computational cost and resource requirements.	Reliance on data availability, simplifications, and assumptions. Limited consideration of external factors. Need for calibration and further research.
Postill et al. (2021b)	Yes	Cut slope	Yes	UK	Innovative numerical model for forecasting cut slope deterioration. Couples hydrological and mechanical behaviour, and validates findings with 16 years of data, providing insights into slope deterioration factors, and significant progress in the field.	Model simplifications and lack of validation for mechanical behaviour. Assumptions about vegetation impact on slope stability. Limited consideration for time-dependent changes and weathering processes. Need for further development and validation of constitutive models.
Stirling et al. (2021)	Yes	Embankment	Yes	UK	Provides insights into weather-driven soil deterioration, fostering improved infrastructure stability assessment and proactive remediation for climate change adaptation.	Complex, non-linear deterioration process necessitates the development of new soil models to fully understand and predict long-term slope stability.
Postill et al. (2021a)	No	Cut slope	Yes	UK	Provides insights into seasonal ratcheting effects on clay cut slopes. Offers guidance for selecting mobilized strength parameters based on slope geometry and material behaviour. Highlights the significance of slope angle and strain-softening behaviour in assessing stability.	Requires complex, detailed analysis for specific design cases. Results are affected by variability in weather patterns and site-specific factors. Understanding of strain-softening behaviour is necessary for meaningful analysis. Detailed analysis may be required for high-risk projects.
Bao et al. (2022)	Yes	Cut slope	No	China	Analyses time-dependent ecological material deterioration in loess slope protection. Quantifies erosion with LiDAR. Establishes a simplified time-dependent deterioration model considering material properties and rainfall.	Limited to guar gum mixed soil (GGS) and polypropylene fibre-reinforced soil (PFS). Narrow model scope (mainly wet-dry cycles). Specific to loess areas. Proposes potential improvements with limited exploration.
Smethurst et al. (2022)	Yes	Cut slope	Yes	UK	Presents 17-years of data on clay highway slope water content and pore water pressure. Offers insights into weather and vegetation effects. Calibrates numerical models. Contributes to understanding climate impact.	Limited to a single UK site. While it discusses the calibration of numerical models, it does not delve into the specific findings or outcomes of these models.

5.3 Limitations

The number of documents selected for the review is limited to 37, which represents all the studies that were found using the search strategy employed. However, it is important to note that the literature on this subject is relatively limited, and all the studies that met the criteria based on the search strategy have been included.

The systematic review utilized the Scopus database as the primary source and employed alternative search strategies in other databases during the analysis and discussion phase. However, the inclusion of these additional papers was not conducted systematically, which may introduce biases in the interpretation of the findings. Additionally, a notable emphasis was observed in the literature regarding the UK, particularly centred around the iSMART and Achilles projects. This geographical and project-specific concentration may restrict the applicability of the findings to other regions and projects.

6. Conclusions

This systematic literature review provides insights into the current state of research on deterioration models of geotechnical slopes and the long-term behaviour of geotechnical assets. The review reveals that there is a limited number of published deterioration models specifically focused on earthwork slopes. However, there is an increasing interest in this field, as evidenced by the growing number of research papers addressing the topic. While comprehensive geotechnical asset deterioration models are scarce, studies focusing on factors and mechanisms that contribute to understanding the long-term behaviour of earthwork slopes have been identified. Monitoring and instrumentation of cut slopes and embankments have received attention in the literature, with varying techniques and approaches employed. Data collection for calibrating models and describing deterioration mechanisms also vary across studies.

The systematic review of deterioration models for earthwork slopes led to the proposition of a framework tailored for in-depth analysis of geotechnical asset behaviour. This framework emphasizes the necessity of integrating laboratory and field-testing approaches, supported by preliminary simulations, to comprehensively understand soil behaviour and develop reliable deterioration models. The need for accurate constitutive soil models accounting for long-term deterioration factors, influenced by weather and external changes, underscores the importance of robust analyses and tailored measurement strategies. This approach serves as a preliminary step toward unravelling material behaviour intricacies and advancing knowledge in this critical field of geotechnical asset management.

An improved understanding of the long-term behaviour and deterioration mechanisms of geotechnical assets is needed. Further research is essential to develop comprehensive deterioration models specifically focused on earthwork slopes. Monitoring, instrumentation, and data collection are crucial for refining models and improving their predictive capabilities. Increased studies on geotechnical asset behaviour contribute to a broader understanding of slope stability and deterioration mechanisms, facilitating the development of comprehensive models. This review provides valuable insights for infrastructure professionals and stakeholders, and future research can be directed towards investigating the long-term behaviour of geotechnical assets under various soil types and different conditions.

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Table captions

- Table 1. Comparative analysis of validated deterioration models for earthwork slopes: Asset characteristics and assessment of approaches.