FINAL

Phase I Summary Report: Geochemical Processes of Geotechnical Significance

International Network for Acid Prevention (INAP) &
Mine Environment Neutral Drainage (MEND)

SRK Consulting (Canada) Inc. ▪ CAPR003302 ▪ October 2025

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Prepared for:
Mine Environment Neutral Drainage (MEND) and
International Network for Acid Prevention (INAP)

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Useful Definitions

This list contains definitions of symbols, units, abbreviations, and terminology that may be unfamiliar to the reader.

DDL	Double-Diffuse Layer
GCM	Geochemical Conceptual Model
HDPE	High-Density Polyethylene
MEND	Mine Environment Neutral Drainage
INAP	International Network for Acid Prevention
SEM	Scanning Electron Microscope
SME	Society for Mining, Metallurgy & Exploration
SSA	Specific Surface Area
TSF	Tailings Storage Facility
UCS	Unconfined Compressive Strength
USGS	United States Geological Society

1 Introduction

In recent years, subject matter experts in industry and academia have raised concerns regarding potential risks to the stability and/or physical performance of tailings storage facilities (TSF) arising from or exacerbated by geochemical processes occurring within tailings, construction and foundation materials, and/or drainage features over time. These geochemical processes are reasonably well understood; however, cross-disciplinary understanding of how these processes result in physical changes, and the geotechnical significance of these changes are not as well established. Although there are reasons to believe that some geochemical processes may contribute to physical stability risks, there is little research published and only a few case studies where geochemical processes or time-dependent physical changes have been identified as specific contributors to tailings dam failures.

To address this knowledge gap, SRK was retained by the International Network for Acid Prevention (INAP) & Mine Environment Neutral Drainage (MEND) to assist with developing an industry focused technical report summarizing key geochemical processes that should be considered when assessing potential risks related to dam stability. The project was divided into two phases, with approval for the second phase pending additional project funding and approval:

- **Phase 1:** Develop the foundation for an industry focused report which effectively defines and communicates the observed and/or documented geochemical processes that could affect a tailings storage facility's intended performance over the required service life of a structure (in many cases this is for thousands of years).
- **Phase 2:** Assess the plausibility and credibility of these risks through the development of a screening-level risk assessment tool that identifies the key characteristics and/or combinations of factors that make tailings facilities more or less prone to stability risks due to geochemical processes.

The purpose of this report is to summarize the work completed in Phase 1 and provide the technical basis for Phase 2. Phase 1 consisted of updating and refining an existing literature review and geochemical conceptual models (GCM) previously conducted on the subject. The technical basis for Phase 2 was advanced by developing an example hazard assessment framework for one geochemically induced physical change. The remainder of this document provides details pertaining to the methodology used to complete these tasks, the results obtained, a discussion of the results, and recommendations for future work that would be completed as part of Phase 2.

This report does not provide a quantitative assessment of the likelihood, or a comprehensive assessment of the consequences associated with the failure of a TSF. Furthermore, this report does not draw connections between geochemically induced physical changes and specific failure scenarios. Both topics would be addressed in Phase 2.

2 Methodology

2.1 Task 100: Review Knowledge Base

Limited case studies or published research are available that consider geochemical processes or time dependent physical changes as contributors to tailings and mine waste physical stability concerns. A recent MSc. thesis (Orcutt, 2023) by SRK staff consultant, Heath Orcutt, advanced this understanding through the compilation of a literature review and geochemical conceptual model (GCM) that highlights the linkages between geochemical processes and the resulting physical changes. INAP and MEND members have determined that the mining industry would benefit from having access to this work and requested an updated version of the literature review and GCM within Phase 1 of the project.

To accomplish this task, meetings were held with INAP, MEND, and SRK to review the information previously identified by Orcutt (2023) and identify supplementary sources of information known to the INAP and MEND committee members. Solicitations for relevant case studies were also sent out via email to INAP and MEND members. Additional sources of information that were reviewed for new publications included university library databases, the SME OneMine digital library, the online MEND document repository, internal SRK projects, suggested reference documents provided by MEND and INAP, and conference proceedings. Conference proceedings scanned for relevant information include Tailings and Mine Waste, International Conference on Acid Rock Drainage, American Society of Reclamation Sciences (formerly known as the American Society of Mining and Reclamation), Australian Centre for Geomechanics, and International Mine Water Association.

The results of the updated literature review were compiled in a tabular format. Prior to finalization, the tabular literature review underwent three rounds of review by INAP and MEND committee members.

2.2 Task 200: Update and Develop Conceptual Models of Geochemical Processes within Tailings Storage Facilities

The geochemical conceptual model (GCM) published in Orcutt (2023) was updated based on discussions with INAP, MEND, and SRK and the findings of the updated literature review. An additional GCM was developed for an alternate tailings storage facility type with different hydraulic properties, material-foundation interactions, and exposure to atmospheric conditions. Similar to the literature review, the GCMs were provided to the INAP and MEND review committee for review prior to finalization.

2.3 Task 300: Establish Linkages Between Geochemical Processes, Physical Changes, and Potential Failure Modes

An internal workshop was held to present the draft GCMs and discuss connections between geochemical processes, the resulting physical changes, and their implications for geotechnical performance. The workshop results were used to develop an initial screening-level hazard framework that mapped the pathways, causal properties, and processes related to one of the physical changes identified in the literature review. As stated previously, the purpose of this task was to provide the technical basis for the development of a screening-level risk assessment tool (Phase 2) that identifies the key characteristics and/or combinations of factors that make tailings facilities more prone to stability risks due to geochemical processes and allow for an assessment of the plausibility and credibility of these risks.

The proposal submitted by SRK stated that an initial “risk” framework would be developed; however, risk is defined as the product of likelihood and consequence. Since Phase 1 did not include an evaluation of consequence, the following subsections are limited to the assessment of likelihood. Accordingly, the terms “likelihood”, “probability”, or “hazard” as opposed to “risk” are used throughout the remainder of this report.

2.3.1 Internal Workshop

The process of linking geochemical processes to physical changes and geotechnical failure modes was initiated through an internal workshop with participants from SRK’s geoenvironmental team. The workshop was held over two, 2-hour sessions on August 21st and 22nd, 2024. Table 1 provides a summary of the participants and their area of expertise.

Table 1: Workshop Participants

Name	Area of Expertise
Kelly Sexsmith	Geochemistry
Heath Orcutt	Geoenvironmental Engineering
Gaston Quaglia	Geotechnical Engineering
Erik Ketilson	Geotechnical Engineering
Holly Williams (Co-Facilitator)	Geotechnical Engineering
Adam Leik (Co-Facilitator)	Geotechnical Engineering

The workshop considered each of the physical changes identified in Sections 2.1 and 2.2. The geochemists were tasked with providing the typical geochemical processes that could produce the physical change and brainstorm factors that would make these reactions plausible. Geotechnical engineers then considered how the physical change could affect fundamental geotechnical material properties, such as permeability or plasticity. Changes in geotechnical material properties were then linked to failure modes or other undesired consequences (e.g., construction delays, repairs, maintenance, etc.) using a flow chart.

The flow chart followed the same basic structure for all types of physical changes. Commentary pertaining to which types of facilities might be more affected by a given physical change, specific geotechnical parameters that were more likely impacted, or when the physical change could be more impactful, were noted. For this report, the annotated flow charts were used to develop the causal network for the physical change: “Generation and Migration of Fines”; however, they could be used for the development of causal networks for other physical changes as well.

2.3.2 Develop Example Hazard Framework

The results of the workshop were used to develop an initial screening-level hazard assessment framework that maps the pathways, causal properties, and processes that lead to physical changes in tailings storage facilities.

A causal network was selected for this task due to its ability to incorporate expert judgment and expand as necessary to include new information. As some readers may not be familiar with this method, the next sections provide an overview of its concept and explain how SRK developed a causal network for this application.

Overview of Causal Networks

Causal networks are a graphical structure that visualize causal linkages between variables, with arrows indicating the direction of influence. Bayesian statistics may be used to calculate the conditional probability of a parameter of interest within a causal network. Unlike frequentist methods, which rely on large sample sizes to quantify uncertainty, Bayesian approaches can handle small sample sizes using Bayes’ theorem, which is shown in Equation 1 below.

$$P(\theta \mid data) \propto P(data \mid \theta) \times P(\theta) \qquad [1]$$

or

Posterior ∝ Likelihood x Prior

Application of Bayes' theorem involves:

- Starting with a 'prior' belief about the parameter of interest before observing any data ($P(\theta)$ in Equation 1). The 'prior' could be based on historical data, similar data, and/or experience and judgement.
- As new data or information is obtained, the 'prior' is multiplied by the likelihood ($P(data \mid \theta)$) which represents the probability of the initial belief being correct based on the data that was actually observed.
- The resulting product is the posterior ($P(\theta \mid data)$), or the revised belief of the parameter of interest after incorporating the new information (also commonly referred to as 'evidence'). As the 'evidence' grows, the reliance on the prior is reduced.

In a causal network, Bayes' theorem can be utilized to compute the conditional probability of any variable, given information about other variables within the same network. This allows the network to function with varying quantities of data, from different sources, with varying levels of reliability. Furthermore, a "complete" dataset is not required to determine a parameter of interest.

Kjærulff & Madsen (2013) provide an example of a simple causal network describing the health of an apple tree (see Figure 1). In this example, there are three variables, each with two states "yes" or "no". The variables "Sick", "Dry" and "Loses" tell us whether or not the tree is sick, whether the tree is dry, and whether or not the tree is losing its leaves, respectively.

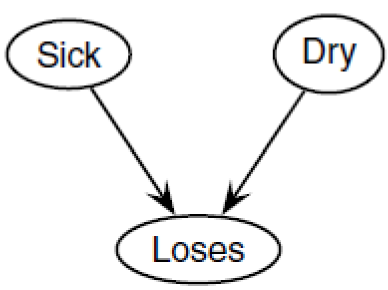


Figure 1: A Simple Causal Network (taken from Kjærulff & Madsen, 2013)

The network implies there is a causal impact from both "Sick" and "Dry" on "Loses", which is consistent with the assumption that, when a tree is sick and/or dry, this might cause the tree to lose its leaves. The arrangement and direction of the arrows in this particular network have been carefully selected to convey this message. When thinking about how to develop this network, it may have initially seemed logical to switch the positions of "Loses" and "Sick"; however, this would be incorrect as the sickness causes the tree to lose its leaves, and lost leaves do not cause the sickness.

In this network there are three different variable types. “Dry” is a type of input variable that provides background information and can be observed in the absence of knowledge about the other variables or the problem. “Loses” is a different type of input variable that is a symptom of the problem and can be observed as a consequence of the problem. Symptom variables in geosciences are often measurements of observations. “Sick” represents the problem variable, and in this case is the parameter of interest. Problem variables usually cannot be observed, which is why the network is necessary. In more complex networks, there is a fourth variable type known as a "mediating variable". These variables are not the immediate parameter of interest and are typically not observable. However, understanding the probability of these variables is important for achieving correct conditional independence and dependence properties, and for improving network efficiency.

The example network discussed provides qualitative results. To enable a quantitative analysis, likelihoods would need to be assigned to each of the input variable types and a conditional probability table would need to be developed to assess the variable “Sick”. By assigning initial probabilities and using Bayes' theorem, the same network can quantitatively determine the likelihood of "Sick" being "yes" based on different input combinations of the input variables.

Development of Causal Network for Example Hazard Framework

There is a relatively well-established understanding within the geotechnical community regarding how physical properties relate to failure modes. For example, the probability of a physical instability failure can be broadly related to a combination of, not only the absolute values of material properties and the quality of the conceptual model (which often culminate as a factor of safety in a limit equilibrium analysis), but also, the uncertainty associated with these inputs.

A geotechnical hazard assessment framework does not typically account for the possibility of geochemically induced changes to material properties. Adding geochemical considerations introduces an additional source of uncertainty to the material properties and the conceptual model (i.e., increased potential for variability in shear strengths or altered drainage conditions).

Given the industries existing experience with estimating the likelihood of failure for TSFs without consideration of geochemical factors, determining the effect of a *geochemically induced physical change* can most easily be assessed by determining the incremental change in total estimated likelihood of failure. Therefore, the proposed hazard framework focuses on assessing the susceptibility of a design element or material to geochemically induced physical changes, rather than how these physical property changes relate to specific failure modes. By approaching the problem in this way, the incremental effect of geochemically induced physical changes can be applied to existing risk assessment methods by adjusting the uncertainty for material inputs or conceptual models.

The causal network developed for the hazard framework focuses on a qualitative assessment of the likelihood of a physical change to occur due to geochemical processes. The example network is intended to serve as a proof-of-concept. The usefulness of this network may not be immediately apparent, but the practical value will emerge once it is populated with insights regarding the likelihood and impact of the identified geotechnical/geochemical hazards. The network itself is not intended to be the end-product for users of the final risk assessment tool, rather it is the underlying workings of the tool that generates results based on a user defined set of inputs.

The physical change "Generation and Migration of Fines" was chosen to demonstrate the causal network approach. Developing the causal network for the example hazard framework involved the following steps:

1. Using the results from the internal workshop to map causal pathways and processes that lead to the likelihood of a geochemically induced physical change to occur. During this stage, commonalities between variables and general trends were examined. Information from this step was used to inform the rest of the process.
2. Establishing suitable input variables. Note that the network generated is not intended to be exhaustive and is only an example. Accordingly, there may be additional variables that require consideration for assessing the likelihood of the generation and migration of fines.
3. Developing the graphical structure for the causal network and assigning which variables have causality on others.
4. Determining different states for each of the input variables. In the simple example network in Figure 1, the states were limited to “yes” or “no”, but background variables for more complex networks can have any number of states.
5. Assessing the significance (or strength of indicator) of each input variable on the parameter of interest.

Steps 4 and 5 were summarized in an Excel Sheet and are herein referred to as the “Input Table”. Although the input table was developed, quantitative values were not assigned to represent a prior distribution of states and conditional probability tables were not developed to determine the likelihood of a parameter of interest occurring. These will be completed in Phase 2 of this project should it proceed.

3 Results

3.1 Tabular Literature Review

The complete tabular literature review is presented in Appendix A and should be read in its entirety. Table A-1 (Appendix A) describes the geochemical processes considered in this review, grouped according to the type of weathering reaction. Table A-2 (Appendix A) describes each of the physical changes, as well as:

- Potential geotechnical significances of the changes
- Examples or case studies where the process has been observed
- Factors or conditions that enhance plausibility, significance, or timescale
- A visual representation of the process.

The goal of this work was to produce a product which can be widely shared and understood by geochemists and geotechnical engineers alike. Connections between geochemical processes, mineralogy, environmental conditions, etc. were linked to potential changes in geotechnical properties and locations/types of facilities where the physical change may be more of a concern. When possible, examples from case studies were provided to strengthen those connections. SRK expertise and experience across a wide variety of projects was leveraged through reference to confidential SRK projects, cross-disciplinary collaboration between geochemists and geotechnical engineers, and collaboration with the INAP/MEND committee.

The literature review tables are summarized in Tables 2 through 4.

Table 2 describes the main types of geochemical processes considered in Table A-1: 1) chemical weathering of primary and secondary minerals, 2) precipitation of secondary solid phases, and 3) other water/rock interactions. All of these geochemical processes are natural weathering reactions that occur over extended time periods. However, mining and mineral processing activities which result in increased physical exposure, changes in moisture content, and/or changes in chemical conditions can result in the acceleration of these reactions.

Table 3 provides a brief description of each of the physical changes. An example of the completed literature review table for the physical change “Generation and Migration of Fines” is provided in Table 4. Physical changes 1-4 occur primarily due to chemical weathering reactions. Physical changes 5-9 are similar in nature but are differentiated by the areas in which secondary mineral precipitation occurs, such as along discontinuities or cracks, between grain contacts, filling part or all of the pore space, within the tailings matrix as a laterally extensive unit, or within drainage pipes. They also differ based on the resulting physical change, from positive volume deformation or heave, brittle behavior, reduced permeability and drainage, reduced permeability and increased strength, or clogging of pipes. Physical changes 10 and 11 occur primarily due to interactions with acidic or saline seepage.

Overall, there were a limited number of case studies found which cite geochemical processes or time dependent physical changes as specific contributors to physical instability. Rather, the majority of case studies reference material property changes or variations from the design conceptual model (either explicitly or inexplicitly). This is most likely due to a lack of research/documentation in this area or awareness. Ideally, this catalogue of case studies can continue to be updated through sharing of this work amongst MEND and INAP members and other geoscientists.

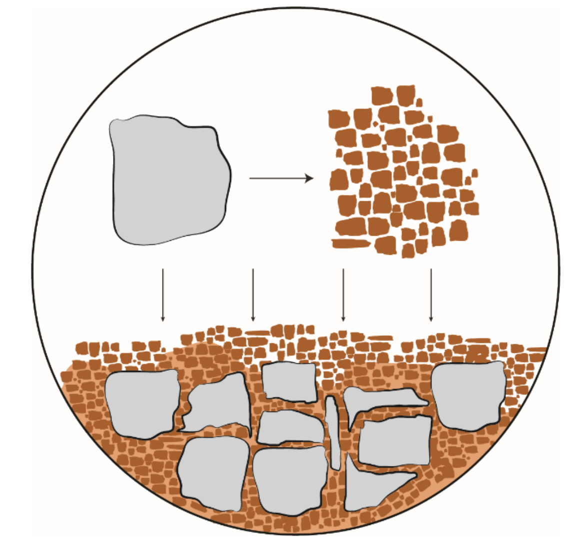
Table 2: Summary of Geochemical Processes Leading to Physical Changes

Geochemical Processes		Description
(W)	Chemical weathering of primary and secondary minerals	Chemical weathering is defined as the breakdown of rocks and primary or secondary minerals by chemical processes such as dissolution, hydrolysis, carbonation, oxidation/reduction, cation exchange, or hydration. Examples include sulfide oxidation, carbonate dissolution, and hydration of silicates.
(P)	Precipitation of secondary solid phases	Precipitation of secondary solids (crystalline and amorphous phases) occurs when solutes released from other geochemical processes reach their solubility limits and the reaction kinetics are favorable for solute precipitation. This may occur as a result of ongoing release of solutes or along transport pathways where there are changes in pH, redox conditions, or volumes of water (i.e., evaporation).
(O)	Other water/rock interactions	Other water/rock interactions which may have geotechnical implications include the effects of water chemistry on the surface properties of minerals and the effects of water chemistry on pipes, concrete, and other infrastructure, including corrosion by salts or acid and scaling.

Table 3: Summary of Physical Changes

	Physical Change	Description
1.	Generation and migration of fines	It is commonly understood and observed that weathering results in the breakdown in particles and a decrease in the average particle size distribution. Higher fines content can have an influence on the shear strength properties of the medium, reduce permeability, and hinder drainage.
2.	Alteration of particle shape and texture	Chemical weathering has the potential to change the individual particle shape (angularity) and texture (roughness) over time, varying from the original design parameters (i.e., internal friction angle, void ratio, density, etc.).
3.	Formation of clay minerals	The presence of silicate minerals in tailings and mine waste facilities, as well as their exposure to weathering agents such as water and oxygen, can result in the formation of weaker clay minerals (phyllosilicates or sheet silicates) over time. Clay minerals, not clay-sized particles, have very different engineering properties than their primary mineral counterparts and can contribute to changes in the permeability and strength of materials.
4.	Mass loss from release of solutes	This is the physical change resulting from the dissolution of soluble minerals. Mass loss can contribute to void development, karst development, preferential flow paths, piping, and internal erosion.
5.	Positive volume change (e.g., sulfide-oxidation induced heave)	Secondary minerals are less dense than their primary counterparts and often form along crack or discontinuities, resulting in positive volume change.
6.	Interparticle cementation or loss of cementation	Secondary minerals can loosely cement particles together along grain contacts and form a metastable structure that fails brittlely upon loading. The same is true for collapsible soils which may be naturally occurring in foundation materials. The important distinction from other physical changes is the brittle response upon loading.
7.	Clogging of pores	High concentrations of dissolved ions, upon reaching saturation and/or favorable environmental conditions, can form secondary solids (amorphous or crystalline phases) within the pore space of construction materials and/or embankments. This can lead to a reduction in porosity and hindered drainage.
8.	Formation of low-permeability zones	Low-permeability layers (e.g., hardpans) form when secondary mineral precipitation occurs in a concentrated, laterally extensive area. This can lead to the formation of perched water tables, limited evaporation, and reduced drain down.
9.	Clogging of drainage and scaling of pipes	Secondary solid phases can precipitate within drainage pipes preventing drainage as designed and potentially leading to a rise in the phreatic surface.
10.	Changes in clay mineral properties under acidic or saline conditions	Acidic and saline conditions have been known to alter the properties and/or particle arrangements of clay minerals.
11.	Corrosion of steel, concrete, and other infrastructure	Acidic conditions and/or high concentrations of sulfate or chloride can result in increased rates of corrosion in steel, expansion/deterioration of concrete, and degradation of various infrastructure components susceptible to acidic conditions such as pumps, monitoring equipment, well casings, rock bolts, etc.

Table 4: Example from Tabular Literature Review for the Generation and Migration of Fines

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(1) Generation and Migration of Fines (W, P)	Weathering and dissolution processes can break down primary minerals or rock particles into smaller fragments and disaggregate mineral grains. Sulfide oxidation and/or the generation of acidic conditions may enhance particle breakdown via dissolution of carbonates along cracks or voids, formation of porous alteration rims and etch pits which weaken the material, and secondary mineral precipitation along intergranular cracks and voids which break the rock apart (USGS et al., 2005). Additionally, precipitation of secondary solid phases can produce fines (Elghali et al., 2021; Filipowicz and Borys, 2007; Forsberg and Ledin, 2001). Fines can lead to pore clogging and reduced permeability (Elghali et al., 2021; Lin, 1997). The influence of fines and/or secondary weathering products on geotechnical properties (e.g., shear strength, compressibility, dry density, water content, etc.) have been observed (Filipowicz and Borys, 2007; Ng et al., 2019; Carelson, 2013).	▪ Decreased average particle size and broadened particle size distribution. – Decreased void ratio. – Decreased permeability. – Increased water retention capacity. – Increased plasticity. – Increased potential for undrained conditions. – Decreased friction angle and shear strength. ▪ Increased specific surface area and affinity for ions. ▪ Decreased self-weight consolidation. Note: Reverse occurs if fines migration lowers fines content.	1. Block caving and in-situ leaching at a copper porphyry deposit resulted in physical and chemical weathering of rock comprising an engineered structure at a site in Arizona. Various indices measuring the extent of chemical weathering were correlated with grain size distribution and showed higher fines content with greater extent of weathering. Coarser material showed higher friction angles and therefore strength (Confidential SRK Project, 2023). 2. Oxidation of Fe(II) to Fe(III) within biotite grains led to an increase in connected porosity, an increase in hydraulic conductivity, an increase in volume, matrix fracturing (fines generation), reduction in tensile strength, and an increase in abrasion rate (Goodfellow et al., 2016). 3. The Joutel Gold Mine tailings developed redox zones within the tailings impoundment that show increased secondary mineral precipitation (gypsum and goethite), decreased average particle size, and increased specific surface area (SSA) at the surface when compared to unoxidized samples below the water table (Elghali et al., 2021). 4. Waste rock at the Dinero mine showed K-jarosite formation along cleavage plans in altered muscovite, expanding and fragmenting the phyllosilicate mineral. SEM images also showed evidence of fines settling out of suspension such as formation of cross beds and soft sediment slumps within void spaces and the presence of microlaminated fines (USGS et al., 2005).	A high sulfide content can encourage fines generation due to the release of acidic byproducts capable of breaking down rock and the formation of secondary solid phases that are smaller in size than their primary counterparts. The presence of mafic minerals, hydrothermally altered minerals, and/or amorphous solid phases can increase fines content due to their susceptibility to breakdown. The presence of carbonate or sulfide veins within rock material can also increase susceptibility to breakdown. Increased fines content is typically limited to the surface of TSFs or within the active oxidation zone. However, fines can be transported by wind or water erosion to the toe of an embankment, leading to a decrease in permeability and increase in pore water pressure (KCB, 2023). Facilities experiencing acidic conditions, such as acidic heap leach facilities, may be more likely to see particle degradation and an increased fines content over time. Fines migration has been documented within waste rock at the Dinero and Questa mines (McLemore et al., 2009; Shaw et al., 2002; USGS et al., 2005). Well-connected flow paths and more porous structures allow fines to migrate throughout a facility. Fines can be transported via suspension or can precipitate at depth. Therefore, the rate of flushing may influence where fines settle.	

Notes: W = Chemical weathering of primary or secondary minerals. P = Precipitation of secondary solid phases.

3.2 Geochemical Conceptual Models

The results of the updated and newly developed GCMs are presented in Figure 2 and Figure 3. The GCMs reflect the updated literature review and reference physical changes 1-11. Figure 2 depicts a highly oxidized, stratified tailings deposit that is contained laterally by a medium permeability sand embankment built using upstream construction methods, without containment of seepage into the foundation. Figure 3 illustrates subaqueous tailings with limited oxidation contained laterally by a high permeability run-of-mine rock fill embankment with an upstream HDPE liner to contain seepage. Both figures include a range of potential foundation conditions. The main differences between Figure 2 and Figure 3 are the permeability of the embankment materials, the containment of seepage into the foundation, and the oxidation of tailings materials. Comparison of the two figures illustrates differences in the locations and materials in which physical changes could occur within these two types of facilities. Site specific conceptual models that include further details on design, the foundation conditions, and the geochemical characteristics of the tailings and construction materials may be helpful in constraining the types of changes that are relevant to a specific tailings facility and the locations (within the facility) where these physical changes are likely to occur.

Future work may benefit from the development of more GCMs for various facility types such as filtered tailings, waste rock, and other TSF dam configurations.

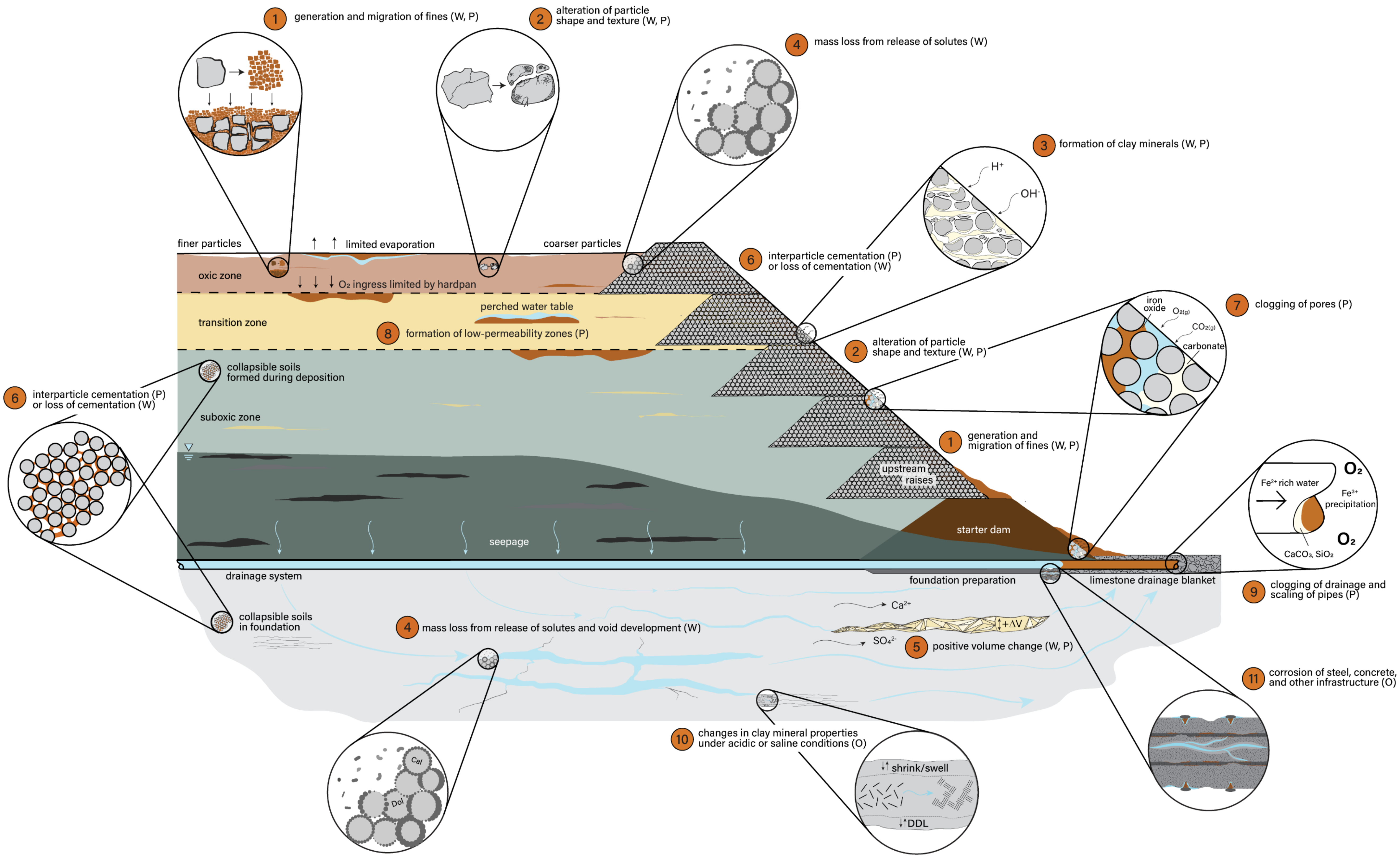


Figure 2: Geochemical conceptual model of an unlined TSF with an upstream embankment that summarizes potential changes in physical material properties resulting from geochemical processes.

Notes: Relevant geochemical processes include the following: W = Chemical weathering of primary or secondary minerals, P = Precipitation of secondary solid phases, O = Other water/rock interactions.

The figure is intended to illustrate the potential range of physical changes that could occur. Site specific design, foundation and geochemical characteristics are likely to further constrain the changes relevant to a specific facility.

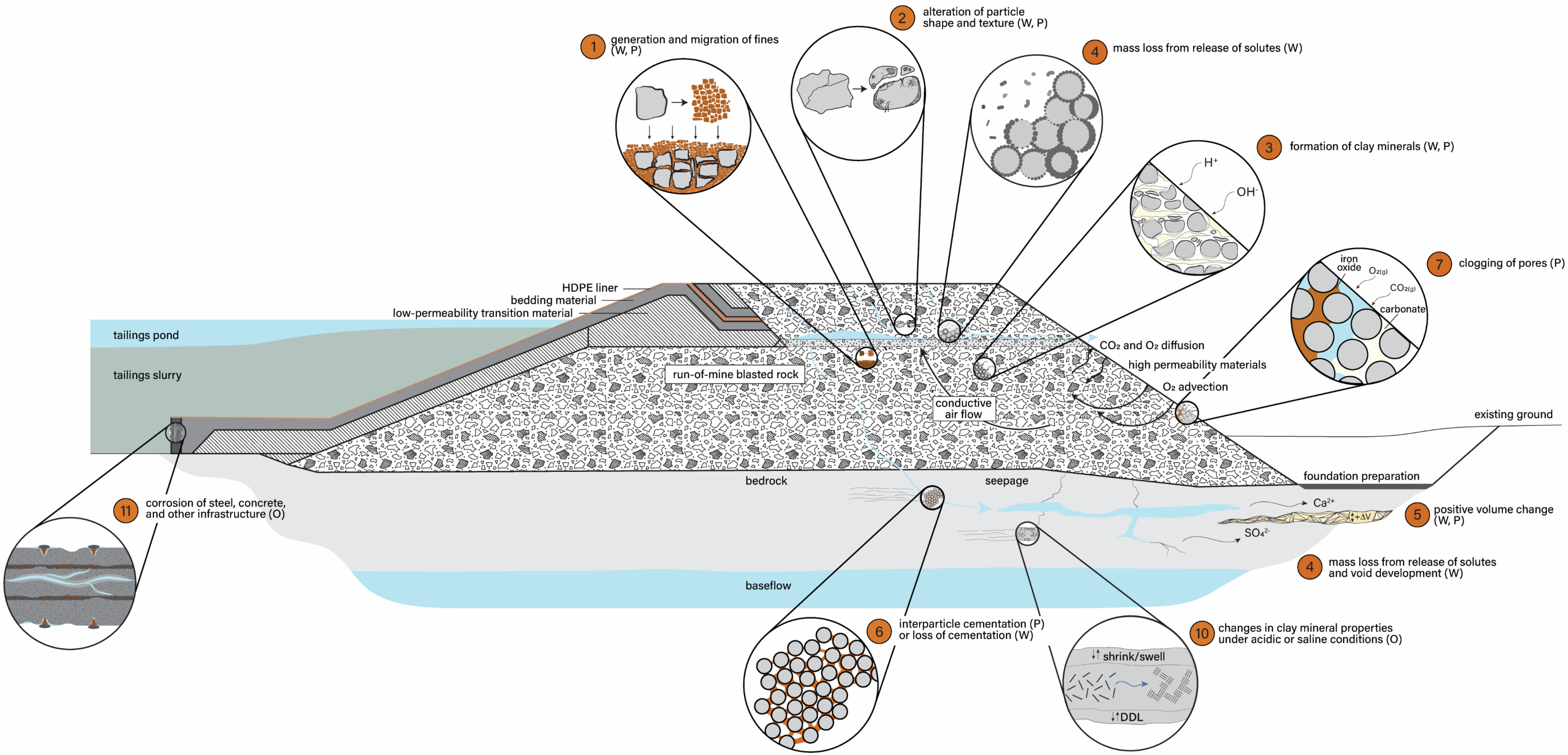


Figure 3: Geochemical conceptual model of a lined rock fill embankment with containment that summarizes potential changes in physical material properties resulting from geochemical processes.

Notes: Relevant geochemical processes include the following: W = Chemical weathering of primary or secondary minerals, P = Precipitation of secondary solid phases, O = Other water/rock interactions.

The figure is intended to illustrate the potential range of physical changes that could occur. Site specific design, foundation and geochemical characteristics are likely to further constrain the changes relevant to a specific facility.

3.3 Hazard Assessment Framework

Appendix B contains the annotated flow charts for all the physical changes considered during the workshop. The annotated flow charts are not intended to be exhaustive, but rather, an initial brainstorming activity to help build a causal network by linking geochemically induced changes to failure modes.

Using the findings from flow charts in Appendix B, an example input sheet (Table 5) and causal network (Figure 4) was developed for assessing the likelihood of generation and migration of fines. Section 4.2 provides additional discussion and examples, illustrating how the input sheet and causal network can be applied in different scenarios. These examples demonstrate the practical utility of the screening-level risk assessment tool in identifying the crucial characteristics and combinations of factors that influence a facility’s vulnerability to stability risks driven by geochemical processes.

3.3.1 Example Input Sheet

The purpose of the input sheet is to prompt the user with a series of questions that serve as input variables for assessing the likelihood of fines generation and migration within the causal network. Selections for each of the input variables will be based on different sources of information, such as site data, climate data, lab testing data, and their own professional judgement.

To use the example input sheet shown in Table 5, the user would first specify their facility type and enter a set of basic facility characteristics. After this initial information is provided, the relative influence of each variable would be determined—either through expert judgement or from statistical data where available. For illustrative purposes, the effect of each input is provided in Tables 5; however, actual assessments would be tailored to site-specific conditions. The user then selects one of five qualitative options (ranging from “Very Likely” to “Very Unlikely”) that best describes how the facility aligns with the descriptive categories listed for each input.

3.3.2 Example Causal Network

The example causal network in Figure 4 is the underlying analytical structure operating behind the scenes that integrates the information entered into the input sheet. In this example network, green nodes represent input variables, yellow nodes indicate mediating variables, and the grey node denotes the outcome of interest: the probability of fines generation and migration at the facility. The network variables have been intentionally generalized, so that the same network can be applied to multiple locations within a facility, allowing for an assessment of the likelihood of fines generation and migration across various areas.

The example network is intentionally focused only on the factors leading to the physical process of fines generation and migration and does not extend to downstream failure modes. As explained previously, the incremental effect of this geochemically induced physical change would be applied to existing risk assessment methods by adjusting the uncertainty for material inputs or conceptual models.

While the network includes several key variables SRK considers to be critical for assessing the likelihood of this process, it can be readily expanded to capture a more comprehensive range of site variables as needed.

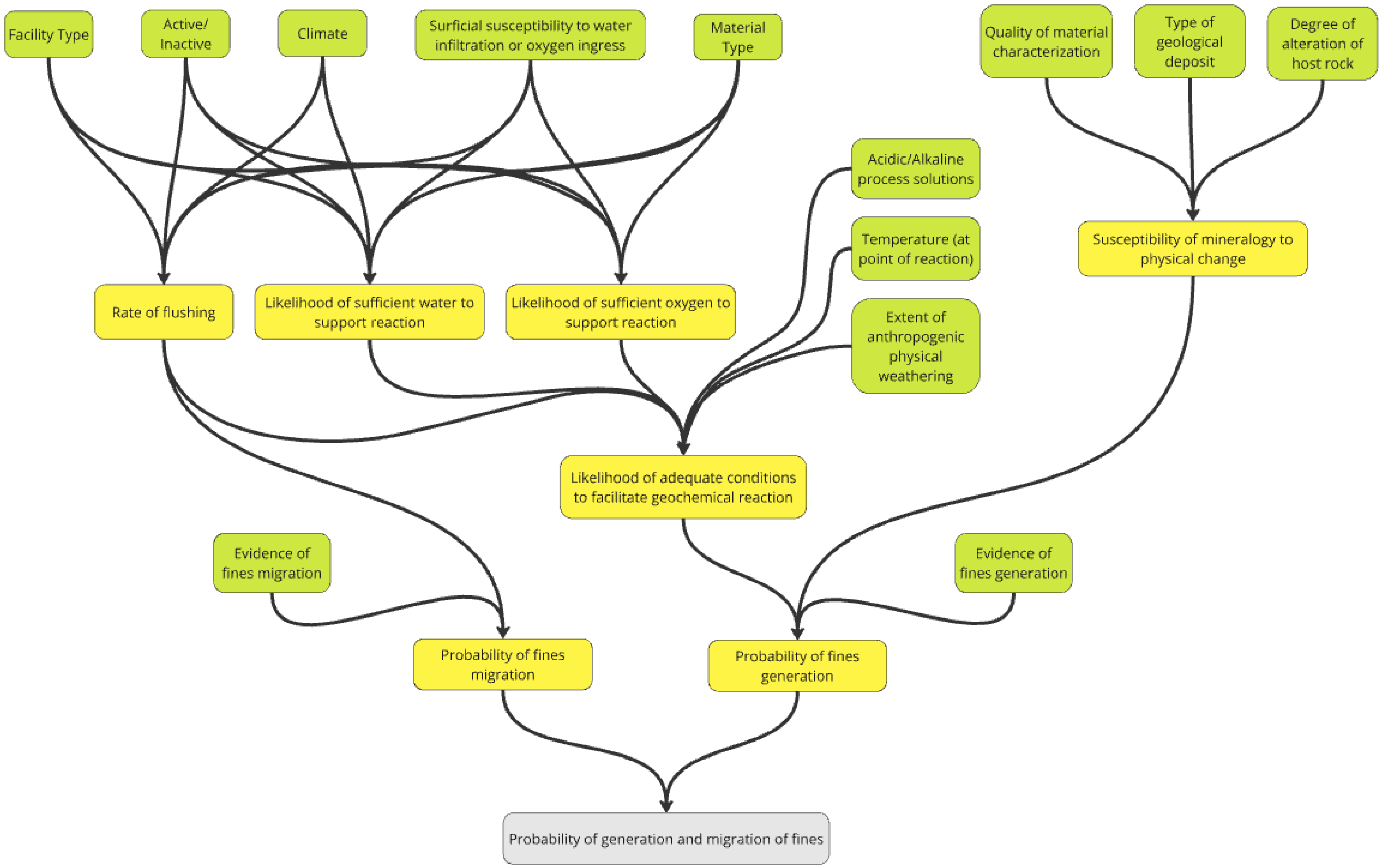


Figure 4: Causal network developed for assessing the likelihood of the physical change "Generation and Migration of Fines".

Table 5: Example Input Sheet for Determining the Likelihood of a Geochemical Reaction Causing the Generation and Migration of Fines

Basic Inputs	**Examples would be…**
Facility Type	*Filtered tailings, conventional slurry tailings, waste rock, run-of-mine embankment fill, etc.*
Active/Inactive	*Active or Inactive.*
Material Type	*Clay-like, silt or tailings-like, sand or filtered tailings-like, gravel-like, boulders, or waste rock-like.*

Guiding Principles										
Qualitative Inputs	**Relative effect on probability of physical change**					**Examples that could be…**				
	Weakest indicator	Weaker indicator	Neutral	Stronger indicator	Strongest indicator	**Very Likely**		**Neutral**		**Very Unlikely**
						Clear indicators for concern or potential for rapid change in physical properties	*Potential concern or potential for moderately rapid change in physical properties*	*No immediate concerns, but limited investigation*	*Used to fit cases in between neutral and strongly positive*	*Clear indicators that there are no concerns or concerns have been appropriately addressed*
Likelihood of sufficient water and/or oxygen to support reaction, rate of flushing										
Climate		X				Warm and humid climates (i.e. tropical climates) can increase the rates of reactions, promote microbial activity, and mineral-water contact. Climates with high rainfall will support consistent flushing of ions and minerals through the system. Furthermore, construction materials typically available in warm and humid climates are already highly weathered (e.g., saprolitic soils).		Temperate climate with minor seasonal fluctuations.		Highly arid environments can slow the rates of reactions that rely on inputs of water (i.e., sulfide oxidation, hydrolysis, etc.). Colder temperatures also slow the rates of reactions. Desert climates with low average annual rainfall will reduce the average rate of flushing, yet may see high precipitation events (i.e., monsoons).
Surficial susceptibility to water infiltration or oxygen ingress		X				Clear evidence of an exposed surface with no barriers to oxygen ingress or water infiltration. Examples include oxidation visible on surface, erosion visible on surface, ponding leading to increased infiltration, etc.	Natural barrier or engineered cover system in place but insufficient or failed in some areas. Slumping has caused enhanced erosion, oxygen ingress, infiltration, and weathering of underlying material.	No engineered cover system in place yet temporary formation of a "natural" cover (i.e., hardpan formation on surface, microbially induced calcite precipitation, salt crust, etc.). Effective at limiting oxygen ingress and water infiltration in the short-term yet lacks robustness as a long-term solution.	Engineered cover system in place yet lacks robustness in design or lack of demonstrated performance.	Clear evidence of an effective, engineered cover system with a robust design to withstand erosion, divert high volumes of water, and of sufficient thickness to limit oxidation of underlying material.
Likelihood of adequate conditions to facilitate geochemical reaction										
Acidic/Alkaline conditions			X			Contact waters are strongly acidic (pH <3) or basic (pH >10) or use of strongly acidic process solutions for a prolonged period of time.		No knowledge of pH conditions in contact water, or mildly acidic (pH 4.5 to 6) or mildly alkaline (pH 9-10) conditions.		Clear evidence of neutral conditions (pH 6 to 9) persisting throughout waste material over time. No clear evidence of enhanced rates of reactions.
Temperature at point of reaction			X			Clear evidence of elevated temperatures (>25°C) at point of reaction or at depth within waste materials. Higher temperatures can increase the rates of reactions by orders of magnitude.		Insufficient monitoring to detect temperatures at depth but no reason to suspect elevated temperatures.	Seasonally frozen through winter, which reduces reactive time to ~ 5 to 6 months per year (June - October).	Clear evidence of consistently frozen conditions (i.e. < 0ºC).
Extent of/anticipated extent of anthropogenic physical weathering			X			Clear evidence of physical weathering of waste materials following placement. Physical weathering can occur due to freeze-thaw cycles, overburden pressure, organic activity, etc. Material which has undergone or that will undergo significant crushing and grinding during metallurgical processing may also be more susceptible to chemical weathering.		Insufficient monitoring to detect extent of physical weathering over time (lack of historic observations or data on material properties, limited knowledge on metallurgical process, etc.)	Low potential for physical weathering processes. Example would be a small facility (limited particle crushing from self-weight), minimal crushing prior to placement (i.e., waste rock vs. tailings), and in a temperate climate (no freeze-thaw potential).	Clear evidence of limited physical weathering of waste materials over extensive periods of time (minimal deformation of structure, maintained particle angularity and size over time, etc.). Analog sites (same material, longer exposure times) may also serve as evidence of limited physical weathering. Full isolation from physical weathering is not practical.

Qualitative Inputs	Relative effect on probability of physical change					Examples that would be…				
	Weakest indicator	Weaker indicator	Neutral	Stronger indicator	Strongest indicator	**Strongly negative**	**Moderately negative**	**Neutral**	**Moderately positive**	**Strongly positive**
Susceptibility of mineralogy to physical change										
Type of geological deposit				X		Clear evidence of an abundance of **soluble minerals** (halides, some sulfates, some carbonates, etc.) or presence of **moderately reactive minerals** (ultra-mafics, sulfides, etc.). Qualified personnel have sufficient evidence that breakdown could occur within a few years of placement OR qualified personnel have not been consulted.	Moderate presence of **soluble minerals** (halides, some sulfates, some carbonates, etc.) or presence of **moderately reactive minerals** (ultra-mafics, sulfides, etc.). Qualified personnel have reason to infer that breakdown could occur within decades.	Minor amounts of **soluble minerals** as well as **moderately reactive minerals**. Presence of **sparingly soluble minerals** (carbonates, gypsum, etc.) and **mafic minerals** (amphiboles, pyroxenes, biotite, plagioclase, etc.). Qualified personnel have reason to infer that breakdown could occur over decades, potentially during life-of-mine.	Trace amounts of **soluble minerals** as well as **moderately reactive minerals**. Predominately **less reactive minerals** (e.g., orthoclase). Qualified personnel have less concern but could anticipate some potential for long-term changes.	Insignificant amounts of **soluble** or **moderately reactive minerals**. Predominately **non-reactive minerals** (e.g., felsic silicates such as quartz and muscovite). Qualified personnel anticipate limited potential for long-term changes.
Degree of alteration of host rock				X		Clear evidence of altered host rock with minerals that may be hydrated in contact with water. Examples include outcrops and road cuts in analogous rock which have undergone significant weathering compared to buried rock.		Incomplete documentation regarding the degree of alteration of host rock.		Clear evidence of minimally altered host rock based on extensive geological investigation and observations of analogous material.
Quality of material selection				X		Clear evidence that weathering susceptible rock types were not removed or otherwise mitigated from sensitive structural zones (i.e., embankment materials, filter materials, etc.). Lack of coordination between geotechnical engineers and geochemists.	Incomplete documentation to determine if weathering susceptible rock types were used in sensitive structural zones.	Qualified geochemists have documented the presence of weathering susceptible rock types within the deposit but there are uncertainties as to whether these rock types were consistently avoided during construction.		Qualified geotechnical engineers have been made aware of weathering susceptible rock types through collaboration with qualified geochemists. Clear evidence and documentation that concerning mineralogy was removed or otherwise mitigated.
Evidence of reaction										
Evidence of fines generation					X	Clear evidence of fines generation. Concerns raised for geotechnical stability.	Clear evidence of fines generation. Potential for future impact to geotechnical stability if fines generation were to go unmitigated.	Clear evidence of fines generation. No short-term or long-term anticipated impacts to geotechnical stability.	No evidence of fines generation to date.	No evidence of fines generation at a legacy facility.
Evidence of fines migration					X	Clear evidence of fines migration. Imminent concerns raised for geotechnical stability.	Clear evidence of fines migration. Potential for future impact to geotechnical stability if fines migration were to go unmitigated.	Clear evidence of fines migration. No short-term or long-term anticipated impacts to geotechnical stability.	No evidence of fines migration to date.	No evidence of fines migration at a legacy facility.

4 Discussion

4.1 Application of Phase 1 Results from Literature Table and GCMs

The findings of the literature review and GCMs should have immediate application in helping to define and communicate observed or documented geochemical processes that could lead to tailings storage facility performance risks to geochemists and geotechnical engineers involved with design, operation and closure. Key considerations include:

- Geochemical processes, including chemical weathering, precipitation of secondary minerals, and other water-rock interactions, may result in physical changes to construction materials and in drainage features that may not have been present or anticipated during the design of a tailings storage facility.
- The rate and extent of physical changes varies according to the susceptibility of the materials used for construction or contained within the facility, the physical and chemical conditions to which they are exposed, and time.
- Materials that are highly susceptible to change include those containing soluble salts, a high sulfide or carbonate mineral content, or ultramafic minerals. Hydrothermal alteration or the presence of clay minerals may also result in rapid physical breakdown of geological materials as these minerals are hydrated. However, many other minerals are susceptible to varying degrees of weathering on breakage and exposure to air and water and a robust understanding of the geological and mineralogical characteristics of all materials within the facility is critical for understanding how they may change over time.
- Strongly acidic or alkaline conditions, warmer temperatures, and higher rates of water ingress may enhance rates of geochemical processes and therefore increase the potential for physical changes in susceptible materials.
- It may not be possible to measure geochemically induced changes in physical properties using conventional laboratory tests, although there may be some exceptions for more susceptible materials.
  - Alternative approaches for determining mineral susceptibility include use of data from weathered materials at geologically analogous sites, observations and sampling of material exposed in road cuts, existing mine facilities – notably pit walls, older drill core, and colluvium (weathered bedrock), including material from gossans overlying the mineral deposit. Additionally, use of mineral weathering indices may aid in developing correlations between extent of weathering and changes in physical properties.
  - In some of the more susceptible materials, it may be possible to design kinetic tests that accelerate geochemical processes through increased temperature, moisture, or the addition of acids or bases. This type of work could be coupled with physical tests on the weathered samples for comparison with the physical properties of fresh samples. If this type of approach is used, it is critically important to ensure tests are continued for sufficient time to ensure that they reach a logical endpoint.

  - Practitioners should be encouraged to develop and trial new methods to address gaps in the established methods for characterizing physical susceptibility to geochemical processes.

- Many of the physical changes that occur as a result of weathering reactions evolve over extended periods, from decades to centuries, depending on site conditions, materials, and climate. This long-term perspective is critical for understanding how such changes may influence post-closure performance, even if they present limited risk during active operations.
- Where possible, materials that are susceptible to change should be avoided for use in construction. If this is not possible, then consideration of the weathered condition of the material should be made in the design, or the material should be blended (sufficiently as to avoid localized weak zones) such that the overall strength of the material meets the design criteria. For example, if weathering results in strength loss, a range of strength parameters for the weathered material should be used in the facility design.
- Where possible, materials that are susceptible to generation of solutes and subsequent precipitation of those solutes should be avoided, or controls should be put in place to limit these processes. For example, air traps can be used to limit oxygen driven precipitation of iron minerals within drainage galleries. If precipitation is inevitable, then drainage systems should be oversized and set up to allow for pigging of the lines or designed to promote precipitation reactions external to the facility (i.e., submerged drainage lines that daylight downstream of the facility). Alternatively, facilities should be designed to avoid reliance on open drains over the longer term.
- Facility designs should be robust enough to account for potential changes in physical properties and drainage conditions.
- Monitoring plans should include regular inspection and periodic sampling of materials to ensure that the physical integrity anticipated at the design state is sustained over time. Additionally, it should include regular inspection of drainage features to ensure that precipitates are not altering the hydraulic conditions.

4.2 Technical Basis for Developing a Screening-Level Risk Assessment Tool

One of the overall objectives of this work was to assess the plausibility and credibility that some geochemical processes may contribute to physical stability risks. To address this objective, SRK proposed a second phase of work to develop a screening-level risk assessment tool that identifies the key characteristics and/or combinations of factors that make tailings facilities more or less prone to stability risks arising from geochemical processes. This second phase of work is subject to additional project funding and approval. However, the current scope of work included provision to advance and provide a technical basis – or “proof-of-concept” for the risk assessment tool.

The technical basis was advanced through the internal SRK workshop described in Section 2.3.1 and subsequent development of an example hazard assessment framework for one of the physical changes – “Generation and Migration of Fines” using a causal network.

The proposed workflow would begin with the user completing an input sheet with site-specific information. This data would then be processed by the causal network, which incorporates site conditions to evaluate variable selections and assess their relative influence on the parameter of interest. The causal network would then produce an overall estimate of the tailings storage facility's susceptibility to physical instability resulting from geochemically induced changes. Note that the user would not interact directly with the causal network; instead, results would likely be provided through a spreadsheet or another suitable format.

Output could be provided in a qualitative, relative manner, or quantitatively. Regardless of the selected approach, conditional probability tables relating the input variable selections to one another would need to be developed to make the tool useful. Efforts to develop conditional probability tables have not been made, as this scope of work is only intended to provide a framework for assessing risks related to geochemically induced physical changes.

An example of how an input sheet may be filled, a demonstration of the utility of the casual network, and some of the challenges associated with assessing the risks of geochemically induced physical changes are discussed in the following subsections.

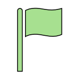
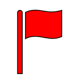
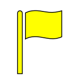
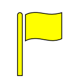
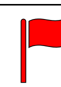
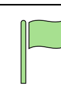
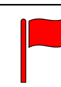
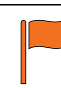
4.2.1 Example Input Sheets for Quantifying Likelihood

The input sheet shown in Table 5 is an example of what would be given to a practicing engineer or geoscientist when performing an evaluation of the effect of a geochemically induced physical change – specifically the likelihood of fines generation and migration. To illustrate how the input sheet may be utilized, an imaginary scenario is proposed below. The completed input sheet for the scenario is presented in Table 6.

> *Scenario: Site engineers at a porphyry copper mine located in a temperate climate with low average rainfall are considering the use of various construction materials for the buttressing of an existing TSF. There is limited room for the buttress, therefore competent material is required to achieve the required degree of stabilization in a small area. An exposed outcrop from the deposit is being considered as potential construction material due to its proximity to the TSF. Mineralogical analyses indicate that sericite (50%), orthoclase (30%), and quartz (17%) are the dominant minerals, and that sulfide minerals are present (~3%). Fines and oxidation products are visible on the surface of the outcrop, and 5-yr old core boxes containing rock core from this deposit have weathered from competent rock to soft clay and sand during storage. Based on this limited information, should the site engineers further consider this material as suitable for construction?*

Table 6 demonstrates why having a non-uniform weight of the variables is important. While there are many weak to strong indicators that increase the probability of fines generation and migration occurring (presence of sulfide minerals, presence of sericite, etc.), one of the strongest indicators, evidence of fines generation, is a Red Flag item. Note that this is just an example, and that the relative weight of each variable would change depending on the facility in question.

Table 6: Example of Completed Input Sheet

Input Variables	Relative Effect on Probability of Physical Change					Input Variable State
	Weakest indicator	Weaker indicator	Neutral	Stronger indicator	Strongest indicator	
Climate		X				
Surficial susceptibility to water infiltration or oxygen ingress		X				
Acidic/Alkaline conditions			X			
Temperature at point of reaction			X			
Extent/anticipated extent of anthropogenic physical weathering			X			
Type of geological deposit				X		
Degree of alteration of host rock				X		
Quality of material selection				X		
Evidence of fines generation					X	
Evidence of fines migration					X	

4.2.2 Example Causal Network and Linkages to Risk Assessment

Figure 4 shows the causal network that was developed to assess the susceptibility of the materials within a given TSF to the generation and migration of fines (due to a geochemical reaction). To provide a conceptual example of how this network could be used, consider a hypothetical TSF that features a rockfill dam, and relies on the strength of the rockfill to maintain stability. During the design of the structure, the strength of the rockfill is relatively well understood and these parameters are used for stability analyses. Within this context, consider the following three scenarios:

1. The rockfill used to construct the dam is susceptible to geochemical reactions that generate fines, and the structure is set in an environment that promotes those geochemical reactions.

2. The structure is constructed using the same rockfill but is not in an environment that typically promotes the necessary geochemical reaction (for example colder or more arid conditions).
3. The structure is set in an environment that is conducive to chemical weathering, but the rockfill is not susceptible to breaking down into fines.

Of these three scenarios, the first would have the most uncertainty in the strength of the rockfill and the greatest potential for the rockfill strength to be lower than what was used in design. All else being equal, these factors would cause the likelihood of failure to be greater for Scenario 1 than the other scenarios. Scenario 2 is similar to the first, as the rockfill is still susceptible to the generation of fines; however, the environment is less likely to provide the necessary conditions to facilitate the necessary geochemical reactions. Accordingly, the likelihood of failure for this condition is less than Scenario 1. Lastly, in the final scenario, since the rockfill is not susceptible to the generation of fines, there is the lowest uncertainty in the rockfill strength, which would translate to the lowest likelihood of failure.

An additional scenario, that cannot currently be assessed using the example network, would be a situation where two rockfill structures are equally prone to fines generation and migration, but one has a safety factor of 1.1 and the other of 1.5. In this scenario, the physical change is likely to be more impactful and consequential for the structure with the lower safety factor. Future work would aim to address this type of scenario.

This example provides a few insights into the utility of the causal network:

- In each of these scenarios, different input variables (whose inputs were available before the problem existed) were altered, impacting the probability of fines generation and migration. As discussed in Section 2.3.2, this change in likelihood can be associated with a variation in material parameter uncertainty. When combined with a traditional geotechnical hazard evaluation tool, the differences in probability of fines generation and migration could be linked to changes in the total probability of failure.
- Although the likelihood of fines generation and migration in Scenario 2 is less than in Scenario 1, there is still some uncertainty as the environment *could* still support the reaction – albeit at lower rates. Therefore, the input variables need to have different states that can accommodate a range of likelihoods.
- As evident from comparison of Scenario 2 and 3, not all input variables will have the same impact on the overall likelihood of a given physical change. In Scenario 3, the resilience of the rockfill negates – or at least greatly diminishes the fact that the environment is conducive to chemical weathering.

From a causal perspective, these observations suggest that if the materials in one facility are highly vulnerable to a specific geochemical reaction while another has more resistant materials, the first facility will exhibit greater uncertainty in the material parameters used to assess its performance. Additionally, when two facilities are constructed with materials that are equally vulnerable to physical changes caused by geochemical reactions, the impact of these changes is likely to be more severe for the facility with lower overall resilience to failure.

Since the causal network shown in Figure 4 is only an example, assessments using the network at this stage are only qualitative. To provide quantitative information, conditional probability tables that properly account for the relative effect of each input variable would need to be developed.

It is anticipated that a future phase of this project would involve assessing the plausibility and credibility of these risks through the development of a screening-level risk assessment tool that identifies the key characteristics and/or combinations of factors that make tailings facilities more or less prone to stability risks due to geochemical processes. The workshop flow charts show that there are potential pathways between geochemical processes, physical changes and failure modes. This type of framework is a starting point for demonstrating plausibility.

As discussed in Section 2.3.2, the causal network is not intended to be the interface that a user of the tool interacts with. The causal network is the analytical engine that operates in the background by incorporating site-specific information (captured within input sheets filled in from Excel) and provides an assessment of how these factors contribute to the facilities vulnerability to geochemically induced physical changes.

4.2.3 Challenges

Developing a tool that can assess the impact of geochemically induced physical changes on a TSFs probability of failure presents several challenges. However, SRK's proposed approach provides a means of overcoming these challenges as discussed below:

1. It is not practical to capture or assess, or achieve consensus on the likelihood of every specific mechanism that could cause a geochemical reaction or series of geochemical reactions to occur;

   Causal networks provide a flexible framework that can be expanded upon as new information becomes available. New information may include additional variables, or adjustments to the impact of variables.

2. A single physical change is likely to affect more than one geotechnical property;

   Traditional risk assessments will typically reveal that there are a few key variables that require critical controls; however, determining these variables is difficult and requires thorough examination. The explicit nature of a causal network allows for the key variables to be more easily identified, furthermore, the impact of controls can also be easily assessed; and,

3. The influence and significance of a physical change will be specific to the characteristics of the facility and location in question. Establishing the relative influence of these variables is challenging.

   Although establishing the network will require subject matter experts and a high degree of judgement during the initial development of the tool, the tool allows for a combination of statistical data and judgement to be incorporated. Furthermore, as additional data is collected, the dependency on judgement can be reduced.

Based on the causal networks ability to address each of these challenges, SRK believes that this approach is the best course of action for developing the risk assessment tool.

5 Summary and Conclusions

The purpose of this report was to provide a summary of the work completed in Phase 1 aimed at addressing how geochemical processes may be of geotechnical significance for TSFs, as well as providing a technical basis for eventual development of a screening-level risk assessment tool. The tasks completed as part of this work included:

- Developing a tabular literature review that elaborates on the relevant geochemical processes, their potential influence on geotechnical parameters, connections to case studies in which physical changes were observed, and factors and conditions which increase the likelihood, plausibility, or significance of the physical change occurring.
- Updating the original geochemical conceptual model from Orcutt (2023) and creating a conceptual model for a rock fill embankment.
- Holding an internal workshop to link geochemical reactions to geotechnical failure modes; and,
- Creating a proof of concept, example hazard framework for assessing the likelihood of one physical change: “Generation and Migration of Fines” with a variety of input variables.
  - The example hazard framework provides the technical basis for assessing the plausibility and credibility of geochemical factors – as well as how geochemical processes may increase the likelihood of failure for a TSF – and demonstrates that this type of approach could be used to develop a screening level risk assessment tool.

Key findings from this study were:

- There are three main types of geochemical processes that can result in physical changes in material properties or design elements; (W) chemical weathering of primary or secondary minerals, (P) precipitation of secondary solid phases, and (O) other water/rock interactions.
- Eleven types of physical changes with potential geotechnical significance were identified, as listed in Table 3.
- The GCMs illustrate locations where each of the eleven physical changes could occur within a tailings facility, although not intended to be exhaustive.
- Certain types of minerals and rocks are more susceptible to weathering than others. Susceptible minerals include halides, certain sulfates, ultra-mafic minerals, sulfides and hydrothermal alteration products that may hydrate upon exposure. Susceptible rocks tend to include one or more of the above listed minerals.
- There are many case studies that demonstrate physical changes occurring in response to geochemical processes. These case studies demonstrate how physical changes can be equated to changes in geotechnical properties such as permeability, shear strength, compressibility, etc.
- There are limited case studies available which cite geochemical processes or time-dependent physical changes as the sole cause of physical instability.
- Many of these processes evolve over extended periods, from decades to centuries, depending on site conditions, materials, and climate. This long-term perspective is critical for understanding how

such changes may influence post-closure performance, even if they present limited risk during active operations.

- The influence and significance of the physical change will be specific to the characteristics of the facility in question and the location within the facility.
- Correlating all the physical changes to particular failure modes does not capture the nuances of conditional probabilities, likelihood, and facility susceptibility as discussed in Section 4.2.
- Increased likelihoods of geochemically induced changes can be tied to an increased uncertainty in material properties. If all else is equal, this increased uncertainty will lead to an increased probability of failure.

Although the likelihood and consequence of physical changes resulting in geotechnical failures was not quantified at this stage, SRK has provided a framework that could be used for this purpose in a second phase of work.

6 Recommendations

The findings of the literature review and GCMs should have immediate application in helping to define and communicate the observed and/or documented geochemical processes that could lead to tailings storage facility performance risks amongst both geochemists and geotechnical engineers involved with design, operation and closure of tailings storage facilities. There may be merit in sharing the findings of the literature review and the considerations identified in Section 4.1 of this report with broader industry at this time.

Based on the work completed in Phase I, SRK suggests the following (Table 7) as next steps to providing an industry guidance document which addresses the objectives of the INAP and MEND organizations.

Table 7: Summary of Recommendations

Relevant Section	Recommendation
3.2	Develop additional geochemical conceptual models for alternate facility types as deemed appropriate.
4.3	An example causal network has been developed for only one of the physical changes. Causal networks could be developed to account for all the physical changes identified in the literature review. These networks would likely incorporate several of the same input variables.
4.3	As noted throughout the previous sections, the current state of the network is qualitative. A logical next step in the development of the network would be to incorporate conditional probability tables to provide quantitative information that gives a more tangible assessment of which scenarios have higher level of risk associated with them. Section 4.3 briefly mentioned that the network is designed for modular use in different facility locations. Unique conditional probability tables may be needed, as variable importance can vary by location.
4.4	The assessment of the likelihood of physical change should be guided by additional subject matter experts who can identify key input variables and their relative importance. A collaborative effort involving these experts would be beneficial in refining the components of the example network and all potential future networks.

Closure

This report, Phase I Summary Report: Geochemical Processes of Geotechnical Significance, was prepared by

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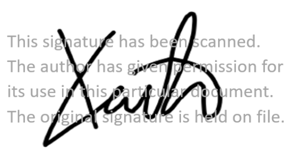

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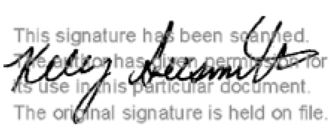
and reviewed by



Kelly Sexsmith Principal Consultant, Geochemistry
Principal Consultant

All data used as source material plus the text, tables, figures, and attachments of this document have been reviewed and prepared in accordance with generally accepted professional engineering and environmental practices.

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Appendix A Tabular Literature Review

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FINAL

Memo

To	Albert Stoffers [MEND], Erin Clyde [MEND], Chris Kennedy [INAP, MEND], Bill Price [MEND], Gilles Tremblay [INAP], Hugh Davies [INAP]	**Client**	INAP and MEND
From	Kelly Sexsmith, Heath Orcutt	**Project**	CAPR003302
		Date	October 30, 2025

Subject Literature Review on Geochemical Processes of Geotechnical Significance

1. Introduction

SRK Consulting (Canada) Inc. have been retained to develop an industry focused report to support assessment of tailings stability risks arising from geochemical reactivity. The first task (Task 100) was to expand on an existing literature review by Orcutt (2023) on geochemical processes that may alter the physical properties of tailings, leach residues, or construction rock (including waste rock, quarry rock, and other types of borrow material). This memo is the deliverable for Task 100.

2. Literature Review

The literature review considers the physical changes that occur as a result of overarching geochemical processes that could occur during construction, operation and long-term post-closure of a facility. The literature review focused primarily on tailings storage facilities (TSF), yet includes case studies from other mine waste facilities where specific physical changes have been observed and documented. While the focus is on the potential implications to tailings stability, many of the findings are transferable to other types of facilities, including heap leach operations, waste rock dumps and pit walls. Site specific conditions, including the facility design, foundation conditions, design life, geochemical characteristics of the tailings and construction materials, as well as external factors such as climate need to be considered in defining the specific processes and physical changes that are relevant to a specific facility.

The geochemical processes identified through the literature review can be organized into three main types, as summarized in Table 1 and described as follows: (W) chemical weathering of primary or secondary minerals, (P) precipitation of secondary solid phases (including both crystalline minerals and non-crystalline amorphous phases), and (O) other water/rock interactions. Each of these geochemical processes contribute individually, collectively, or some combination thereof to a variety of physical changes which are illustrated collectively in Figure 1 and 2. Table 2 describes each of the physical changes, as well as:

- Potential geotechnical significance of the changes
- Examples where the process has been observed
- Factors or conditions that enhance plausibility, significance, or timescale, and
- A visual representation of the process.

Physical changes 1-4 occur primarily due to chemical weathering of primary or secondary minerals. They are:

1. Generation and migration of fines: It is commonly understood and observed that weathering results in the breakdown of particles and a decrease in the average particle size distribution. Higher fines content can have an influence on the shear strength properties of the medium, reduce permeability, and hinder drainage.

2. Alteration of particle shape and texture: Chemical weathering has the potential to change the shape (angularity) and texture (roughness) of individual particles over time. This can influence geotechnical properties such as the internal friction angle.

3. Formation of clay minerals (i.e., weaker phyllosilicates): The presence of silicate minerals in tailings and mine waste facilities, as well as their exposure to weathering agents such as water and oxygen, can result in the formation of weaker clay minerals over time. Clay minerals, such as sericite and smectite, have very different physical and chemical properties than their primary mineral counterparts, such as biotite, and can contribute to changes in the permeability and strength of materials.

4. Mass loss from release of solutes: This is the physical change resulting from the dissolution of highly soluble to moderately soluble minerals. Mass loss can contribute to void development, karst development, preferential flow paths, piping, and internal erosion.

Physical changes 5-9 occur primarily due to precipitation of secondary solid phases. They are:

1. Positive volume change (e.g., sulfide-oxidation induced heave): Secondary solid phases are less dense than their primary counterparts and, when forming along cracks or discontinuities, can result in positive volume change.

2. Interparticle cementation or loss of cementation: Secondary solid phases can cement particles together along grain contacts and form a metastable structure. The same is true for some types of collapsible soils which may be naturally occurring in foundation materials. An important geotechnical distinction from other physical changes is the potential for brittle response upon loading and rapid failure.

3. Clogging of pores: High concentrations of dissolved ions, upon reaching saturation and/or favorable environmental conditions, can form precipitates within the pore space of construction materials and/or embankments. This can lead to a reduction in porosity, hinder drainage, and a rise in the phreatic surface.

4. Formation of low-permeability zones: Low-permeability layers (e.g., hardpans) form when secondary mineral precipitation occurs in a concentrated, laterally extensive area. This can lead to the formation of perched water tables, limited evaporation, and reduced drain down.

5. Clogging of drainage and scaling of pipes: Secondary solid phases can precipitate within drainage pipes and/or porous drain media preventing drainage as designed and potentially leading to a rise in the phreatic surface.

While physical changes 5-9 originate from similar geochemical reactions, the distinctions are made primarily on the:

- **Different areas** in which secondary solid phase precipitation occurs: 5) along discontinuities or cracks, 6) between grain contacts, 7) filling part or all the pore space within areas of construction materials and/or embankments, 8) within the tailings matrix as a laterally extensive unit, and 9) within drainage pipes and porous drain media.
- **Resulting (potentially adverse) physical changes**: (5) positive volume deformation or heave, (6) brittle behavior, (7) reduced permeability and drainage, (8), reduced permeability and increased strength, and (9), clogging of pipes.

Physical changes 10 and 11 occur primarily due to interactions with acidic or saline seepage. They are:

1. Changes in clay mineral properties under acidic or saline conditions: Clay minerals (phyllosilicates) can undergo alteration of their mineral structure and fabric upon contact with an acidic or saline solution. Low pH solutions can alter the surface charge of clays, which in turn influences the interparticle dispersion (suspension, flocculation, etc.), and saline solutions, or solutions with high concentrations of multi-valent cations, can change the swelling behavior of clays by replacing the monovalent cations within clay minerals.

2. Corrosion of steel, concrete, and other infrastructure: Acidic conditions and/or high concentrations of sulfate or chloride can result in increased rates of corrosion in steel, expansion/deterioration of concrete, and degradation of various infrastructure components susceptible to acidic conditions such as pumps, monitoring equipment, well casings, rock bolts, etc.

Key references are cited within the tables and included in the list of references.

Sources of information that were considered in this literature review include online university library databases, the SME OneMine digital library, the online MEND document repository, internal SRK projects, suggested reference documents provided by MEND and INAP, and conference proceedings. Conference proceedings scanned for relevant information include Tailings and Mine Waste, International Conference on Acid Rock Drainage, American Society of Reclamation Sciences (formerly known as the American Society of Mining and Reclamation), Australian Centre for Geomechanics, and International Mine Water Association.

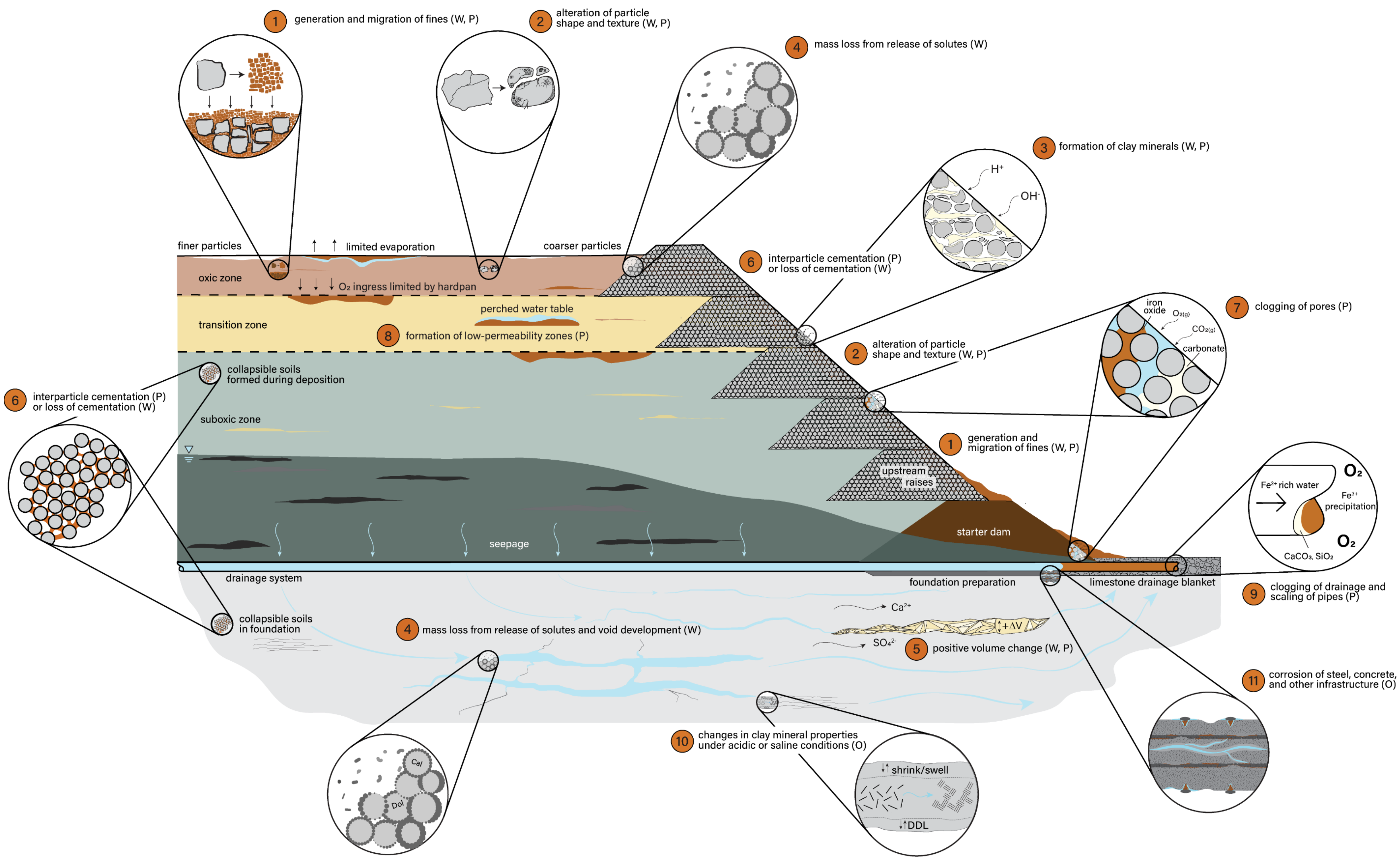


Figure 1: Geochemical conceptual model of an unlined TSF with an upstream embankment that summarizes potential changes in physical material properties resulting from geochemical processes.

Notes: Relevant geochemical processes include the following: W = Chemical weathering of primary or secondary minerals, P = Precipitation of secondary solid phases, O = Other water/rock interactions.

The figure is intended to illustrate the potential range of physical changes that could occur. Site specific design, foundation and geochemical characteristics are likely to further constrain the changes relevant to a specific facility.

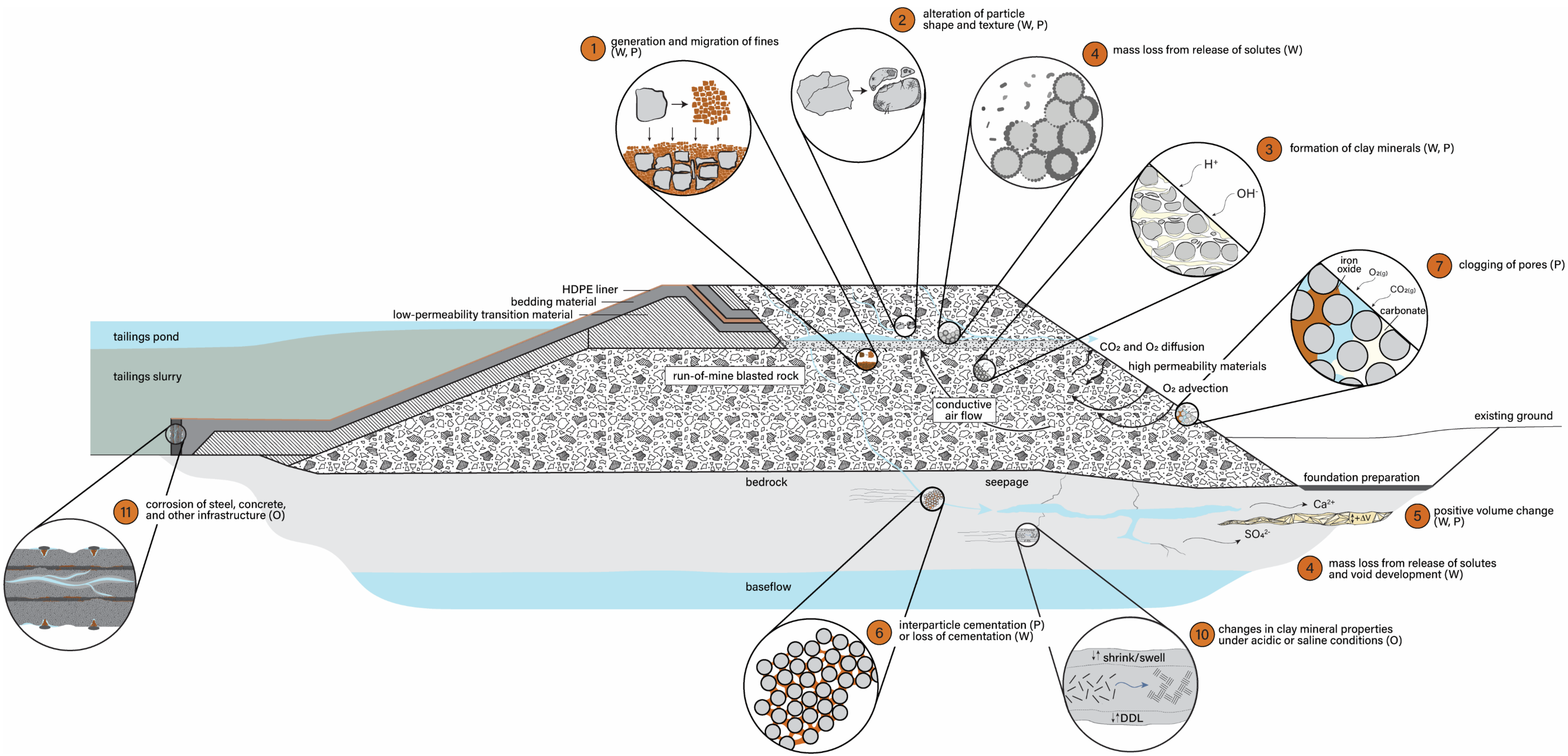


Figure 2: Geochemical conceptual model of a lined rock fill embankment with containment that summarizes potential changes in physical material properties resulting from geochemical processes.

Notes: Relevant geochemical processes include the following: W = Chemical weathering of primary or secondary minerals, P = Precipitation of secondary solid phases, O = Other water/rock interactions.

The figure is intended to illustrate the potential range of physical changes that could occur. Site specific design, foundation and geochemical characteristics are likely to further constrain the changes relevant to a specific facility.

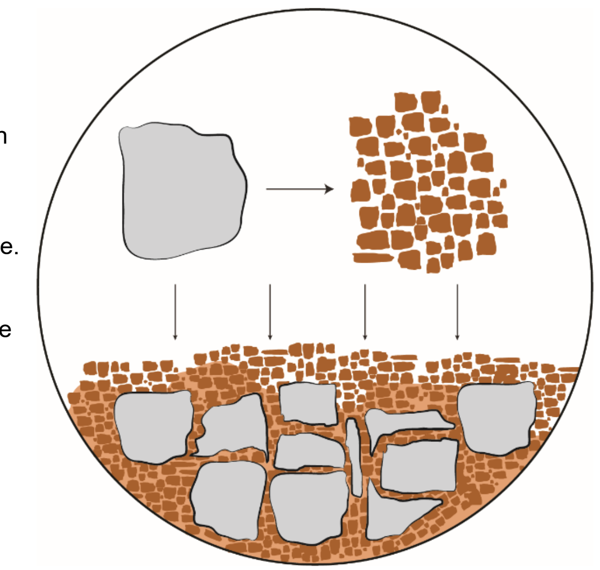
Table 1: Overarching Geochemical Processes Leading to Physical Changes

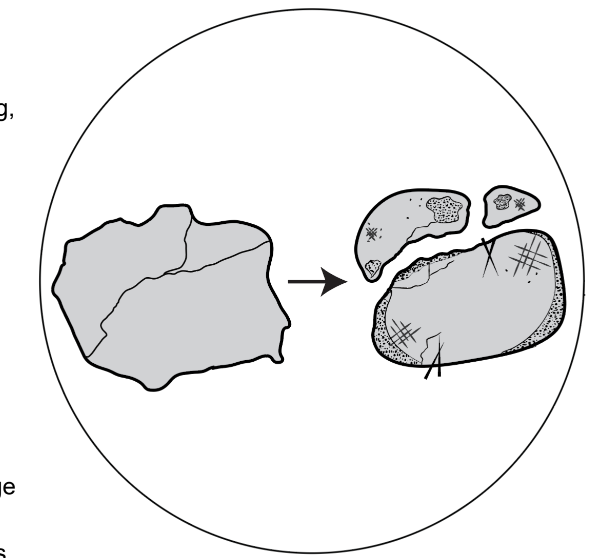
<table>
<tr><th>Geochemical Process</th><th>Description</th><th>Physical Changes*</th></tr>
<tr><td>Chemical weathering of primary or secondary minerals (W)</td><td>Chemical weathering is defined as the breakdown of rocks and minerals by chemical processes such as dissolution, hydrolysis, carbonation, oxidation/reduction, cation exchange, or hydration.
■ Dissolution of primary or secondary minerals is the most basic form of chemical weathering that can affect soluble minerals (e.g., halides, efflorescent salts, some sulfates), moderately reactive minerals (e.g., ultra-mafics, sulfides, etc.), sparingly soluble minerals (e.g., carbonates, gypsum, oxides), less reactive minerals (e.g., orthoclase) or highly resistant minerals (e.g., quartz, muscovite, etc.) given sufficient time. Rates of dissolution depend on rates of water exchange, solubility limits, pH, and kinetic rates. Dissolution of carbonate minerals can be enhanced by the presence of carbon dioxide and/or acid generated from the oxidation of sulfide minerals. Iron and manganese oxides are also susceptible to dissolution under reducing conditions (oxygen limited conditions), which can occur in saturated mine wastes or other environments where oxygen is excluded.
– Example: The dissolution of calcium carbonate ($CaCO_3$) releases Ca^{2+} and CO_3^{2-} into solution.
■ Hydrolysis is the reaction of a mineral with water (H^+ and OH^- ions) which, due to their small particle size, integrate themselves into the mineral lattice and replace existing ions (Mitchell and Soga, 2005). Most hydrolysis associated with the weathering of minerals is acid hydrolysis, in which protons (H^+) attack chemical bonds in mineral crystals. The source of protons can be dissolved carbon dioxide (carbonic acid), sulfuric acid, or organic acids.
– Example: Hydrolysis of iron sulfate to iron hydroxide, $FeSO_4 + 2H_2O \rightarrow Fe(OH)_2 + H_2SO_4$. In this case, the sulfate ion (SO_4) is replaced by hydroxide (OH^-).
■ Carbonation is the reaction of earthen materials with carbonate or bicarbonate ions originating from atmospheric CO_2 (Mitchell and Soga, 2005).
– Example: Carbonation of dolomitic limestone to secondary carbonate minerals, $CaMg(CO_3)_2 + 2CO_2 + 2H_2O \rightarrow Ca(HCO_3)_2 + Mg(HCO_3)_2$.
■ Oxidation is the loss of electrons whereas reduction is the gain of electrons. Oxidation is often stimulated by the reaction of a mineral with an oxidizing agent such as oxygen, ferric-iron (Fe[III]), or nitrate (NO_3^-), and results in the subsequent breakdown of minerals. Reduction reactions can be important for promoting microbial and plant growth that later contribute to further weathering (Michell and Soga, 2005).
– Example: Oxidation of pyrite (FeS_2) generates dissolved acid (H^+), sulfate (SO_4^{2-}), and iron (Fe [II]). Fe(II) can then be oxidized to Fe(III) by microbial activity, oxygen, or another oxidizing agent. Fe(III) can react with water to form secondary minerals such as ferrihydrite, $Fe(OH)_3$. Fe(III) can also react with water, ions, and sulfate to form secondary minerals such as jarosite, $KFe_3(SO_4)_2(OH)_6$, which can serve as a long-term source of acidity and contribute to further chemical weathering .
■ Cation exchange is the replacement of one cation with another cation. Cation exchange can alter the surface charge of minerals, as well as physical properties such as permeability (Mitchell and Soga, 2005).
– Example: Exchange of sodium (Na^+) in sodium bentonite with calcium (Ca^{2+}). The smaller size of calcium compared to sodium results in a decrease in the thickness of the minerals double-diffuse layer (DDL) and an overall increase in permeability.
■ Hydration is the surface adsorption of water and is often the first step to chemical weathering (Mitchell and Soga, 2005). Hydration reactions can occur when anhydrous minerals are exposed by mining and react with water. Hydration can also transform oxides to hydroxides, silicates to phyllosilicates, etc.
– Example: Hydration of anhydrite ($CaSO_4$), resulting in the formation of gypsum ($CaSO_4 \cdot 2H_2O$).
Chemical weathering rates depend on the mineral composition and structure, climatic conditions, accessibility to weathering agents, the chemistry of the solution interacting with the rock mass, and rates of physical weathering. The specific conditions which may enhance certain physical changes are discussed in Table 2.
Silicates are the most common group of minerals and are present in almost all types of mine waste. Some types of silicate minerals are more susceptible than others and generally follow the opposite trend of the Bowen's reaction series (olivine > amphiboles and pyroxenes > biotite and plagioclase > orthoclase (K-spar) > muscovite >> quartz) (White and Buss, 2014). In general, rocks of mafic or ultra-mafic composition (rich in magnesium and iron) weather more rapidly, while rocks with a more felsic composition (containing mostly silicates) weather more slowly. Silicate weathering products include phyllosilicates (clay minerals), dissolved solutes, iron and aluminum oxides, and in the case of quartz – some dissolution results in more rounded quartz grains. Weak phyllosilicate minerals are often formed by hydrothermal alteration and metamorphism (including faulting), as well as weathering of pre-existing phyllosilicate minerals. As described below, breakdown of silicate minerals can be enhanced by the presence of other types of chemical weathering processes such as sulfide oxidation or hydration.</td><td>(1) Generation and migration of fines
(2) Alteration of particle shape and texture
(3) Formation of clay minerals
(4) Mass loss from release of solutes
(6) Loss of interparticle cementation**</td></tr>
</table>

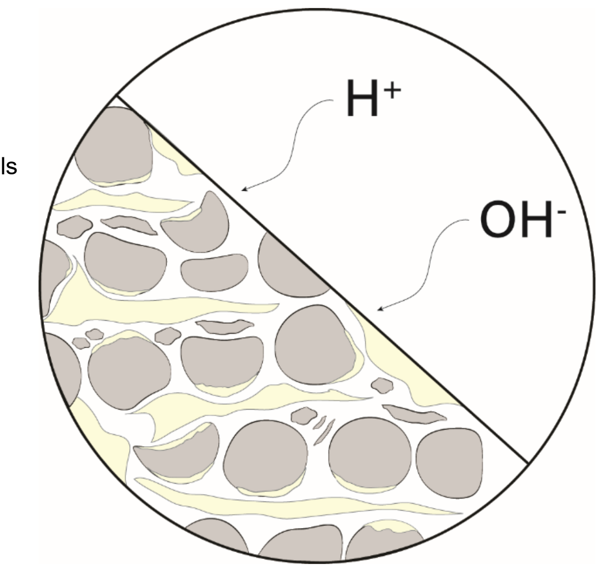
Geochemical Process	Description	Physical Changes*
	The sulfide mineral content of mine waste can vary widely depending on many factors including the deposit type. Sulfide oxidation produces dissolved acid (H^+), metals, and sulfate (SO_4^{2-}). Acid generation may result in an acidic pH and acidic conditions can greatly enhance the rates of other geochemical reactions, while metals and sulfate may precipitate as various secondary solid phases (e.g., oxides and sulfate minerals). Acidic conditions can also occur due to the reaction of water with carbonic acid from the atmosphere (i.e. acid rain) or nearby processing facilities (e.g., roaster stacks). Higher temperatures and greater rainfall can enhance the rate of chemical weathering. The permeability of a material and the rate of water exchange also influences the rate of chemical weathering. Microbial activity can also enhance weathering rates. Microbes are ubiquitous in mine waste and their contribution to acid-generation and subsequent weathering of mine waste is well established (Blowes et al., 1998; Nordstrom et al., 2015; Nordstrom and Southam, 1997, Schippers et al. 2010). The cycle of Fe(II) to Fe(III) is accelerated by microbial activity because iron-oxidizing bacteria (e.g., *Acidithiobacillus ferrooxidans*) are known to be capable of accelerating the rate of iron oxidation by up to six orders of magnitude relative to the abiotic rate under optimal pH conditions (Nordstrom, 2003; Singer and Stumm, 1970).	
Precipitation of Secondary Solid Phases (P)	Precipitation occurs when solutes released from geochemical processes reach their solubility limits and the reaction kinetics are favorable for solute precipitation. This may occur due to the ongoing release of solutes or along transport pathways where there are changes in pH, redox conditions, or volumes of water (i.e. evaporation). – Example: Calcium and sulphate released into solution from sulfide oxidation and buffering by carbonate minerals results in the formation of gypsum ($CaSO_4 \cdot 2H_2O$). The factors which influence solute precipitation are pH, solute concentrations, redox, solubility, reaction kinetics, temperature, and mineral saturation. Some of these factors are interrelated; for example, the solubility of some minerals will increase at lower pH values and remain in solution until reaching a different geochemical environment (such as the surface or a neutral pH zone). Saturation is also an important factor and can vary based on the rate of flushing (i.e., diffuse seepage zones are more likely to have low enough flow rates to precipitate solids while still renovating pore volumes). Temperature increases will often increase the rate of a reaction, as seen in the Arrhenius equation. While the solubility of many secondary solid phases increases with temperature, some become less soluble (e.g., calcite). pH and redox determine the type of mineral which forms and whether solutes remain dissolved, as seen in Pourbaix (Eh-pH) diagrams. The reaction kinetics will determine the rate of formation and if it is relevant on a geological timescale or not.	(1), (2), and (3) as above (5) Positive volume change (6) Interparticle cementation** (7) Clogging of pores (8) Formation of low-permeability zones (i.e., hardpans) (9) Clogging of drainage and scaling of pipes
Other Water/Rock Interactions (O)	Other water/rock interactions that may have geotechnical implications include: ▪ effects of water chemistry on the surface properties of minerals – particularly phyllosilicate clays. ▪ effects of water chemistry on pipes, concrete, and other infrastructure, including corrosion by salts or acid and scaling.	(10) Changes in clay mineral properties under acidic or saline conditions (11) Corrosion of infrastructure

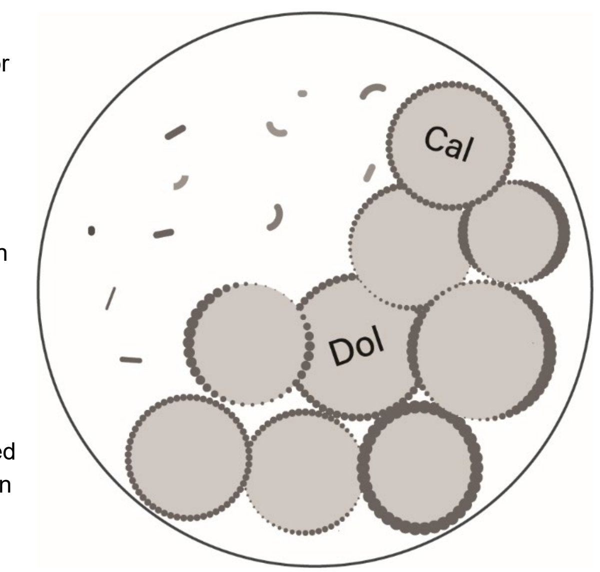
Notes: *Numbering corresponds to those shown in Figures 1 and 2. **Duplicates of Item 6 are for both the gain and loss of cementation.

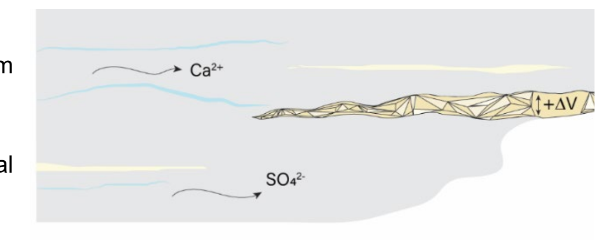
Table 2: Physical Changes Resulting from Geochemical Processes

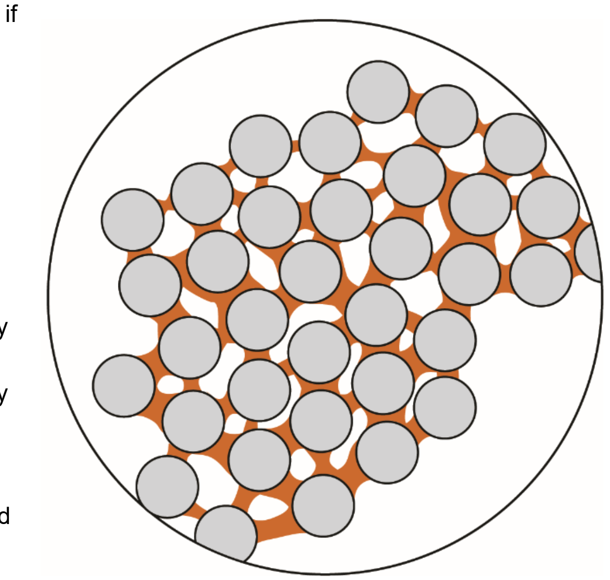
Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(1) Generation and Migration of Fines (W, P)	Weathering and dissolution processes can break down primary minerals or rock particles into smaller fragments and disaggregate mineral grains. Sulfide oxidation and/or the generation of acidic conditions may enhance particle breakdown via dissolution of carbonates along cracks or voids, formation of porous alteration rims and etch pits which weaken the material, and secondary mineral precipitation along intergranular cracks and voids which break the rock apart (USGS et al., 2005). Additionally, precipitation of secondary solid phases can produce fines (Elghali et al., 2021; Filipowicz and Borys, 2007; Forsberg and Ledin, 2001). Fines can lead to pore clogging and reduced permeability (Elghali et al., 2021; Lin, 1997). The influence of fines and/or secondary weathering products on geotechnical properties (e.g., shear strength, compressibility, dry density, water content, etc.) have been observed (Filipowicz and Borys, 2007; Ng et al., 2019; Carelson, 2013).	▪ Decreased average particle size and broadened particle size distribution. – Decreased void ratio. – Decreased permeability. – Increased water retention capacity. – Increased plasticity. – Increased potential for undrained conditions. – Decreased friction angle and shear strength. ▪ Increased specific surface area and affinity for ions. ▪ Decreased self-weight consolidation. Note: Reverse occurs if fines migration lowers fines content.	1. Block caving and in-situ leaching at a copper porphyry deposit resulted in physical and chemical weathering of rock comprising an engineered structure at a site in Arizona. Various indices measuring the extent of chemical weathering were correlated with grain size distribution and showed higher fines content with greater extent of weathering. Coarser material showed higher friction angles and therefore strength (Confidential SRK Project, 2023). 2. Oxidation of Fe(II) to Fe(III) within biotite grains led to an increase in connected porosity, an increase in hydraulic conductivity, an increase in volume, matrix fracturing (fines generation), reduction in tensile strength, and an increase in abrasion rate (Goodfellow et al., 2016). 3. The Joutel Gold Mine tailings developed redox zones within the tailings impoundment that show increased secondary mineral precipitation (gypsum and goethite), decreased average particle size, and increased specific surface area (SSA) at the surface when compared to unoxidized samples below the water table (Elghali et al., 2021). 4. Waste rock at the Dinero mine showed K-jarosite formation along cleavage plans in altered muscovite, expanding and fragmenting the phyllosilicate mineral. SEM images also showed evidence of fines settling out of suspension such as formation of cross beds and soft sediment slumps within void spaces and the presence of microlaminated fines (USGS et al., 2005).	A high sulfide content can encourage fines generation due to the release of acidic byproducts capable of breaking down rock and the formation of secondary solid phases that are smaller in size than their primary counterparts. The presence of mafic minerals, hydrothermally altered minerals, and/or amorphous solid phases can increase fines content due to their susceptibility to breakdown. The presence of carbonate or sulfide veins within rock material can also increase susceptibility to breakdown. Increased fines content is typically limited to the surface of TSFs or within the active oxidation zone. However, fines can be transported by wind or water erosion to the toe of an embankment, leading to a decrease in permeability and increase in pore water pressure (KCB, 2023). Facilities experiencing acidic conditions, such as acidic heap leach facilities, may be more likely to see particle degradation and an increased fines content over time. Fines migration has been documented within waste rock at the Dinero and Questa mines (McLemore et al., 2009; Shaw et al., 2002; USGS et al., 2005). Well-connected flow paths and more porous structures allow fines to migrate throughout a facility. Fines can be transported via suspension or can precipitate at depth. Therefore, the rate of flushing may influence where fines settle.	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(2) Alteration of Particle Shape and Texture (W, P)	Weathering of primary minerals has the potential to alter the particle shape (angularity) and surface texture (roughness) of individual grains. The precipitation of secondary minerals and amorphous solids on the surface of individual grains (coatings) can also alter the particle shape and texture. Precipitated secondary solids will likely have different surface properties than their primary counterparts. Some precipitated solids are smooth, amorphous minerals that exhibit less particle interlocking while some are needle-like minerals (e.g., goethite) that increase surface roughness.	▪ Decreased or increased surface roughness. ▪ Decreased or increased angularity and particle interlocking. – Decreased or increased friction angle and shear strength. ▪ Decreased durability.	1. Pb-Zn tailings sands from a mine in Hunan Province were analyzed in a laboratory to determine the effect of acidification on the internal friction angle of individual grains and the cohesion force. A fractal dimension approach was used to generate a 2D crystal edge map and 3D structure surface map from SEM imaging. The results indicated a decrease in internal friction angle with an increase in oxidation (Wang et al., 2023). 2. Waste rock piles from the Dinero mine exhibited breakdown of individual galena (PbS) minerals upon interaction with acidic pore fluid and the formation of anglesite ($PbSO_4$) alteration rims, resulting in a porous outer layer. Evidence of euhedral voids and skeletal remains of primary minerals were also seen in SEM images. The impact of these changes on geotechnical stability is unclear (USGS et al., 2005). 3. A weathered residual soil containing high concentrations of needle-like goethite minerals showed an increase in surface roughness and the formation of large, structure supported voids and aggregates (Airey et al., 2012).	Changes are likely to be observed more rapidly in materials with high concentrations of sulfide minerals or where highly acidic solutions are present. Microbial activity can also accelerate the process, as microbes form acidic "micro-environments" which locally accelerate weathering, mineral precipitation, and alteration of the mineral surface (Lui et al., 2021). Amorphous phases, rather than crystalline minerals, are also more susceptible to alteration due to their structure. Wet conditions and higher temperatures may accelerate alteration, as seen in the Dinero waste rock piles. Typically enhanced within the oxidation zone due to interaction with acidic pore fluid and oxygen. Can also occur along seepage paths or in drainage zones. Changes will increase over time and are more likely to be observed in older legacy facilities than new facilities.	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(3) Formation of Clay Minerals (W, P)	Primary silicates can weather to phyllosilicates (clay minerals) over extended periods of time (Mitchell and Soga, 2005; McBride, 1994). The primary mechanism for silicate weathering is hydrolysis (interaction with H^+ and OH^- ions) or dissolution. Acidic conditions may accelerate this process and/or alter the chemical and mechanical behavior of clays (see item 10). Hydrothermal alteration associated with mineral deposits often results in the formation of clay minerals in fresh waste rock and ore which can be difficult to distinguish from clay minerals that develop as a result of weathering. Nonetheless, they are still susceptible to physical breakdown upon hydration and can result in more rapid changes in physical properties. The presence of clay minerals within mine waste materials is significant because clay minerals have significantly different mechanical properties than primary silicates and tend to be weaker materials.	▪ Reduced porosity and void ratio. – Reduced permeability. – Increased tendency to shear undrained. – Increased liquefaction potential. ▪ Lower density minerals. – Reduced self-weight consolidation. – Potential expansion along cracks or voids. ▪ Increased affinity for water and/or ions due to the electrostatic bond of clay minerals. ▪ Increased tendency for shrink/swell behavior.	1. Sulfide oxidation in the active oxidation layer of high sulfide (up to 30% S) tailings at the Lilla Bredsjön mine led to primary silicate dissolution (i.e., talc, chlorite, and biotite – all mafic or ultra-mafic minerals) and subsequent formation of jarosite and mixed-layer chlorite-vermiculite-smectite. The active oxidation layer contains 10-20% mixed-layer phyllosilicates and a 5% reduction in biotite content compared to the water saturated zone (Lin et al., 1997). 2. In the Dinero waste rock piles, the release of potassium for formation of K-jarosite between phyllosilicate layers serves as evidence of the weathering of primary silicates such as biotite and muscovite (USGS et al., 2005). 3. The Questa Waste Rock Stability Report includes a detailed analysis of clay minerals in waste rock piles, ultimately determining that the clay minerals present were of hydrothermal origin and not a result of chemical weathering. Analogs such as unweathered drill core, accompanied by detailed chemical and mineralogical comparisons between the weathered and unweathered materials, allowed for this conclusion. However, the rock could be susceptible to further chemical weathering if pH conditions within the pile were to change (McLemore et al., 2009; Morkeh and McLemore, 2012). 4. Sericitic schist (containing phyllosilicates) from the South Waste Rock Dump at La Mine Doyon, demonstrated weathering to more than 40% fines (< 2mm). Sericitic waste rock is more susceptible to physical degradation than other rock types due to the shrink/swell capacity of clays and expansion along the interparticle layers, therefore, this site experienced more weathering than typically observed for waste rock (Choquette and Gélinas, 1994).	Silicate minerals are abundant in tailings and mine waste; however, they typically experience much slower rates of weathering compared to other mineral types. Many studies have attempted to quantify the risk posed by silicate weathering in waste rock piles and have determined that the slow rate of weathering negates the risk posed by silicates. However, mafic and ultra-mafic rocks and minerals such as olivine can decompose much more rapidly. The presence of hydrothermal clays can lead to physical property changes upon hydration, cation exchange, or hydrolysis (see item 10). Enhanced rates of weathering can also occur via acid leaching and microbial activity. Acidic conditions can alter the mechanical behavior of clays regardless of their origin (see item 10). More likely to form in areas that experience continuous flushing of water (along seepage paths, drain down areas, etc.). More likely to be of significance if formed as a weak layer within the embankment or within the foundation.	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(4) Mass loss from release of solutes (W)	Soluble minerals (halides, efflorescent salts, some sulfates, etc.), sparingly soluble minerals (carbonates, gypsum, etc.), and moderately reactive minerals (ultra-mafics, sulfides, etc.) can dissolve upon interaction with acidic and/or neutral pore water, resulting in loss of solids mass. Carbonates dissolve 4-6 orders of magnitude faster under acidic conditions whereas, generally, the dissolution of halides and sulfates are less influenced by pH. Oxidation of sulfide minerals can also lead to mass loss as reaction products are released into solution and flushed from materials. The oxidation of sulfide minerals may also be the source of acidity that enhances carbonate dissolution. Carbonate dissolution along veins can create localized fractures in rock materials that lead to the development of preferential flow paths and particle degradation. These fractures may expose sulfide minerals to oxidation, further accelerating the degradation and mass loss process. Where there is extensive mass loss within discrete areas, karstic conditions can develop, leading to preferential flow paths, internal erosion, and/or piping. Mass loss can be accompanied by precipitation of secondary solid phases which can fill the void space with lower density minerals (see item 7).	■ Mass loss. – Increased void ratio. – Increased permeability. – Increased compressibility. – Local fractures. ■ Potential for differential settlement. ■ Development of preferential flow paths. – Potential for piping/internal erosion. – Increased hydraulic conductivity. ■ Development of karst. – Potential for collapse.	1. Caliche soils comprised of halite, sodium and potassium nitrate, calcite, gypsum and anhydrite are present in the foundation and construction materials of a tailings embankment in Chile. Introduction of process solutions led to rapid dissolution of soluble salts, development of voids, and loss of process solutions to the underlying groundwater system (Confidential SRK Project, 2023). 2. Dissolution pits, or voids, (0.5 mm) from complete oxidation and depletion of sulfide minerals were observed throughout the tailings at depths of approximately 0.3 to 0.5 m below ground surface in highly acidic tailings from a massive sulfide tailings deposit in the Yukon. These dissolution pits could allow for increased percolation of water into the tailings particles over time (Confidential SRK Project, 2021). 3. Mass balance calculations completed to assess rates of carbonate depletion in non-acid generating tailings deposits in British Columbia and Arizona with low to moderate amounts of carbonate minerals showed that it would take thousands of years for carbonate depletion to occur due to the relatively low solubility and low rates of percolation through the tailings mass (Confidential SRK Projects 2022, 2023). 4. Dissolution of salt and gypsum beds in the foundation of the Red Bluff reservoir in Texas, USA resulted in stability concerns before mitigation efforts were performed (Johnson et al., 2021). Similar examples include the Quail Creek Dyke failure in Utah, USA due to flow through an undetected gypsum-karst unit underlying the earth-fill embankment (O'Neill and Gourley, 1991).	Factors that increase the extent of mass loss are low-pH environments (high sulfide content), presence of soluble minerals, and wet environments. The rate of carbonate dissolution can be accelerated to relevant time scales under acidic conditions. Sulfate mineral dissolution is less influenced by pH and can still occur under neutral conditions in situations where there are high rates of water exchange (e.g. wet climates and coarser grained materials). In general, dissolution rates are controlled by mineral specific solubility limits and the amount and composition of the water interacting with the solids. For example, process water reacting with waste materials during operations will be near saturation and, as such, will have less capacity for dissolving ions than fresh water. In general, percolation rates through fine tailings are limited compared to percolation rates through coarse rock or sand embankments. In these systems, the water tends to reach equilibrium with respect to secondary solid phases quite rapidly. Therefore, unless highly soluble minerals are present or the tailings are unusually coarse or have preferential flow paths that channel flow through sensitive areas, depletion of sparingly soluble carbonate and sulfate minerals is expected to be very slow. Dissolution rates may be higher in systems with higher flushing rates or acidic porewater. An example carbonate depletion rate from an acidic tailings impoundment is 0.03 m/yr (Price, personal comm). Karstic conditions generally take a very long time to develop and, in most conditions, and it is more likely that karst formation occurred prior to mining activity. The location and extent of the soluble minerals is important for determining consequence. For example, calcite dissolution is not likely to be a stability concern within the tailings but could be a concern if occurring laterally continuously in foundation materials or embankment materials. Overall, the sensitivity of the structure to deformation will determine the importance of dissolution.	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(5) Positive volume change (e.g. sulfide-oxidation induced heave) (W, P)	Many secondary minerals and amorphous phases are less dense than their primary mineral counterparts and therefore occupy a larger volume. Examples of positive volume deformation resulting from chemical weathering include sulfide-oxidation induced heave, gypsum precipitation, Fe(III) precipitation, salt heave, bacterially induced heave, and hydration of sulfates (e.g., anhydrite). Sulfide-oxidation induced heave occurs due to oxidation of sulfide and precipitation of sulfate minerals (e.g., gypsum), resulting in less dense byproducts and volumetric expansion (Bryant, 2003). Gypsum formation can also occur when anhydrous minerals such as anhydrite are extracted from deep areas of a mine and are allowed to react with water. This can result in a positive volume change (Alonso and Ramon, 2013; Einfalt and Götz, 1976). Clay hydration and/or swelling depends on the surface charge density, cation valence, electrolyte concentration, and dielectric constant (Mitchell and Soga, 2005). Common swelling clays include smectites and vermiculites.	▪ Positive volume change. – Potential for heave. – Potential for differential settlement. ▪ Potential for damage to: – Lighter infrastructure, such as buildings. – Cover systems. – Rigid core facilities (i.e., asphalt core, concrete core, etc.). – Abutments.	1. Sulfide-oxidation induced heave and gypsum formation occurred along discontinuities in disturbed and undisturbed pyritic shale underlying the Johnson City Public Library. Deformation was ultimately substantial enough (up to 11 cm in some areas) that the building was demolished only 21 years after initial construction (Bryant, 2003; Hawkins and Pinches, 1997). 2. Bacterially induced heave occurred in Iwaki City, Japan as a result of increased ground temperatures from 18°C to 25°C, which promoted acidophilic iron-oxidizing, sulfate-reducing, and sulfur-oxidizing bacteria. This led to gypsum and jarosite formation and substantial heave (48 cm) of the original mudstone foundation (Yamanaka et al., 2002). 3. Salt heave can occur due to hydration of highly saline soils. An observation of salt heave was seen in the highly saline soils containing sodium sulfate (Na_2SO_4) outside of Las Vegas. Colder temperatures (<10°C) promoted hydration of the sodium sulfate ($Na_2SO_4 \cdot 10H_2O$) and subsequent volume change and damage to light structures (Mitchell and Soga, 2005). 4. Hydration of smectite along pit wall joints at the Tellnes open pit mine in Norway has led to swelling of up to 230% and decreased frictional resistance to sliding. Failures in the pit wall have been observed during heavy rainstorms and as a result of repeated freeze/thaw (Nilsen and Ballou, 2006).	Soil and rock types with higher concentrations of sulfide are more likely to exhibit volume change (e.g., pyritic shales, mudstone, etc.); however, volume change has been observed in materials containing <0.1% sulfide-sulfur (Belgeri and Siegel, 1998). The precipitation of gypsum (heave) is most likely to occur in waste materials that contain both sulfides (source of elevated sulfate) and carbonates (source of elevated calcium). Gypsum is sparingly soluble and tends to form in unsaturated zones with neutral pH values. Gypsum precipitation may result from evaporation and is less likely to occur if water flow is high, such as in times of seasonal precipitation or along preferential flow paths. Sulfide and iron oxidation can be accelerated by microbial activity, as seen in the Iwaki City example (Yamanaka et al., 2002). Most substantial observations of volume change are going to occur in foundational materials and will depend upon the mineralogy and hydraulic conductivity of the underlying layers. Gypsum tends to form in areas of decreased stress such as along discontinuities or between rock layers (Bryant, 2003). Overall, the sensitivity of the structure will determine the consequence of positive deformation.	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(6) Interparticle cementation or loss of cementation (W, P)	Precipitates and clay minerals form coatings and/or bridges between individual particles which may contribute to brittle and/or collapsible soils. Brittleness is defined as a sudden loss of shear strength without signs of prior deformation. Furthermore, it is important to consider the rate of strength loss, rather than just the brittleness index (IB), as IB solely considers the ratio of peak to residual stress, rather than the “suddenness” of a material’s strength loss (Herza and Singh, 2022). Collapsible soils are defined as soils with an open structure supported by inter-particle bonds of salts, carbonates, clay minerals, iron oxides, etc. that, upon dissolution or contact with the wetting front, result in an unexpected decrease in soil strength (Milodowski et al., 2015; Opukumo et al., 2022). Cementation is a particular concern where it could “lock-in” a loose, metastable structure .This can occur as materials are deposited in a loose state and do not undergo consolidation prior to cementation via carbonates, clay minerals, or secondary iron minerals. The material will show no obvious signs of deformation prior to failure and will require small amounts of strain to reach peak strength.	▪ Decreased compressibility and consolidation due to rigid soil skeleton. – Lack of deformation prior to failure. – Potential for “undrained brittleness”, or a buildup of excess pore water pressure due to cemented materials resisting contraction. This may increase the liquefaction potential of the soil (Herza and Singh, 2022). ▪ Increased peak shear strength and low residual strength. – Potential for rapid failure. ▪ Loose, metastable structure. – Wetting and/or dissolution of cementitious bonds can result in a sudden loss in strength.	There are many examples of interparticle cementation in natural and anthropogenic soils (e.g. Opukumo et al., 2022). The same phenomenon has also been observed in TSFs. Specific examples include: 1. A significant increase in soil compressibility was observed in undisturbed clay samples from Osaka Bay, Japan following exposure to acidic conditions. Dissolution of the calcium carbonate and iron oxide cements led to the formation of a loose structure with larger voids and greater compressibility (Gratchev and Towhata, 2011). 2. Collapsible soils were detected in the foundation of a proposed TSF near Nazca, Peru. The soils were characterized as relatively low density, high porosity, low moisture content, and partially cemented via salt deposits with moderate to high shear strengths in a dry state yet exhibited significant strength loss upon wetting. This led to a detailed geotechnical investigation which found that excavation/replacement of the soil or installation of a geomembrane liner were required for ensuring physical stability (Sotelo and Paihua, 2017). 3. Samples of coarse tailings and slimes were collected from an area under the seventh dam raising following the Feijão failure. SEM images revealed high iron content, angular to sub-angular particle sizes with pitted surfaces, and cementation between particles, primarily composed of iron oxide. While cementation was not the primary cause of failure, cementation contributed to the formation of a brittle, contractive behavior with a high peak shear strength and low residual strength that showed little deformation prior to failure (Robertson et al., 2019).	Interparticle cementation is the result of solute precipitation after deposition of the material. Cementation occurs when the dissolved phase reaches the solubility limit, and the transport of water is slow enough that precipitates can accumulate. Unsaturated materials will more likely form cement bridges than a conglomerate. Iron minerals precipitate when the pH > 3.5 under oxygenated environments. Carbonate cementation will occur on the surface upon contact with atmospheric CO_2 but could be entrained at depth if this process occurs during deposition. The loss of cementation can occur due to dissolution of carbonate bonds and/or iron oxide cements. Acidic conditions can enhance dissolution; however, carbonates and iron oxides can still dissolve under neutral conditions at a much slower rate. Some cements, such as calcite and gypsum, may be found throughout the tailing’s facility, while others, such as iron oxides and iron sulfates, may be restricted to the oxidized zone due to higher solubilities under anoxic conditions. The evaporation of recently deposited tailings and formation of cementitious minerals prior to consolidation can lock in a loose state that will collapse upon loading or become interbedded within future lifts. Collapsible soils are typically found in arid to semi-arid regions and form during geological deposition (i.e., aeolian or alluvial fills) under unsaturated conditions. Upon wetting, collapsible soils will experience a large decrease in volume and strength. Naturally occurring collapsible soils are formed prior to mining activity and could be present in the foundation.	

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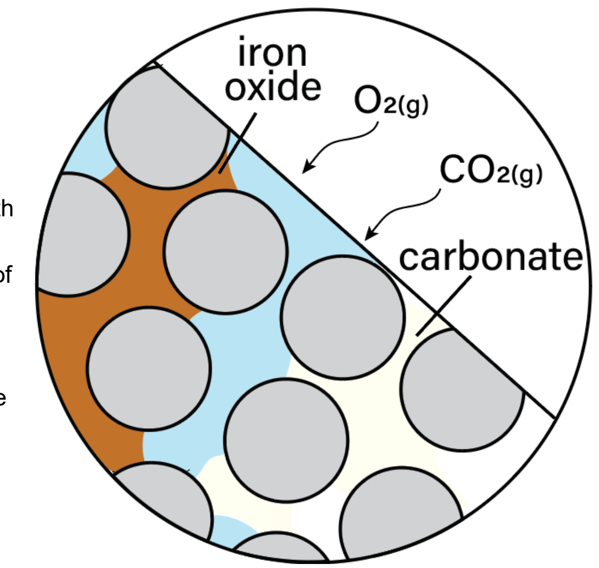
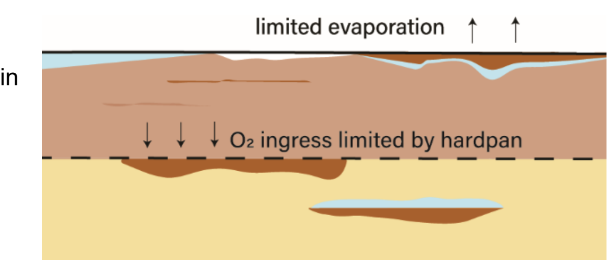
(7) Clogging of Pores (P)	Pore clogging can occur due to solute precipitation. Pore clogging often occurs in unsaturated zones with high concentrations of dissolved metals and sulfates and low pore flushing. Common secondary solid phases that lead to pore clogging include iron oxides and oxyhydroxides, carbonates, and sulfates. Bioclogging can also occur due to algae formation. Pore clogging results in low permeability materials that may hinder drainage and lead to a buildup of pore water.	▪ Reduced porosity. – Reduced permeability and drainage (Wang et al., 2021). – Potential rise in phreatic surface. – Increased potential to shear undrained. ▪ Increased stiffness.	1. Carbonation field experiments were performed on ultramafic (Mg-rich) tailings at the Mount Keith nickel mine to access their potential for carbon sequestration. Tailings were mixed with organic and inorganic amendments to increase microbial activity which generated higher concentrations of CO_2 and formed Mg-carbonate cements. The results indicate extensive clogging of pores, volumetric expansion, and an increase in unconfined compressive strength (UCS). Higher water contents enhanced cementation and strength (Power et al., 2021). 2. A confidential KCB report, commissioned by MEND/INAP, summarized the conditions favorable for pore clogging along drainage zones of an active and inactive upstream TSF and the resulting mitigation practices. Iron- and sulfate-rich seepage water daylighted at the toe of the embankment leading to the precipitation of secondary solids (both amorphous and crystalline phases) between the pore space. Secondary solid precipitation occurred in higher abundance in diffuse seepage zones rather than preferential seepage zones due to the high flow velocities which limited complete pore clogging. Pore clogging resulted in an order of magnitude decrease in in-situ permeability in the toe zone versus mid-slope locations in both active and inactive facilities. Mitigation efforts included regular toe maintenance to clear fines, monitoring of seepage quality and quantity, evaluation of TSF improvements such as buttressing, and soil cover improvements which limit further sulfide oxidation and erosion (KCB, 2023).	Seepage water emerging from shallow pore water will be more likely to precipitate secondary solids due to high metal/metalloid concentrations, moderate to low redox potential, and under mildly acidic conditions. (Durocher and Roberston, 2017, 2019). Seepage pH and metal/metalloid concentrations can alter over time as seepage comes into contact with less weathered materials, as the carbonate potential is depleted, or as surface conditions change (placement of tailings, covers, etc.). Pore clogging via carbonate precipitation is typically a result of the degassing of CO_2 from seepage waters upon interaction with the atmosphere. High $CO_{2(g)}$ can be seen in zones with active sulfide oxidation, microbial activity, organic decomposition, gypsum precipitation, dissolution of iron carbonates, or weathering of limestone drainage blankets. Pore clogging is more likely to occur at the surface (including embankment materials) upon exposure to atmospheric conditions. Pore clogging is more likely to occur in diffuse seepage zones with low pore flushing (Durocher and Roberston, 2017, 2019; KCB, 2023). Complete pore clogging is typically limited in preferential seepage zones, but precipitates can accumulate between preferential seep locations (KCB, 2023). Seepage emerging from below the phreatic surface will tend to precipitate solids further downstream (Durocher and Robertson, 2017).	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(8) Formation of Low Permeability Zones (P)	Hardpans are thick, impenetrable layers consisting of cementitious minerals such as gypsum, iron oxides and/or oxy-hydroxides, and iron sulfates. Hardpans typically form in zones where there is a change in pH, redox, or chemical composition. On a local scale, hardpans can act as inhibitors to flow and/or oxygen diffusion (Blowes et al., 1998; Elghali et al., 2019; Lin, 1997). On larger field scales, hardpans have not been found to be sufficiently continuous to reduce infiltration (Ahmed, 1995). However, hardpans have been known to form perched aquifers and zones of low shear strength that could compromise stability (Whiting, 1985). Hardpans are highly resistant to shear and penetration (Forsberg and Ledin, 2002). Often, field geologists classify hardpans as impenetrable with field shovels. Hardpans have been studied for their use in remediation due to their tendency to limit sulfide oxidation, increase runoff, and retain heavy metals (Ahn et al., 2011; Blowes et al., 1991; Lin, 1997). Overall, the long-term stability of hardpans, from a geochemical and geotechnical perspective, is unclear.	▪ Reduced porosity. – Reduced permeability. – Potential for perched aquifers and zones of low shear strength due to buildup of porewater. – Slowed drainage. – Slowed sulfide oxidation due to coating of individual grains and reduced water infiltration and oxygen ingress. ▪ Increased resistance to shear and penetration. – Increased resistance to erosion. ▪ Potential to undergo dissolution (i.e., should not be relied upon for long-term stability).	Several examples of hardpans forming at mine sites under field conditions have been observed (Agnew and Taylor, 2000; Alakangas and Öhlander, 2006; Blowes et al., 1998; Elghali et al., 2019; Lui et al., 2018; McGregor and Blowes, 2002). Specific examples include: 1. The Verona copper leach dump at Kennecott's Bingham Canyon Mine formed perched water tables on top of jarosite hardpans. The impeded drainage led to a buildup of pore water pressure and a sudden blowout. The failure was approximately 100 ft below the surface of the dump and resulted in blown material extending several hundred feet in the air. This is an extreme example as the waste rock contained a high limestone content and was percolated with acid (Pernichele and Kahle, 1971; Whiting, 1985). 2. Three different hardpan layers from the Nickel Rim, Fault Lake, and East Mine tailings impoundments in Northern Ontario were characterized. Hardpans varied from 8 to 20 cm thick and formed at the surface, within the oxidized zone, and in the transition zone. All hardpans showed an increase in bulk density, a decrease in porosity, and an accumulation of trace metals (McGregor and Blowes, 2002). 3. The penetration resistance of unoxidized tailings, oxidized tailings, and tailings amended with organic substrates was measured in a field study at the Aitik copper mine in northern Sweden. The results indicate that penetration resistance increases with oxidation and can become impenetrable with the addition of organic amendments (Forsberg and Liden, 2002). 4. A hardpan observed on a legacy tailings deposit at the end of a natural lake in British Columbia formed a near-impervious layer at the depth of saturation. The strong hardpan was attributed to the high sulfide/high carbonate content of the tailings which resulted in gypsum formation.	Hardpans typically form in zones which exhibit a change in pH, redox, or chemical composition. Higher contents of sulfides (particularly pyrrhotite) will encourage hardpan formation (Ahmed, 1995, Blowes et al., 1991). The presence of carbonates will also contribute to hardpan formation. Sulfide oxidation on the surface often results in low-pH waters with high concentrations of dissolved SO_4^{2-}, Fe, and other metals. As the low-pH pore water travels downwards, the drainage is neutralized and the pH goes up, providing favorable conditions for mineral precipitation (Blowes et al., 1991). Hardpans can form on the surface of a TSF, within the oxidized and transition zones, or near the phreatic surface of dormant TSFs. Hardpans can also form at the placement of a cover as the system transforms from oxic to anoxic conditions (Alakangas and Öhlander, 2006). Common in inactive tailings impoundments. The Bingham Canyon example demonstrates that they can also occur in leach dumps. Can be laterally continuous or discontinuous and anywhere from a few millimeters thick to several centimeters.	

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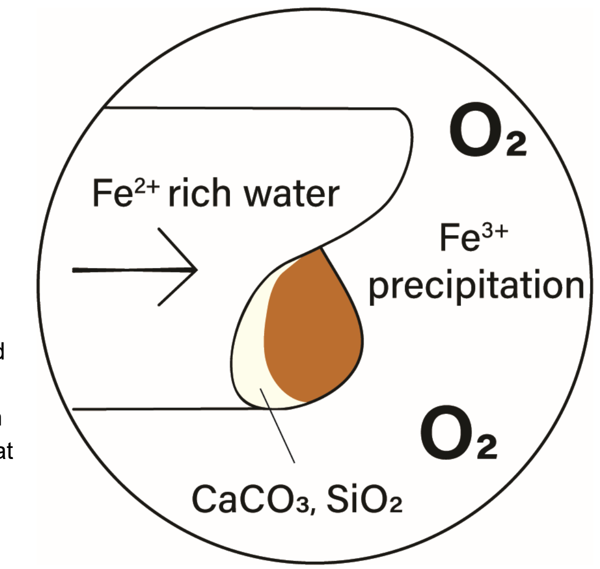
(9) Clogging of Drainage and Scaling of Pipes (P)	Secondary solid phase formation occurs in drains, drainage pipes and seepage collection systems when saturated pore water "daylights" and, upon interaction with O_2 and CO_2 in the atmosphere, precipitates solids in order to re-equilibrate with surrounding conditions or when seepage interacts with porous media within the drainage gallery and experiences a chemical change. Common drain clogging minerals are iron oxides, iron oxyhydroxides, manganese oxides, secondary silicates, sulfate minerals (e.g. gypsum), and carbonates. Whereas the majority of pipe clogging materials form upon interaction with atmospheric O_2, carbonates precipitate in drainage pipes due to degassing of CO_2 that builds up in the seepage (see Item 7). Bioclogging of pipes can also occur due to algae, organic matter, etc. Several mitigation options exist for drain clogging (e.g., gooseneck pipes, saturated effluent pipes, etc.) which limit O_2 ingress and premature CO_2 degassing, reducing the likelihood of precipitation occurring. Scaling of pipes can also occur due to high concentration of suspended solids in these systems.	■ Limited or slowed drainage. – Rise in phreatic surface. – Rise in degree of saturation. – Reduced shear strength. – Increased potential for liquefaction. ■ Slowed consolidation. ■ Slowed water recovery. ■ Potential for buildup of unsafe levels of CO_2 (see Carsington dam failure). ■ Increased operation and maintenance.	1. At the Lixi tailings dam in Shaanxi Provence, China clogging of drains resulted in a rise in the phreatic surface. Clogging occurred when Fe(II), soluble under reducing conditions, came into contact with atmospheric oxygen and precipitated as secondary minerals such as ferrihydrite, goethite, akageneite and hematite (Wu et al., 2007, 2008). 2. Dissolved silica can precipitate as opal and/or chalcedony in drainage pipes (J. Ridley, personal communication). 3. The Carsington Dam in Derbyshire, UK experienced structural failure due to the clogging of drainage and degradation of the pyritic mudstone core. Oxidation of pyritic generated sulfuric acid capable of dissolving the limestone drainage blankets. The geochemical reactions led to precipitation of gypsum and iron hydroxides in the drains and a buildup of unsafe levels of carbon dioxide gas in the drains, manholes, and excavations which resulted in four fatalities at the site. In the second design of the dam, shear strength parameters were selected to allow for weathering of the pyritic mudstone and drainage blankets were constructed out of non-calcareous material (Bryant, 2003).	More likely to occur in facilities with high sulfide contents and high concentrations of dissolved metals. The rate of precipitation will depend on the concentration of dissolved ions, solubility, redox, and the rate of flow. The solubilities of secondary solid phases are temperature dependent, therefore various reactions such as carbonate precipitation and bioclogging may occur at higher rates during summer months or during pumping (warmer temperatures). Scaling of pipes is enhanced along with higher concentrations of dissolved solids. Occurs in drains, drainage collection systems and seepage pipes upon interaction with atmospheric oxygen, changes in the partial pressure of carbon dioxide, and/or other geochemical interactions that change the solubility conditions.	

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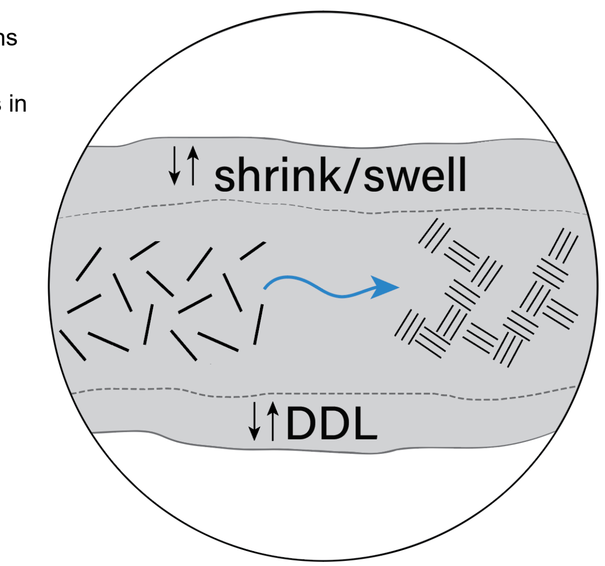
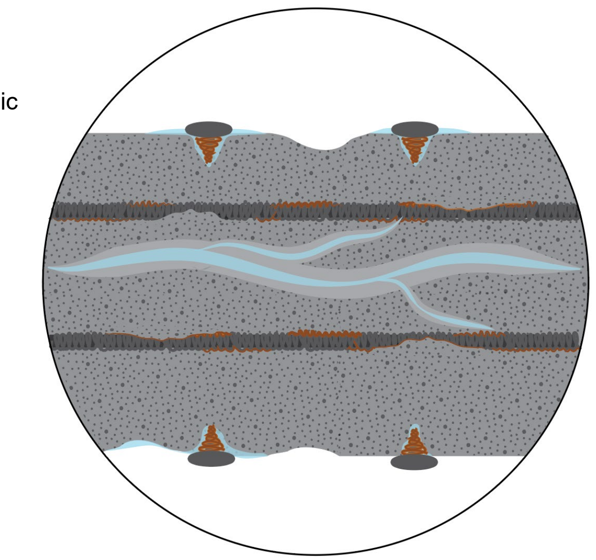
(10) Changes in clay mineral properties under acidic or saline conditions (O)	▪ Acidic and saline conditions have been known to alter the behavior of clay minerals due to: (1) Substitution of monovalent cations for multivalent cations (2) Change to the thickness of the double-diffuse layer (DDL) (3) Change to the surface charge of clay particles (1) will influence the hydraulic conductivity of clays by altering (2). Multivalent cations (e.g., Ca^{2+}, Al^{3+}) are smaller than monovalent cations (e.g., Na^{+}) and therefore substitution will result in shrinkage of clays. ▪ (2) and (3) will influence the attractive and repulsive charges between clays and their subsequent particle arrangement, also known as the soil fabric. Various particle arrangements exist, such as: • Edge-to-Face (E-F), flocculated • Edge-to-Edge (E-E), flocculated • Face-to-Face (F-F), aggregated • Dispersed or deflocculated clays have no association between aggregates (Mitchell and Soga, 2005). ▪ Clay properties and particle arrangements have been proven to influence geotechnical properties such as consolidation, settling, plasticity, shear strength, and hydraulic conductivity (Gratchev and Towhata; 2011, 2013). ▪ Mitchell and Soga (2005) provide an overview of the different types of clay minerals and their various properties and behaviors.	▪ Suppression of DDL (extremely acidic or saline conditions) – Increase or decrease in permeability. – Increase or decrease in compressibility. – Increase or decrease in liquid limit. – Increase or decrease in shear strength. ▪ Flocculated (E-F) structure (e.g., kaolinites at pH <5.5) – Increased compressibility. – Increased permeability. – Increased liquid limit. – Loose structure (+u). – Decreased effective stress. ▪ Increased salinity – Reduced osmotic consolidation. – Reduced plasticity. – Increased permeability.	1. The response of clays to acidic conditions greatly depends on the mineralogy of the clay and the soil structure. Various observations from Gratchev and Towhata include: – The structure of kaolinite is highly dependent on pH. Under acidic conditions, the adsorption of H^{+} ions to kaolinite edge groups resulted in a flocculated, edge-to-face structure which exhibited greater compressibility, permeability, and liquid limit. Acidic conditions may have also dissolved some calcium carbonate and iron oxide bonds between clay particles. Overall, the loose fabric resulted in a decrease in effective stress (2013). – Conversely, montmorillonite clay under highly acidic conditions (pH 3) resulted in collapse of the DDL and subsequent decrease in compressibility and liquid limit (2011). – Montmorillonite under slightly acidic conditions (pH 6) resulted in an increase in strength due to depression of the DDL, a decrease in repulsive forces, and an increase in aggregate formation (2013). 2. An increase in undrained shear strength at low (pH 3) and high (pH 8) was observed for kaolinite and smectite. At low pH values, the dissolution of Al^{3+} and subsequent formation of Al-hydroxide coagulants increased the shear strength of kaolinite whereas at high pH values, kaolinite formed face-to-face aggregates which also increased undrained shear strength. This effect is further accelerated by solutions of increasing ionic strength (Spagnoli et al., 2012). 3. The influence that GuCl, a monovalent saline solution, has on Regina Clay, a high activity clay containing montmorillonite, illite, kaolinite, and chlorite, was studied under laboratory conditions. Findings suggest an increase in salinity resulted in formation of an aggregated soil structure, increased permeability, and increased residual shear strength which did not appear to diminish upon continuous flushing with DI water. Additionally, a reduction in plasticity and osmotic consolidation was observed (Leik, 2020).	Changes in clay mineral properties depend on the mineralogy of clays and the extent of changes in pore water chemistry, including changes in pH, dielectric constant, and electrolyte concentration (Mitchell and Soga, 2005). ▪ For example, montmorillonite is a higher activity clay than kaolinite and, as such, has a more negative charge and is more susceptible to changes in porewater chemistry (Mitchell and Soga, 2005). ▪ Changes in clays can occur in tailings, waste rock, foundational materials, and liners. Moreover, they can occur within a few months to years of operations due to the relatively rapid response of these minerals to changes in chemistry.	

Physical Change	Description	Potential Geotechnical Significance	Examples	Factors/Conditions that Enhance Plausibility, Significance, or Timescale	Visual Representation
(11) Corrosion of steel, concrete, and other infrastructure (O)	Acidic conditions and/or high concentrations of sulfate or chloride can greatly increase rates of corrosion in steel, concrete, and various infrastructure components such as pumps, monitoring equipment, well casings, rock bolts, etc. Acidic or saline conditions can develop over time as a result of sulfide oxidation and/or management of saline groundwater, reverse osmosis brines high in dissolved ions (i.e., sulfate, chloride, magnesium, etc.), and/or other types of salt brines in TSFs. Concrete degradation occurs when acidic seepage dissolves the concrete agglomerate mineral or if concrete is contacted by water containing sulfate that attacks the mineral structure and causes swelling, cracking, and strength loss (Bryant, 2003; Chinchon et al., 1995). Concrete is used for various functions in tailings and mine waste construction including, but not limited to, leveling of foundations, starter dams, securing of HDPE liners, spillways, water conveyance pipelines, and more. Steel corrosion can be induced by acidic or corrosive (high chloride) conditions, leading to breakdown of rock bolts, pumps, monitoring well casings, rock gabion baskets, and drainage pipes (Aziz et al., 2014).	■ Potential for failure of earthen materials relying on structural support from concrete/steel materials. ■ Breakdown of infrastructure over time. ■ Increased operation and maintenance. ■ Potential for secondary effects such as failure of monitoring equipment, loss of containment, etc.	1. An experimental study analyzed the corrosion of high carbon manganese X-grade rock bolts often used as ground support in mines and tunneling. Pitting (localized holes) and crevices (along joints) occurred in low pH environments. Corrosion resulted in weight loss, a reduction in borehole diameter (11.7% over 3.5 years), and a reduction in ultimate tensile strength (20-40% reduction) (Aziz et al., 2014). 2. The National Association of Home Builders estimated that sulfate attack can decrease the useful life of concrete from 150 to 15 years or less (Kasdan Simonds and Epstein, 2002). 3. Concrete culverts in Virginia have been known to degrade within two years following acid attack (Bryant, 2003). 4. The Carsington embankment dam generated acidic conditions due to the oxidation of pyritic mudstone used in the shoulders and core. The generation of sulfuric acid resulted in dissolution of underlying concrete materials (limestone drainage blankets), clogging of drains via iron hydroxide precipitates, and a toxic buildup of CO_2(g) which resulted in the asphyxiation of four workers. In the second design of the dam, coatings of bitumen were placed on all concrete structures to protect against acid attack (Bryant, 2003).	Rates of corrosion are highest in areas where acidic or highly saline solutions are present. Therefore, the presence of sulfide minerals and subsequent oxidation can release sulfate and generate acidic conditions which enhances corrosion. The presence of saline minerals such as halite can also enhance corrosion. Corrosion can occur anywhere where steel or concrete components come into contact with acidic water. Effects can occur rapidly and lead to a failure within a few years to decades of construction in extreme cases.	

Notes: W = Chemical weathering of primary and secondary minerals, P = Precipitation of secondary solid phases, O = Other water/rock interactions.

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