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TAILINGS LIQUEFACTION AND DAM STABILITY: ADVANCES IN DIAGNOSIS, MONITORING, STANDARDS AND MITIGATION – A CRITICAL REVIEW

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Abstract

This review synthesizes advances from 2020 to 2025 in the understanding, diagnosis, modelling and governance of tailings liquefaction, drawing on a PRISMA-based assessment of scientific literature, case histories, technical guidelines and regulatory frameworks. Recent findings clarify the distinct roles of critical state and steady-state concepts in interpreting the behaviour of sandy, silty and structured tailings, while new evidence highlights the importance of depositional fabric, partial drainage and anisotropy in governing undrained softening and liquefaction susceptibility. Progress in CPTu/SCPTu interpretation, shear-wave velocity–based correlations and multi-parameter diagnostic frameworks has strengthened field evaluation but remains limited by heterogeneous stratigraphy and incomplete calibration across tailings typologies. Multi-source monitoring approaches—integrating InSAR, piezometry, geodetic instrumentation and operational data—have improved the detection of precursors and the interpretation of hydraulic and mechanical triggers. Hybrid numerical workflows combining FEM and MPM have advanced the modelling of triggering, strain softening and runout, although significant uncertainties persist regarding residual strength and softening laws. Regulatory developments, including GISTM (2020), ICOLD Bulletin 194 (2022) and Brazil's ANM Resolution 95/2022, have shifted industry expectations toward life-cycle, evidence-based risk management. Collectively, the literature reveals substantial conceptual and technological progress but also persistent gaps in data integration, partially drained behaviour, decharacterization criteria and portfolio-scale governance, underscoring the need for more robust, adaptive and mechanistic approaches to TSF stability.

Keywords. Tailings Liquefaction; Static and Cyclic Instability; State Parameter (Ψ); CPTu/SCPTu Diagnostics; TSF Monitoring and Governance; Numerical Modelling and Runou

Graphical abstract

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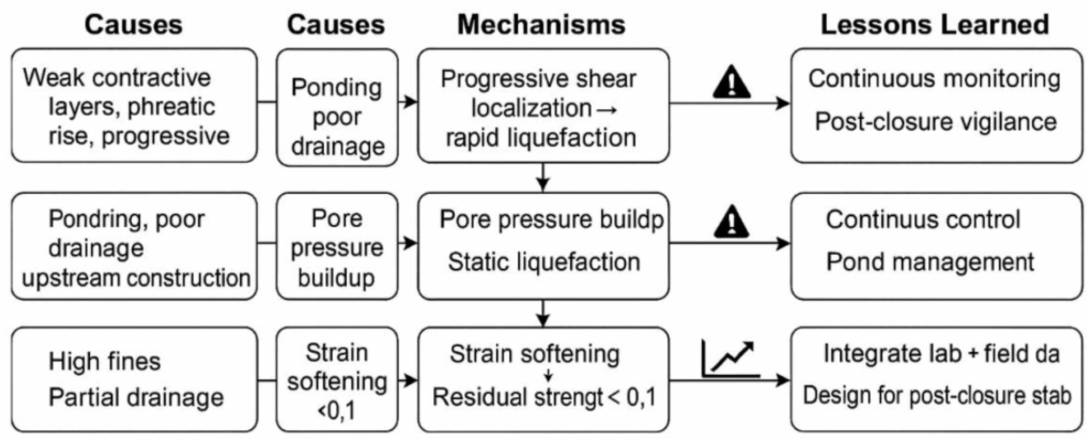

1. Introduction

The stability of tailings storage facilities (TSFs) has become a significant challenge on modern mining geotechnics. The catastrophic failures at Fundão (2015) and Brumadinho (2019) heightened global scrutiny of how tailings are managed, prompting a reevaluation of design approaches, regulatory standards, monitoring methods, and liquefaction assessment procedures. Post-Brumadinho investigations uncovered the combined effects of static liquefaction mechanisms, undrained deformation, and failure to detect warning signals, revealing systemic weaknesses in engineering oversight and operational management. These incidents accelerated worldwide demand for more straightforward guidelines, better governance, and risk management grounded in solid evidence (Almeida et al., 2025; Pereira, 2025a).

In response, significant regulatory developments took place. The Global Industry Standard on Tailings Management (GISTM) introduced a risk-based framework focused on zero harm, independent oversight, and improved monitoring. National authorities also enhanced their regulations, including Brazil's Law 14.066/2020 and ANM Resolution 95/2022, which updated classification systems, inspection standards, and stability criteria. At the international level, ICOLD Bulletin 194 further unified guidance on governance and engineering practices, emphasizing the need for consistent, auditable procedures. Despite these advances, considerable scientific and operational uncertainties remain, especially regarding liquefaction triggers, diagnostic thresholds, constitutive modeling, and the integration of monitoring data into decision-making processes (Pereira, 2025b; Pereira et al., 2025).

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Scientific progress from 2020 to 2025 has significantly improved the understanding of static and cyclic liquefaction in mine tailings. Advances in laboratory testing and on-site characterization have refined interpretations of the state parameter, fabric evolution, and critical-state behavior. Constitutive models such as NorSand, PM4Sand, PM4Silt, and CSSM-based formulations have been further validated for tailings, though challenges remain in capturing contractive behavior under the complex and variable loading paths typical of TSFs. Additional progress in multi-source monitoring—including satellite InSAR, surface displacement trends, and pore-pressure tracking—has enhanced the ability to detect early signs of instability, an important step given the heterogeneous and metastable traits of many tailings deposits (Piciullo et al., 2022). Simultaneous collection of global TSF failure data has also improved statistical understanding of causes, failure modes, and societal risks (Cascini et al., 2024).

Even with these advances, key gaps remain. Diagnostic thresholds for liquefaction susceptibility in silty, transitional, or partially structured tailings are not unified; post-liquefaction residual strength remains difficult to predict; and many regulatory documents offer limited procedural guidance for integrating constitutive modelling, monitoring evidence, and risk governance. Additional stressors—such as climate extremes and operational variability—further complicate stability assessments, underscoring the need for adaptive and multi-disciplinary approaches.

This review aims to provide a thorough overview of recent scientific, technical, and regulatory progress related to tailings liquefaction and TSF stability. It updates core concepts of static and cyclic liquefaction, along with recent advances in laboratory and field testing, including interpretation of state parameters—and the increasing understanding of triggers, loading paths, and constitutive models (NorSand, CASM, PM4Sand, PM4Silt). The methodological framework involves systematic database selection, clear inclusion/exclusion criteria, temporal filtering (2020–2025), thematic coding, and the integration of scientific, regulatory, and operational evidence.

In the post-Brumadinho context, emerging research and new standards still disproportionately focus on large, well-instrumented operations, leaving smaller operators and legacy TSFs underrepresented. Implementation gaps—such as limited regulatory capacity, varied EoR practices, and fragmented portfolios of “sub-critical”

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dams—remain inadequately addressed. Despite advances in modeling, diagnostics, and monitoring, their integration into corporate decision-making remains poorly documented. As a result, progress from 2020 to 2025 remains uneven, with scientific, regulatory, and operational domains only partially aligned.

2. Methodology (PRISMA 2020)

This review was conducted in accordance with the PRISMA 2020 framework to ensure transparency, traceability, and reproducibility in the identification, screening, and synthesis of scientific and technical literature on tailings liquefaction and tailings storage facility (TSF) stability from 2020 to 2025. The guiding research question was: "What advances have occurred between 2020 and 2025 in the mechanisms, diagnosis, monitoring, modeling, regulatory standards, and mitigation strategies related to tailings liquefaction and TSF stability?" (Pereira, 2025a)

A structured search strategy was used across major scientific databases (Scopus, Web of Science, ScienceDirect, SpringerLink, ASCE Library, Taylor & Francis, IEEE Xplore), comprehensive search engines (Google Scholar), repositories of technical and regulatory documents (ICOLD, ICMM, UNEP, ANCOLD, ANM, UNECE), and preprint servers (arXiv, ResearchGate). Search terms and Boolean combinations included "tailings liquefaction," "static liquefaction," "TSF stability," "CPTu/SCPTu," "state parameter," "InSAR monitoring," "NorSand," "critical state," "GISTM," and "ICOLD 194," among others. Only publications from 2020 to 2025 were reviewed, except for regulatory standards or foundational references still in effect.

Inclusion criteria included peer-reviewed articles, theses, technical reports, standards, case histories, numerical modeling studies, and engineering documents that provide evidence or analysis related to liquefaction mechanisms, geotechnical parameters, triggering conditions, diagnostic methods, monitoring technologies, constitutive modeling, failure statistics, governance frameworks, and mitigation practices. Exclusion criteria eliminated documents with insufficient technical basis, redundant materials, or studies unrelated to tailings, liquefaction, or TSF stability.

Screening was performed in two stages: an initial review of titles and abstracts to eliminate unrelated works, followed by a full-text assessment based on predefined eligibility criteria. Data extraction was consistent and included key elements such as

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tailings properties, laboratory and in situ methods, monitoring strategies, constitutive models, regulatory requirements, mitigation measures, and main findings. Due to the diversity of methods among the included sources, the synthesis was conducted narratively and integratively, combining experimental, numerical, observational, and regulatory evidence. A complementary PRISMA 2020 flow diagram (Figure 1) summarizes the steps of identification, screening, eligibility, and inclusion.

This structured methodological approach underpins the critical analysis in the following sections, allowing for a clear integration of scientific, technological, and regulatory advances that define the current practices in tailings liquefaction and TSF stability.

3. Critical state vs. steady state frameworks

Recent syntheses published between 2023 and 2024 highlight the importance of clearly distinguishing between the critical-state and steady-state frameworks when analyzing liquefaction mechanisms in soils and mine tailings (Almeida et al., 2022). Although these frameworks are often used interchangeably in practice, they originate from different theories and imply different things for stability analysis. As Verdugo (2024) explains, critical state soil mechanics (CSSM) provides a strong foundation for describing materials where structure, fabric, and bonding remain significant even at large strains—conditions commonly observed in fines-rich or metastable tailings. The findings from Liu et al. (2024) and Macedo & Verga (2022) further support CSSM's relevance to fine-grained, partially structured tailings, where destructuration dominates during undrained loading (Riveros, 2019).

In contrast, the steady-state framework, originating in the work of Been and Jefferies and widely used in tailings engineering, emphasizes the unique shear resistance that develops when granular assemblies deform continuously at constant volume, stress, and fabric. This makes it particularly suitable for sandy and silty tailings, where particle rearrangement outweighs structural deterioration (Been et al., 2020; Liu et al., 2024). The steady state concept underpins many modern constitutive models and field-based susceptibility assessments in mining geotechnics. Studies by Robertson (2021), Riveros & Sadrekarimi (2021), and Monforte et al. (2023)

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demonstrate its key role in interpreting CPTu/SCPTu data, particularly in estimating the state parameter (Ψ) and related liquefaction criteria (Pereira et al., 2025b).

Understanding the difference between static and cyclic liquefaction is essential in this conceptual framework. Static liquefaction happens when monotonic loading causes a contractive, undrained response and a rapid loss of strength—a process that has been linked to upstream-raised TSFs and well documented in post-failure studies (Riveros & Sadrekarimi, 2021; Macedo & Verga, 2022; Fonseca et al., 2022; Alshawmar et al., 2022; Reid, 2022). Cyclic liquefaction, however, relates to repeated loading and gradual pore-pressure buildup, which is more common in seismic environments (Chen et al., 2020; Rana et al., 2021). Both mechanisms can be analyzed within either a critical-state or a steady-state framework; however, their occurrence primarily depends on material type, fabric, and drainage conditions—features highlighted in laboratory and ring-shear tests (Simms et al., 2025).

Recent literature (2020–2025) shows increasing convergence on the mechanisms governing liquefaction in fines-rich tailings. These materials commonly display contractive behavior, metastable structures, and partial drainage during loading, making CSSM-based approaches useful for capturing destructuration and volumetric tendencies (Liu et al., 2024; Rawat & Sasanakul, 2024). For sandy or intermediate tailings, however, the steady-state framework remains more practical for defining Ψ, assessing flow-liquefaction susceptibility, and estimating residual strength—key parameters in constitutive models such as NorSand and PM4Sand/Silt (Bokkisa et al., 2024; Muñoz-Gaete et al., 2025; Liu et al., 2025). The growing reliance on CPTu and SCPTu methods to estimate Ψ further reinforces the applicability of steady-state concepts in field-scale evaluations (Ayala et al., 2022; Monforte et al., 2023; Qi et al., 2024).

Figure 1 compares the Critical State Soil Mechanics (CSSM) framework with the family of steady-state shear-stress envelopes often used in liquefaction assessments. While CSSM describes a specific stress path governed by the critical state, steady-state envelopes can vary greatly depending on fabric, contractive tendency, and depositional history—factors especially important in silty, metastable, or weakly cemented tailings. This comparison highlights how different mechanistic assumptions can lead to significantly different estimates of residual strength and liquefaction risk.

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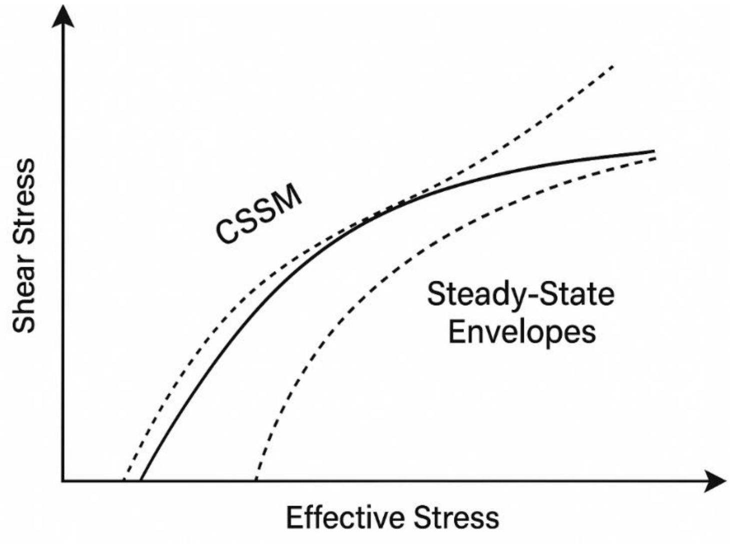

Figure 1 Conceptual comparison between the Critical State Soil Mechanics (CSSM) shear-stress curve and representative steady-state envelopes for tailings materials. adapted from conceptual CSSM and steady-state frameworks in the liquefaction literature.

The practical implications of choosing between critical-state and steady-state frameworks are substantial. Residual shear strength, the post-trigger factor of safety (FOS), and the shape of undrained softening curves vary significantly between the two approaches (Simms et al., 2025; Santos Junior et al., 2022). Analyses based on steady-state assumptions typically yield lower residual strengths for sandy tailings, while CSSM-based interpretations may show higher or strain-dependent strength plateaus for fine-grained tailings with partial drainage or fabric collapse. These differences impact numerical modeling, especially in coupled FEM–MPM simulations of runout, where the softening law is critical for determining failure geometry and mobility (Sordo, Conte et al., 2024; Sordo, Rathje & Kumar, 2025; Ma et al., 2025).

To make these conceptual issues more practical, Table 1 summarizes the main differences between the critical-state and steady-state frameworks, emphasizing how each addresses fabric, drainage conditions, calibration needs, and residual strength within heterogeneous TSFs. This overview highlights that careful framework choice and precise state-parameter calibration are crucial for accurate liquefaction assessment and post-trigger deformation modeling, especially when stratigraphy and tailing types vary significantly (Liu et al., 2024; Robertson, 2021; Naftchali et al., 2024).

Table 1. Practical Differences Between the Frameworks. Adapted from Been et al. (2020); Almeida et al. (2022); Arnold et al. (2023); Ayala et al. (2022); Liu et al. (2024); Robertson (2021); Schnaid (2022); Verdugo (2024); Simms et al. (2025)

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Aspect	CSSM (Critical State Soil Mechanics)	Steady State Framework	Implications for TSFs
Conceptual origin	Describes volumetric tendencies, destructuration, and evolution of fabric toward the critical state.	Describes the unique shear resistance achieved when soil deforms at constant volume, fabric, and stress.	Framework selection affects interpretation of contractive behavior and residual strength.
Typical materials	Silty, fine-grained, metastable, partially structured tailings with fabric sensitivity.	Sandy to silty, granular tailings with limited structure and clear dilatancy behavior.	Heterogeneous TSFs may require hybrid or layer-specific treatment.
Role of structure (fabric)	Dominant—structure, bonding, cementation, and anisotropy explicitly influence behavior.	Assumes negligible fabric effects once the steady state is reached.	Ignoring fabric in metastable silty tailings may overpredict liquefaction potential.
Softening curve	May show gradual softening or strain-dependent plateaus influenced by drainage and destructuration.	Typically shows abrupt strength loss toward a well-defined low residual strength.	Strongly influences post-trigger FOS and runout predictions.
Residual strength	Can be higher or strain-dependent; controlled by destructuration rate.	Generally lower and sharply defined.	Critical for FEM/MPM modelling of flow failure and inundation envelopes.
Calibration requirements	Requires extensive laboratory testing (triaxial, ring shear, destructuration studies).	Can be inferred from CPTu/SCPTu using state parameter (Ψ) correlations.	In data-poor TSFs, steady-state is often adopted for practicality.
Dependence on drainage conditions	Strong—partially drained behavior significantly alters the response.	Assumes essentially undrained conditions during failure.	Operational TSFs often undergo drainage transitions not captured in steady-state assumptions.
Primary application	Fine-grained, structured, metastable tailings; materials with suction or bonding.	Sandy and transitional tailings; materials dominated by granular rearrangement.	Layered deposits may require framework switching across depth.
Interpretation of Ψ	Less directly applicable; the critical-state definition depends on the destructuration path.	Ψ is central and operationally derived from CPTu/SCPTu.	Ψ-based approaches dominate field applications even where CSSM is conceptually more appropriate.
Constitutive models	CASM, CSSM-based anisotropic/destructuration models.	NorSand, PM4Sand, PM4Silt, and flow-type constitutive laws.	Affects the prediction of triggering, post-trigger softening, and runout in TSF simulations.

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Despite the maturity of critical-state and steady-state frameworks, their application in tailings engineering remains fragmented. Many studies use steady-state concepts without verifying assumptions like fabric independence or constant-volume conditions, which may not hold for metastable or cemented fines. CSSM interpretations are often cited, yet laboratory data needed to calibrate destructuration or anisotropy effects are limited. Comparisons of how model choice influences residual strength, post-trigger FOS, or runout predictions are scarce, leading to epistemic bias. Although hybrid methods for stratified TSFs are increasingly recognized, practical guidance for their implementation remains underdeveloped.

The next section examines the geotechnical properties and mechanisms that affect liquefaction behavior across different types of mine tailings, serving as the foundation for future diagnostic and modeling techniques.

4. Properties and mechanisms in mine tailings

Understanding the textural continuum of tailings is fundamental for interpreting their hydraulic response, fabric evolution, propensity for contractive behaviour, and susceptibility to static liquefaction. As shown in Figure 2, tailings distributions range from predominantly sandy to silty, ultra-fine, and paste-like materials, each characterized by distinct grain-scale arrangements, pore structures, and rheological behaviour. These textural domains exert strong control over permeability, drainage transitions, strain-softening patterns, and the development of metastable fabric factors repeatedly highlighted in recent investigations of TSF instability mechanisms.

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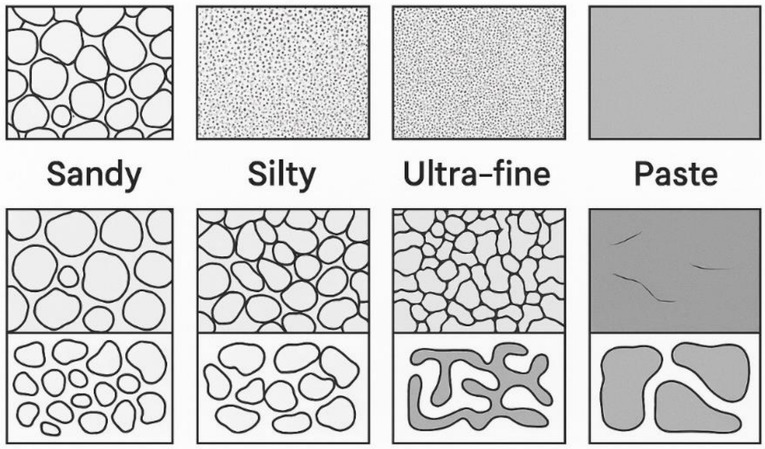

Figure 2. Textural classes of tailings ranging from sandy to paste-like materials, illustrating differences in grain geometry, fabric, and pore structure. Adapted from Been et al. (2020) and Simms et al. (2025).

Mine tailings include a variety of materials—from sandy and silty hydraulically deposited tailings to clayey or ultra-fine residues, including filtered and paste tailings with increased structure and suction. Their behavior under monotonic and cyclic loading is heavily influenced by microstructure, depositional history, and grain-scale features. Sandy tailings usually display a fabric dominated by granular rearrangement and dilatancy, while finer, silt-rich tailings often have metastable structures that are very sensitive to destructuration and pore-pressure buildup (Macedo & Verga, 2022; Riveros & Sadrekarimi, 2021; Sarkar & Sadrekarimi, 2022). Filtered and partially saturated tailings add further complexity because of matric suction, bonding, and cemented microfabric—factors that need careful interpretation under undrained loading (Soares et al., 2023; Sottile et al., 2020).

Experimental evidence from 2021–2024 shows consistent mechanical trends: fine-grained tailings—especially non-plastic silts—exhibit strong contractive tendencies, rapid pore-pressure buildup, and significant undrained softening even under low confining stresses (Chen et al., 2020; Arnold et al., 2023; Vergaray et al., 2023; Fonni et al., 2025; Rawat & Sasanakul, 2024). Figure 3 demonstrates this behavior, indicating how contractivity sharply increases with void ratio, with the shaded area marking where liquefaction is most likely. Small changes in void ratio, fabric, depositional layering, and consolidation conditions lead to notable differences in peak and post-peak strength, highlighting the impact of stratigraphy and microstructure (Rodríguez-Pacheco et al., 2022; Muñoz-Gaete et al., 2025). These findings align with

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case histories and ring-shear tests showing that residual strength after liquefaction depends on void ratio, particle breakage, and strain-softening traits (Simms et al., 2025; Rana et al., 2021; Salam, 2020).

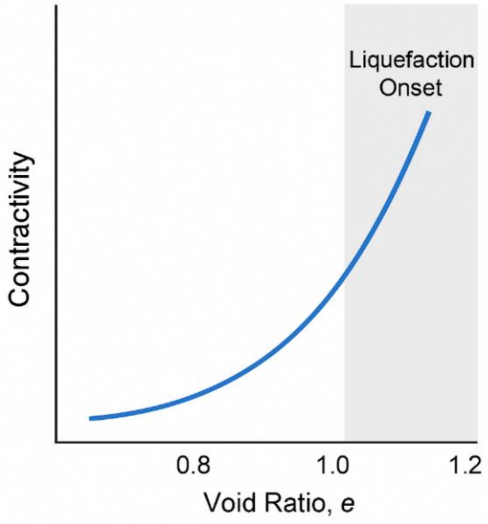

Figure 3. Relationship between void ratio and contractivity, highlighting the range associated with liquefaction onset. Adapted from Arnold et al. (2023), Rodríguez-Pacheco et al. (2022), and Simms et al. (2025).

A recurring theme in recent literature is the importance of contractivity in influencing susceptibility to static liquefaction. Materials with higher void ratios or metastable structures exhibit sharp declines in undrained shear resistance once triggered, while more dilative materials tend to develop strain-hardening behavior. Evidence from 2020–2025 confirms that the void ratio–state parameter (Ψ) relationship remains a reliable indicator of this tendency, linking depositional fabric and effective stress state to liquefaction potential (Ayala et al., 2022; Monforte et al., 2023; Mozaffari et al., 2023; Verdugo, 2024). This aligns with broader critical-state frameworks for tailings behavior (Pestana & Whittle, 1999; Been et al., 2020; Etezad et al., 2025).

Within this context, shear-wave velocity (Vs) has become a practical and increasingly validated indicator of liquefaction susceptibility in tailings. Recent empirical methods (2021–2024) suggest correlations between Vs, mean effective stress, and void ratio to estimate proxies for undrained strength during softening. These approaches are especially valuable for tailings where penetration-based indices (e.g., CPT tip resistance) may be ambiguous due to partial drainage, fabric sensitivity, or layering effects (Liu et al., 2024; Naftchali et al., 2024; Qi et al., 2024).

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Figure 4 shows how differences in undrained shear response between granular (dilatant) and silty, contractive tailings lead to significantly different peak and residual strengths, highlighting the importance of Vs-based methods for distinguishing these behavioral regimes. Additionally, combined interpretations using Vs and CPTu/SCPTu offer improved estimates of Ψ, especially in intermediate silty tailings where depositional fabric strongly influences the mechanical response (Ayala et al., 2022; Liu et al., 2025).

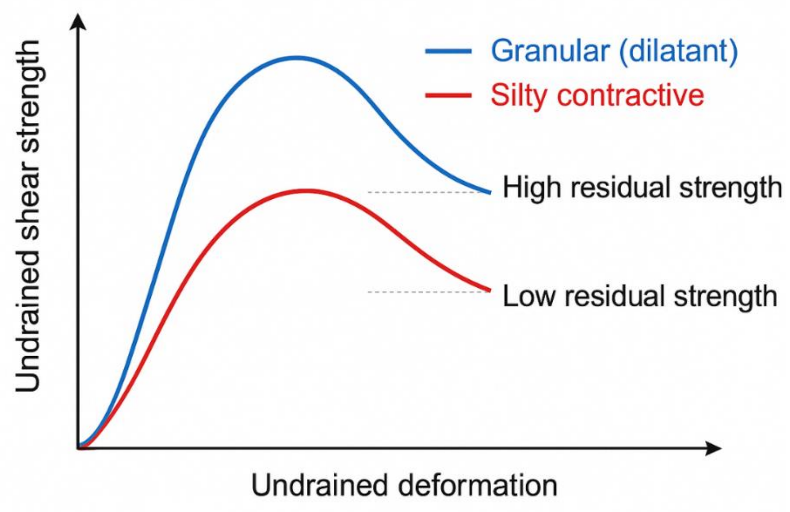

Figure 4. Undrained shear-strength response for granular (dilatant) versus silty contractive tailings, highlight differences in peak and residual strengths. Adapted from Arnold et al. (2023), Ayala et al. (2022), and Liu et al. (2025)

A growing body of experimental and field evidence published between 2020 and 2025 indicates that liquefaction susceptibility in TSFs is strongly influenced by tailings typology, especially through differences in fabric, contractivity, and post-peak softening behavior. These properties affect not only the onset of instability but also the severity of flow-type deformation once triggered. To compare these differences across common depositional products, Table 2 summarizes the key mechanical characteristics of major tailings types—ranging from sandy and silty materials to ultra-fine, filtered, and paste tailings—highlighting how fabric and drainage conditions determine their liquefaction risk.

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Table 2. Critical properties by tailings typology. Adapted from Been et al. (2020); Almeida et al. (2022); Ayala et al. (2022); Arnold et al. (2023); Liu et al. (2024); Naftchali et al. (2024); Qi et al. (2024); Simms et al. (2025).

Tailings type	Fabric	Contractivity	Strength loss	Liquefaction tendency
Sandy tailings	Open, granular structure with low fines; weak particle interlocking.	Low to moderate; dilation may dominate at low confining stress.	Moderate; peak-to-residual drop is smaller.	Lower; failures typically require high contractive tendencies or loose state.
Silty tailings	Mixed fabric; partial structure from fine-grained matrix surrounding sand grains.	Moderate to high, especially when metastable or lightly cemented.	Significant; may show abrupt softening after peak.	Highly susceptible under rapid loading or partial drainage.
Ultra-fine tailings	Dense, cohesive-like microfabric; intense pore-water pressure buildup.	High; strong contractive response under undrained loading.	Very high; significant drop from peak to residual strength.	Very high; prone to flow liquefaction even at moderate stresses.
Filtered tailings	Structurally bonded through partial consolidation; low saturation.	Low when unsaturated; increases when saturated.	Low to moderate; depends on the degree of wetting or disturbance.	Low when placed dry; moderate to high if saturation reset occurs.
Paste tailings	Highly consolidated, cohesive, low-permeability matrix.	Very low; material behaves more like stiff soil than granular tailings.	Low; strength loss is limited unless remolded.	Very low; liquefaction unlikely unless fully remolded and resaturated.

Although progress from 2020 to 2025 has enhanced understanding of tailings behavior through experimental and mechanistic studies, significant limitations still exist. Most data rely on reconstituted specimens, raising questions about how properties such as contractivity, peak strength, and residual behavior translate to actual field stratigraphy that includes preserved fabric, cementation, and suction. Few studies assess how operational factors—such as spigotting, depositional variability, saturation cycles, and drainage—impact fabric or void ratio, making Ψ–e and Vs-based correlations less dependable. Real TSFs often consist of transitional or layered mixes, but combined datasets that include geotechnical, hydraulic, and depositional data are still rare. These gaps restrict the practical application of improved mechanistic insights in susceptibility assessments.

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Overall, the developing experimental database shows a more detailed understanding of tailings behavior, where void ratio, fabric, grain-size distribution, fines content, and degree of structure influence the transition between dilative and contractive responses. These factors form the basis for evaluating susceptibility to static and cyclic liquefaction, as discussed in the diagnostic frameworks introduced in the next section.

5. Diagnostic of susceptibility: CPTu/SCPTu, Vs, and the state parameter Ψ

Recent advances in diagnosing liquefaction susceptibility focus on interpreting the state parameter (Ψ) from in situ tests—especially CPTu and SCPTu—as a way to relate penetration characteristics to the soil's position relative to the critical or steady state line. In tailings engineering, Ψ has become a key indicator because it combines the effects of void ratio, effective stress, and fabric on contractive tendencies, offering a more mechanistic alternative to empirical liquefaction charts (Riveros & Sadrekarimi, 2021; Robertson, 2021; Verdugo, 2024). For my tailings, particularly those with silty or fine-grained textures—Ψ provides valuable insights into metastability and the risk of rapid undrained softening during monotonic loading (Soares et al., 2023; Santos Junior et al., 2022; Schnaid, 2022). Figure 5 details the typical workflow used in recent studies to determine liquefaction susceptibility classes from Ψ, connecting field measurements (CPTu/SCPTu and Vs) to interpretive criteria and classification results.

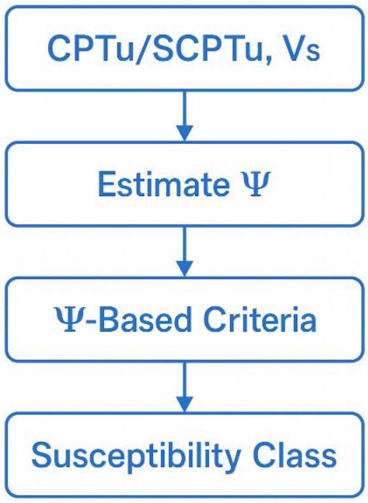

Figure 5. Workflow for estimating liquefaction susceptibility using the state parameter (Ψ). Adapted from Robertson (2021); Riveros & Sadrekarimi (2021); Soares et al. (2023); Schnaid (2022); Verdugo (2024)

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A major advancement in 2023 was achieved by Monforte, Arroyo, and Gens (2023), who introduced an analytical method to directly determine Ψ from CPTu data during undrained loading, using the interaction among tip resistance, sleeve friction, and pore-pressure response. At the same time, Mozaffari et al. (2023) created material-specific interpretations of Ψ based on calibrated constitutive models derived from CPT data, strengthening the link between fabric, penetration indices, and static-liquefaction susceptibility. These developments support broader understanding of state-dependent behavior in tailings (Simms et al., 2025; Ayala et al., 2022). Figure 6 illustrates the conceptual basis of these methods, showing how variations in cone resistance, sleeve friction, and excess pore pressure can be used to estimate the state parameter Ψ.

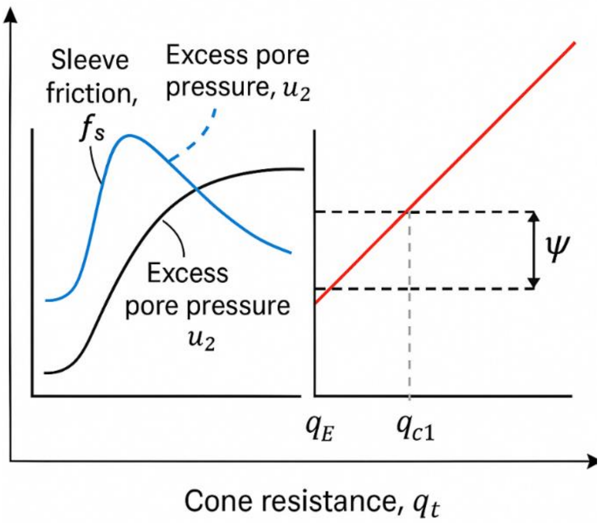

Figure 6. Conceptual interpretation of Ψ from CPTu signals. Adapted from Monforte et al. (2023); Mozaffari et al. (2023); Robertson (2021).

Further progress was made in 2024 with SCPTu-based interpretations. Liu et al. (2024) and Ayala, Fourie, and Reid (2022) expanded Ψ estimation by including shear-wave velocity (Vs), suggesting classification schemes for non-plastic silts and fine tailings where traditional sand-based methods may be unreliable. SCPTu-derived Ψ is particularly valuable for heterogeneous stratigraphies, as Vs offers better resolution of stiffness contrasts, layering effects, and fabric variations that significantly influence liquefaction behavior (Zhang et al., 2023; Lin et al., 2024).

To better understand how recent analytical methods extract the state parameter directly from CPTu signals, Figure 7 shows the interaction between cone resistance,

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sleeve friction, and excess pore-pressure response during undrained penetration. This conceptual relationship provides the foundation for estimating Ψ from in situ data and supports the 2023–2024 advancements in state-parameter interpretation for mine tailings.

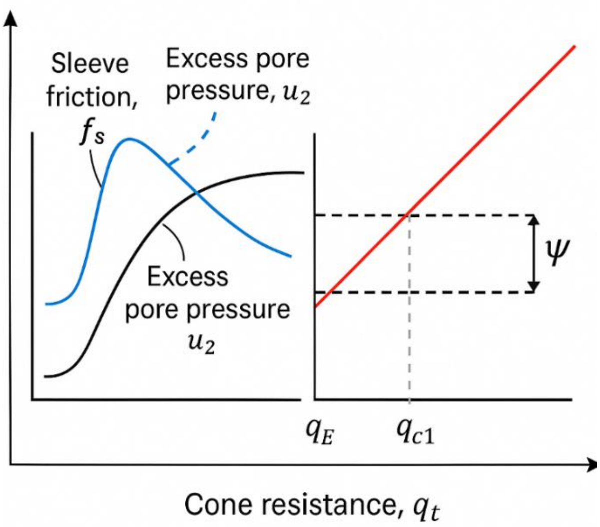

Figure 7. Conceptual interpretation of Ψ from CPTu response. Adapted from Monforte et al. (2023); Mozaffari et al. (2023); Robertson (2021).

Despite these advances, several limitations still exist. Partial drainage during CPTu testing in fine tailings—especially in layers of intermediate permeability—can distort pore-pressure responses and lead to biased Ψ estimates (Santos Junior et al., 2022; Soares et al., 2023). Factors like plasticity, cementation, and depositional structure further complicate interpretation by influencing penetration resistance and pore-pressure development in ways not fully captured by traditional correlations (Riveros & Sadrekarimi, 2021; Macedo & Verga, 2022). Anisotropy—both fabric- and stress-induced—also adds to the variability of CPTu-derived properties, particularly in TSFs with alternating silt–sand layers (Ayala et al., 2022; Simms et al., 2025).

Despite the increasing reliance on CPTu- and SCPTu-based interpretations for estimating the state parameter (Ψ), several inherent limitations still exist—especially in fine-grained, partially structured, or ultra-low-permeability tailings. These uncertainties arise from drainage conditions, fabric sensitivity, stratigraphic heterogeneity, anisotropy, bonding effects, and equipment-related artifacts, all of which can distort penetration resistance and pore-pressure signals. Table 3 summarizes the primary sources of uncertainty, their effects on interpretation, and

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recommended mitigation strategies, consolidating the diagnostic insights reported in recent experimental and field-based studies (Simms et al., 2025; Lin et al., 2022). When integrated into multi-parameter assessment frameworks, these considerations significantly enhance the reliability of liquefaction susceptibility evaluations.

Table 3. Limitations of CPTu/SCPTu in fine-grained tailings

Source of Uncertainty	Effect on Interpretation	Mitigation Strategies
Partial drainage during penetration	Underestimation or distortion of pore-pressure response; bias in qc–u_2 calibration; misestimation of Ψ	Use SCPTu + Vs; conduct rate-controlled penetration tests; compare against laboratory undrained response.
Fabric sensitivity and destructuration	Tip resistance and friction ratio do not reflect the true in situ structure; apparent variability in Ψ.	Combine CPTu with microstructure tests; integrate depositional history; use fabric-aware constitutive models.
Layering and stratigraphic heterogeneity	Difficulty identifying thin contractive silty layers; smoothed qc profiles; masked liquefaction intervals	Increase CPT spacing; integrate SCPTu for stiffness contrast; use Vs for layer resolution.
Anisotropy in stress and fabric	Variability in qc and fs unrelated to material type; misleading state-parameter trends	Interpret CPTu with stress normalization; embed anisotropy in constitutive calibration.
Cementation or bonding	Artificially high qc; false sense of dilative behavior; underestimated liquefaction susceptibility.	Combine CPTu with suction/bonding tests; use ring-shear data to validate residual strengths.
Very low permeability (ultra-fine tailings)	Pore pressures may not dissipate uniformly, causing oscillations or spikes in u_2 measurements.	Use a piezocone with high-resolution transducers; compare multiple penetration speeds.
Transition zones (silt–sand)	qc may not distinguish contractive vs dilative units; ambiguous Ψ estimates	Combine qc with Vs and fines content; use hybrid Ψ estimation frameworks
Equipment saturation issues (CPTu filters)	Delayed pore-pressure response; undermeasured u_2 peaks	Strict pre-saturation protocols; field verification; redundant tests
Stress history effects	Overconsolidation and desiccation layers distort qc–Ψ correlations	Use OCR estimation Vs; integrate laboratory stress-path testing
Operator-induced variability/penetration rate inconsistencies	Non-representative qc and u_2; false liquefaction indicators	Use automated rigs; quality control logs; repeat penetration tests

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Although recent advances have strengthened the scientific basis for Ψ-based methods, significant conceptual advances in liquefaction diagnosis have not yet translated into consistent practical implementation of CPTu/SCPTu–Ψ approaches. Idealized assumptions—such as fully undrained penetration, fabric independence, and homogeneous stratigraphy—stand in stark contrast to the heterogeneous, partially drained, and fabric-sensitive nature of real tailings. Existing correlations are often specific to commodities, while small calibration datasets still limit Vs-based indicators. Uncertainties from partial drainage, anisotropy, and cementation are rarely quantified, even though they can significantly influence Ψ and alter susceptibility assessments. Multi-parameter frameworks hold promise, but inconsistent data integration and the lack of standardized protocols restrict practical use, emphasizing the need for broader calibration and better uncertainty quantification.

As tailings storage facilities adopt risk-based assessment frameworks aligned with GISTM (2020) and ICOLD Bulletin 194 (2022), diagnostic methods that incorporate Ψ, CPTu/SCPTu, and Vs have become essential for producing robust, evidence-based stability evaluations. The following section examines the triggers and loading paths that initiate liquefaction mechanisms and their implications for TSF performance.

6. Triggers and stability of tailings storage facilities

The influence of triggering mechanisms on flow-liquefaction behavior becomes even more evident when examining how variations in residual undrained shear strength affect post-failure mobility. Numerical back-analyses and runout modeling conducted between 2021 and 2025 show that lower residual strengths—typically associated with contractive silty or ultra-fine tailings—result in significantly longer runout distances and steeper initial acceleration phases, while higher residual strengths reduce mobility and energy dissipation (Riveros & Sadrekarimi, 2021; Macedo & Verga, 2022; Lin et al., 2022; Verdugo, 2024; Rana et al., 2021). Figure 8 demonstrates these trends by comparing runout profiles for hypothetical residual strengths of 5, 10, and 20 kPa, highlighting how small decreases in post-liquefaction strength markedly impact travel distance and final deposition height. This behavior emphasizes the importance of accurately characterizing residual strength in susceptibility assessments and runout modeling of TSFs.

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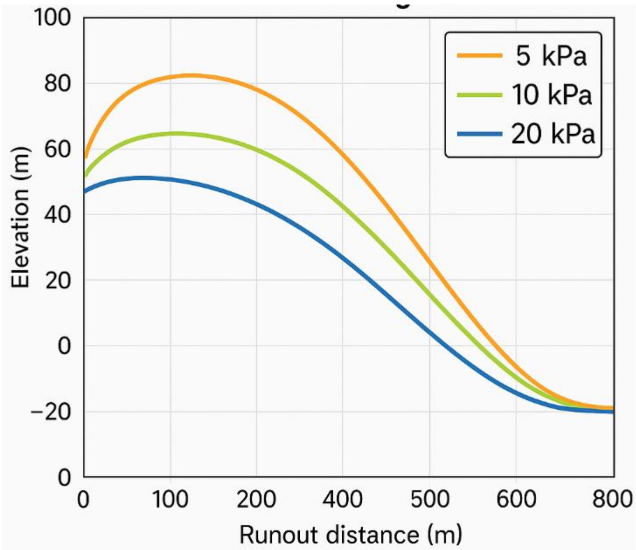

Figure 8. Modeled runout profiles for residual undrained shear strengths of 5, 10, and 20 kPa. Adapted from Rana et al. (2021); Verdugo (2024); Lin et al. (2022).

Understanding how different triggering mechanisms cause mechanical effects is essential for assessing liquefaction risks in tailings storage facilities. Recent studies (2020–2025) reveal that triggers do not act uniformly across layered deposits; instead, their effects depend on fabric, saturation level, drainage conditions, and the in-situ stress path (Macedo & Verga, 2022; Lin et al., 2022; Verdugo, 2024). As illustrated in Table 4, each trigger type follows a typical sequence from Trigger → Mechanical Effect → Observable Field/Lab Indicators, enabling practitioners to identify early signs of instability and enhance numerical models for onset and post-trigger softening. This detailed mapping is especially useful for upstream TSFs with heterogeneous, fines-rich layers, where multiple triggers may operate simultaneously or sequentially.

Table 4. Trigger → Mechanical Consequence → Field/Lab Indicators. Adapted from Riveros & Sadrekarimi (2021); Macedo & Verga (2022); Lin et al. (2022); Verdugo (2024).

Trigger Type	Mechanical Consequence	Diagnostic Indicators (Field / Lab)
Static trigger (e.g., loading from raises, local shear stress increase, loss of confinement)	Undrained shearing in contractive layers → rapid pore-pressure generation → collapse of effective stress → static liquefaction	• Low Vs zones (soft, contractive layers) • CPTu: low qc / high Rf • u_2 spikes under slow penetration • High inferred Ψ (> 0) • Sensitive/fabric-dependent response in triaxial tests
Hydraulic trigger (e.g., rapid rise in piezometric levels, seepage reversal,	Reduction in effective stress without significant shearing → approach to instability line → hydraulic softening	• Rising water table / piezometers • CPTu: reduced effective stress profiles • High B-value in lab samples • Loss of suction in partially saturated layers •

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blockage of drains)		FEM seepage analysis showing critical gradients
Cyclic trigger (e.g., blasting, machinery vibration, seismic loading)	Cyclic mobility → progressive pore-pressure buildup → potential transition to flow liquefaction if stress path crosses instability boundary	• CPTu: low normalized qc1Ncs • Vs degradation under cyclic loading • Cyclic triaxial: rapid ru accumulation • High contractivity index • Historical vibration monitoring / PSD analysis
Operational trigger (e.g., bulldozer surcharge, rapid deposition, pumping instability, pipeline discharge)	Local overstressing → disturbance of fabric → possible undrained response in weak layers → localized failure propagating upslope	• CPTu: heterogeneous qc, thin weak layers • Variability in Vs correlating with deposition history • Drone/LiDAR: slope changes or deflection • Moisture increase in active beaches • Nonuniform density measured during QC

A key difference between conventional shear failure and static liquefaction is found in the stress-path response during undrained loading. When a contractive tailings layer is sheared, pore pressure builds, decreasing the effective mean stress rapidly and pushing the material toward instability. As shown in Figure 9, the stress path sharply curves toward lower effective stresses, crossing the failure envelope at a point where shear resistance fails. This decrease in σ′ during undrained conditions—rather than an increase in applied shear stress—is what defines static liquefaction. It explains why metastable silty and ultra-fine tailings can suddenly fail even under moderate external loads.

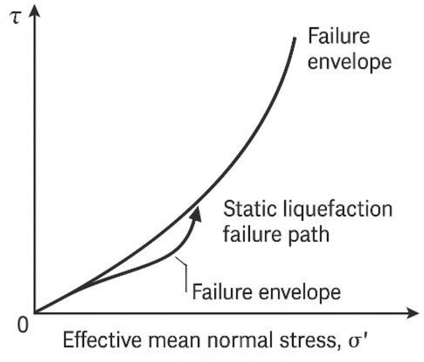

Figure 9. Static liquefaction stress-path behavior. Adapted from Verdugo (2024) and Riveros & Sadrekarimi (2021).

Cyclic triggers are still important in seismically active areas. Earthquakes cause repeated loading that can create excess pore pressures in tailings with low permeability or limited dilatancy, potentially leading to cyclic liquefaction. Although the mechanism differs from static liquefaction, the result—rapid loss of strength—is

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similar. Laboratory studies show that some silty tailings exhibit hybrid responses in which static and cyclic effects interact, depending on drainage conditions, loading amplitude, and fabric (Chen et al., 2020; Fonni et al., 2025; Soares et al., 2023; Zhang et al., 2023). Observations from centrifuge tests and numerical back-analyses also emphasize how cyclic behavior is affected by stratigraphy and contractive interbeds within TSFs (Ng et al., 2023; Simms et al., 2025).

In heterogeneous TSFs, constitutive modeling must account not only for triggering mechanisms but also for the internal stratigraphy that influences drainage, contractivity, and the development of instability. Layered sequences with alternating dilative and contractive units can respond very differently during undrained loading, where thin silty or silty–sand contractive layers may localize deformation and cause liquefaction even if nearby sandy layers remain dilative. Figure 10 illustrates a simplified stratigraphic layout commonly found in upstream-raised deposits: contractive, metastable layers are interbedded with denser, more dilative sands, creating a vertically varying susceptibility profile that significantly impacts shear-band formation, strain localization, and post-trigger deformation patterns. These stratigraphic factors interact directly with constitutive models such as NorSand and PM4Silt, which use state-based formulations to capture layer behavior under static or cyclic loading.

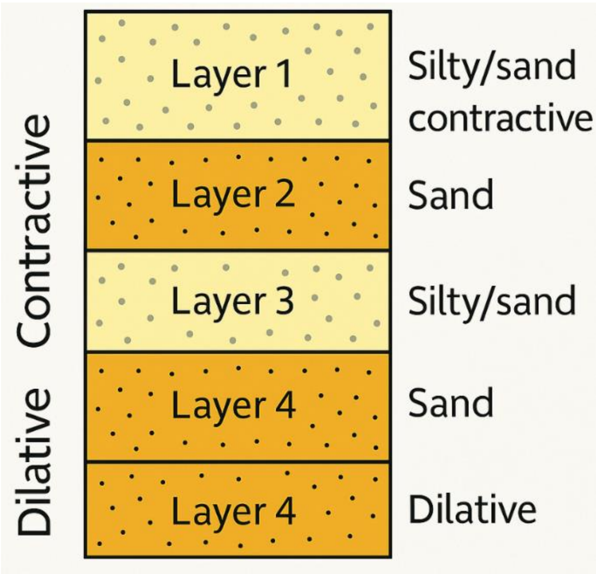

Figure 10. Representative layered stratigraphy in tailings deposits, showing alternation between contractive and dilative units. Adapted from Macedo & Verga (2022) and Riveros & Sadrekarimi (2021).

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Operationally induced triggers have gained significant attention in the 2020–2025 literature. Studies indicate that moderate increases in deposition rates, changes in spigotting patterns, and water management adjustments can lead to local increases in pore pressure that extend into deeper, contractive layers. When combined with limited drainage or elevated phreatic surfaces, these transient conditions can be sufficient to trigger static liquefaction in upstream-raised or fines-rich TSFs (Das et al., 2024; Reid et al., 2021; Dares Technology, 2024). Remote sensing analyses using InSAR and optical data identify early signs of deformation before failures, highlighting that operational and hydraulic triggers often act together rather than independently (Grebby et al., 2021; Rana et al., 2024; UNECE, 2025; Lin et al., 2024).

Notably, several studies indicate that TSFs classified as “stable” under traditional drained or undrained limit-equilibrium assumptions might transition into strain-softening regimes when evaluated with realistic operational procedures, deposition history, or transient hydraulic conditions. This is especially evident in stratified tailings with alternating silt–sand layers, where minor changes in stress path or drainage state can lead to significant increases in contractive response (Das et al., 2024; Ayala et al., 2022; Santos Junior et al., 2022).

Despite notable advances in concepts and modeling, understanding TSF triggering remains limited due to fragmented methods and poor integration of field observations, operational data, and constitutive models. Real failures often result from combined triggers—hydraulic transients, metastable fabrics, and operational disturbances—but most studies analyze these factors separately. Constitutive frameworks rely on idealized drainage and calibration datasets that do not fully represent fine or partially saturated tailings. While monitoring can identify precursors, few analyses link them to changes in stress paths or Ψ shifts. As a result, the development of coupled triggers remains poorly understood, highlighting the need for integrated multi-physics approaches that connect hydraulics, deposition, and constitutive behavior to real-time risk.

Overall, the literature from 2020–2025 indicates that liquefaction susceptibility is not just a material property but also depends on the evolving interaction between stress history, drainage development, hydraulic control, and operational practices. Correctly identifying and modeling static, cyclic, hydraulic, and operational triggers is

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vital for understanding and managing TSF stability. The next section explains how multiple-source monitoring technologies can detect early signs and support proactive risk management.

7. Monitoring and prediction (multi-method approaches)

To enhance these traditional datasets, recent research has highlighted the importance of combining remote-sensing tools—especially InSAR time-series analysis—with ground-based measurements to develop a unified, continuous evaluation of dam performance (Das et al., 2024; Rana et al., 2024; Grebby et al., 2021). Figure 11 depicts a simplified conceptual workflow where multiple monitoring methods, including InSAR, piezometry, inclinometry, GNSS/total station surveys, and routine field inspections, are integrated into a monitoring hub that can generate automated alerts. This multi-source setup enhances the ability to detect precursors to instability, supports probabilistic risk updates, and enables early detection of subtle deformation patterns that may occur before static liquefaction.

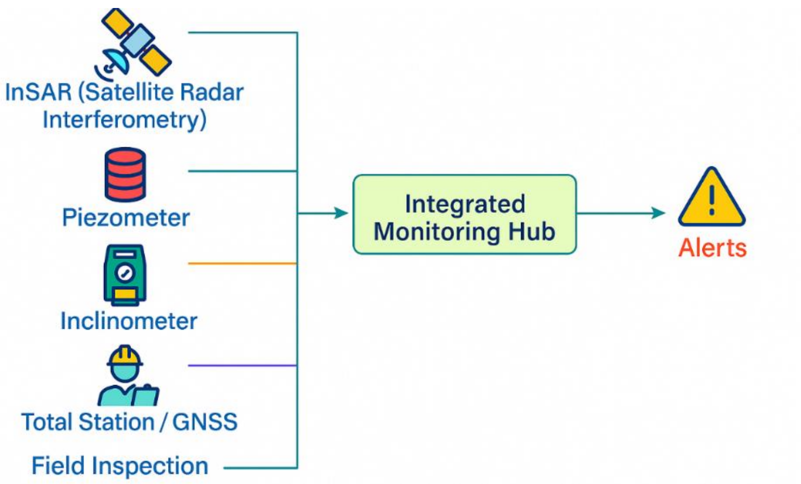

Figure 11. Integrated multi-source monitoring architecture for TSFs, consolidating satellite-based, in situ, and observational datasets into a unified alert system. Adapted from Das et al. (2024), Grebby et al. (2021), and SRK Consulting (2024).

To demonstrate how these deformation patterns usually appear in remotely sensed datasets, Figure 12 shows a simplified InSAR displacement contour map that highlights concentric zones of subsidence. These spatial patterns—marked by millimeter to sub-centimeter vertical movements—are often linked to consolidation processes, localized weakening, or ongoing strain buildup within tailings deposits. As noted in Grebby et al. (2021) and Rana et al. (2024), the detection of persistent,

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spatially consistent displacement bowls is key to early identification of instability precursors in TSFs. More recent developments, including consolidation–mechanical separation frameworks (Yang et al., 2025; Lin et al., 2024), further improve the ability to distinguish between harmless settlement and deformation caused by structural deterioration, thus increasing the diagnostic power of satellite-based monitoring.

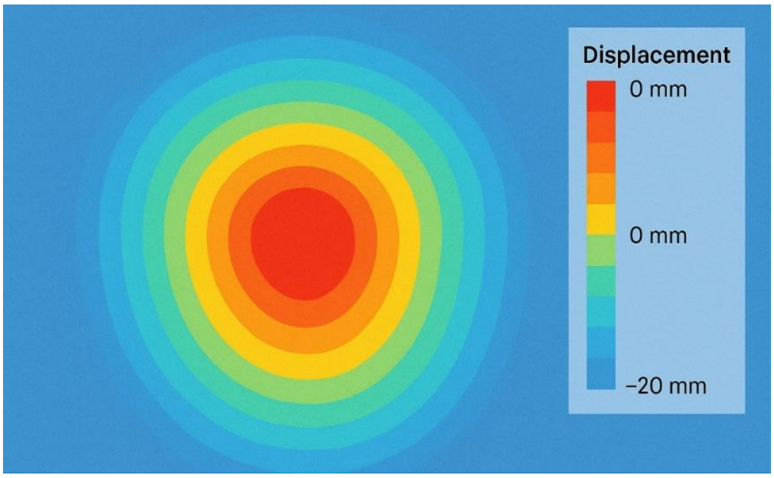

Figure 12. Example of an InSAR-derived displacement field showing concentric subsidence patterns typical of consolidation- or deformation-driven ground movement in TSFs. Adapted from Grebby et al. (2021), Rana et al. (2024), and Yang et al. (2025).

Therefore, modern practice emphasizes data integration, combining InSAR observations with piezometric data, surface displacement measurements, visual inspections, and operational information to gain a more comprehensive understanding of TSF behavior. This integrated approach enables the detection of precursor signals—such as increasing displacement, rising pore pressures, inversion of hydraulic gradients, abnormal crest migration, or displacement patterns that do not align with operational history (Pacheco et al., 2025; Lin et al., 2022). Such precursors have been observed in several failures and near-failures following Brumadinho, underscoring the need for cross-validation across multiple monitoring methods (Grebby et al., 2021; Sebothoma et al., 2020; Xie et al., 2023; Carlà et al., 2022), Rana et al., 2024; Fu et al., 2025).

A recurring insight from the 2020–2025 literature is the difficulty of defining reliable warning windows—the interval between detectable precursor signals and rapid failure. Although these windows vary with material properties, saturation conditions, and monitoring density, multiple studies show that systematically combining indicators extends lead time and reduces uncertainty (Rana et al., 2024;

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Carlà et al., 2022; Islam et al., 2021). However, implementing such integrated frameworks across large corporate portfolios faces logistical challenges, including data heterogeneity, limited connectivity in remote areas, sensor reliability issues, staffing constraints, and the need for automated anomaly-detection tools (UNECE, 2025; Dares Technology, 2024; Lin et al., 2024).

Figure 13 illustrates how governance requirements are applied in practice through a simplified escalation and decision-flow framework. This framework links trigger exceedances, persistence checks, alert generation, and formal notification to the Engineer of Record (EoR). Recent standards and case studies emphasize that timely interpretation of data—beyond just collecting is essential to avoid delays in responding to changing instability conditions (Global Tailings Review, 2020; Pacheco et al., 2025). The framework also highlights the need to integrate monitoring systems into organizational decision-making processes, ensuring consistent escalation, documentation, and coordinated event management.

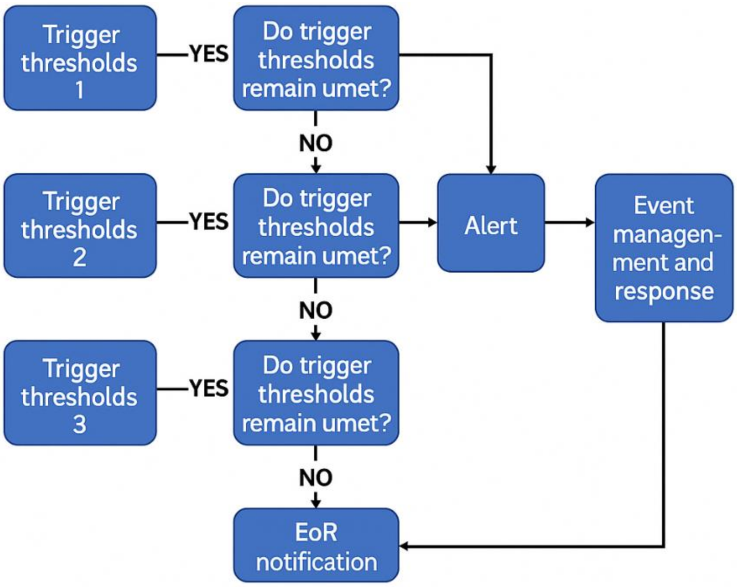

Figure 13. Example of an escalation and decision-flow sequence for monitoring trigger exceedances, alert generation, and EoR notification. Adapted from Global Tailings Review (2020), Piciullo et al. (2022), and Lin et al. (2024).

To illustrate how different triggering mechanisms result in mechanical responses and observable signs in the field or the laboratory, Table 5 organizes the most common trigger–response–indicator relationships reported in the 2020–2025 literature. This clear layout explains why similar macroscopic failures can arise from different fundamental processes and why successful diagnosis requires combining hydraulic,

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mechanical, and operational data rather than relying solely on single-parameter thresholds. The table also highlights practical diagnostic' indicators—such as pore-pressure patterns, stiffness differences, state-parameter trends, and deformation signatures—that have proven most reliable for detecting precursors to instability in heterogeneous tailings stratigraphy.

Table 5. Trigger → Mechanical consequence → Field/Lab indicators. Adapted from Riveros & Sadrekarimi (2021); Macedo & Verga (2022); Lin et al. (2022); Soares et al. (2023); Simms et al. (2025).

Technology	Advantage	Limitation	Temporal Scale	Spatial Scale
InSAR (Satellite Radar Interferometry)	Wide-area coverage; millimetric deformation detection; retrospective analysis possible	Susceptible to atmospheric noise; decorrelation over vegetated or saturated areas; low revisit frequency	Weekly to biweekly (satellite-dependent)	Regional to facility scale (km^2 to tens of km^2)
Piezometers (Vibrating Wire / MEMS)	Direct pore-pressure measurement; high precision; excellent for identifying contractive behavior and rising pore pressures	Point measurement only; requires installation and protection; cable damage risk	Minutes to hours	Very local (cm to m)
Inclinometers (Casing or MEMS chain)	Measures internal shear displacement; highly sensitive to layer movement	Installation required; limited depth; cannot detect rapid failures if not automated	Hours to daily	Local (meters along borehole)
Total Station / GNSS	High accuracy for crest and slope displacement; real-time capability	Requires line of sight; GNSS can drift; vulnerable to weather	Seconds to minutes	Local to site-wide (meters to km)
Extensometers / Settlement Plates	Direct measurement of vertical settlement; simple and robust	Low temporal resolution unless automated; maintenance required	Daily to weekly (manual) or minutes (automated)	Very local (single point)
Microseismic / Acoustic Emission	Early detection of internal cracking; excellent precursor for brittle failures	Requires complex interpretation; noise interference	Seconds	Local (tens to hundreds of meters)
Drones (Photogrammetry / LiDAR)	Rapid coverage; high-resolution DEMs; suitable for change detection	Weather- and visibility-dependent; requires processing time	On demand (days to weeks)	Facility scale (hectares to km^2)

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Manual Field Inspection	Contextual, qualitative, essential for validating anomalies	Subjective; intermittent; depends on observer training	Weeks to months	Facility scale but non-continuous

Although multi-source monitoring has improved significantly, its ability to predict TSF performance remains limited. Most systems detect deformation or pore-pressure changes but lack mechanistic connections to constitutive behavior, evolving Ψ, or failure progression. Cross-modal integration—InSAR, piezometry, inclinometers, operational data—still relies heavily on heuristics rather than automated, physics-based fusion. Sparse deep instrumentation and mismatches between monitoring frequency and precursor timescales further limit reliability. Governance gaps, including unclear escalation thresholds and inconsistent communication, also reduce operational effectiveness. Overall, monitoring now provides broader diagnostic coverage but still needs stronger mechanistic links and decision-support frameworks to become truly predictive.

Overall, the literature confirms that predictive ability results from combining multiple sources and scales of data, not from isolated tools. When these systems are integrated with operational records and field observations, they form the basis of proactive risk management aligned with GISTM and ICOLD 194 standards. The next section discusses how the evolving standards framework (2020–2025) influences monitoring, design, and governance practices for TSFs.

8. Standards and regulatory framework (2020–2025)

Implementing the Plan–Do–Check–Act (PDCA) cycle in the GISTM signifies a move from isolated operational tasks to an ongoing, adaptable risk-management system for TSFs. Figure 14 shows how PDCA connects design, monitoring, evaluation, and corrective actions into a single governance process throughout the facility's lifecycle. In this framework, liquefaction assessment, instrumentation planning, trigger-level reviews, independent oversight, and escalation procedures become continuous responsibilities instead of separate tasks. This structured approach supports the governance principles emphasized in recent regulatory and technical literature (Global Tailings Review, 2020; Pacheco et al., 2025).

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Figure 14. Plan–Do–Check–Act cycle applied to TSF governance. Adapted from Global Tailings Review (2020).

Complementing this governance-oriented standard, ICOLD Bulletin 194 (2022) introduces detailed technical expectations for TSF safety. The bulletin calls for explicit evaluation of static and cyclic liquefaction, incorporating state parameter Ψ interpretation, strain-softening behavior, and post-trigger residual strength from construction through closure. Recent publications reinforce the importance of these requirements, particularly regarding pore-pressure generation and undrained response in silt-rich tailings (Monforte et al., 2023; Mozaffari et al., 2023). ICOLD further emphasizes integrating monitoring data, numerical analyses, and geotechnical characterization into a unified risk framework, consistent with advances such as CPTu/SCPTu-based Ψ estimation and Vs-based susceptibility assessments (SRK Consulting, 2024). Importantly, the bulletin positions liquefaction as a life-cycle hazard requiring continuous management rather than a one-time geotechnical check (ICOLD, 2022).

In Brazil, major reforms following the Brumadinho disaster redefined national TSF regulation. Law 14.066/2020 banned upstream construction and introduced stricter requirements for emergency preparedness, inspections, and independent reviews. The National Mining Agency (ANM) enhanced this framework through Resolution ANM nº 95/2022, which mandated periodic stability assessments, clear documentation of liquefaction susceptibility, and mandatory reporting via the SIGBM platform (Agência Nacional de Mineração, 2022). These measures emphasize

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transparency, traceability, and ongoing updates of geotechnical models based on monitoring—an approach aligned with international recommendations on deformation precursors and early-warning strategies (Lin et al., 2024; Monforte et al., 2023). To clarify how these frameworks differ in scope, requirements, and governance focus, Table 6 summarizes the main differences among the GISTM (Global Tailings Review, 2020), ICOLD Bulletin 194 (ICOLD, 2022), and ANM Resolution 95/2022 (Agência Nacional de Mineração, 2022).

Table 6. Comparison of GISTM, ICOLD Bulletin 194, and ANM Resolution 95/2022. Adapted from Global Tailings Review (2020); ICOLD (2022); Agência Nacional de Mineração (2022).

Aspect	GISTM (2020)	ICOLD Bulletin 194 (2016–2022)	ANM Resolution 95/2022 (Brazil)
Scope	Global standard for all TSFs with a strong ESG and governance orientation	Technical guidance for design, operation, monitoring, and risk management	National regulatory framework for TSFs; mandatory for all Brazilian operations
Risk Classification	Uses Consequence Classification (Extreme → Low) linked to performance objectives	Technical hazard categorization; engineering focus	Includes DPA (Potential Damage), CRI (Risk Category), mandatory PRAD, and PAEBM
Design Basis	Performance-based; requires independent review and risk-informed criteria	Relies on engineering principles, stability analyses, and design methods	Requires compliance with geotechnical factors of safety, stability proofs, and safety audits
EoR Requirement	Mandatory EoR for all TSFs by 2023	Recommends an independent review, but not compulsory	Requires a Responsible Technical Professional (RTP), not explicitly an EoR
Monitoring Requirements	Multi-source monitoring mandatory; real-time systems for Extreme & Very High consequence	Provides guidance but not prescriptive; focuses on instrumentation	Requires continuous monitoring; specific rules for pore pressure, deformation, reporting
Emergency Preparedness	Requires Emergency Response Plans (ERPs), trigger action response plans, and community engagement.	Advises emergency planning without formal ESG obligations	Mandatory PAEBM, public disclosure, periodic drills
Public Disclosure	Strong transparency requirements aligned with ESG frameworks	Not required	Annual stability declarations are made public; high transparency relative to many countries.

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Governance & Accountability	Strong emphasis on corporate governance, Board oversight, and independent audit	Professional responsibility; less emphasis on governance layers	Operator must maintain documentation; liability is assigned to the operator and RTP
Implementation Difficulty	High – requires corporate restructuring, digital systems, and governance layers.	Moderate – engineering-centered adoption	High for smaller operators due to mandatory instrumentation and reporting

Taken together, GISTM, ICOLD 194, and the Brazilian regulatory framework show notable similarities: all require life-cycle management, independent reviews, explicit liquefaction assessments, and thorough monitoring capable of detecting signs of instability. They also highlight the importance of clear documentation, effective risk communication, and institutional accountability. However, significant differences remain. GISTM is global and emphasizes governance; ICOLD provides technical details with flexible governance requirements; and Brazilian regulations are legally binding, focus on compliance, and are tailored to specific local TSF types—especially the ban on upstream dams.

For practitioners, these frameworks collectively signify a shift from traditional factor-of-safety approaches toward comprehensive stability management. This includes enhanced material characterization—such as Ψ-based methods—along with multi-source monitoring, routine use of InSAR, and systematic documentation of operational decisions affecting pore pressure and deformation. Recent evidence indicates that many failures are not due to insufficient shear strength but result from limited understanding of pore-pressure evolution, triggering mechanisms, and early deformation signals (Pacheco et al., 2025; Lin et al., 2022). Consequently, the 2020–2025 standards ecosystem emphasizes continuous, evidence-based practices that integrate geotechnical science, monitoring technologies, and governance requirements.

Figure 15 depicts the global status of GISTM adoption as of 2024, highlighting clear regional differences in regulatory alignment. Major mining jurisdictions in the Americas, Europe, and Oceania mainly fall under “adopted or moving toward GISTM,” reflecting strong alignment with international ESG standards. Other countries have instead developed or proposed domestic alternatives based on local regulatory traditions. Significant variation remains across Africa and parts of Asia, where

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modernization efforts are ongoing and public transparency is limited. Overall, the map emphasizes that although GISTM has become an international benchmark, its implementation largely depends on regional governance capacity and industry participation.

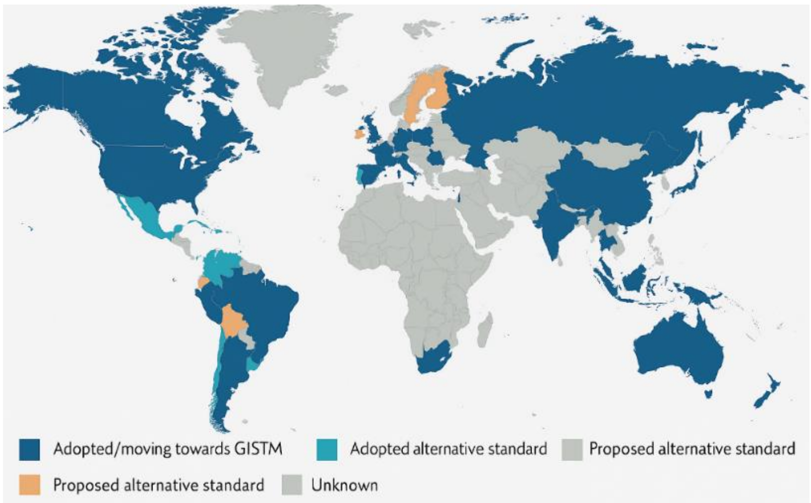

Figure 15. Worldwide progress toward the implementation of the Global Industry Standard on Tailings Management (GISTM). Adapted from ICMM (2023).

Despite notable progress in governance, technical standards, and regulatory clarity from 2020 to 2025, significant structural limitations still exist in how standards are interpreted and applied across the mining industry. First, although GISTM provides a globally consistent governance framework, its non-binding status results in inconsistent adoption, especially among operations outside ICMM membership or in regions with limited regulatory oversight. Conversely, legally binding frameworks like Brazil's Law 14.066/2020 and ANM Resolution 95/2022 enforce strict compliance but often lack the technical depth and flexibility needed to address different types of tailings or incorporate new scientific insights about liquefaction susceptibility. ICOLD 194 partially fills this gap by offering detailed guidance, yet its recommendations are advisory rather than enforceable, leading to variability in interpreting key concepts such as Ψ-based evaluation, residual strength selection, and the integration of strain-softening behavior into stability analyses.

A persistent gap exists between governance expectations and operational capacity: many operators lack the instrumentation density, data systems, staffing, and expertise needed to meet GISTM and ICOLD standards, especially at legacy TSFs with incomplete records or inaccessible stratigraphy. Formal compliance often

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conceals weak escalation protocols, inconsistent EoR interpretation, and delays in turning observations into action. An additional challenge is the limited integration of recent geotechnical advancements—such as state parameters, softening laws, Vs-based indicators, and hybrid CPTu–SCPTu diagnostics—into regulatory practices, leaving operators dependent on outdated tools that fail to capture transient liquefaction processes adequately.

Ultimately, the regulatory ecosystem from 2020 to 2025 represents a significant step forward but continues to develop. Fully achieving the goals of GISTM, ICOLD 194, and national regulations will require better alignment between governance frameworks and mechanistic geotechnical knowledge, along with advances in instrumentation, data integration, and decision-support systems. Without these enhancements, the aim of a fully evidence-based, life-cycle approach to tailings management will only be partially realized.

The following section examines how these evolving standards influence mitigation and retrofit strategies for active and legacy TSFs.

9. Mitigation and retrofit strategies

A core aspect of modern tailings dam risk management is understanding that failure prevention and emergency response happen in two separate yet linked phases. Recent frameworks highlight that effective prevention requires constantly updating knowledge of failure mechanisms, regularly reviewing design, and using multiple sources of monitoring to detect early signs before they become serious problems. When a trigger occurs—whether hydraulic, mechanical, or operational—the system shifts into a post-trigger phase focused on quick emergency response, stabilizing the facility, and planning for long-term recovery. This two-stage approach improves governance, clarifies escalation procedures, and aligns monitoring practices with consequence-based risk management strategies that have been increasingly adopted since 2020. Figure 16 shows this pre-trigger/post-trigger framework and its importance in current TSF governance.

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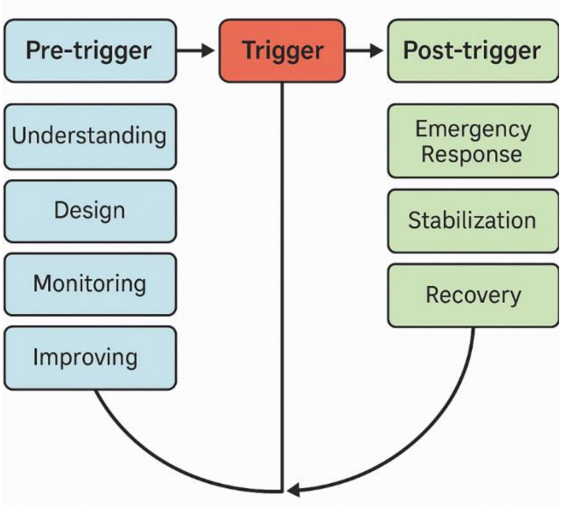

Figure 16. Pre-trigger and post-trigger risk-management framework for tailings storage facilities. Adapted from Pacheco et al. (2025)

Table 7 highlights key mitigation measures commonly used to reduce liquefaction susceptibility and improve the stability of tailings storage facilities. These measures operate through hydraulic, mechanical, and operational methods, and their effectiveness largely depends on site-specific conditions such as tailings gradation, permeability, stress history, and facility design. The table compares their effectiveness, main advantages, and potential limitations, serving as a practical tool for decision-making when selecting risk-reduction strategies for both active and legacy TSFs.

Table 7. Summary of mitigation measures for reducing liquefaction risk in tailings storage facilities, including mechanisms, relative effectiveness, advantages, and key limitations. Adapted from Pacheco et al. (2025), Pereira et al. 2025 and international tailings management guidelines.

Mitigation Measure	Primary Mechanism	Effectiveness (Relative)	Advantages	Limitations / Risks
Horizontal Drain Installation	Reduction of pore pressure; improved drainage and dissipation of ru	Moderate to High (site-dependent)	Rapid effect in permeable layers; relatively low cost; enhances FoS	Limited in low-permeability silty/ultrafine tailings; installation constraints;

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			under static loading	performance declines if drains clog
Buttress Construction (Downstream or Toe Buttress)	Increases resisting forces; improves slope stability; reduces deformation	High	Strong mechanical stabilization; effective for contractive layers; widely documented success	High cost; requires large material volumes; may reduce storage capacity; long construction time
Spigot Relocation / Deposition Control	Alters tailings gradation and density distribution; shifts phreatic surface and flow paths	Moderate	Flexible operational measure; low capital cost; can improve beach geometry and desaturation	Effectiveness depends on operational discipline; limited if deposition area is constrained; slow response
Beach Slope Optimization	Promotes drainage toward decant structure; increases desaturation of upper layers	Moderate	Improves phreatic control; simple to implement; synergistic with spigot relocation	Sensitive to tailings rheology; extreme rainfall can negate effect; requires continuous management
Decharacterization / Closure Transformation	Eliminates hydraulic containment; reduces stored volume and risk state; converts TSF to drained landform	Very High	Permanent risk reduction; removes reliance on monitoring; aligns with ESG and GISTM objectives	Very high CAPEX; multi-year execution; geochemical risks (AMD); requires permitting and community engagement

Recent case histories and technical guidance published between 2020 and 2025 show that effectively reducing liquefaction risk in tailings storage facilities (TSFs) requires coordinated, multi-layered mitigation strategies that span pre-trigger, trigger, and post-trigger conditions. Evidence from regulatory and industry guidance (ANCOLD, 2022; ICOLD, 2022) and independent technical evaluations (E-Tech International, 2024; Pacheco et al., 2025) indicate that midstream design modifications—implemented while a TSF remains operational—have become more common, especially in facilities with contractive silty tailings, high phreatic surfaces, or persistent deformation patterns identified through InSAR or geodetic monitoring (Dares Technology, 2024; Yang et al., 2025). These measures reflect an industry shift

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from maintenance-focused methods toward system-level redesign, where dam shape, tailings behavior, and operational controls are viewed as parts of an integrated geotechnical–hydraulic system.

Among the most common pre-failure mitigation strategies are downstream buttressing, structural berms, drainage improvements (such as horizontal drains, relief wells, and drainage galleries), improved water management, and controlled lowering of pond levels. Studies from 2021 to 2024 show that even modest enhancements in drainage efficiency or stress redistribution can greatly reduce the undrained softening potential in fine tailings (Monforte et al., 2023; Mozaffari et al., 2023; SRK Consulting, 2024). These measures are especially effective when the state parameter Ψ is positive, and the tailings have high contractivity—conditions often found in silty, low-plasticity materials typical of many upstream-raised TSFs.

A second type of intervention involves midstream project modifications documented across multiple jurisdictions, including ANCOLD and ICOLD member countries. Figure 17 shows how combined drainage and buttressing measures can change the internal hydro-mechanical conditions of a tailings deposit, thereby decreasing liquefaction risk. Lowering the phreatic line with horizontal drains helps dissipate excess pore pressures, while constructing a downstream buttress increases shear resistance and creates a mechanically stronger zone. These combined efforts improve overall stability and help counteract contractive tendencies that may develop as tailings deposition progresses. This conceptual model emphasizes the importance of adaptive design, especially in facilities where stratigraphy, saturation patterns, or material behavior change over time (Lin et al., 2024; Pacheco et al., 2025).

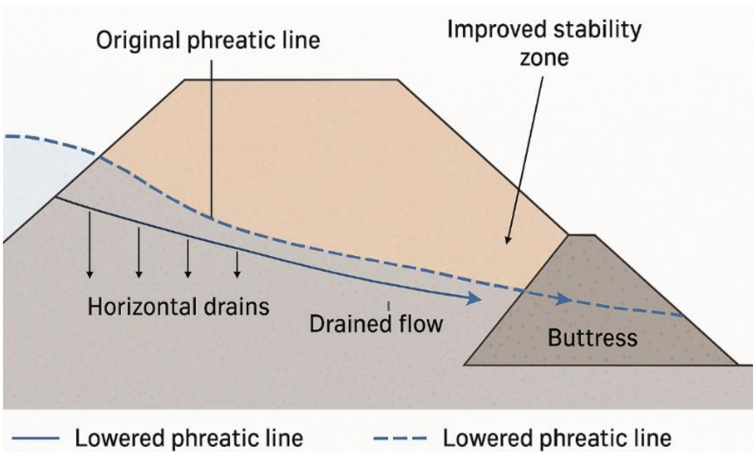

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Figure 17. Conceptual representation of phreatic-line reduction via horizontal drains and mechanical reinforcement through a downstream buttress, illustrating the resulting improvement in slope stability. Adapted from Pacheco et al. (2025) and standard tailings engineering practice.

Where risk levels exceed tolerable thresholds, more comprehensive interventions—such as targeted removal of tailings, controlled discharge, or complete decharacterization—are increasingly implemented. Brazilian programs under Lei 14.066/2020 and ANM Resolution 95/2022 demonstrate that decharacterization, combined with drainage improvements and structural reinforcements, can effectively reduce residual liquefaction potential by removing conditions that promote undrained instability (Vale S.A., 2023; GISTM, 2020). These measures directly address the combination of high saturation, contractive behavior, and limited confinement.

A major progress from 2020 to 2025 has been the development of vulnerability frameworks that clearly connect pre-trigger, trigger, and post-trigger states. These frameworks, supported by monitoring-based performance assessments (Yang et al., 2025; Dares Technology, 2024), help identify where mitigation efforts are most effective in reducing risks—whether by lowering the probability of hydraulic or operational triggers, decreasing strain-softening potential through drainage or densification, or controlling consequences with containment and runout barriers. This aligns with the risk-based approach of the GISTM (2020) and ICOLD Bulletin 194 (2022), which emphasize ongoing performance evaluation, transparent governance, and independent oversight via the Engineer of Record.

In practice, mitigation strategies must be prioritized across corporate portfolios where TSFs vary widely in deposition history, geometry, and consequence classification. Recent portfolio-level analyses (Lin et al., 2024; Pacheco et al., 2025) show that decisions increasingly depend on multi-source monitoring that integrates InSAR deformation trends, piezometric data, and operational records to identify facilities where susceptibility and trigger likelihood align. Such integrated frameworks support more defendable, risk-informed investment decisions in reinforcement, drainage upgrades, operational adjustments, or decharacterization.

Although mitigation and retrofit strategies for TSFs have progressed, their implementation remains inconsistent. Most measures—such as drainage upgrades, buttressing, and deposition adjustments—are still reactive, carried out only after

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precursor signals become well developed. This highlight challenges in translating real-time monitoring into timely action within unclear governance pathways. Their effectiveness also varies significantly by site: interventions that improve stability in sandy or intermediate tailings often offer limited benefits in contractive silty deposits with positive Ψ or severe saturation. Case histories demonstrate that such variability is often overlooked in portfolio-level decisions, leading to misallocated resources and suboptimal sequencing of interventions.

A third major limitation is the lack of long-term validation for many midstream design modifications. Measures such as upstream sector conversion, spigot relocation, and beach slope adjustments are theoretically sound, but few studies show their performance over time under changing hydraulic conditions or depositional fabrics. This lack of evidence increases uncertainty about the durability of mitigation methods, especially in rapidly depositing or stratigraphically complex TSFs. Also, large-scale interventions like decharacterization, although very effective, are often economically and logistically difficult for many legacy facilities, which widens the gap between best-practice recommendations and the industry's actual capabilities.

Mitigation strategies are increasingly focusing on integrated, system-level designs that combine hydraulic, mechanical, and operational controls. However, such integration is hampered by fragmented datasets, inconsistent monitoring systems, and the lack of unified geotechnical–hydraulic models that include Ψ-based assessments and transient softening behavior. Without these tools, interventions may only address symptoms rather than root causes, especially when triggers result from coupled drainage, deposition, and material responses. While conceptual advances from 2020 to 2025 are significant, applying them across diverse TSF portfolios remains difficult. This underscores the need for improved data fusion, model calibration, independent review, and adaptive life-cycle management.

Overall, literature from 2020 to 2025 indicates that liquefaction mitigation is not just a single design decision, but an iterative, adaptable process shaped by changing depositional conditions, operational practices, monitoring data, and governance needs. The next section describes how modern numerical modeling—including coupled FEM, MPM, and large-deformation analyses—assists in evaluating triggering, post-trigger softening, and runout within current geotechnical risk frameworks.

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10. Numerical modelling and runout

Recent advances in the numerical modeling of liquefaction triggering and runout reveal a clear shift toward hybrid approaches that combine small-deformation stability analyses with large-deformation frameworks capable of representing post-trigger flow mechanisms. Conventional finite-element and finite-difference analyses remain crucial for characterizing pore-pressure generation, evolution of state parameters, and the onset of undrained instability, but their usefulness becomes limited once strains localize and large deformations dominate the response. Recent state-based and constitutive-model investigations—particularly those examining the evolution of the state parameter through CPTu/SCPTu interpretation (Monforte et al., 2023; Mozaffari et al., 2023; SRK Consulting, 2024)—offer the foundation for integrating triggering analyses with flow-type deformation modeling.

Between 2023 and 2025, studies have increasingly combined descriptions of contractive tailings with large-deformation solvers, including Mesh-Free and MPM-type algorithms. Although the specific implementation varies, these hybrid workflows enable models to shift from pre-trigger stiffness-controlled behavior to post-trigger strain-softening flow, better capturing the mechanics of flow liquefaction in tailings storage facilities. Insights from regional and site-specific assessments (Lin et al., 2024; Pacheco et al., 2025) highlight that failure progression is strongly influenced by the softening law used for liquefied tailings and by assumptions regarding residual undrained strength.

Figure 18 summarizes the workflow commonly used in modern liquefaction-assessment frameworks for tailings storage facilities (TSFs). The process starts with laboratory characterization, usually monotonic triaxial, direct simple shear (DSS), or ring-shear testing—to determine steady-state strength parameters and contractive behavior. These parameters are then incorporated into numerical models (FEM or MPM) to assess the onset of instability and potential post-trigger deformation. When analyses show unstable or marginally stable conditions, engineers implement site-specific mitigation strategies like drainage enhancements or pore-pressure control. Conversely, when models confirm acceptable performance, the results directly inform the facility’s risk assessment and operational decisions. This workflow emphasizes the

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importance of linking geotechnical testing, constitutive modeling, and risk management in a consistent, evidence-based approach.

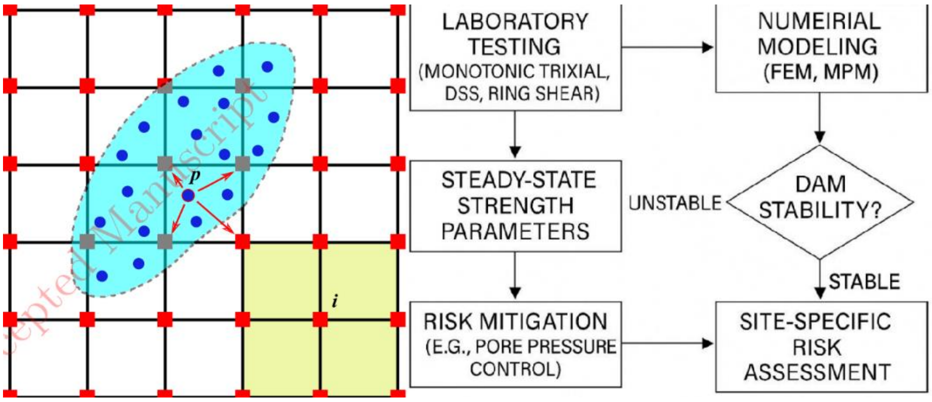

Figure 18. Integrated workflow for assessing static liquefaction potential in tailings, combining laboratory testing, steady-state parameter derivation, numerical modeling (FEM/MPM), and site-specific risk mitigation. Adapted from precedent methodologies in liquefaction analysis frameworks.

A key insight from this body of work is that post-liquefaction material properties mainly determine the predicted runout distance, deposition pattern, and flooding extent. Even small changes in assumed residual strength or viscous resistance can significantly affect runout forecasts, highlighting the challenge of defining constitutive inputs for liquefied tailings without high-quality reconsolidation tests or well-documented depositional histories (Monforte et al., 2023). This uncertainty underscores the need for parametric and probabilistic sensitivity analyses, especially under regulatory frameworks that require multiple consequence-based scenarios (ICOLD, 2022; GISTM, 2020). Table 8 summarizes the main mechanical and numerical factors affecting runout behavior in liquefaction-induced flow modeling, emphasizing mechanistic roles, sensitivity levels, and implications for TSF numerical analysis.

Table 8. Principal mechanical and numerical factors controlling runout behavior in liquefaction flow modelling, with mechanistic effects, sensitivity levels, and implications for TSF numerical analysis. Adapted from contemporary liquefaction modelling frameworks and FEM/MPM sensitivity studies.

Parameter / Condition	Mechanistic Effect	Influence on Runout Distance	Notes for TSF Modelling
Residual undrained strength (Su,res)	Controls post-trigger resistance and shear stress available to limit flow mobility	Strong sensitivity – small reductions in Su,res may produce *significant increases* in runout and affected area.	Most influential parameter; should be bracketed with lower-bound, median, and upper-bound scenarios

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Softening law (strain-softening curve shape)	Defines transition from peak → residual strength and governs strain localization	Moderate to strong sensitivity – sharper softening increases mobility and decreases containment.	MPM/FEM–MPM workflows highly dependent on softening curve adopted; site-specific calibration preferred
Viscous or numerical damping	Represents energy dissipation during flow and controls oscillatory numerical behaviour	Moderate sensitivity – over-damping reduces runout; under-damping may overestimate mobility.	Requires careful tuning; non-physical damping should be minimized or justified
Stratigraphy and layer contrast	Determines localization paths, sliding surfaces, drainage barriers, and weak horizons	High sensitivity – contractive silt layers drastically increase runout; dilative sands may limit mobility.	Heterogeneous TSFs require layered models; simplified stratigraphy often underestimates risk.
Degree of saturation / pore-pressure regime	Affects triggering and effective stress collapse	High sensitivity – high ru accelerates flow and increases runout	Difficult to characterize in the field; integrate piezometry + InSAR settlement patterns
Material-point resolution (MPM)	Controls the spatial accuracy of large deformations	Indirect sensitivity – low resolution may suppress localization or distort runout shape	Mesh/point density should align with the expected shear-band width
Boundary conditions and confinement	Controls lateral spread and flow channelization	Moderate sensitivity	

Integrating numerical modeling with formal risk assessment frameworks has become standard global practice. Modern workflows merge triggering analysis, runout simulation, inundation mapping, and downstream consequence evaluation into unified decision-support systems that leverage InSAR deformation trends, satellite analytics, and operational datasets (Yang et al., 2025; Dares Technology, 2024). These combined models provide a traceable basis for emergency response planning, design prioritization, and risk management at the portfolio level.

Overall, literature from 2020–2025 highlights that predictive modeling is most effective when built with numerical frameworks.

(i) accurately represent the pre-trigger stress path and pore-pressure evolution.

(ii) transition properly to large-deformation physics at the onset of instability.

(iii) explicitly investigate uncertainties in softening behavior and liquefied material properties; and

(iv) interface directly with governance and regulatory requirements.

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These trends suggest that hybrid FEM–MPM frameworks, supported by improved monitoring datasets and uncertainty quantification, will likely become standard tools for assessing liquefaction-induced failure progression and runout in TSF engineering.

Although numerical modeling has advanced significantly, key limitations remain. Hybrid FEM–MPM workflows still depend on assumptions about residual strength, softening laws, and drainage conditions that are poorly supported by laboratory data, leading to a wide range of predicted runouts. Many applications also oversimplify stratigraphy and fabric effects, which reduces realism for operational TSFs in heterogeneous and evolving depositional environments. Furthermore, despite the growing use of InSAR and monitoring data, most models are not updated dynamically, diminishing their usefulness for real-time risk management. Consequently, runout simulations provide valuable insights into potential failure modes but should be approached with caution, explicitly recognizing uncertainty and sensitivity, especially when used for regulatory or emergency planning.

11. Failure trends and statistics

Recent updates to global tailings failure databases—including the World Mine Tailings Failures repository and regional/global compilations published in the geoscience literature—show that the worldwide frequency of major TSF failures has stayed around three to five significant events per year, with notable variation from year to year (World Mine Tailings Failures, 2020–2025; Islam et al., 2021; Piciullo et al., 2022; Lin et al., 2022; Lin et al., 2024). Although the overall rate has not decreased significantly, datasets after 2020 show a higher proportion of failures involving active upstream or centerline facilities operating under increased pore pressure or challenging hydraulic conditions, consistent with pre-Brumadinho patterns.

A consistent conclusion from these studies is that most recent failures cannot be attributed solely to geotechnical miscalculations. Instead, root-cause analyses reveal recurring patterns such as poor governance, inadequate monitoring, incomplete documentation of depositional history, production-driven operational pressures, and systemic underestimation of precursor signals (Santamarina et al., 2019; E-Tech International, 2024; Kemp et al., 2021). These findings support the longstanding view in the risk-governance literature that catastrophic failures result not only from technical

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errors but also from organizational drift, weak risk communication, and inadequate change-management processes.

Figure 19 offers an integrated overview of the main human activities that can alter subsurface stress conditions and trigger complex geomechanical responses, including induced earthquakes, pore-pressure changes, and instability in slopes and containment structures. Different industrial sectors—such as traditional oil and gas extraction, hydraulic fracturing of unconventional resources, enhanced geothermal systems (EGS), underground mining, deep-well wastewater disposal, geological CO_2 storage, and hydroelectric reservoir impoundment—cause various disturbances in the geological medium. These activities can modify permeability, shift stresses, and change preferred flow paths, highlighting the need for combined geotechnical, geomechanical, and hydrogeological evaluations to enable effective monitoring and risk mitigation.

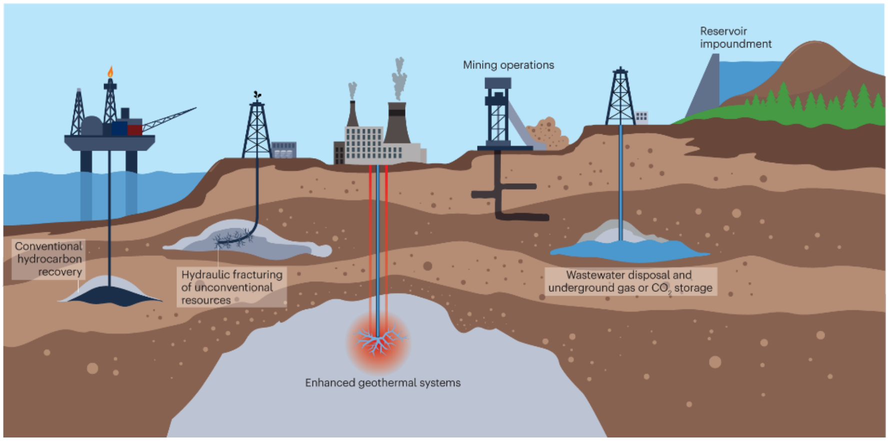

Figure 19. Conceptual illustration of major anthropogenic subsurface perturbations associated with energy production, mining, fluid injection, and reservoir impoundment. Adapted from: ANCOLD (2019/2022)

To synthesize the key insights from post-Brumadinho investigations and the 2020–2025 research framework, shown in Table 9, organizes the leading causes linked to recent tailings dam failures. The framework highlights how failures in governance, monitoring gaps, hydraulic triggers, material contractivity, and documentation issues interact to create conditions that promote undrained softening and potential liquefaction. Instead of occurring independently, these factors often combine—such as governance failures increasing technical weaknesses or monitoring gaps concealing hydraulic transients—emphasizing the need for

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integrated, multi-layered risk management aligned with modern standards like GISTM and ICOLD's recent bulletins.

Table 9. Integrated framework summarizing aggregated causes of tailings dam instabilities, their mechanistic roles, observable field evidence, and implications for stability and governance. Adapted from: Global Industry Standard on Tailings Management (GISTM, 2020) and ICOLD Bulletin 194 (2016–2022).

Aggregated Cause	Description / Mechanistic Role	Typical Evidence in 2020–2025 Cases	Implications for Stability & Risk Governance
Governance deficiencies	Weak oversight, unclear responsibilities, inadequate EoR interaction, and lack of escalation procedures	Delayed interventions, inconsistencies between monitoring data and operational decisions, and the absence of formal PDCA practices	Highest-impact systemic factor; amplifies technical vulnerabilities and reduces the effectiveness of controls
Monitoring gaps	Insufficient instrumentation density, poor data integration, lack of cross-validation (InSAR–piezometry–inspections)	Undetected pore-pressure rise; unnoticed deformation trends; fragmented datasets	Reduces ability to identify precursor signals; shortens warning windows; increases false stability assumptions
Hydraulic triggers	Phreatic rise, artesian pressures, drainage impairment, pond mismanagement	Rapid pore-pressure accumulation preceding instability; mismatch between hydraulic and operational models	Potent initiator of static liquefaction in contractive layers; requires continuous hydraulic management.
High contractivity / metastable fabric	Loose, silty, weakly structured, or partially saturated tailings with a positive state parameter (Ψ)	Sharp undrained softening; low residual strength; strain localization	Controls failure mechanism and runout potential; demands typology-specific characterization
Missing or incomplete documentation	Absent deposition records, unknown stratigraphy, missing operational logs, and outdated design assumptions	Inconsistent models, misinterpreted stratigraphy, and incorrect calibration for numerical analyses.	Leads to epistemic uncertainty; limits the reliability of stability analyses and emergency preparedness.

From a societal risk perspective, updated consequence analyses indicate that TSF failures continue to be among the most serious industrial disasters, with disproportionate impacts on downstream populations, river ecosystems, and critical

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infrastructure (Pacheco et al., 2025; Lin et al., 2024). Coupled with increased public scrutiny following recent high-profile failures, these impacts have resulted in a significant decline in societal tolerance for high-consequence events and increased demands for transparency, ongoing monitoring, and independent oversight (Marais et al., 2024).

These insights directly influence modern governance and regulatory standards. Recent guidelines, notably the Global Industry Standard on Tailings Management (ICMM-UNEP-PRI, 2020) and ICOLD Bulletin 194 (2022), specifically acknowledge that preventing liquefaction-related failures requires comprehensive, life-cycle approaches that extend beyond factor-of-safety assessments. This includes risk prioritization across portfolios, mandatory disclosure of monitoring data, the creation of independent review functions, and the implementation of formal observational and audit-based procedures.

Despite the growth of global datasets and stricter regulations since 2020, high-consequence TSF failures have not decreased significantly. This highlights a gap between technical understanding and effective action: advancements in diagnostics, monitoring, and liquefaction modeling have not addressed organizational and governance flaws that continue to cause catastrophic events. Many investigations after failures still lack complete or transparent data, which hampers root-cause analysis and limits improvements in predictive tools. Repeated failures at sites with known risk factors—such as high pore pressures, upstream construction, or poor depositional records—show that learning across the industry remains uneven. Overall, statistical trends offer useful insights, but reducing risk meaningfully depends on enforceable governance, transparent reporting, and institutional learning that turn empirical data into lasting safety improvements for TSFs.

Overall, the trend analyses from 2022 onward show that engineering competence, while important, is not enough: long-term TSF safety mainly relies on governance quality, operational discipline, and system-level risk management—areas now essential to regulatory reform, investor expectations, and public accountability.

12. Research gaps and agenda (2020–2025 Perspective)

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Table 10 summarizes the main research gaps that continue to constrain the accuracy of liquefaction assessments and TSF stability evaluations. Despite advances since 2020, major uncertainties persist—particularly regarding tailings behavior under partially drained, structured, or anisotropic conditions. Current interpretations of the state parameter Ψ still rely heavily on idealized, normally consolidated or reconstituted materials tested under fully undrained conditions (Riveros & Sadrekarimi, 2021; Macedo & Verga, 2022; Verdugo, 2024), whereas real deposits exhibit heterogeneous fabrics, bonding, and complex drainage paths. Recent efforts to link CPTu/SCPTu data with Ψ and instability potential (Ayala et al., 2022; Monforte et al., 2023; Mozaffari et al., 2023; Liu W. et al., 2024; SRK Consulting, 2024; Naftchali et al., 2024) highlight the promise of state-based in situ methods but also the need for broader validation. Table 10 outlines these gaps, their practical implications, and the research pathways required to enhance predictive modeling and monitoring-informed TSF management.

Table 10. Summary of key research gaps in tailings liquefaction assessment, their practical implications, and recommended research pathways. Adapted from insights synthesized in Riveros & Sadrekarimi (2021); Verdugo (2024); Monforte et al. (2023); Mozaffari et al. (2023); Liu W. et al. (2024); SRK Consulting (2024).

Research Gap	What is Missing	Consequence for Practice	Research Pathway
1. Ψ under partially drained, structured and anisotropic conditions	Lack of calibrated CPTu/SCPTu interpretations for partially drained penetration; limited datasets on intact fabric, cementation and anisotropy	Misclassification of liquefaction susceptibility; incorrect triggering thresholds; underestimation of instability in layered deposits	Advanced lab testing with partial drainage; anisotropy-controlled triaxial tests; CPTu/SCPTu modelling under mixed drainage; fabric-sensitive constitutive laws
2. Vs–Ψ calibration across tailings typologies	Scarcity of large datasets combining Vs, CPTu, gradation, void ratio and stress history for different commodities	Limited reliability of Vs-based susceptibility charts; difficulty applying methods outside original calibration domain	Multi-site Vs–Ψ databases; machine-learning calibration; typology-specific Vs envelopes; integration with depositional history
3. Dynamic PDCA integration: monitoring → models → decision-making	No unified framework linking piezometry/InSAR/displacement data to real-time updates of stability models	Monitoring remains observational, not predictive; lag between precursor detection and operational action	Digital twins; automated data fusion; real-time updating of constitutive parameters; alert

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			thresholds tied to modelled Ψ evolution
4. Lack of harmonized decharacterization & closure criteria	No global consensus on minimum residual liquefaction tolerance or verification standards for decharacterized TSFs	Highly variable decharacterization outcomes; regulatory uncertainty; uneven protection levels	International guidelines for post-closure hydromechanical performance; runout verification protocols; probabilistic closure criteria
5. Portfolio-scale risk and governance deficiencies	Incomplete datasets for national-level TSF inventories; weak integration of socio-environmental exposure; limited transparency	Persistent recurrence of failures despite technical advances; uneven allocation of mitigation resources	Portfolio-level risk models combining hazard × exposure × governance metrics; open data platforms; standardized reporting

A second gap involves calibrating Vs–Ψ and other proxy relationships across different tailings types and depositional settings. Empirical frameworks that combine shear-wave velocity, grain size, plasticity, and peak strength have shown promising results (Soares et al., 2023; Santos Junior et al., 2022; Simms et al., 2025; Zhang et al., 2023; Liu H. et al., 2024), but robust calibration across various commodities, slurry processing methods, and beach geometries is still lacking. The absence of comprehensive, shared geotechnical databases that include Vs profiles, CPTu/SCPTu data, depositional history, and laboratory characterizations remains a major obstacle.

A third gap exists at the junction between behavioral models and governance frameworks. The PDCA principles incorporated in the GISTM and related guidance (International Council on Mining and Metals et al., 2020; Global Tailings Review, 2020; ICOLD, 2022; UNECE, 2020, 2022) require that behavioral models (e.g., NorSand, CSSM, steady state) be regularly updated using multiple sources of monitoring data. However, methods for integrating streaming information—such as InSAR, pore pressures, and displacement metrics—into dynamic stability models are still underdeveloped (Grebby et al., 2021; Das et al., 2024; Rana et al., 2024; Yang et al., 2025; Dares Technology, 2024; UNECE, 2025). Comparative analyses of constitutive models show substantial differences in predicted softening paths and residual strength (Muñoz-Gaete et al., 2025), highlighting the need for unified approaches.

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A fourth gap concerns the lack of consistent standards for decharacterization and end-of-life criteria. Although Brazilian regulations and industry guidance have improved post-closure governance (Brasil, 2020; Agência Nacional de Mineração, 2022; CREA-MG, 2023; Vale S.A., 2023), there is still no international consensus on minimum performance targets or residual liquefaction tolerances for decharacterized facilities. Reviews of breach and outflow modeling (Gildeh et al., 2020; Sreekumar et al., 2024) show significant variability in predicted runout and deposition patterns, highlighting the need for clearer verification protocols during extreme events (Ming et al., 2022; Lin et al., 2024; Pacheco et al., 2025).

Finally, countries with large TSF inventories face research needs related to portfolio-scale risk, societal exposure, and long-term governance. Recent statistical and regional assessments (Islam et al., 2021; Piciullo et al., 2022; Lin et al., 2022, 2024; Rana et al., 2021; Lyu et al., 2019; Pacheco et al., 2025) demonstrate that national-scale risk assessment must include socio-environmental vulnerability and transparency practices. Industry analyses indicate that governance failures and lack of disclosure remain key factors in tailings disasters (E-Tech International, 2024; Kemp, Owen & Lèbre, 2021).

Together, these gaps outline a research agenda focused on: (i) Ψ and liquefaction under partially drained and structured conditions; (ii) calibration of Vs–Ψ and residual strength specific to different typologies; (iii) integrating monitoring dynamically into PDCA cycles; (iv) standardizing decharacterization and closure criteria; and (v) developing portfolio-scale tools tailored for countries with large TSF inventories.

Despite notable conceptual and technological progress from 2020 to 2025, critical gaps still exist in the scientific, operational, and governance foundations of TSF liquefaction management. Diagnostic tools remain reliant on idealized assumptions that do not accurately depict partially drained, anisotropic, and structured tailings. Proxy methods like Vs–Ψ correlations continue to be poorly calibrated across various materials and depositional environments. The integration of monitoring data into dynamic, PDCA-based stability models is limited, and differences among constitutive models and decharacterization criteria hinder consistency. As summarized in Figure 20, addressing future failures will require coordinated short-, mid-, and long-term

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efforts—from improved laboratory and in situ characterization to hybrid numerical frameworks and governance-supported early warning systems—ultimately enabling more quantitative and defensible safety measures.

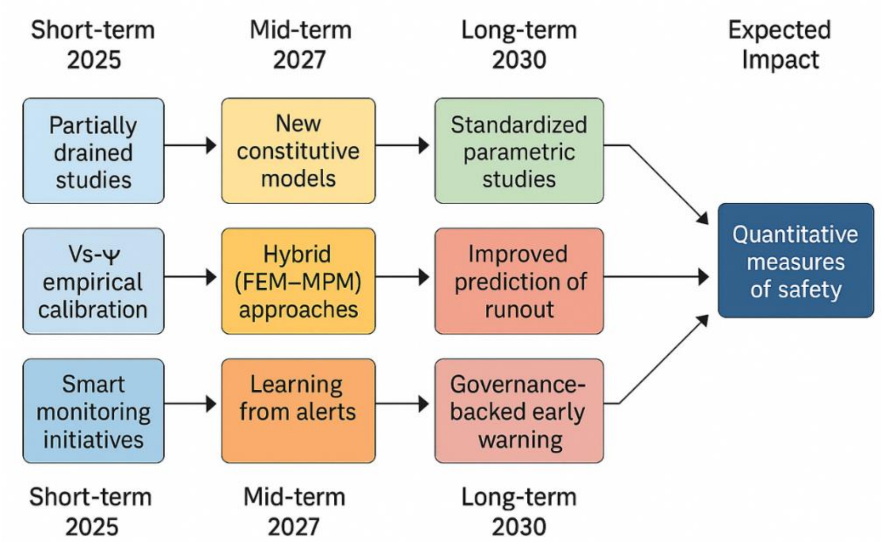

Figure 20. Roadmap of short-, mid-, and long-term research and governance priorities needed to strengthen liquefaction assessment and tailings dam safety. Adapted from Pereira (2025a).

13. Conclusions

The evidence gathered from 2020 to 2025 shows that managing liquefaction risk in tailings storage facilities requires a comprehensive approach. This approach combines advanced geotechnical analysis, multi-source monitoring, numerical modeling capable of capturing large deformations, and governance aligned with modern international standards. Although scientific understanding of liquefaction mechanisms and diagnostic tools has significantly improved, recent failures still reveal that operational vulnerabilities, inadequate monitoring, and weak decision-making frameworks remain key factors contributing to instability.

From an engineering perspective, a core set of practices is essential: explicit assessment of liquefaction susceptibility using CPTu/SCPTu, shear-wave velocity, and state parameter interpretations; laboratory confirmation of undrained softening behavior; integration of piezometric, deformation, and InSAR data into routine monitoring; and the use of numerical tools that can simulate both the initiation and runout of liquefied tailings.

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On governance, the main goal is to strengthen lifecycle management by clearly assigning responsibilities, setting up structured independent review processes, keeping traceable documentation, and continuously including diagnostic findings into operational and maintenance decisions. For higher-risk facilities, proactive mitigation measures—such as drainage improvements, operational changes, reinforcement, or decharacterization—are crucial.

In summary, preventing future catastrophic failures depends not only on technological advancements but also on the consistent and disciplined application of current best practices. The main challenge for engineers, operators, and regulators is to incorporate this knowledge into a systematic, transparent, and preventative approach to tailings dam management.

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