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COMPARATIVE GLOBAL REVIEW OF DAM FAILURES: MINING TAILINGS VERSUS HYDRO, INDUSTRIAL, AND CIVIL DAMS — CAUSES, MECHANISMS, AND LESSONS LEARNED

REVISÃO GLOBAL COMPARATIVA DE FALHAS DE BARRAGENS: REJEITOS DE MINERAÇÃO VERSUS BARRAGENS HIDRELÉTRICAS, INDUSTRIAIS E CIVIS — CAUSAS, MECANISMOS E LIÇÕES APRENDIDAS

REVISIÓN GLOBAL COMPARATIVA DE FALLAS DE PRESAS: RELAVES MINEROS FRENTE A PRESAS HIDROELÉCTRICAS, INDUSTRIALES Y CIVILES — CAUSAS, MECANISMOS Y LECCIONES APRENDIDAS

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ABSTRACT
Dam failures constitute some of the most severe technological disasters worldwide. Their impacts extend far beyond infrastructure loss, resulting in significant human, environmental, economic, and social consequences. Although failures of mining tailings dams have attracted intensified scrutiny in recent decades, dams associated with hydroelectric generation, industrial residue containment, civil infrastructure, road works, and agricultural water storage have also experienced recurrent—and often catastrophic—failures throughout history. Despite sharing fundamental geotechnical and hydraulic principles, these structures differ markedly in design philosophy, construction methods, operational practices, and regulatory oversight. This review presents a comprehensive comparative analysis of dam failures across mining and non-mining sectors. Historical and contemporary case studies are integrated to systematically examine failure causes, rupture mechanisms, triggering factors, and resulting consequences. Particular emphasis is placed on distinguishing mechanisms characteristic of tailings dams—such as static and dynamic liquefaction of contractive materials—from those more prevalent in conventional embankment and concrete dams, including overtopping, internal erosion, and foundation instability. Beyond technical factors, the analysis highlights the critical role of governance, operational decision-making, and risk management in shaping failure outcomes across all dam categories. Many catastrophic events are shown to arise from common vulnerability pathways, including inadequate water management, insufficient monitoring, underestimation of extreme events, and weak regulatory enforcement. By identifying transferable lessons and cross-sectoral insights, this review supports the development of more robust, integrated, and risk-based dam safety frameworks. These frameworks are essential for improving prevention, early warning capacity, and the long-term resilience of dams worldwide.

KEYWORDS. Dam failure. Tailings dams. Hydroelectric dams. Industrial dams.

RESUMO
As falhas de barragens constituem alguns dos desastres tecnológicos mais severos em escala mundial, com impactos que vão além da perda de infraestrutura, acarretando consequências humanas, ambientais, econômicas e sociais significativas. Embora as falhas de barragens de rejeitos de mineração tenham atraído maior escrutínio nas últimas décadas, barragens associadas à geração hidrelétrica, à contenção de resíduos industriais, à infraestrutura civil, a obras viárias e ao armazenamento de água para uso agrícola também apresentam, historicamente, falhas recorrentes e, em muitos casos, catastróficas. Apesar de compartilharem princípios geotécnicos e hidráulicos fundamentais, essas estruturas diferem de forma marcante quanto à filosofia de

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projeto, aos métodos construtivos, às práticas operacionais e aos regimes regulatórios. Esta revisão apresenta uma análise comparativa abrangente das falhas de barragens nos setores de mineração e não mineração, integrando estudos de caso históricos e contemporâneos para examinar sistematicamente as causas das falhas, os mecanismos de ruptura, os fatores desencadeantes e as consequências resultantes. Dá-se especial ênfase à distinção entre mecanismos característicos das barragens de rejeitos — como a liquefação estática e dinâmica de materiais contrativos — e aqueles mais prevalentes em barragens convencionais de enrocamento e de concreto, incluindo galgamento, erosão interna e instabilidade de fundação.

PALAVRAS-CHAVE: Falha de barragens. Barragens de rejeitos. Barragens hidrelétricas.

RESUMEN
Las fallas de presas constituyen algunos de los desastres tecnológicos más graves a nivel mundial, con impactos que van más allá de la pérdida de infraestructura y generan consecuencias humanas, ambientales, económicas y sociales significativas. Aunque las fallas de presas de relaves mineros han recibido un escrutinio intensificado en las últimas décadas, las presas asociadas a la generación hidroeléctrica, a la contención de residuos industriales, a la infraestructura civil, a obras viales y al almacenamiento de agua para uso agrícola también han experimentado, a lo largo de la historia, fallas recurrentes y, en muchos casos, catastróficas. A pesar de compartir principios geotécnicos e hidráulicos fundamentales, estas estructuras difieren notablemente en su filosofía de diseño, métodos constructivos, prácticas operativas y marcos regulatorios. Esta revisión presenta un análisis comparativo integral de las fallas de presas en los sectores minero y no minero, integrando estudios de caso históricos y contemporáneos para examinar de manera sistemática las causas de las fallas, los mecanismos de ruptura, los factores desencadenantes y las consecuencias resultantes. Se pone especial énfasis en distinguir los mecanismos característicos de las presas de relaves —como la licuefacción estática y dinámica de materiales contractivos— de aquellos más prevalentes en presas convencionales de terraplén y de hormigón, incluidos el sobrevertido, la erosión interna y la inestabilidad de la cimentación.

PALABRAS CLAVE: Fallas de presas. Presas de relaves. Presas hidroeléctricas.

1. INTRODUCTION

Dams are critical infrastructure supporting water supply, hydroelectric generation, flood control, industrial waste containment, and agricultural activities worldwide. While their societal and economic benefits are well established, dam failures can lead to severe human, environmental, economic, and social consequences. Historical evidence demonstrates that such failures are not isolated events but recurring phenomena arising from complex interactions among design assumptions, construction practices, operational decisions, and external loading conditions (Rico *et al.,* 2008; Foster *et al.,* 2000).

Research on dam safety has traditionally focused on hydroelectric and civil embankment dams, identifying overtopping, internal erosion, and foundation instability as dominant failure mechanisms (Foster *et al.,* 2000; Xu; Zhang, 2009). This body of work has supported the development of robust design standards and risk-based safety frameworks. Nevertheless, failures continue to occur, frequently associated with underestimated hydrological extremes, aging infrastructure, and deficiencies in maintenance and monitoring (ICOLD, 2011; Zhang et al., 2016).

Mining tailings dams have distinct structural and operational characteristics that fundamentally influence their failure behavior. These structures are commonly raised incrementally throughout the mine's life. Tailings are often used as construction material. When combined with fine-grained, saturated, contractive materials, this practice substantially increases susceptibility to static and dynamic liquefaction. This mechanism is rarely observed in conventional water-retaining dams (Rico *et al.,* 2008; Davies, 2002). Statistical assessments further indicate that tailings dams fail more frequently than other dam types and tend to produce more severe downstream impacts (Bowker; Chambers, 2015; Lumbroso *et al.,* 2021).

Beyond just technical details, recent studies are showing how important good governance, proper oversight, and smart decision-making are in preventing dam failures across all sectors. Common issues like poor water management, inadequate monitoring, lack of independent reviews, and weak emergency plans show up in both mining and non-mining dam failures, revealing shared vulnerabilities that go beyond just the type of dam (ICOLD, 2020; Morgenstern *et al.,* 2016). These insights challenge the idea that tailings dam failures are only about material qualities or how they were built. Instead, they point to deeper systemic problems in risk management and accountability that need attention.

Despite the expanding literature, dam failure studies remain largely sector-fragmented, with tailings dams and conventional dams typically examined within separate disciplinary and regulatory frameworks. This compartmentalization has limited cross-sector learning and hindered the identification of transferable lessons related to water management, monitoring, decision-making under uncertainty, and governance. As a result, dam failures are often treated as isolated technical events rather than systemic outcomes shaped by both technical and non-technical factors.

The objective of this review is to provide a comparative synthesis of dam failures across mining tailings dams and other major dam categories, including hydroelectric, industrial, civil, and agricultural structures. By integrating historical and contemporary case studies, the review examines failure causes, dominant mechanisms, triggering factors, and associated consequences, with particular emphasis on distinguishing sector-specific behaviors—such as liquefaction in tailings dams—from failure drivers common to all dam types. The following section describes the methodological framework adopted to support this comparative analysis.

2. METHODOLOGY (PRISMA-ORIENTED APPROACH)

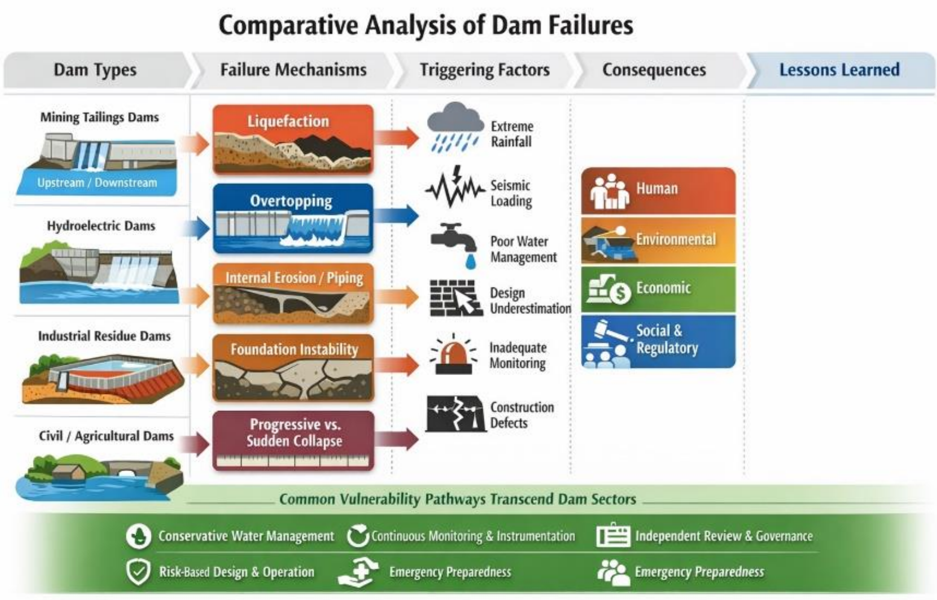
This review was conducted following the PRISMA 2020 principles for transparency and reproducibility, adapted to the scope of a qualitative and comparative review rather than a meta-analysis (Page *et al.,* 2021). The literature base was constructed using peer-reviewed journal articles, authoritative technical reports, and international standards already consolidated in Section

1, focusing on dam failures across mining tailings dams and non-mining dams, including hydroelectric, industrial, civil, and agricultural structures.

The selection process had four stages: identification, screening, eligibility, and inclusion. Publications on dam failure causes, mechanisms, consequences, and governance were compiled during identification. Screening excluded documents lacking failure analysis or detail. Eligibility was based on relevance to failure mechanisms, dam typology clarity, and cross-sector contribution. Final inclusion prioritized studies with mechanistic insight, actual failure events, or safety frameworks (e.g., Foster *et al.,* 2000; Rico *et al.,* 2008; ICOLD, 2011, 2020).

Data extraction targeted dam type, failure modes (e.g., overtopping, erosion, foundation issues, liquefaction), triggers, and consequences. An atemporal approach integrated seminal and recent studies to identify persistent vulnerabilities. Comparative synthesis distinguished sector-specific behaviors, especially liquefaction in tailings dams, from common failure pathways across all dam types.

Based on the PRISMA-guided selection and classification of the literature, the following section presents a structured overview of dam typologies and representative failure cases, providing the technical foundation for contextualizing the comparative analysis of failure causes and mechanisms.



3. COMPARATIVE FRAMEWORK FOR DAM TYPOLOGY AND FAILURE MECHANISMS (TAILINGS VS. NON-TAILINGS)

A meaningful comparison between tailings storage facilities (TSFs) and non-mining dams requires a shared analytical framework that distinguishes (i) function and operational loading, (ii) structural typology and construction method, and (iii) dominant failure pathways and progression-to-breach. This section establishes a harmonized taxonomy to support consistent cross-sector classification of case histories and to reduce “apples-to-oranges” comparisons that arise when TSFs (often raised progressively and operated as continuously evolving containment systems) are evaluated using the same assumptions traditionally applied to water-retaining dams (Kossoff *et al.,* 2014; Owen *et al.,* 2020).

3.1. Dam categories and “function-driven” design differences

Across sectors, dams can be grouped by primary retained medium and by mission-critical performance requirement:

- **Hydro/civil water-retaining dams**: prioritize controlled storage and release, flood routing, and spillway adequacy, with safety strongly conditioned by hydrological extremes and reservoir operations (Darling, 2011; FEMA, 2015).
- **Industrial containment dams** (e.g., process-water ponds, residue impoundments): often emphasize containment reliability, seepage management, and chemical compatibility; externalities may include chronic leakage and downstream water-quality impacts even without breach (FEMA, 2015).
- **Agricultural dams** (irrigation reservoirs, farm ponds): typically smaller, but frequently numerous; risk is powerfully shaped by governance, maintenance capacity, and hydrological exceedance (FEMA, 2015).
- **Mining tailings dams (TSFs)**: retain a **soil–water–solid slurry** whose properties evolve over time (segregation, consolidation, desiccation, saturation, and fabric changes). TSFs are commonly expanded during operation, making them “construction-in-service” structures with coupled geotechnical and operational uncertainties (Kossoff *et al.,* 2014; Islam; Murakami, 2021).

This distinction matters because loading and boundary conditions differ: water-retaining dams have well-defined reservoir levels and controlled releases, but TSFs often face variable pore-pressure regimes, evolving deposition beaches, and changing drainage, which can speed up instability and flow failure, especially with contractive tailings (Wang *et al.,* 2024; D’Hyppolito *et al.,* 2024).

3.2. Structural typology: materials and construction methods

Most non-tailings dams can be classified as embankment dams (earthfill/rockfill) or concrete dams (gravity/arch/buttress). By contrast, TSFs are usually embankment structures, but their distinctive raising methods strongly influence failure susceptibility (Read; Stacey, 2009; McLeod; Bjelkevik, 2017):

- Upstream raising, common in mining, involves successive raises on tailings that can be saturated and contractive, increasing susceptibility to static liquefaction and strength loss under modest triggers (Tuomela *et al.,* 2021; Wang *et al.,* 2024).
- Centerline and downstream raising involves adding fill in engineered zones or moving the crest downstream, generally enhancing stability margins compared to upstream methods under the same material conditions (Kossoff *et al.,* 2014; Stefaniak; Wróżyńska, 2018).

While "classical" embankment dam safety literature emphasizes failure modes such as overtopping and internal erosion/piping, TSF case histories frequently show undrained instability and flow liquefaction as dominant rupture pathways, with breach development sometimes following rapid strength collapse rather than gradual erosion and enlargement (Fell *et al.,* 2003; Wan; Fell, 2008; Agurto-Detzel *et al.,* 2016).

3.3. Failure mechanisms: from initiating event to breach evolution

To enable cross-sector comparisons, this review classifies failures using a two-step framework:

Initiating mechanism (triggering domain)

1. Hydrologic exceedance/operational water mismanagement (e.g., spillway insufficiency, blocked outlets, rapid drawdown mismanagement) (FEMA, 2015).
2. Seepage-driven internal erosion and piping (including suffusion and concentrated leak erosion through defects or at contacts) (Fell *et al.,* 2003; Wan; Fell, 2008).
3. Foundation instability/slope instability (static or seismic; includes weak layers, sensitive soils, and strain-softening behavior).
4. Liquefaction-driven instability (tailings-dominant)—static or cyclic, often conditioned by contractive tailings state, high pore pressures, and inadequate drainage (Wang *et al.,* 2024; D'Hyppolito *et al.,* 2024).
5. External disturbances (earthquakes, extreme rainfall, cascading upstream failures, or construction incidents).

Breach progression (how the dam actually "opens")

- Erosion-dominated breach formation: typical of overtopping in earth embankments and some piping cases, where breach enlarges through progressive erosion (Rodríguez *et al.,* 2021; FEMA, 2015).

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- Strength-collapse/flow-slide breach formation: more common in liquefaction-driven TSF failures, where large volumes mobilize rapidly and downstream consequences depend on runout, channel confinement, and exposure (Islam; Murakami, 2021; Wang *et al.,* 2024).

Figure 1 provides a taxonomy of initiating mechanisms and breach progression pathways for analyzing dam failure processes across different dam types. The framework separates common triggers—such as hydrologic exceedance, internal erosion, and slope instability—from tailings-specific mechanisms, particularly liquefaction, which lead to distinct rupture behaviors. By connecting initiation modes to breach development styles, the figure underscores shared vulnerabilities and key mechanical differences between mining and non-mining dams.

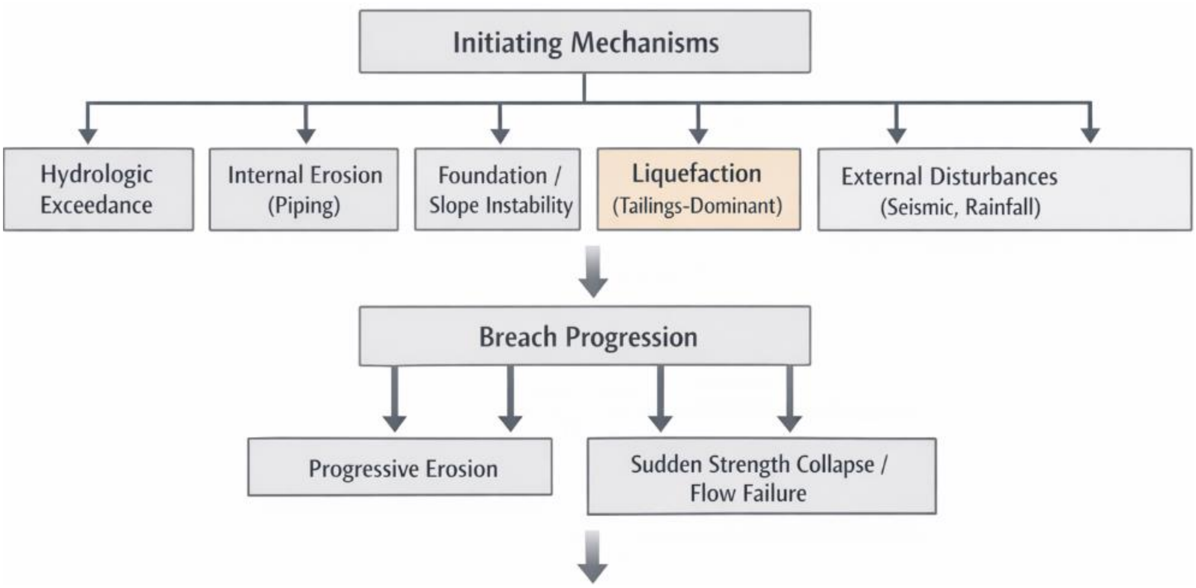

Figure 1. Taxonomy of dam failure initiating mechanisms and breach progression pathways. Adapted from: Foster et al. (2000); Fell et al. (2003); Davies (2002); Azam & Li (2010); Rico et al. (2008); Morgenstern et al. (2016); ICOLD (2011, 2020); Lumbroso et al. (2021)

Initiating mechanisms include hydrologic exceedance, internal erosion (piping), foundation or slope instability, liquefaction (tailings-dominant), and external disturbances such as seismic loading or extreme rainfall. These triggers can evolve into distinct breach progression modes, ranging from progressive erosion to sudden strength collapse and flow failure. Although several initiating mechanisms are standard across dam sectors, liquefaction-driven flow failures are predominantly associated with tailings dams, leading to markedly different failure velocities and consequences.

To facilitate a structured comparison across dam typologies, Table 1 synthesizes the dominant initiating mechanisms, breach development modes, typical warning times, and failure velocities observed in hydroelectric, civil/agricultural, industrial, and tailings dams. Rather than focusing solely on triggering events, this comparison emphasizes how differences in rupture progression and available response time fundamentally shape risk outcomes. In particular, the table highlights the distinct behavior of tailings dams, where liquefaction-driven flow failures lead to rapid breach development and severely constrained warning windows, contrasting sharply with the more progressive failure modes typical of water-retaining dams.

Table 1. Dominant failure mechanisms and breach characteristics by dam category. Adapted from: Foster et al. (2000); Fell et al. (2003); Davies (2002); Azam & Li (2010); Rico et al. (2008); Morgenstern et al. (2016); ICOLD (2011, 2020); Lumbroso et al. (2021)

Dam category	Initiating mechanism	Breach development	Typical warning time	Failure velocity
Hydroelectric	Overtopping	Progressive erosion	Moderate–long	Moderate
Civil/agricultural	Piping / overtopping	Progressive erosion	Long	Low–moderate
Industrial	Seepage / instability	Mixed	Variable	Variable
Tailings dams	Liquefaction	Sudden flow failure	Short–none	High

Comparison of dominant initiating mechanisms, breach development modes, warning times, and failure velocities across dam categories. While overtopping and internal erosion govern most failures in hydroelectric and civil dams—typically evolving through progressive erosion with measurable warning times—tailings dams are uniquely characterized by liquefaction-driven flow failures that develop abruptly and at high velocities, often with little or no warning. This asymmetry explains the disproportionate human and environmental consequences of tailings dam failures, even when triggering factors appear comparable.

Figure 2 offers a conceptual synthesis of how dominant failure mechanisms translate into distinct rupture modes and downstream consequences across dam typologies. By explicitly linking initiating mechanisms—such as overtopping, internal erosion, foundation instability, and liquefaction—to breach evolution pathways, the figure clarifies why tailings dams experience disproportionately severe impacts despite sharing several triggering factors with non-mining dams. This integrative visualization supports cross-sector comparisons and helps disentangle cause, rupture process, and consequence severity within a unified analytical framework.

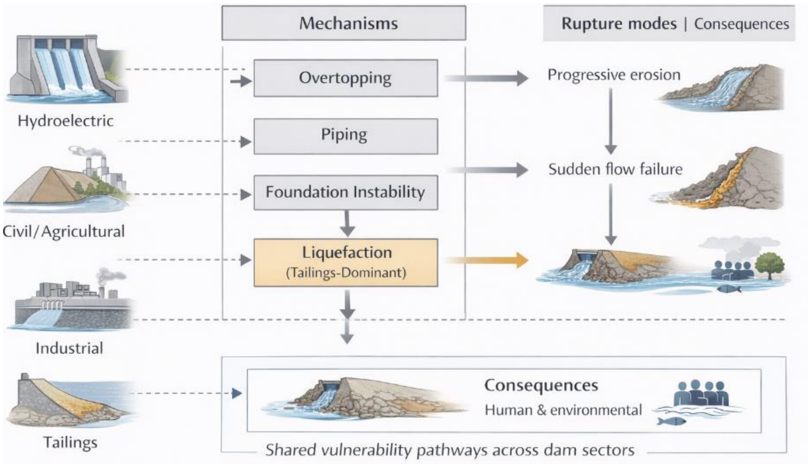

Figure 2. Taxonomy of dominant dam failure mechanisms, rupture modes, and consequences across mining and non-mining dams. Adapted from: Davies (2002); Fell et al. (2003); Azam & Li (2010); Morgenstern et al. (2016); ICOLD (2011, 2020); Bowker & Chambers (2015); Morrison (2022); Pereira (2025a, 2025b)

The diagram illustrates how different dam types (hydroelectric, civil/agricultural, industrial, and tailings dams) are linked to initiating mechanisms that influence rupture progression and severity. Water dams often face overtopping, piping, and foundation instability, leading to erosion and longer warning times. Conversely, liquefaction failures in tailings dams cause sudden flow failures with minimal warning, increasing human and environmental risks. The figure highlights common vulnerability pathways across sectors and stresses the unique risk asymmetry of tailings facilities.

Recent global syntheses show TSF failures, though less common than minor incidents, can cause severe downstream impacts during catastrophic flow, highlighting the importance of treating hazard and vulnerability as a coupled system (Owen *et al.,* 2020; Islam; Murakami, 2021). Additionally, seismological and monitoring reconstructions reveal some TSF collapses are preceded by detectable precursors, indicating potential for earlier detection with robust governance and monitoring systems (Agurto-Detzel *et al.,* 2016; Clarkson; Williams, 2021; Vergaray, 2023).

3.4. Governance and inventory context for cross-sector comparison

Because failure rates depend heavily on inventory quality, claims about "relative failure frequency" are considered conditional on database completeness and classification rigor. ICOLD's World Register of Dams is a key global reference for large dams, but its completeness varies by country and reporting channel (ICOLD, n.d.). For TSFs, recent work emphasizes updating databases and spatialization to enable consistent impact comparisons over a century (Islam; Murakami, 2021). Professional initiatives also warn against global counts that lack traceable,

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robust inventories, highlighting the need for transparent data provenance when comparing TSFs and other dams (World Mine Tailings Failures, 2020).

To enable consistent comparisons across dam typologies, this study adopts a structured analytical framework that links dam characteristics to failure mechanisms, rupture evolution, and ultimate consequences. Figure 3 summarizes the stepwise logic used throughout the comparative analysis, ensuring that differences in failure outcomes are interpreted as the result of interacting structural, operational, and governance-related factors rather than isolated technical triggers.

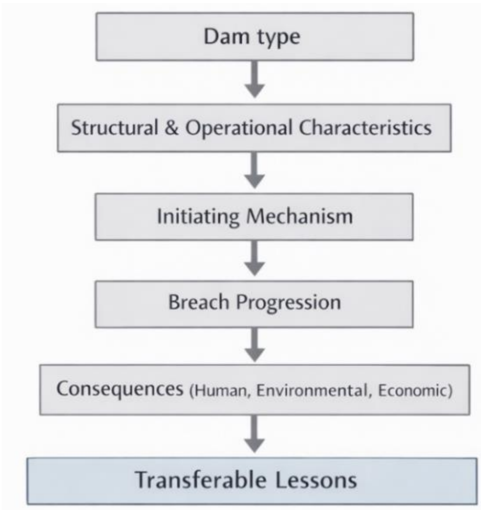

Figure 3. Analytical framework adopted for cross-sector comparison of dam failures. Adapted from: Davies (2002); Fell et al. (2003); Azam & Li (2010); Morgenstern et al. (2016); ICOLD (2011, 2020); Bowker & Chambers (2015); Morrison (2022); DeNeale et al. (2019); World Bank (2021)

The framework clarifies the sequence among dam type, structural and operational characteristics, initiating failure mechanisms, breach progression modes, and resulting human, environmental, and economic consequences. By explicitly linking consequences to transferable lessons, the framework supports cross-sector learning and shows how insights from one dam category can inform safety improvements in others.

Despite advances in classification and inventory efforts, comparative analysis of tailings dams and non-mining dams remains hampered by persistent inconsistencies in typology, failure reporting, and interpretive frameworks. Many databases implicitly privilege either structural form or triggering event, without adequately capturing the coupled evolution of material behavior, operational loading, and governance decisions that ultimately control failure progression. In particular, treating liquefaction-driven failures in tailings dams as fundamentally anomalous can obscure their conceptual parallels with strength-loss mechanisms observed in conventional embankment dams founded on sensitive or strain-softening soils. Conversely, erosion-dominated failure models developed for water-retaining dams are often inappropriately extrapolated to tailings

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facilities, where breach formation may be governed by rapid undrained collapse rather than progressive material removal. These limitations demonstrate that dam failures cannot be fully understood through typology alone. Instead, they must be interpreted as system-level phenomena in which design philosophy, construction sequence, evolving pore-pressure regimes, and institutional controls interact over time. A critical implication is that meaningful cross-sector learning requires harmonized analytical frameworks that integrate mechanics, operations, and governance, rather than parallel, sector-specific narratives.

With this typology and mechanism taxonomy established, the next section applies them to systematically classify documented failure case histories from mining and non-mining dams, comparing (i) triggering domains, (ii) dominant rupture mechanisms, (iii) breach progression patterns, and (iv) consequence profiles (human, environmental, and economic), thereby extracting transferable lessons for integrated dam safety practice.

4. COMPARATIVE ANALYSIS OF FAILURE DRIVERS, RUPTURE PROCESSES, AND CONSEQUENCES

This conceptual synthesis reinforces the argument that rupture mechanics, rather than failure probability alone, are the dominant control on disaster magnitude, underscoring the need for consequence-based risk governance.

This conceptual synthesis reinforces the argument that rupture mechanics, rather than failure probability alone, are the dominant determinant of disaster magnitude, underscoring the need for consequence-based risk governance. The comparative framework in Section 3 enables a systematic evaluation of how failure drivers and rupture processes manifest across mining and non-mining tailings dams, highlighting both sector-specific mechanisms and convergent vulnerability patterns. Across all dam types, failures rarely stem from a single cause; instead, they arise from interactions among material behavior, hydraulic loading, construction sequence, and operational decision-making, often compounded by governance deficiencies (Foster *et al.,* 2000; ICOLD, 2011).

4.1. Dominant failure drivers across dam sectors

For hydroelectric and civil embankment dams, historical databases consistently show that hydrologic exceedance and internal erosion dominate failure initiation. Overtopping from inadequate spillway capacity or mismanaged reservoir levels remains the most frequent trigger, while piping and suffusion often control delayed failures during long-term operation (Fell *et al.,* 2003; Wan; Fell, 2008; Xu; Zhang, 2009). These mechanisms are generally progressive, providing warning signs such as increased seepage or deformation, though these indicators are not always adequately interpreted or acted upon (FEMA, 2015).

In contrast, mining tailings dams exhibit a markedly different failure signature. Statistical and mechanistic studies indicate that static and dynamic liquefaction are dominant failure mechanisms, particularly in upstream-raised facilities founded on saturated, contractive tailings (Davies, 2002; Bowker; Chambers, 2015; Wang *et al.,* 2024). Unlike erosion-dominated failures, liquefaction-driven instability can cause near-instantaneous loss of strength, drastically reducing available warning time and increasing downstream hazard intensity (Azam; Li, 2010).

Table 2 synthesizes the dominant failure drivers observed across major dam sectors, highlighting how different combinations of primary mechanisms, secondary contributing factors, and triggering conditions influence warning time and failure dynamics. By organizing failure pathways in a comparative format, the table clarifies why similar initiating conditions—such as overtopping or seepage—can lead to markedly different rupture behaviors and consequences depending on dam type and stored material.

Table 2. Dominant failure drivers and initiating mechanisms across dam sectors. Adapted from: Davies (2002); Fell et al. (2003); Azam & Li (2010); Morgenstern et al. (2016); Rico et al. (2008); Bowker & Chambers (2015); ICOLD (2011, 2020); Morrison (2022); Lumbroso et al. (2021)

Dam sector	Primary failure driver	Secondary drivers	Typical trigger	Warning time
Hydroelectric dams	Overtopping	Piping, foundation instability	Extreme rainfall	Moderate–long
Civil/agricultural dams	Piping	Overtopping	Prolonged seepage	Long
Industrial dams	Seepage/instability	Chemical degradation	Operational mismanagement	Variable
Tailings dams	Liquefaction	Overtopping, instability	Pore pressure rise	Short–none

This table compares the primary and secondary failure drivers across hydroelectric, civil/agricultural, industrial, and tailings dams, emphasizing the role of common triggering conditions and available warning time. The synthesis shows that tailings dams are uniquely characterized by liquefaction-driven failures, which significantly shorten warning time compared with erosion-dominated failures in water-retaining dams.

4.2. Rupture evolution and breach formation

Rupture progression further distinguishes tailings dams from non-mining dams. In water-retaining dams, breach formation is commonly governed by erosional enlargement, with breach width and outflow evolving as functions of material resistance and hydraulic gradients (Xu; Zhang, 2009). Conversely, tailings dam failures often involve flow-slide behavior, in which large volumes mobilize rapidly after undrained instability, producing long runout distances and high-impact sediment-laden flows (Rico *et al.,* 2008; Lumbroso *et al.,* 2021).

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Figure 4 illustrates the fundamental contrast between erosional and flow-slide breach evolution pathways, emphasizing that rupture mechanics directly govern warning time, breach velocity, and downstream impact severity. Erosional failures typically evolve through progressive material removal under sustained hydraulic loading, whereas flow-slide failures associated with liquefaction involve abrupt loss of shear strength and rapid mass mobilization, leaving little to no opportunity for effective intervention.

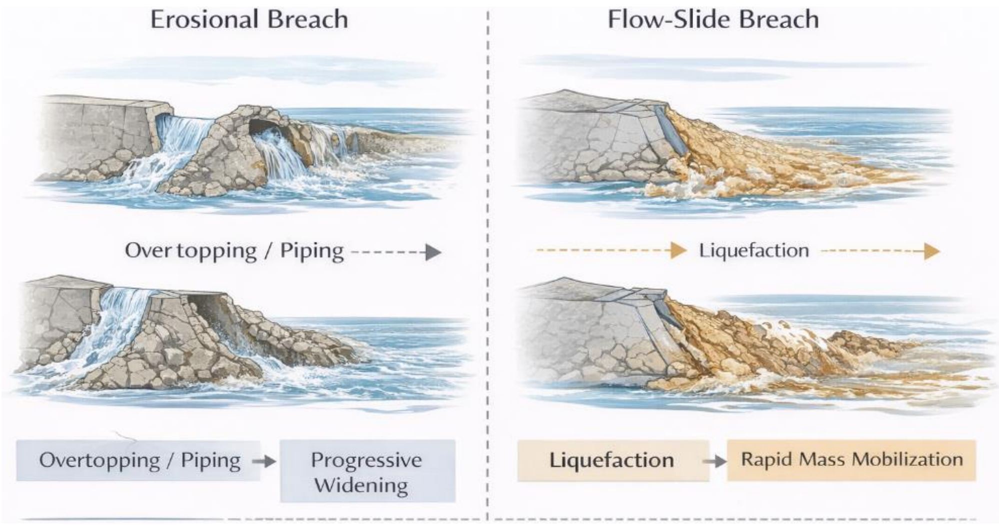

Figure 4. Conceptual comparison of erosional and flow-slide breach evolution pathways in dams. Adapted from: Fell et al. (2003); Rico et al. (2008); Azam & Li (2010); Davies (2002); Morgenstern et al. (2016); Lumbroso et al. (2021); Pereira (2025a, 2025b).

The figure contrasts two dominant mechanisms of rupture evolution. Left panel: Erosional breach progression driven by overtopping or internal erosion (piping), characterized by progressive widening of the breach and longer warning times. Right panel: Flow-slide breach progression triggered by liquefaction, marked by sudden loss of strength and rapid mass mobilization, resulting in minimal warning time and high downstream hazard intensity. The comparison highlights why tailings dam failures often have disproportionately severe consequences compared with conventional water-retaining dams.

Table **3** synthesizes the relationship between breach dynamics and consequence severity across dam types, highlighting how rupture speed and runout distance fundamentally govern impact intensity. Rather than reflecting only structural scale or stored volume, the table shows that rapid breach development, combined with long runout distances, significantly amplifies human and environmental consequences, particularly in tailings dam failures.

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Table 3. Breach characteristics and consequence profiles by dam type. Adapted from: Rico et al. (2008); Azam & Li (2010); Davies (2002); Fell et al. (2003); Lumbroso et al. (2021); Morgenstern et al. (2016); Pereira (2025a, 2025b)

Dam type	Breach speed	Runout distance	Impact intensity	Typical consequences
Hydroelectric	Moderate	Limited	Medium	Flooding, infrastructure damage
Civil/agricultural	Slow–moderate	Short	Low–medium	Localized flooding
Industrial	Variable	Variable	Medium	Contamination
Tailings dams	Very high	Long	Very high	Fatalities, environmental disaster

The table compares dam types by breach speed, runout distance, and resulting impact intensity. Conventional water-retaining dams typically breach slowly and with limited runout, causing primarily flooding and infrastructure damage. In contrast, tailings dams are characterized by very high breach speeds and long runout distances associated with flow-slide failures, resulting in disproportionately severe consequences, including loss of life and large-scale environmental contamination.

Recent seismological reconstructions of catastrophic tailings dam failures indicate that such events may be preceded by detectable precursory deformation or microseismic activity, suggesting that early-warning opportunities exist but are strongly dependent on monitoring coverage and institutional response capacity (Agurto-Detzel *et al.,* 2016). This contrasts with many non-mining dam failures, where long-term degradation processes are known but often under-prioritized due to aging infrastructure and resource constraints (Oliva-González *et al.,* 2025).

4.3. Consequence profiles and risk asymmetry

Although non-mining dams vastly outnumber tailings dams globally (ICOLD, n.d.), comparative analyses reveal a pronounced risk asymmetry: tailings dam failures, though less frequent, tend to produce disproportionately severe human and environmental consequences per event (Owen *et al.,* 2020; Islam; Murakami, 2021). This asymmetry is driven by the rapid onset of failure, high-density flows, and the frequent presence of downstream receptors in confined valleys or populated corridors (Rico *et al.,* 2008).

Beyond immediate physical impacts, tailings dam failures often cause long-term socioeconomic disruption, including loss of livelihoods, land-use sterilization, and persistent contamination, reinforcing their classification as systemic disasters rather than isolated engineering failures (Pereira, 2025d). Importantly, similar cascading effects have been observed following failures of significant civil and hydroelectric dams, indicating that the severity of consequences is ultimately determined by exposure and vulnerability, not by dam function alone (Petley, 2012; Petley *et al.,* 2017).

This conceptual representation underscores that dam safety governance must account not only for failure probability but also for failure mode and rupture dynamics, particularly where liquefaction-driven flow failures can produce disproportionate consequences.

4.4. Implications for cross-sector learning

The comparative evidence shows that although tailings dams exhibit unique failure mechanisms, particularly liquefaction, many underlying drivers—such as inadequate water management, insufficient monitoring, and delayed intervention—are common across dam sectors. This convergence suggests that improving dam safety requires moving beyond typology-specific prescriptions toward integrated, risk-based frameworks that explicitly link material behavior, operational controls, and governance accountability (ICOLD, 2020; FEMA, 2015). The following section builds on this analysis to distill transferable lessons and identify priority actions to enhance dam safety and resilience across sectors.

To emphasize that dam failures arise from cumulative system-level processes rather than isolated technical events, Figure 5 presents a simplified causal sequence linking design assumptions, operational practices, and monitoring effectiveness to failure initiation, rupture progression, and ultimate consequences. This framework integrates engineering, operational, and organizational dimensions, highlighting how early-stage decisions shape downstream failure pathways.

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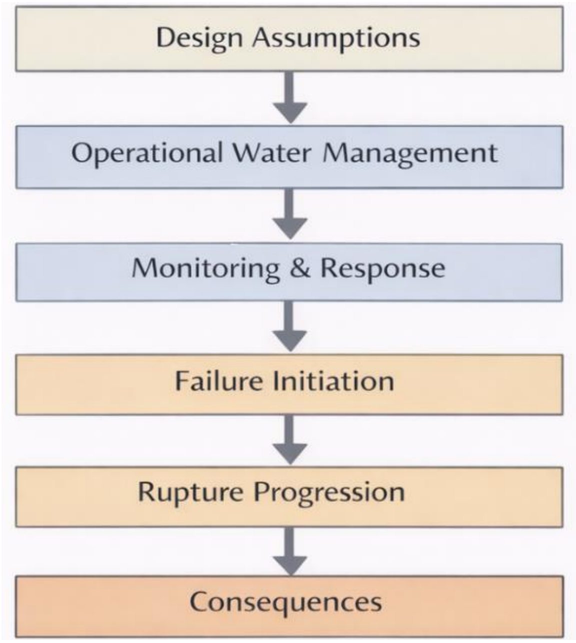

Figure 5. System-level development of dam failures from initiating drivers to consequences. Adapted from: Davies (2002); Foster et al. (2000); Fell et al. (2003); Morgenstern et al. (2016); ICOLD (2011, 2020); DeNeale et al. (2019); Morrison (2022); Pereira (2025a, 2025b)

Conceptual flowchart illustrating the progressive evolution of dam failures as a multi-stage process. The sequence highlights how design assumptions, operational water management, and monitoring–response effectiveness collectively influence the initiation of failure, the progression of rupture, and the final consequences. The figure emphasizes that catastrophic outcomes typically arise from cumulative deficiencies across multiple system layers rather than from a single triggering event.

This system-level representation reinforces the view of dam failures as socio-technical processes, in which organizational decisions and delayed responses often play a more decisive role than the initial triggering mechanism.

Despite clear advances in understanding dam failure mechanisms, the comparative evidence synthesized in this section reveals persistent limitations in how failure drivers are interpreted and managed across sectors. A recurring issue is the tendency to emphasize proximal technical triggers—such as overtopping, piping, or liquefaction—while underestimating the systemic conditions that allow these mechanisms to develop unchecked. Across both mining and non-mining dams, failures frequently reflect delayed recognition of evolving risks, inadequate integration of monitoring data into operational decision-making, and fragmented accountability structures. Moreover, the disproportionate consequences observed in tailings dam failures underscore that risk is not determined solely by failure probability, but also by exposure, vulnerability, and the speed of rupture progression. Taken together, these findings challenge purely typology-based safety approaches and reinforce the need for holistic, risk-informed frameworks that explicitly couple geotechnical behavior, water management, and governance processes throughout the dam life cycle.

Building on this comparative assessment of failure drivers, rupture processes, and consequences, the next section focuses on lessons learned and transferable best practices, with particular emphasis on governance, monitoring strategies, and risk management approaches that enhance dam safety across the mining and non-mining sectors.

5. LESSONS LEARNED AND PATHWAYS TOWARD IMPROVED DAM SAFETY

To provide an integrated overview of how recurrent failure drivers translate into actionable safety improvements, Figure 6 synthesizes the causal chain linking failure drivers, lessons learned, and best practices for dam safety. The graphical summary emphasizes that effective risk reduction requires not only technical controls but also governance mechanisms that transform lessons from past failures into systematic preventive actions.

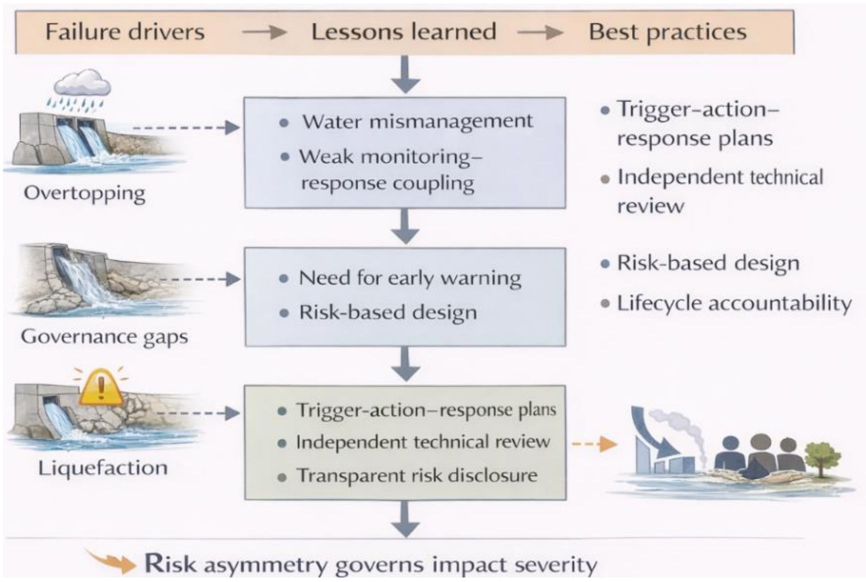

Figure 6. Graphical summary of lessons learned and pathways toward improved dam safety. Adapted from: Davies (2002); Fell et al. (2003); Azam and Li (2010); Bowker and Chambers (2015); Morgenstern et al. (2016); ICOLD (2011, 2020); Owen et al. (2020); Pereira (2025a, 2025b)

Conceptual framework showing the progression from dominant failure drivers (e.g., overtopping, governance gaps, liquefaction) to key lessons learned and corresponding best practices. The figure highlights the central roles of water management, monitoring–response coupling, risk-based design, independent technical review, and lifecycle accountability in reducing both the probability and severity of consequences. The synthesis reinforces that addressing risk asymmetry requires coordinated technical, organizational, and governance responses.

This synthesis supports the argument that dam safety improvements depend less on isolated technical upgrades than on institutionalizing learning processes that convert early warning signals and historical evidence into decisive preventive action.

The comparative assessment developed in the preceding sections shows that dam failures—whether involving mining tailings dams or conventional water-retaining structures—are rarely attributable to isolated technical deficiencies. Instead, they reflect systemic shortcomings in design conservatism, operational discipline, monitoring effectiveness, and governance accountability. Across sectors, one of the most consistent lessons is the central role of water management in preventing failures. Inadequate control of pond location, seepage, and pore-pressure evolution has repeatedly been identified as a primary precursor to instability, particularly in tailings dams but also in embankment dams affected by overtopping and internal erosion (Fell *et al.,* 2003; ICOLD, 2011; Pereira, 2025a).

Table 4 consolidates the principal lessons learned from historical dam failures across the mining and non-mining sectors, highlighting how recurring technical and organizational deficiencies contribute to catastrophic outcomes. The synthesis shows that failures are rarely caused by isolated deficiencies but by the interaction of inadequate water management, ineffective monitoring-response coupling, static design assumptions, and fragmented governance structures.

Table 4. Key lessons learned from historical dam failures across sectors. Adapted from: Davies (2002); Fell et al. (2003); Azam and Li (2010); Bowker and Chambers (2015); Morgenstern et al. (2016); ICOLD (2011, 2020); Owen et al. (2020); Pereira (2025a, 2025b)

Domain	Recurrent issue	Evidence from failures	Lesson learned
Water management	Poor pond control	Overtopping, liquefaction	Water control is critical
Monitoring	Signals ignored	Late intervention	Data must trigger action
Design	Static safety margins	Changing conditions	Continuous reassessment
Governance	Fragmented accountability	Delayed decisions	Clear responsibility

The table synthesizes recurring technical and organizational deficiencies identified in failure investigations of tailings and conventional water-retaining dams. The lessons emphasize the central role of water management, effective monitoring-to-decision pathways, adaptive design philosophy, and robust governance structures in preventing catastrophic failures.

Collectively, these lessons reinforce that dam safety depends less on prescriptive compliance and more on the institutional capacity to translate evolving risk signals into timely preventive action throughout the dam life cycle.

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5.1. Monitoring, early warning, and decision-making

Figure 7 illustrates the critical role of the monitoring–interpretation–decision–intervention chain in dam safety outcomes. Although monitoring systems are increasingly sophisticated across dam sectors, historical failures show that catastrophic events often stem not from a lack of data but from misinterpretation of signals, delayed decisions, and insufficient or untimely intervention. The comparison shows that risk is governed by institutional response capacity rather than by technical instrumentation alone.

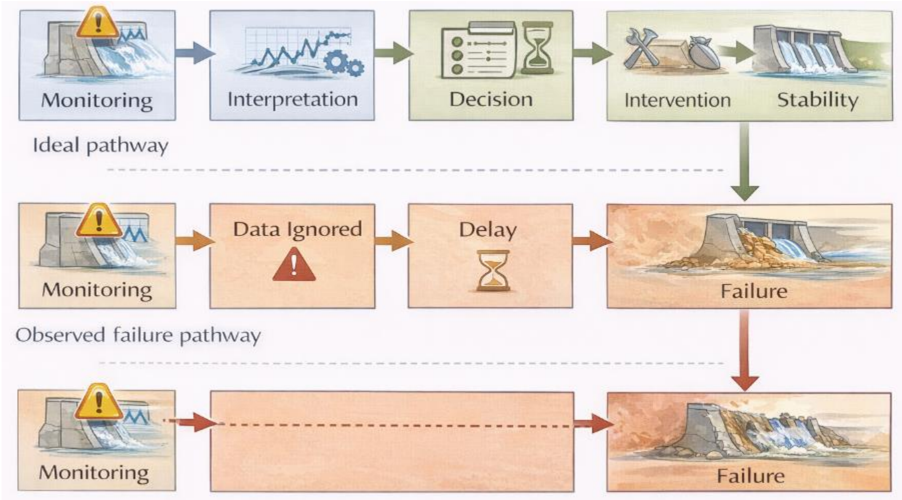

Figure 7. Divergence between ideal and observed monitoring–response pathways in dam safety management. Adapted from DeNeale et al. (2019); Clarkson and Williams (2021); Oboni and Oboni (2020)

The upper pathway represents the ideal safety sequence, in which monitoring data are correctly interpreted, decisions are made promptly, and preventive interventions restore system stability. The middle and lower pathways depict common failure trajectories in which warning signals are ignored or undervalued, leading to delayed action and eventual structural failure. This figure reinforces that dam safety is fundamentally a socio-technical problem: monitoring systems reduce risk only when embedded within governance frameworks capable of translating signals into decisive action.

Early warning indicators are widely recognized as essential to modern dam safety systems, particularly at facilities exposed to progressive degradation or sudden instability. However, historical dam failures show that monitoring data alone are insufficient to prevent catastrophic outcomes. Instead, failures often stem from weak coupling among data acquisition, interpretation, and timely decision-making. Table 5 synthesizes typical early warning indicators reported across dam sectors and contrasts their widespread technical availability with the observed effectiveness of operational responses, highlighting a recurrent gap between detection capability and risk-informed action.

Table 5. Typical early warning indicators and observed response effectiveness. Adapted from Fell et al. (2003), Morgenstern et al. (2016), ICOLD (2020), Independent Expert Panel (2020), and DeNeale et al. (2019)

Indicator	Detection method	Typical availability	Response effectiveness
Pore pressure rise	Piezometers	High	Often delayed
Deformation	InSAR / prisms	High	Frequently underestimated
Microseismicity	Geophones	Moderate	Rarely operationalized

Advances in instrumentation, remote sensing, and real-time data analytics have significantly expanded the technical capacity for early detection of dam instability. Case studies show that precursory signals—such as accelerating deformation, rising pore pressures, or microseismic activity—are often detectable before catastrophic failure, including in tailings dams that ultimately failed by liquefaction (Agurto-Detzel *et al.,* 2016; Lumbroso *et al.,* 2021). However, the effectiveness of monitoring systems depends not only on data acquisition but also on institutional readiness to act on warning signals, a factor repeatedly found to be deficient across dam sectors (Davies, 2002; Morgenstern *et al.,* 2016).

5.2. Risk-based design and life-cycle management

A second critical lesson is the need to transition from prescriptive design checks to risk-informed, life-cycle approaches. Modern dam safety practice increasingly recognizes that safety margins must be reassessed continuously as loading conditions, material properties, and downstream exposure evolve (FEMA, 2015; ICOLD, 2020). For tailings dams, this means explicitly considering liquefaction susceptibility, consequence classification, and closure-phase risks, rather than relying on historical performance or static factors of safety (D'Hyppolito *et al.,* 2024; Pereira, 2025b).

Dam safety cannot be treated as a static design attribute but rather as a dynamic process that evolves throughout the facility's life cycle. Comparative analyses across dam sectors show that risk profiles change significantly from design through post-closure stages as hazard conditions, exposure pathways, and potential consequences evolve.

Traditional dam safety frameworks (Table 6) have long relied on prescriptive criteria, emphasizing fixed safety margins and compliance-based design checks. While effective for conventional structures under stable conditions, these approaches have limitations when applied to complex systems operating in evolving operational, environmental, and social contexts. In contrast, risk-informed dam safety frameworks explicitly integrate failure probability, consequence severity,

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and uncertainty, enabling adaptive decision-making across dam sectors and throughout the asset life cycle.

Table 6. Comparison between prescriptive and risk-informed dam safety approaches. Adapted from Fell et al. (2003); FEMA (2015); DeNeale et al. (2019); ICOLD (2011, 2020); Slingerland and Morgenstern (2020); Lacasse et al. (2023)

Aspect	Prescriptive approach	Risk-informed approach
Safety margins	Fixed	Adaptive
Design checks	Static	Continuous
Decision basis	Compliance	Risk and consequence
Applicability	Limited	Cross-sector

As shown in Table, risk-informed approaches go beyond compliance-oriented checks by explicitly incorporating consequence severity, uncertainty, and system evolution into dam safety management. This shift is particularly relevant for complex, high-consequence structures, such as tailings dams, where adaptive decision-making throughout the life cycle is essential for managing asymmetric risk profiles.

5.3. Governance, transparency, and accountability

Beyond engineering controls, failures in both mining and non-mining dams consistently reveal weaknesses in governance frameworks (ICMM, 2025; Kengni, 2020).

To synthesize the institutional and technical dimensions of dam safety performance, a multi-layered governance framework is presented that highlights the interplay among corporate accountability, regulatory oversight, independent technical review, emergency preparedness, and community engagement.

Independent technical review, transparent risk disclosure, and clearly defined accountability structures are widely recognized as essential to dam safety systems. Comparative analyses indicate that failures are more likely when regulatory oversight is fragmented, emergency preparedness is underdeveloped, or economic pressures incentivize risk deferral (Bowker; Chambers, 2015; Owen *et al.,* 2020). These findings support recent international initiatives advocating unified, consequence-based standards applicable across jurisdictions and dam types (Doyle, 2023; Jarvie-Eggart, 2015; UNEP *et al.,* 2020).

5.4. Toward transferable best practices across sectors

The synthesis of lessons learned indicates that meaningful improvements in dam safety will not be achieved through sector-specific technical fixes alone. Instead, transferable best practices—such as conservative water management, robust monitoring tied to clear trigger–action–

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response plans, independent review throughout the dam life cycle, and transparent risk communication—must be systematically embedded across both mining and non-mining dam sectors. Importantly, the distinction between tailings and conventional dams should inform, but not constrain, safety philosophy. Many catastrophic outcomes stem from common vulnerability pathways that transcend dam typology. Recognizing dam failures as socio-technical events, rather than purely engineering anomalies, provides a more robust foundation for preventing future disasters (Kursunoglu, 2025; Macedo *et al.,* 2025).

Table 7 shows that several best practices originally emphasized in tailings dam management are broadly applicable across other dam sectors. Trigger–action response plans and independent technical review are universally applicable measures that reinforce the need for proactive, risk-informed decision-making regardless of dam purpose. Although formal risk disclosure is more advanced in the mining sector, its progressive adoption in non-mining dams offers a scalable pathway to enhance transparency and societal risk governance across infrastructure systems.

Table 7. Adapted from: ICOLD (2011, 2020); Independent Expert Panel (2020); Morrison (2022); Morrison & Adams (2025); World Bank (2021); Slingerland & Morgenstern (2020)

Practice	**Tailings dams**	**Non-mining dams**	**Transferability**
Trigger-action plans	High relevance	High relevance	Universal
Independent review	Essential	Essential	Universal
Risk disclosure	Increasing	Limited	Expandable

Recent advances in monitoring, risk-based design, and standards mark progress in dam safety, yet a gap remains between technical capability and effective implementation. Failures occur not from a lack of knowledge but from delayed decisions, poor data integration, and governance that neglects low-probability, high-consequence risks. In mining, tailings dam safety has improved after recent disasters, but systemic issues such as underestimating hazards, fragmented accountability, and economic pressures persist in conventional dams (Osmanova, 2025). Improvements must go beyond technology and standards, addressing organizational culture, enforcement, and timely risk response (Đokić *et al.,* 2020).

6. ORGANIZATIONAL AND GOVERNANCE STANDARDS FOR DAM SAFETY

The comparative evidence reviewed in this study shows that dam failures—across mining tailings dams and conventional water-retaining dams—are as much organizational and governance failures as engineering failures. Although technical mechanisms such as overtopping, internal erosion, and liquefaction ultimately govern rupture initiation and progression, their development is strongly conditioned by institutional decisions about risk tolerance, information flow, accountability, and long-term stewardship. This conclusion aligns with a growing consensus that dam safety must be addressed as a socio-technical system, integrating engineering controls with robust organizational structures and governance frameworks (Yu *et al.,* 2025).

6.1. From prescriptive compliance to risk governance

Traditional dam safety regimes have relied heavily on prescriptive design criteria and regulatory compliance, often emphasizing minimum factors of safety and periodic inspections.

Figure 8 illustrates the conceptual transition from traditional prescriptive dam safety frameworks to a risk-based governance model. This shift reflects growing recognition that compliance-oriented approaches, based on fixed safety factors and periodic inspections, are insufficient to address evolving hazards, uncertainty, and high-consequence failure modes, particularly for tailings storage facilities.

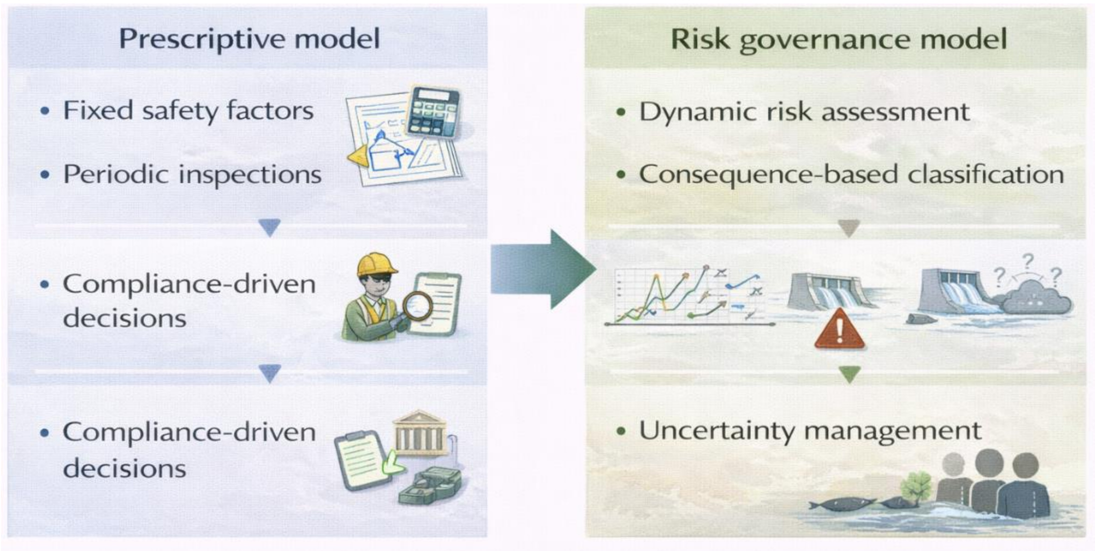

Figure 8. Transition from prescriptive compliance to risk-based governance. Adapted from: ICOLD (2011, 2020); World Bank (2021); Independent Expert Panel (2020); Slingerland & Morgenstern (2020); Oboni & Oboni (2020); Morrison (2022); Lacasse et al. (2023)

Comparison of prescriptive dam safety models, characterized by fixed safety margins, periodic inspections, and compliance-driven decision-making, with risk governance models, which emphasize dynamic risk assessment, consequence-based classification, uncertainty management, and proactive decision-making across the dam life cycle.

Table 8 synthesizes key governance dimensions that directly influence dam safety performance, emphasizing how institutional and organizational weaknesses can lead to delayed

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decisions, ineffective risk management, and increased vulnerability throughout the dam life cycle, including post-closures.

Table 8. Governance dimensions influencing dam safety performance. Adapted from: ICOLD (2011, 2020); World Bank (2021); Independent Expert Panel (2020); Morrison (2022); Slingerland & Morgenstern (2020); Oboni & Oboni (2020)

Governance dimension	Typical weakness	Observed consequence
Risk tolerance	Production-driven bias	Deferred mitigation
Information flow	Fragmented reporting	Late intervention
Accountability	Diffuse responsibility	Inaction
Long-term stewardship	Discontinuous ownership	Post-closure failures

However, post-failure investigations repeatedly show that compliance-based approaches are insufficient for managing low-probability, high-consequence risks, particularly for tailings dams whose conditions evolve continuously throughout operations and closure (Morgenstern *et al.,* 2016; ICOLD, 2020). Contemporary governance models increasingly advocate risk-based decision-making, with hazard identification, consequence classification, and uncertainty management explicitly integrated into corporate and regulatory processes (Amoah; Eweje, 2022; Kellow; Simms, 2021; Slingerland; Morgenstern, 2020).

Table 9 highlights the key differences between prescriptive dam safety regimes and risk-governance frameworks. Prescriptive systems emphasize minimum regulatory compliance and implicitly account for uncertainty, whereas risk-governance approaches explicitly incorporate uncertainty, promote anticipatory risk management, and enable adaptive decision-making. These characteristics make risk-governance frameworks particularly suitable for tailings dams, where evolving operational conditions and high-consequence failure modes demand continuous reassessment beyond static design assumptions.

Table 9. Comparison between prescriptive dam safety regimes and risk-governance frameworks. Adapted from: ICOLD (2011, 2020), DeNeale et al. (2019), Oboni & Oboni (2020), Morrison (2022), and World Bank (2021)

Aspect	Prescriptive regime	Risk-governance regime
Safety philosophy	Minimum compliance	Risk anticipation
Treatment of uncertainty	Implicit	Explicit
Adaptability	Low	High
Applicability to tailings	Limited	High

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6.2. Institutional accountability and independent oversight

A recurring governance weakness identified across failure case histories is the lack of clear accountability for safety-critical decisions.

Independent technical review boards, separation between production-driven incentives and safety oversight, and clear escalation pathways for identified risks have emerged as essential governance elements. Empirical analyses indicate that organizations with strong independent review and transparent reporting structures are better positioned to detect emerging instability and intervene before failure occurs (Sego *et al.,* 2017; Fasking *et al.,* 2015). These principles apply equally to mining and non-mining dams, particularly where infrastructure is aging or operating beyond its original design assumptions (de Souza Lima, 2025; Vinet *et al.,* 2025).

To move beyond descriptive governance principles, it is necessary to evaluate how specific governance elements perform in practice to prevent dam failures. Table 10 synthesizes evidence from historical failures and post-incident investigations, highlighting the relative effectiveness of key governance mechanisms when implemented consistently.

Table 10. Effectiveness of governance elements in preventing dam failures. Adapted from: ICOLD (2011, 2020), DeNeale et al. (2019), Oboni & Oboni (2020), Morrison (2022), and World Bank (2021)

Governance element	Presence	Failure prevention effectiveness
Independent review	High	High
Clear escalation paths	Moderate	Moderate
Production–safety separation	Variable	High when present

The effectiveness is reflected in observed outcomes reported in failure investigations, independent review reports, and risk governance assessments across tailings and non-mining dam sectors.

6.3. Transparency, disclosure, and stakeholder engagement

Recent catastrophic failures have underscored how information asymmetry amplifies disaster consequences.

Limited public disclosure of dam conditions, uncertain emergency preparedness, and weak engagement with downstream communities heighten vulnerability and delay response. Governance frameworks that require transparent risk disclosure and community-informed emergency planning have been shown to reduce social and economic impacts, even when technical failures occur (Aprahamian *et al.,* 2022; Owen *et al.,* 2020; World Bank, 2021).

This shift reflects a broader redefinition of dam safety as a public-risk issue rather than an internal engineering matter (Franken; Schütte, 2022; Guimarães *et al.,* 2022; Osmanova, 2025; Vulević *et al.,* 2023).

6.4. Lifecycle governance and long-term stewardship

Figure 9 illustrates the dam lifecycle from design through post-closure, underscoring that accountability, financial assurance, and monitoring must be maintained continuously across all phases. Rather than being confined to operational stages, governance responsibilities persist beyond closure, reflecting the long-term risk profile and potential consequences of dam structures. The framework emphasizes that effective dam safety depends on sustained institutional commitment, clear ownership of responsibility, and continuous risk reassessment throughout the lifecycle.

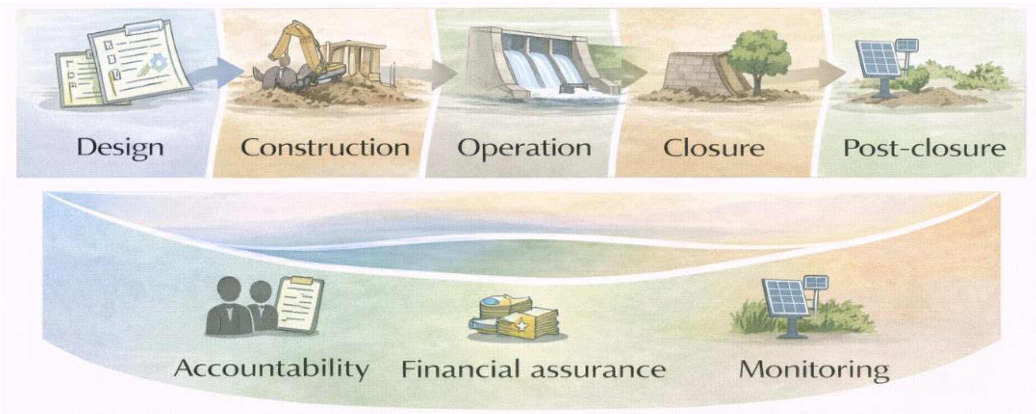

Figure 9. Lifecycle governance and long-term stewardship of dams. Adapted from: ICOLD (2011, 2020), Morrison (2022), Oboni & Oboni (2020), World Bank (2021), and Independent Expert Panel (2020)

An additional governance challenge concerns the long-term stewardship of dams beyond active operation, particularly for tailings facilities entering closure and post-closure phases. Organizational discontinuity, ownership changes, and regulatory gaps often erode institutional memory and reduce monitoring intensity over time. International guidance increasingly emphasizes the need for lifecycle-based governance models that ensure continuity of responsibility, financial assurance, and monitoring capability for decades after closure (Morrison, 2022; Schafer, 2022). Similar issues are observed in non-mining dams, where aging infrastructure and deferred maintenance have contributed to failures long after construction (Adamo *et al.,* 2021).

6.5. Toward harmonized governance standards across dam sectors

The evidence synthesized in this review indicates that meaningful improvements in dam safety require harmonized governance principles across dam sectors, rather than siloed regulatory regimes. While technical standards must remain context-specific, core governance elements—such as risk-based classification, independent oversight, transparent disclosure, and life-cycle accountability—are broadly applicable across dam types. The Global Industry Standard on Tailings Management is a significant step in this direction, offering a governance-oriented framework that could inform safety practices for other dam categories (Independent Expert Panel, 2020). Ultimately, preventing future dam failures depends on aligning engineering rigor with organizational culture and governance systems capable of anticipating evolving risks, rather than merely reacting to failures (Morrison; Adams, 2025).

The governance-oriented evidence reviewed in this section underscores that improvements in dam safety are constrained less by technical uncertainty than by persistent organizational and institutional limitations. Despite the availability of international standards, risk-informed frameworks, and extensive post-failure knowledge, many dam-owning organizations continue to operate under governance structures that inadequately address long-term accountability, cross-disciplinary integration, and the management of extreme but plausible scenarios. Across both mining and non-mining contexts, safety-critical decisions are frequently influenced by short-term economic pressures, fragmented regulatory oversight, and unclear lines of responsibility throughout the dam life cycle. These conditions foster a reactive safety culture in which emerging risks are acknowledged but not decisively mitigated. As a result, dam failures should be understood not as anomalies but as predictable outcomes of systemic governance deficiencies.

To consolidate the cross-sectoral insights discussed in Sections 6 and 7, Table 11 summarizes a set of harmonized governance principles applicable to both tailings dams and non-mining dam infrastructure. These principles reflect converging international practices in risk-based regulation and institutional accountability, highlighting areas where governance frameworks can be effectively transferred and scaled across different dam typologies.

Table 11. Harmonized governance principles applicable across dam sectors. Adapted from: ICOLD (2011, 2020), Oboni & Oboni (2020), DeNeale et al. (2019), Morrison (2022), World Bank (2021), and Independent Expert Panel (2020)

Principle	Tailings dams	Non-mining dams	Transferability
Risk-based classification	Essential	Applicable	High
Independent oversight	Essential	Beneficial	High
Lifecycle accountability	Critical	Increasing	High
Transparency	Emerging	Limited	Expandable

The table highlights governance principles that consistently shape dam safety outcomes across sectors, despite differences in operational context and regulatory maturity. Although some practices—such as independent oversight and lifecycle accountability—are already well established in tailings governance, their adoption in non-mining dams remains uneven, underscoring significant potential for cross-sector learning and regulatory convergence.

7. COMPARATIVE DISCUSSION

Recurrent pathways of risk normalization, fragmented accountability, and economically driven decision-making have been identified in failure case histories of mining tailings dams and conventional water-retaining dams. Despite differences in dam function and rupture mechanics, similar organizational vulnerabilities persist across the design, operation, closure, and post-closure stages.

7.3. Common patterns of organizational failures across dam typologies

A cross-sector comparison of dam-failure case histories shows that, regardless of dam function or retained material, organizational failures follow remarkably similar patterns. Investigations consistently demonstrate that catastrophic outcomes are preceded by extended periods of risk normalization. During these periods, anomalous monitoring data, operational deviations, or exceedances of design limits are acknowledged but not translated into decisive corrective actions (Davies, 2002; Foster et al., 2000; Morgenstern *et al.,* 2016). This phenomenon has been documented not only in mining tailings facilities, but also in civil and hydroelectric dams. In these systems, aging infrastructure, deferred maintenance, and unclear escalation protocols progressively undermine timely intervention (FEMA, 2015; ICOLD, 2011).

Another recurring pattern is the institutional fragmentation of responsibility across the dam life cycle. Different organizational units or entities often manage design, construction, operation, closure, and post-closure phases. This separation creates discontinuities in risk ownership and progressively erodes institutional memory. Comparative analyses indicate that such fragmentation substantially increases vulnerability to low-frequency, high-consequence events, particularly when economic pressures incentivize production continuity over conservative safety margins (Bowker; Chambers, 2015; Owen *et al.,* 2020).

7.4. Differences in rupture mechanics and their systemic implications

While organizational weaknesses show strong convergence across dam typologies, rupture mechanics introduce fundamental asymmetries that shape failure progression and consequences. In conventional embankment and hydroelectric dams, failure mechanisms are primarily governed by hydraulic loading and erosional processes, such as overtopping and internal erosion. These mechanisms typically evolve gradually and may provide observable precursors over extended timeframes (Fell *et al.,* 2003; Wa; Fell, 2008; Xu; Zhang, 2009).

In contrast, mining tailings dams—particularly upstream-raised facilities—are uniquely susceptible to undrained instability and static or dynamic liquefaction, which can trigger abrupt loss of strength and rapid flow failures (Azam; Li, 2010; Wang *et al.,* 2024). This failure behavior drastically reduces available warning time and amplifies downstream hazard intensity, thereby contributing to the disproportionate human and environmental impacts observed in major tailings dam disasters (Rico *et al.,* 2008; Lumbroso *et al.,* 2021). Importantly, these differences imply that governance and operational systems must be calibrated not only to the probability of failure but also to failure velocity and consequence severity. This distinction remains inadequately reflected in many current regulatory frameworks.

7.5. The need for integration across sectoral standards and governance frameworks

This review's comparative evidence points out a key limitation of sector-specific regulatory silos. While mining tailings dams and non-mining dams are governed by different standards and institutional setups, many root causes of failures are common to both. These include poor water management, lack of independent review, weak links between monitoring and decision-making, and limited transparency (ICOLD, 2020; Morrison, 2022). This overlap indicates that safety issues are not mainly due to technical guidance gaps but result from the lack of unified, risk-based governance principles that apply across all dam types (Cruz *et al.,* 2024; Oboni, F.; Oboni, C., 2020).

Recent advances in tailings governance—such as consequence-based classification, independent oversight, and explicit life-cycle accountability—are transferable and could substantially strengthen safety practices in civil and hydroelectric dam sectors (Independent Expert Panel, 2020; Schafer, 2022). Conversely, the water-dam sector's long-standing experience in hydrological risk management, spillway safety, and oversight of aging infrastructure offers valuable lessons that remain underutilized in mining contexts (Zhang *et al.,* 2009; ICOLD, n.d.). Bridging these domains requires a shift from typology-driven compliance to integrated governance models that recognize dam safety as a shared societal risk that transcends sectoral boundaries (DeNeale *et al.,* 2019; Lacasse *et al.,* 2023).

To consolidate the comparative discussion in this section, Table 12 presents a qualitative synthesis of dominant technical failure mechanisms and recurrent governance-related weaknesses across major dam typologies. Rather than focusing on individual case histories, the table highlights cross-sector patterns that consistently emerge from both historical and contemporary failure analyses. This synthesis emphasizes the convergence of organizational vulnerabilities despite fundamental differences in rupture mechanics among dam types.

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Table 12. Comparative synthesis of technical failure mechanisms and governance gaps across dam typologies. Adapted from Davies (2002), Foster et al. (2000), Bowker and Chambers (2015), Morgenstern et al. (2016), Rico et al. (2008), ICOLD (2011, 2020), and Owen et al. (2020)

Aspect	**Mining tailings dams**	**Hydroelectric dams**	**Civil/agricultural dams**	**Cross-sector insight**
Dominant rupture mode	Liquefaction-driven flow failure	Progressive erosional breach	Progressive erosional breach	Mechanics differ, governance failures converge
Warning time	Short to none	Moderate to long	Long	Faster failures demand stronger governance
Water management sensitivity	Very high	High	High	Water control is a universal driver
Monitoring capability	High (often available)	High	Variable	Data availability ≠ decision effectiveness
Decision latency	Frequent	Frequent	Frequent	Risk normalization common
Accountability continuity	Often fragmented	Often fragmented	Often fragmented	Lifecycle governance gaps dominate
Regulatory approach	Sector-specific	Sector-specific	Sector-specific	Need for harmonized risk governance

Note: This table presents a qualitative and conceptual synthesis derived from multiple literature sources rather than a single unified statistical database

To synthesize the comparative argument developed in Section 7, Figure 10 presents a conceptual representation of risk asymmetry across dam typologies, highlighting the structural disconnect between failure probability and consequence severity. The diagram shows that although tailings dams do not necessarily have the highest failure probabilities, their consequences are disproportionately severe, particularly in terms of loss of life and environmental damage. This asymmetry underscores the need for risk governance frameworks that explicitly prioritize consequence severity alongside failure likelihood, rather than relying solely on probabilistic metrics.

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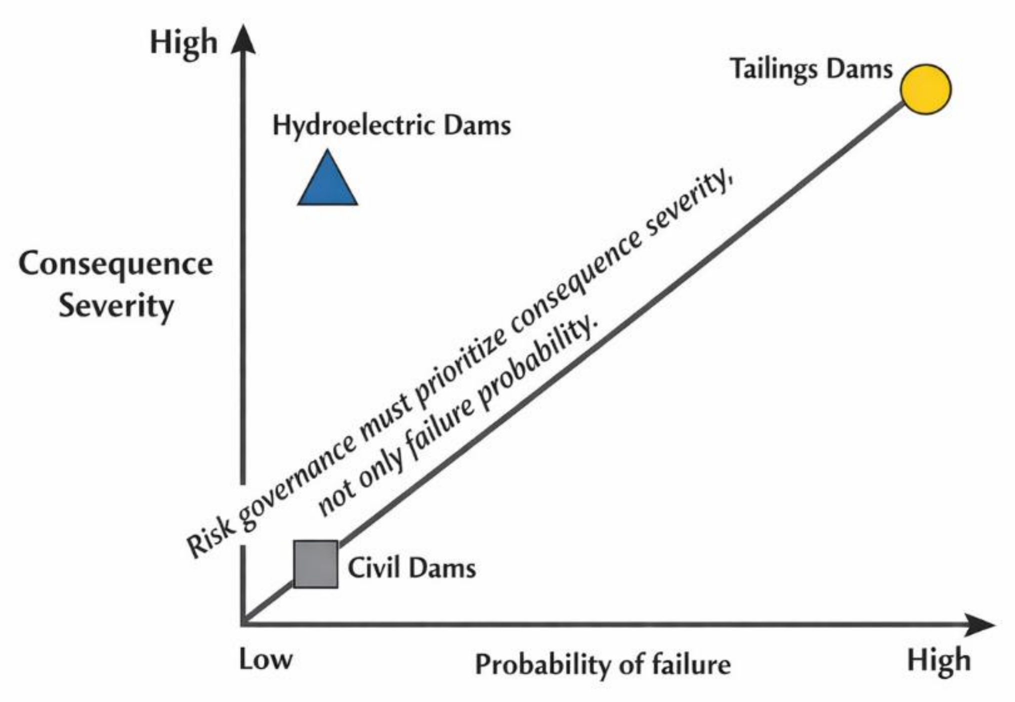

Figure 10. Risk asymmetry across dam typologies: probability of failure versus consequence severity. Adapted from: Azam & Li (2010); Bowker & Chambers (2015); Morgenstern et al. (2016); Rico et al. (2008); Islam & Murakami (2021); Lumbroso et al. (2021); ICOLD (2020); World Bank (2021); Yu et al. (2025)

This figure presents a conceptual two-dimensional comparison of tailings, hydroelectric, and conventional civil dams. Tailings dams have moderate failure probabilities but very high consequence severity, primarily due to flow failures and rapid downstream propagation. Hydroelectric dams typically have low failure probabilities but potentially severe consequences, whereas conventional civil dams generally combine lower failure probabilities with more moderate consequences. The diagonal guideline underscores that effective risk governance must prioritize consequence severity rather than focusing solely on failure probability.

The comparative evidence in this section reinforces that dam safety challenges cannot be effectively addressed through isolated technical measures or sector-specific interventions. Although differences in rupture mechanics—particularly the prevalence of liquefaction-driven flow failures in tailings dams—clearly influence failure dynamics and the severity of consequences, the underlying pathways that enable catastrophic outcomes are predominantly organizational and systemic. Across dam typologies, failures consistently stem from similar patterns of risk normalization, fragmented accountability, delayed responses to warning signals, and regulatory silos that impede cross-sector learning. The persistence of these patterns, despite decades of documented failures and increasingly sophisticated technical guidance, indicates that current

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safety paradigms remain insufficiently aligned with the complexity of the socio-technical risks governing large dam systems.

Building on this comparative discussion, the following section presents the review's final conclusions, synthesizing technical, organizational, and governance insights and outlining their implications for advancing integrated dam safety practices across the mining and non-mining sectors.

8. CONCLUSION

This comparative review examined dam failures in mining tailings dams and non-mining dams—including hydroelectric, civil, industrial, and agricultural structures—to identify convergent and divergent patterns in failure causes, rupture mechanisms, consequences, and governance arrangements. The analysis confirms that, although dam typologies differ significantly in function, materials, and construction methods, catastrophic failures are rarely driven by isolated technical deficiencies. Instead, failures result from interactions among geotechnical behavior, water management practices, organizational decision-making, and governance structures throughout the dam life cycle.

From a mechanical perspective, the review highlights a fundamental asymmetry between tailings dams and conventional water-retaining dams. In civil and hydroelectric dams, overtopping and internal erosion dominate failure initiation and typically evolve gradually. In contrast, tailings dams are uniquely susceptible to undrained instability and static or dynamic liquefaction, which can trigger rapid flow failures with limited warning and disproportionately severe consequences. This distinction underscores the need for more conservative design assumptions, tighter operational controls, and faster decision–response pathways for tailings facilities, particularly those built using upstream or hybrid methods.

Despite these mechanical differences, a key finding of this study is the strong convergence of organizational and governance-related failure patterns across dam sectors. Recurrent themes include the normalization of deviance, delayed responses to monitoring data, fragmented accountability across life-cycle phases, insufficient independent oversight, and regulatory silos that impede cross-sector learning. Collectively, these patterns indicate that many dam failures are predictable outcomes of systemic governance weaknesses rather than unforeseeable engineering anomalies.

The review further shows that recent advances in tailings governance—such as consequence-based classification, life-cycle accountability, independent technical review, and transparent risk disclosure—constitute transferable best practices that could substantially strengthen safety management in non-mining dams. Conversely, the water-dam sector’s long-standing experience in hydrological risk management, spillway safety, and oversight of aging infrastructure offers valuable lessons that remain underutilized in mining contexts. Bridging these domains requires moving beyond typology-driven regulation toward harmonized, risk-informed governance frameworks applicable across all dam types.

In conclusion, improving dam safety globally requires an integrated socio-technical approach that aligns engineering rigor with a robust organizational culture and governance systems capable of anticipating evolving risks rather than merely reacting to failures. Future efforts should prioritize cross-sector integration of standards, continuous risk reassessment throughout the dam life cycle, and institutional mechanisms that ensure accountability, transparency, and timely intervention. Only through such an integrated framework can the frequency and severity of dam failures—and their profound human, environmental, and societal impacts—be meaningfully reduced.

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