CHAPTER V
MINE TAILINGS – A SYSTEMS APPROACH

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1. INTRODUCTION

There have been tailings facility failures since the inception of placing tailings on land in facilities versus the practice until about 100 years ago of directly placing all tailings into watercourses. Over the past 100 years, the amount of tailings produced has continued to increase as global ore grades decline and the economics of mining drive towards larger operations. While the number of failures per tonne of tailings produced on an annual basis has declined, the number and nature of facility failures remains wholly unacceptable. The recent failures of tailings facilities have turned the public and technical spotlights on tailings management at mines and the mining industry in general. In the last six years, major failures at Mount Polley, Samarco, Cadia and Brumadinho have led to a loss of confidence in the mining industry to manage the risk of tailings facility failures. Given the communication age upon us, failures that may have happened a few decades ago that only received regional attention, if any, are occurring in front of a global audience.

These failures have resulted in a renewed focus on the impact on lives and on the importance of tailings management relative to a potential failure, as well as the financial and reputational impact to mining companies. Mining is an essential industry to our modern world – it is not an optional industry or one that is likely to reduce in its importance to people in the future. As such, it has become increasingly clear that tailings facilities are important elements of mining operations and their safety must be considered within a larger framework in order to improve overall tailings risk management. The silver lining of the crisis created by the high-profile tailings failures is the enhanced opportunity to improve practices in the area of tailings management so this essential industry can continue with far less impact to the communities where mining takes place.

Progress in tailings management requires taking into consideration that tailings are part of a complex system. There is more complexity to managing tailings than can be handled by simple linear cause-and-effect approaches, and therefore a systemic approach is required. The tailings system needs to balance important components, which can be both interconnected and competing, such as: risk management, societal expectations regarding risk and environmental performance, tighter regulatory requirements, economic expectations from investors, and capital, operational and closure costs. The communities living near a mine, their livelihoods and well-being, are a central consideration necessitating an increased level of systemic risk management at tailings facilities. Further, tailings facilities will exist essentially in perpetuity making them not only complex systems to manage but entities that once developed will exist for generations. Managing the changes that will occur to the facility over those generations is part of the system management challenge.

Significant progress has already been made in addressing these challenges, with corporations and investors increasingly taking longer term views on social, environmental and economic objectives relative to mining, and to tailings management in particular. The drive towards responsible mining needs to incorporate a systems approach to tailings facilities that is designed to prevent significant failures.

According to Garbolino, Chéry and Guarnieri (2019, p.1), the advent of the systemic approach, which considers phenomena and problems as systems, 'heralded a turning point in the history of science and its application to the organisation, and to production'. By recognising that all components of a system are interconnected, the systemic approach highlights emerging behaviour and links knowledge, expertise and data from various elements and disciplines that affect the system. This is precisely what allows significant progress compared to compartmentalised, single-discipline, linear approaches.

This chapter introduces the systems approach to tailings management including the systems that produce tailings, and the systems associated with the design, management and operations of tailings facilities. All of this is seen as part of the broader community and environmental realities at and near mine sites.

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2. SYSTEM CHARACTERISTICS

A socio-technical system includes several groups of people at multiple levels who are involved in performing a technological task to produce an expected result. A socio-technical system has the following features (Durand 2006):

Interaction – elements of a system interact performing actions on other elements while being subject to actions by other elements. The system includes feedback loops.

- Comprehensiveness – a system cannot be reduced to the sum of its parts. There are specific properties to each subset of the system.
- Organisation – refers to both the structure and operation of a system designed to achieve a goal and assures the functions and processes of a system.
- Complexity – systems have complexity that can have several characteristics:
  - new and dynamic system properties can emerge
  - a complex system can change its organisation without external influences
  - sensitivity to conditions and constraints influence subsequent dynamics and adaptability
  - temporal dynamics can produce events that change the system dynamics
  - there is uncertainty in intricately organised systems
  - it is difficult to predict the evolution of a complex system.

According to Garbolino, Chéry and Guarnieri (2019, p.7), unpredictability in a complex system 'can be reduced by taking into account those elements that were originally excluded from the system, but which are subsequently found to have strong causal relationships with those items that were originally included in the system'.

Box 1: Factors in complex socio-technical systems that have the potential to have an adverse impact on safety

1. Performance is an emergent property of a complex socio-technical system. It is impacted by the decisions of all the actors– politicians, managers, safety officers and work planners – not just the front-line workers alone
2. Sub-optimal performance is usually caused by multiple contributing factors, not just a single catastrophic decision or action.
3. Sub-optimal performance can result from a lack of vertical integration (i.e., mismatches) across levels of a complex socio-technical system, not just from deficiencies at any one level.
4. The lack of vertical integration is caused, in part, by a lack of feedback across levels of a complex socio-technical system. Actors at each level cannot see how their decisions interact with those made by actors at other levels, so the threats to safety are far from obvious before an accident.
5. Work practices in a complex socio-technical system are not static. They will migrate over time under the influence of a cost gradient driven by financial pressures in an aggressive competitive environment and under the influence of an effort gradient driven by the psychological pressure to follow the path of least resistance.
6. The migration of work practices can occur at multiple levels of a complex socio-technical system, not just one level alone.
7. Migration of work practices causes the system's defences to degrade and erode gradually over time, not all at once. Sub-optimal performance is released by a combination of this migration in work practices and a triggering event, not just by an unusual action or an entirely new, one-time threat to safety.

Source: Rasmussen (1997) as summarised in Donovan et al. (2017).

Rasmussen (1997) has argued that in complex socio-technical systems, risk management must be done in a cross-disciplinary manner and requires a system-oriented approach, since safety is impacted by decisions, behaviours and actions of actors across all levels of a work system (see Box 1).

3. HOW COMPLEX SYSTEMS FAIL

The terms of reference of recent failure investigation panels were narrowly focused on the immediate technical causes of the failure events. Valuable learnings emerged from these investigations. However, although there are always immediate technical reasons for tailings facilities failures, the overarching technical and governance reasons that allowed the situation to get to the point of failure are, in most cases, the root cause of the failure (see Hopkins, this volume). For example, while it may be true that a flood event caused the overtopping that lead to the facility failure – what was the flaw in the governance process that led to the planner, operator, designer, reviewer and regulator failing to notice the lack of system capacity for either storing this flood event or passing it safely through an adequately designed and constructed spillway? While overtopping may have been the immediate technical cause of the failure event, a series of poor decisions were involved that were most assuredly part of the root cause of that event.

An important consideration for the overall management of tailings is how to characterise and work towards understanding and preventing systems failures, whether these relate to the physical system, the communication system, the management system or any other component of the overall system.

In his book *Drift into Failure*, Sidney Dekker (2011) describes five elements that together may characterise this 'drift to failure', meaning the multiple factors that have been derived from evaluating many systems failures. These elements are listed below; the terminology used by Dekker is inside the parentheses.

1. **Constraints impacting decision-making ('scarcity and competition')** –Three types of constraints have been recognised in complex systems: economic boundary, safety boundary and workload boundary. Economic pressure to reach higher efficiencies will push the system's operations closer to the workload and safety boundaries. If economic pressure wins it may result in borrowing from safety to accomplish the efficiency. Decision-making within these constraints may contribute to failure. There are real constraints on mining companies including: market and political pressures, schedule and budget considerations, development and engagement of a high-quality workforce, and establishment of systems to help maintain the stability of tailings operations.
2. **A series of small decisions can have a large impact ('decrementalism, or small steps')** – Many of the decisions that are made over time in tailings management do not necessarily result in major changes; in most cases they present small incremental changes. However, a series of small, apparently unrelated decisions may in the long-term significantly impact outcomes if their system impacts are misunderstood or neglected.
3. **Misunderstanding of interdependencies ('sensitive dependence on initial conditions')** – An incomplete understanding of system conditions that are interrelated can have significant impacts on outcomes due to a series of decisions that misunderstand and neglect the interdependencies. Anyone who is involved with a tailings facility may be unaware of the interdependencies of some decisions as they may have an incomplete understanding of how they are related to the specific tailings system at that site.
4. **Models may not be reliable ('unruly technology')** – Parameter uncertainties can be included in evaluations before a decision is made. However, the models may not always be reliable. Despite our best attempts, there can be unknowns that are not effectively evaluated due to incomplete information or other factors. Models may not capture everything that could go wrong and there is a danger that the 'calibrations' may not be correct.
5. **Failure to benefit from available governance and other systems ('contribution of protective structure')** – There are many regulations, management procedures, governance measures, institutional knowledge, etc. in place that can provide support in maintaining systems integrity. These measures and procedures must be identified and applied in the day-to-day approach to the management of complex systems.

These concepts indicate the difficulty of analysing systems failures using a linear cause-and-effect Newton/Descartes approach (Box 2). While it is a challenge to find the 'immediate technical cause of a failure', it is much more difficult to find the cause of failure of the entire complex system.

Box 2: Investigating Failures in Complex Systems

We can all work on letting a post-Newtonian ethic of failure emerge if we embrace systems thinking more seriously than we have before. In a post-Newtonian ethic, there is no longer an obvious relationship between the behavior of parts in the system (or their malfunctioning, for example 'human errors') and system-level outcomes. Instead, system level behaviors emerge from the multitude of relationships, interdependencies and interconnections inside the system, but cannot be reduced to those relationships or interconnections. In a post-Newtonian ethic, we resist looking for the 'causes' of failure or success. System-level outcomes have no clearly traceable causes as their relationships to effects are neither simple nor linear.

Source: Dekker 2011, p. 201

A critical governance concept that must be addressed in the safe design, construction, operations and closure of tailings facilities is normalisation of deviance (Dekker 2011; Pinto 2014; Vick 2017). In summary 'normalisation of deviance suggests that the unexpected becomes the expected, which becomes the accepted' (Pinto 2014, p.377). Vick (2017) describes three tailings facility and conventional water dam projects where this concept was demonstrated. In these cases, the failure modes were recognised but not adequately acted upon due to a normalisation of deviance: repeated deviations from intended performance became accepted as normal, deviations were rationalised, and warning signs were ignored. The accepted deviances allowed the failure triggers to go unrecognised. Another related human-issue concern are the hierarchical models that are prevalent in companies/society that limit communication that can prevent root causes of failures (e.g., where concerns are not raised out of fear of retribution), or simply structures that allow the strongest personalities to dominate the decision-making process.

In reviewing possible ways of preventing failure of complex systems, Dekker (2011) suggests that the inclusion of diversity can reduce the overall chances for drifting into failure. Diversity impacts the five elements identified above and results in a much more resilient outcome. Safety-critical organisations are complex adaptive systems. These organisations must pay attention to diversity that brings a larger number of perspectives resulting in a wider range of possible outcomes.

4. TAILINGS PRODUCTION, OPERATIONS AND MANAGEMENT

The production and management of tailings can be thought of as part of a larger system consisting of several interconnected systems. Although much can be said about this larger system, this chapter focuses on the systems and the aspects of these systems that most directly affect tailings. This encompasses:

- Mine-related factors – the location and nature of resources, and the landscape in which they occur. These variables determine the location and type of mine, and ultimately the amount and character of the tailings. These characteristics are inflexible, and they constrain the system.
- Processing plant characteristics – these affect the physical and chemical nature of the tailings produced.
- Tailings facility planning, design and operation.
- Tailings facility governance and oversight (inclusive of independent review and the regulatory system).
- Mine operation, governance and social performance.
- Local and regional social and environmental system.

Combining all these layers and contextual factors effectively defines the overall tailings system, which both affects and is affected by these broader systems and cannot be adequately conceived or managed without taking account of this context.

The community and its social, cultural and economic framework are critical elements of the overall system. The environmental system upstream and downstream of the tailings facility is also a critical component. A defined ore deposit – the prospective mine – will be located within a broad landscape, where people may live and pursue a variety of activities. Further, mines can exist over many decades and even more than a century so what may start as a remote site for a mine can evolve into a mine with many interfaces with people and their economic and/or recreational pursuits. Traditionally, a new or established mine interfaces with the social, cultural and economic landscape through national and regional government regulators on one hand, and communities and civil society on the other hand. Many aspects of a proposed mine will come under scrutiny – access, energy and water use, potential effects on local livelihoods and traditional culture and heritage, biodiversity and the environment. Among these, the siting of the tailings facility and the associated risks – real and perceived – are critically important and perhaps an important decision in terms of the relationship between the value from the mine for society and the potential impacts that value entails. Once in production, concerns and opposition among local people may decrease or increase depending on performance and the relationship between the mine and the communities.

An understanding of this broader system is required from the start of a project and effective interactions with the broader system need to be maintained for the long term. This is the overarching system that needs to be continuously recognised, respected and improved upon.

The remainder of this chapter focuses on the more local, mine specific tailings systems and how they can be improved to minimise the risk of failures of tailings facilities. The local systems, which interact as an operation-wide system, include both tailings as part of the mine and processing plant system, and the tailings facility as a system in itself.

5. TAILINGS AS PART OF THE MINE AND PROCESSING PLANT SYSTEM

The production and processing of tailings relates to the orebody, the ore processing and extraction technology, and the overall mine infrastructure.

Many of the major metals used by society occur in specific types of ore deposits defined by geological, geometric and mineralogical characteristics. Each deposit type has a range of distinct chemical and physical properties. The nature of the ore deposits largely determines how they are mined (e.g., at surface or underground), how the ore is processed, and the scale of the mining operation (e.g. tonnes of ore treated by the plant per day). These factors also determine the amount of waste rock and tailings that will be produced by the mine, and the mineralogical, chemical and physical nature of the tailings.

Major ore deposits contain metals in concentrations that range from a few parts per million (ppm) to more than 65 per cent, with the remainder of the mined rock following removal of metal-bearing minerals constituting waste rock and/or tailings. In some cases, metal can be recovered by direct leaching of broken or fragmented rock piles, a process known as 'heap leaching'. This is restricted to near-surface ore deposits where surficial weathering has changed the mineralogy allowing leach solutions to capture the metals of interest, most commonly copper, nickel and gold. No tailings are produced in the leaching process, but the leached rock represents volumes of waste rock, some of which may contain significant concentrations of deleterious elements both inherent to the waste and added during processing.

The metal concentration and mineralogy of the ore constrain the processes used to extract the mineral or metal of interest. Detailed assessment of the defined ore body generates extensive data on the mineralogy, concentrations of all elements (including those that may be deleterious to humans or the environment), and the physical properties of the rocks. These data are used to design the mine and processing facilities and assess detailed economic feasibility. In addition, these data are used to evaluate the tailings that will be produced, and to assess how the tailings volumes and character may change over time due to variability of the ore body and the related adjustments to the processing plant.

While the volume and character of tailings are strongly influenced by the type of ore deposit, including its metal concentration and mineralogy, mining and processing options also influence tailings (see also Williams, this volume). For example, new ore sorting technologies deployed on shovels or conveyer belts at the mine may remove rock with low metal concentrations prior to crushing or grinding, hence decreasing the material that is fully processed and the resulting amount – and, in some cases, properties – of tailings that are produced. Processing technologies that can have a significant impact on tailings properties include the degree of ore grinding, the flotation process, the use of thickeners or centrifuges to decrease the water content of tailings, and the use of additives such as flocculants and coagulants.

Traditionally, ore processing technology tended to be exclusively focused on maximising recovery and minimising costs, however currently there is an increasing trend of taking into consideration the resulting tailings properties. There are examples of secondary processing that both enhance recovery and optimise tailings properties. Governance decisions are evolving into a bigger picture business analysis of the system that considers optimising not only recovery but also tailings management operations, facility construction and closure, and environmental management.

6. TAILINGS FACILITY DEVELOPMENT AND MANAGEMENT AS A SYSTEM

After the processing plant, tailings may be further processed and then are conveyed to a tailings storage facility, which in itself is part of a complex system. The tailings facility system, as other parts of the mine operations system, includes both a technical and a governance system, which are intimately connected. This is the system that is most directly related to – and has the most influence on – reducing the risk of failure of the tailings facility. This section describes the tailings facility system, starting from its most local components and expanding into the broader systems.

6.1 THE TAILINGS FACILITY PLANNING, DESIGN AND OPERATION (THE INNER CIRCLE)

Tailings facilities are distinct from infrastructure projects where a design is done according to pre-established planning parameters, followed by construction to implement the design, supported by a quality assurance / quality control process (QA/QC) until the project is complete. Tailings facility projects, by contrast, require continual involvement of the planning, design, construction, QA/QC, and operations functions, all linked to the overall mining development, and undertaken in a dynamic environment with changes due to ore variability, processing plant issues and market pressures. In other words, a tailings facility is a highly integrated dynamic system with a high degree of complexity.

The diagram in Figure 1 provides an idealised depiction of common elements of the local system ('inner circle') that represents the fundamental circle of activities for the development and operation of a tailings facility: tailings facility planning, design and operations, and the relationships between these activities. For simplicity, inputs and outputs of this system are not illustrated.

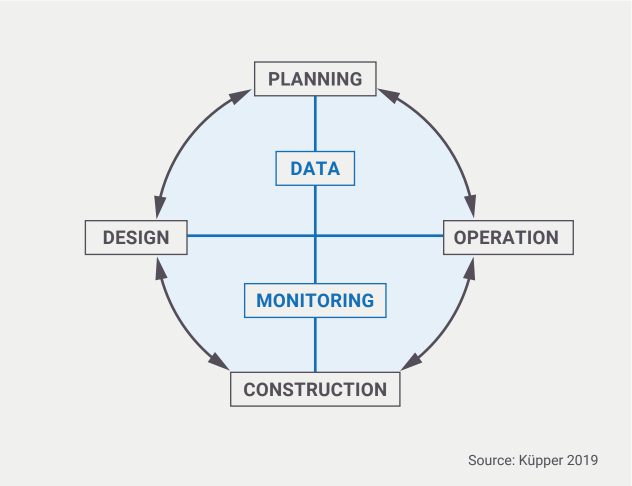

Figure 1. Simplified diagram of the 'inner circle' of the tailings facility system

This inner circle includes the typical day-to-day activities that involve the planning, design, construction and operations functions and the important interactions between these groups. The inner circle can be more complex in larger operations and involve more 'boxes', but the key issues remain similar. The main sub-systems that form the inner circle system are described below.

Planning

The Planning work for a tailings facility involves several aspects. One of the main activities involves determining the volume of tailings and water that requires deposition and containment with time and consequently the required rate of rise of the tailings facility. It also involves defining the construction process to meet the storage requirements according to the design. For example, some of the important considerations are the availability of construction materials (borrow material, tailings, overburden, waste rock or other mine waste), access from the material source to the construction area, location of tailings and water lines, as well as recycle water facilities. For larger operations, the Planning function may include several teams such as mine planning and tailings planning, or short-term planning and long-term planning. Material quality, quantity and availability schedule have a profound impact on design and construction and, in some cases, safety of a tailings facility. For this reason, planners need to work in effective collaboration with geologists, mineral processing engineers and geotechnical engineers (both the designers and the monitoring team) to support the safe construction and operation of a tailings facility. Involvement of the designers at an earlier stage allows cost savings: for example, by developing a design that seeks to optimise the use of available materials and the site development schedule, and by piggy-backing on geology drilling programmes for geotechnical characterisation of overburden materials and tailings facility foundation. Finally, planning that does not take closure considerations into account will almost never lead to an integrated tailings facility concept. All tailings facilities will spend more of its lifecycle in the closed configuration than in operation, so commensurate attention to this condition during the planning stage is paramount to the safety of the tailings facility throughout its lifecycle.

Design

The Engineer of Record (EOR) is responsible for the design of the tailings facility, which is a critical element of the safety of the facility. Fundamental elements supporting a 'solid blue' robust design are shown in the diagram of Figure 2: get the geology 'right', get the soil mechanics 'right', get the hydrology 'right', and get the implementation 'right'. To accomplish this, the EOR team needs to have both competency and experience commensurate with the specific requirements of the project. Further, it is necessary to have an appropriate level of competent and credible review that is independent of the EOR and the facility owner – this review is further described in the 'outer circle' following in this chapter. Effective collaboration with Planning, Operations and Monitoring is critical for the EOR to: (1) produce a design that is calibrated to the site conditions and performance; (2) adjust this design as the site conditions evolve; and (3) bring to the system a depth of understanding of the design assumptions, design intent, uncertainties and an appreciation of the risks of each structure and how they are managed in the design. An effective and balanced collaboration among the Design, Planning, Operations and Monitoring functions can reduce costs and manage risks to the integrity of the tailings facility.

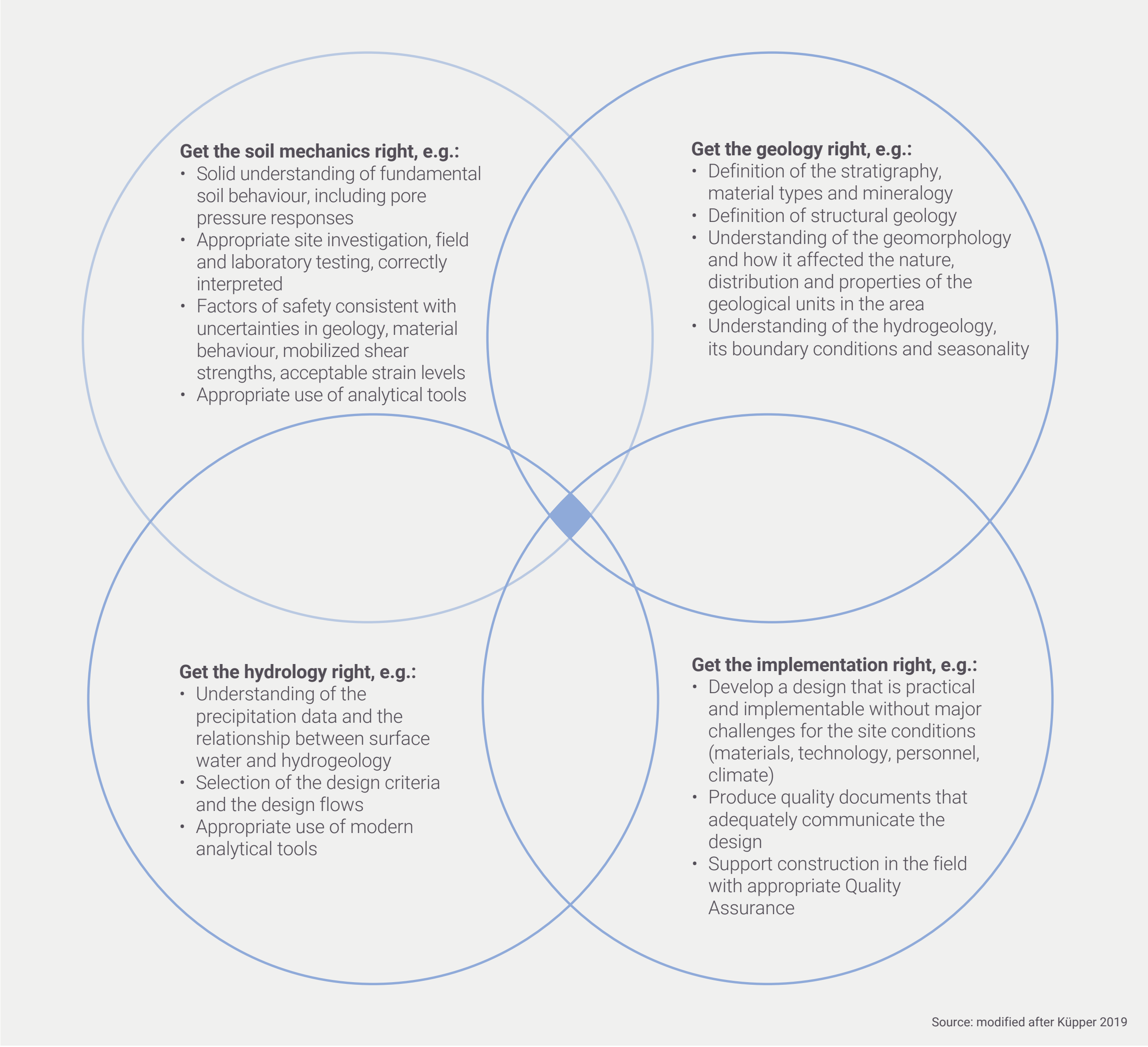

Figure 2. Simplified diagram of elements of the design of a tailings facility

Construction and Operation
In some cases, construction of the starter dyke, if there is one, is carried out by a contractor. However, when construction of the starter dyke is complete, Construction and Operations often become the same as these activities are taken care of by the mine operations. This merger of functions increases the complexity of the system and the interaction between its parts. Operations is affected by Planning, for example, as material availability may affect the rate of construction. Operations can also influence Planning; for example, by providing feedback and contributing to make future plans more realistic and better suited to tailings facility operation and safety. An important interaction between Design and Operations occurs through QA. Beyond checking the QC programme, QA should have sufficient understanding of the design to assess whether construction meets the design intent and to identify whether there is a need to adjust the design to the observed site conditions, including materials. Operations interacts with the other sub-systems of the inner circle, but also with the physical environment; for example, having to manage high precipitation events by adjustments to the normal operations.

At the centre of the inner circle is the data system required for all the sub-systems to work adequately. The quality of the work product is only as good as the quality of the data that the work is based on. The data system includes the geological data and model, geotechnical data (e.g., borehole logs, sampling, test results, instrumentation readings, etc.), planning data, construction QA/QC and as-built data, monitoring data, operational data, and social and environmental data. It is essential to have complete, detailed and accurate data that are easily accessible to all parties involved and that are geo-referenced where appropriate. Data integrity is critical.

Another essential element of the tailings planning process is the use of risk assessments. These are employed throughout the design process and necessarily inform all aspects of the planning and operating phases for the facility.

All the people involved in the inner circle of work need to understand the purpose, importance and potential consequences of their work. This is regardless of whether they are in planning, design, construction, operation, or are involved in obtaining the data (for example, instrumentation monitors, surveyors, drillers and geo-professionals on site investigation or in the laboratory). Moreover, their practical knowledge and observations need to be considered in planning and designing the tailings facility. This is important for improving the quality of the work and the safety of the facility.

6.2 THE TAILINGS FACILITY GOVERNANCE AND OVERSIGHT SYSTEM (THE OUTER CIRCLE)

Tailings facilities are also part of a management system that relates to the various layers of governance and oversight. This system includes company personnel, consultants, regulators, and local and non-local communities. The diagram in Figure 3 (below) provides an idealised representation of common elements of a tailings facility management system and the relationships between these elements. Again, for simplicity, the fundamental drivers – input and output – of this system are not illustrated. This 'outer circle' provides support and oversight to enable participants in the inner circle to get their best work done. This circle also provides important 'end goals' for the inner circle and links to the broader systems. The outer circle is formed by senior management, independent reviewers, regulators and communities that provide oversight of the tailings facility. The blue shading in the diagram in Figure 3 emphasises that the entire system must be supported by high quality, accessible data. Like the inner circle, each rectangular box of the outer circle is a system in itself; however, in the case of the outer circle, these systems involve more complexity.

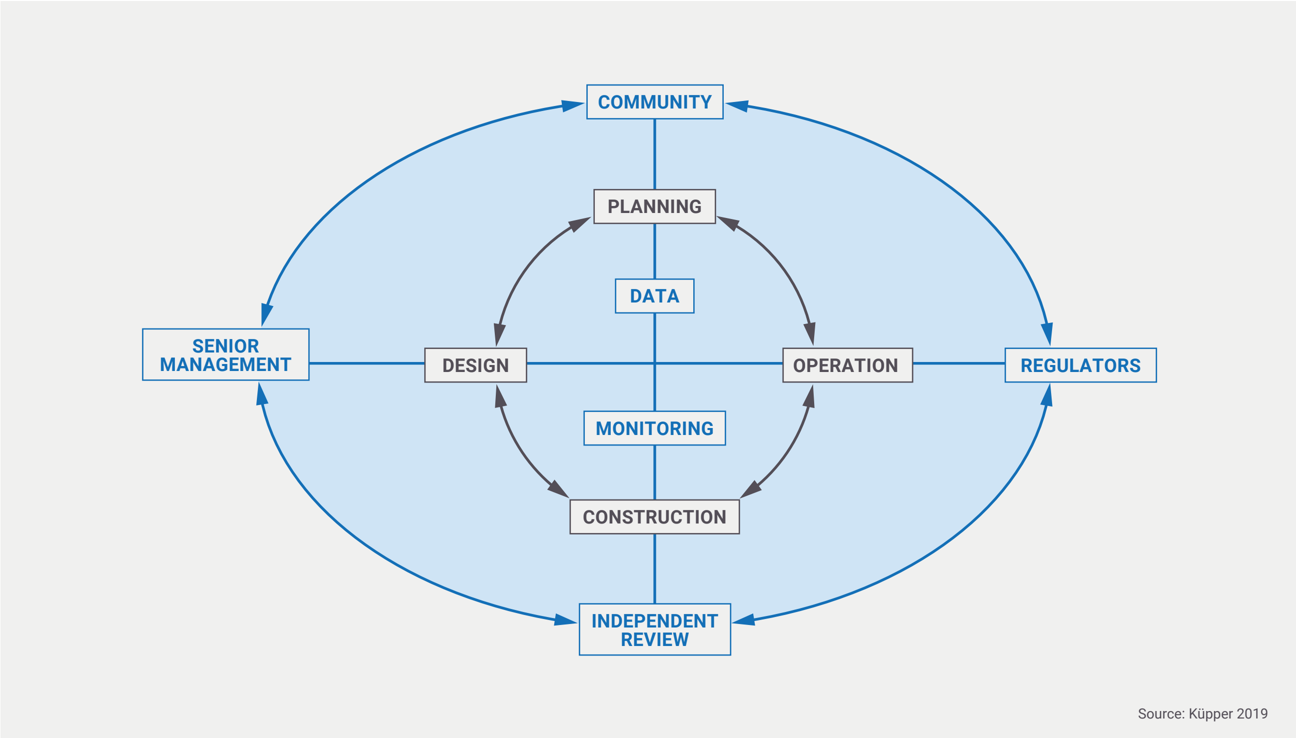

Figure 3. Simplified diagram of the 'inner circle' and 'outer circle' of the tailings facility system

The oversight provided by the outer circle includes the governance of the mining company, local and general, as well as through its board of directors. The governance system includes risk management and technical and operational reviews provided by independent reviewers and auditors. The other important elements are the regulatory system and the community, which provide oversight of the tailings facility. The main sub-systems that form the outer circle are described below.

Senior Management
Senior managers are responsible for development and continuous improvement of tailings stewardship and governance throughout the company's operations, including the implementation of audits, conformance reviews and independent technical reviews. Senior managers can support building a quality and safety culture. They interact with other senior managers, communicate with the executive and board on tailings matters, and are typically actively involved in national and international tailings activities. It is essential that senior management be receptive to input from the team at all levels when concerns are raised. Past examples of retribution to individuals approaching senior management and/or fear of such reprisals have left senior management uninformed and ill-equipped for decision making. A healthy organisation is one where the senior management understand that their role in governance is to facilitate and encourage a flow of information in all directions that will meet the needs of the safety culture required for the tailings facility management.

Independent Review
Independent technical review of the design, construction, operation and closure of tailings facilities is an important element of risk management. The independent review also helps identifying opportunities for improvement. The expertise of the reviewers relates to the specific technical aspects of the tailings facility site, material and design characteristics. The quality of reviews is directly affected by the information presented to the reviewers, the core competency of the reviewers relative to the nature of the facility being reviewed, and by the nature of the communications.

Regulators
This term encompasses all relevant public sector agencies. At the highest level, regulators are responsible for legislation, regulations and guidelines that ideally support the entire system without stifling creativity and technical development by being too prescriptive. Regulators have a unique position of independent oversight of the construction, operation, maintenance, and closure of tailings facilities. Discharging this role effectively, requires a comprehensive understanding of the planning and engineering necessary to build, operate, maintain, and ultimately close tailings facilities. Ideally, regulators should also be in a position to set up a professional inspection and enforcement programme capable of identifying problems and making sure those problems are corrected promptly before they increase the risk of catastrophic failures.

Community involvement
Communities also have an important role to play in participating as stakeholders who bring diversity of input and accountability to the system. The community brings a diversity of perspectives, providing a broader context of the local environment and areas of most concern to them. These contributions should be incorporated into the system. See Box 3 for a community-society perspective.

Box 3: A community-society role

Communities are also proxies for society in general and therefore can play an important role in tailings management. Mining has historically been driven towards a 'Net Present Valuation' for commodity development which is a logical approach for the orebody evaluation. However, for the perpetual legacy of tailings facilities this is a false premise as there is no discounting of future risks by present risk transference or vice versa. Consequently, tailings management requires a much broader view, which takes account of how the true cost of a commodity includes the cost of tailings management. Society, as driven by its communities, sets values for raw materials through consumptive patterns and if those patterns were to insist on more life-cycle investment in mine tailings as part of the cost of a mined commodity, one of the significant barriers existing in many parts of the world to improved tailings management could be overcome.

Source: Michael P. Davies, personal communication

The outer circle, again similarly to the inner circle, needs competent people in all functions (see Evans and Davies, this volume) who understand the importance of their work for the overall system and who can work collaboratively with others in the system. Their work also needs to be based on high quality, accessible, data, and information sharing.

6.3 THE COMPLETE TAILINGS FACILITY LOCAL SYSTEM

For the tailings facility system to work well and for risks to be adequately managed, not only it is necessary to have competent and experienced personnel leading all the functions represented by the 'boxes' in the diagram in Figure 3 but the interaction between the boxes needs to be cooperative and effective.

Integration and communication across the overall tailings system are fundamental. Risk assessments support the overall work of the tailings system by helping communicate and provide clarity on the requirements and the uncertainties, and by allowing risk mitigation across all elements of the system. Risk assessments form part of the basis for risk-informed decision making for follow-up action to manage risk. In addition to be an element of the risk management framework, risk assessments are a powerful tool to help individuals in all functions of the tailings system recognise the risk elements, the inter-dependencies, and the potential impact of their decisions on the tailings facility, while supporting vertical and horizontal integration across the system.

Leadership throughout the entire tailings system is required to create, implement and maintain a culture of quality, safety and transparency. Continuity of personnel is another key element of tailings storage facilities stewardship. It is invaluable to have institutional memory and people in the system who are well calibrated to site conditions, local materials and practices, and who will mentor others as part of a well laid out succession plan. The cult of personality, where decisions are owned by the loudest voices or the most senior opinion, is to be avoided and challenged by the healthy organisation – one that sees all individuals and all information as part of the overall management of a safe facility.

The safety of tailings facilities can only be improved by each person in the system, no matter which role they play. This entails being technically competent, understanding what needs to be achieved and why, having a view of the causes and consequences, and producing detailed and accurate data to support each other's work, within a culture where effective, collaborative relationships promote quality work.

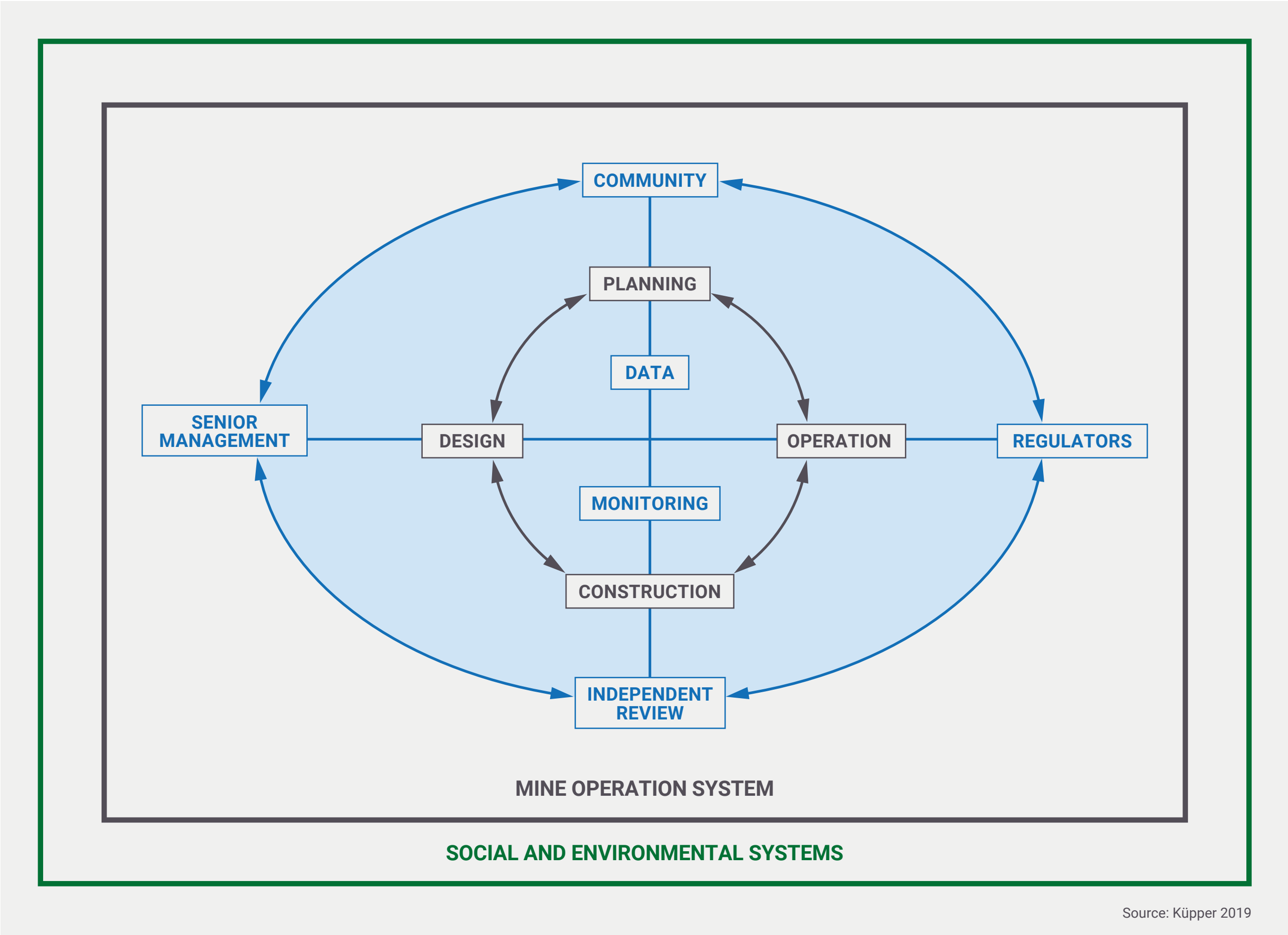

Figure 4. Simplified diagram of the elements of the tailings storage facility system

Note: Each rectangular box in this diagram represents a system in itself.

6.4 THE MINING OPERATIONS SYSTEM

The tailings facility system is an integral part of the mine operations system (Figure 4). It is affected by the mine and the processing plant (as discussed above) while at the same time enabling the functioning of these operations. It is also a critical component of the overall mine infrastructure, personnel and governance system.

6.5 THE SOCIAL AND ENVIRONMENTAL SYSTEM

As Figure 4 also shows, the tailings facility and the mine operations system are in turn embedded into larger social and environmental systems. This overall system is complex, intricate, and governance happens at many levels with several groups of people involved.

The selection of the tailings facility site is an activity where the interaction with the broader social and environmental system is particularly critical. The site selection process must consider and optimise a variety of aspects related to: the physical and social environment within which the facility is located; parameters from the ore body; the processing plant; the conveyance system; the design, construction and operation of the facility; and its closure and final land use. Some of these items have competing requirements and the optimisation process is not simple. Techniques, such as risk assessments, multiple account analyses and others, can be used to support the process. However, most importantly, it is necessary that specialists from all these areas work in collaboration, sharing the same goals, to achieve a solution that appropriately considers all the relevant elements.

Ideally, the selected site:

- minimises impact to people, their culture and livelihood

- minimises impact to the environment, including fauna, flora, hydrological resources, air and water quality
- has adequate foundation conditions for a stable structure, along with sufficient storage capacity for tailings
- is located at a relatively short distance from the processing plant, and
- is feasible for closure in a manner consistent with future land use by the local communities.

The interaction with the social and environmental system during construction, operations and closure of a tailings facility includes many important aspects, such as: environmental monitoring and management (with modification of plans and designs, and implementation of remedial measures as required); open lines of communication with communities; assessment and management of social impacts; management and communication of risks; and regulatory compliance and regulatory oversight.

7. RECOGNISING AND MANAGING TAILINGS FACILITIES AS A SYSTEM

The tailings facility system is complex and typically involves many people in different groups with different objectives and different responsibilities. The importance of treating it as a system comes from the need to align the objectives and responsibilities from all areas of the system, such that sound stewardship is achieved.

Several organisations within the mining industry have recognised that tailings must be managed as a system. The Mining Association of Canada (MAC) has been one of the pioneers in the governance of tailings facilities as a system. Its publications in this area (MAC 2019 and 2018, for example) have been helpful in promoting awareness and the implementation of a systemic approach to governance of tailings facilities. The Global Tailings Review further reinforces and broadens this perspective.

Some mining companies have also recognised the need for a systemic approach for the technical and operational aspects of tailings facilities and have established tailings stewardship programmes aimed at a more effective risk management of their facilities.

An example of an area where the mining industry has used the systemic approach with significant success is the management of occupational health and safety. By approaching occupational risk management as a system, the industry has involved engineering, process technology, information technology, ergonomics, sociology and psychology to build a positive cultural change in the workplace supported by tools that lead to a decrease in occupational accidents. Key features of the systemic approach are demonstrated in the modern management of occupational health and safety that are familiar in the mining industry (see Box 4).

Box 4: Systemic approach features in the modern management of occupational health and safety

- Vertical integration – there is support to safety from all levels within the organisation.
- Horizontal integration – all groups within the organisation participate in safety programmes and safety training.
- Knowledge from individuals in all levels within the organisation is respected and integrated into improved procedures, policies, etc. 'Safety shares' are common and frequent.
- Information is gathered, valued, and compiled to improve the organisation through continued education, awareness, and knowledge sharing; this includes access to knowledgeable specialists inside and outside the organisation and use of a wide variety of monitoring technologies.
- There is a clear understanding of the role of everyone at all levels within the organisation in improving safety by taking personal responsibility for individual actions as well as the actions of others, and by implementing correct procedures, use of adequate equipment, developing positive attitudes, and seeking continuous improvement.
- Governance support is provided, including through the continuous updating of regulations.

Most mining companies have developed a solid safety culture; thus, the systemic approach and its implementation would be familiar. The same type of processes, level of effort and emphasis can be applied successfully to tailings facilities risk management.

8. THE PATH FORWARD

A path forward to the improvement of the safety of tailings facilities would involve a deeper understanding and a broader implementation of a systemic approach, along with an improvement of the technical knowledge related to tailings facilities across the entire system.

There is a varied level of awareness within the mining industry in regard to a tailings facility being a system and the requirement to be managed as such. Moreover, there have been varied levels of success in managing tailings facilities using a systemic approach. However, anywhere within this spectrum, improvements could be made for continuing improvement to the management of these facilities.

A systemic approach to tailings facilities should include understanding the system for a specific site and managing this system by considering the intricacies of complex systems. The approach should involve identifying all elements that directly or indirectly affect the system and addressing all these elements and their interaction in a governance system (structure and operation) that promotes collaboration towards the common goal of tailings facility safety. Management of tailings facilities benefits from applying a multi-disciplinary perspective. It can also benefit from recognising that complex systems are dynamic, so adaptability needs to be promoted along with a robust approach to handling of uncertainty.

The specifics of implementing a systemic approach will vary in each case, however some common elements include:

- Vertical integration from the worker level to the board of directors, where there is support for and understanding of the measures, activities and attitudes required for safe tailings management.
- Horizontal integration, with all groups within the operation supporting tailings facility safety as one of their key objectives.
- Knowledge integration from all levels within the operation – from workers to the C-suite. Knowledge is gathered, respected and integrated into improved plans, designs, operational procedures and policies.
- Information gathered and compiled to improve the organisation and support continued education, awareness, knowledge sharing, including access to knowledgeable specialists, inside and outside the organisation.
- Development and implementation of a robust data management system where all data relative to geology, hydrology, materials, volumes, schedule, designs, specifications, surveys, photographs, as-builts, reports, instrumentation, monitoring data, etc., are easily accessible and available in an efficient, timely and practical manner to the entire organisation. Data accuracy and data integrity are a must.
- Consistent use and application of risk assessments and risk management principles with program priorities being informed by these assessments.
- Clear understanding of the role of everyone at all levels within the organisation in improving safety of the tailings facility by adopting correct procedures, adequate equipment, positive attitudes, and continuous improvement approaches.
- Transparency in internal and external communications and a supportive culture such that problems can be aired and addressed in a constructive manner.
- Establishment of tailings as a career path in the organisation and within the mining industry with well-defined objectives, technical knowledge and experience expectations, and with growth opportunities.
- Clear succession plans, with candidates identified, for all key roles in the organisation related to tailings management.
- A strong governance framework that supports and reinforces all the above.

With the concepts mentioned above in mind, a management framework can be developed such that tailings management is supported by effective communication, underpinned by an accessible and robust data management, flow of information and adequate levels of knowledge and experience. A management structure that includes embedded monetary and non-monetary incentives to support the alignment of the objectives and promotes vertical and horizontal integration is more likely to minimise the risk of catastrophic failures of tailings facilities, improve efficiency and reduce unnecessary costs. Leadership and personality traits from individuals at all levels within complex socio-technical systems can also affect the outcome. These factors need to be managed to promote the best culture and the best outcome for the work system.

9. CONCLUSION

It has become increasingly clear that tailings facilities are important elements of mining, an essential industry, and that the safety of tailings facilities must be managed within a larger framework in order to improve overall risk management and to renew confidence in tailings facility management. Tailings facilities are a highly integrated dynamic system with a high degree of complexity. Therefore, risk must be managed using a system-oriented approach in a cross-disciplinary manner, since safety is impacted by decisions, behaviours and actions of actors across all levels of the system. This chapter has provided an overview of the elements needed to incorporate a systemic approach to effective tailings management.

KEY MESSAGES

1. Tailings facilities are complex entities that operate as a system within the broader context of mining operations, their external societal and environmental settings, and their potential to last in perpetuity.

2. Tailings facilities are complex systems that need to be managed with a systemic approach for effective risk management

3. Although there are always immediate technical reasons for tailings facilities failures, the overarching technical and governance factors that allowed the facilities to approach a critical state are, in most cases, the root cause of the failure.

4. The systematic management approach for tailings facilities involves vertical and horizontal integration of all functions (planning, design, construction, operation, management, oversight) that operate and collaborate within a broader framework.

5. The resulting management framework must be supported by effective communication, transparent and robust data management, and information flows that builds knowledge and experience. Success also requires leadership, appropriate incentives and a culture of performance.

6. Ultimately, the framework and resulting systems management has to be based on leadership that drives a culture of system-level performance.

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