srk news
Tailings Management

Partnering with BHP for long-term risk reduction

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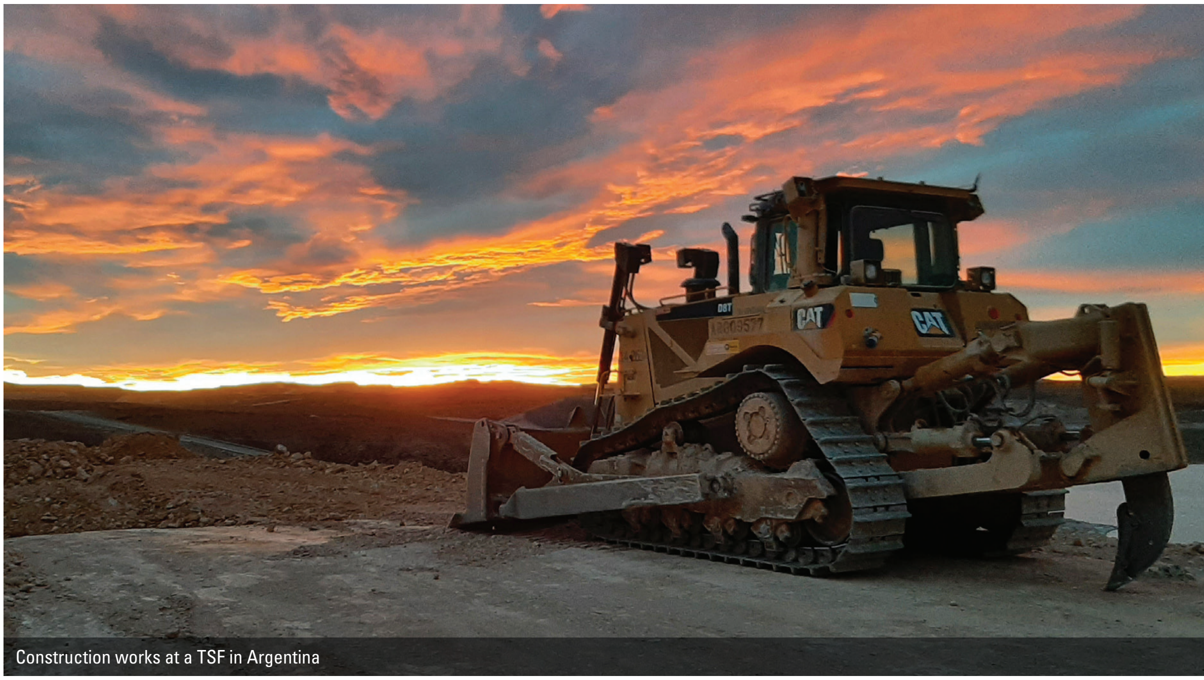

Construction works at a TSF in Argentina

Tailings storage facilities (TSFs) represent one of the most critical liabilities associated with the mining industry. With the spotlight focused on ESG, investors and communities perceive the risk posed by TSFs as less tolerable than ever before. There has been a shift in how these facilities are managed, with a focus on sustainability and proactive tailings management strategies.

The response from the industry, and community in general, was a deep concern that mining houses did not have a good grasp of the risks related to TSFs, and a general sentiment that closer scrutiny of the quality of the design, operations and closure of TSFs was required. This is how the Global Industry Standard on Tailings Management (GISTM) was presented to the community – as a vehicle to restore confidence that our mining industry can operate in a more sustainable manner.

The process of implementing the GISTM at the Olympic Dam operations has been very positive in improving transparency and ensuring there is accountability for systems and structures. A few years before the launch of the GISTM, BHP appointed SRK as the Engineer of Record (EOR) for its Olympic Dam (BHPOD) operations. Pepe Moreno assumed the EOR role, with Joe Rola as a deputy EOR. Since then, SRK has provided support to BHPOD on a wide range of services, working in partnership with BHPOD's responsible dam engineer and dam team.

…continued

Partnering with BHP for long-term risk reduction *(continued)*

Olympic Dam has six upstream tailings dams and six evaporation ponds, with some of these being dormant. Since appointment to the EOR role in 2017, SRK has introduced many initiatives and designs to reduce the risk profile of all facilities.

BHPOD and SRK have invested significant resources to evaluate the fundamental behaviour of the Olympic Dam tailings, including advanced in situ and laboratory testwork employing critical state soil mechanics theory.

The staged approach used in this investigation has assisted BHPOD to gain more confidence in the evaluation of TSF stability in the short and long term, and now also in worst-case liquefaction conditions. The investigation findings have been used to design appropriate mitigation measures and targeted monitoring programs.

In 2019, ANCOLD published an addendum to its original Guidelines on Tailings Dams (ANCOLD, 2012), which recommended additional governance requirements and introduced a more defined set of loading conditions related to undrained shearing such as static liquefaction – when materials can develop contractive brittle behaviour during shearing. This was reinforced in 2020 with the GISTM requiring brittle failure modes to be assessed and addressed. The substantial body of work completed by SRK has enabled BHPOD to address these elements of the standards, and allowed SRK to complete a quantitative risk assessment within reasonable accuracy.

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PEPE MORENO

Pepe is a civil engineer with over 30 years' experience working in geo-environmental engineering for the mining industry. He is a world leader in management and design of mine waste facilities, with particular expertise in the design of tailings disposal systems using a range of dewatering strategies. Pepe is currently engineer of record for four leading mining operations in Australia, member of several Independent Technical Review Boards and expert tailings reviewer for due diligence and valuation for banks and potential investors.

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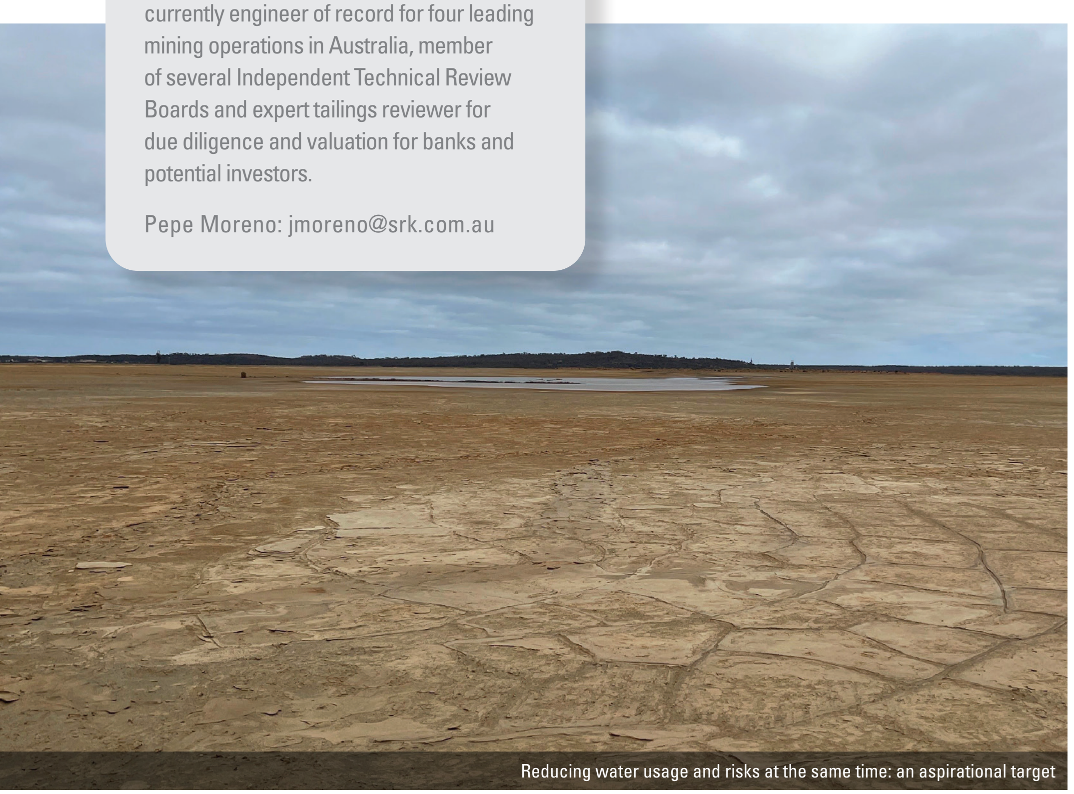
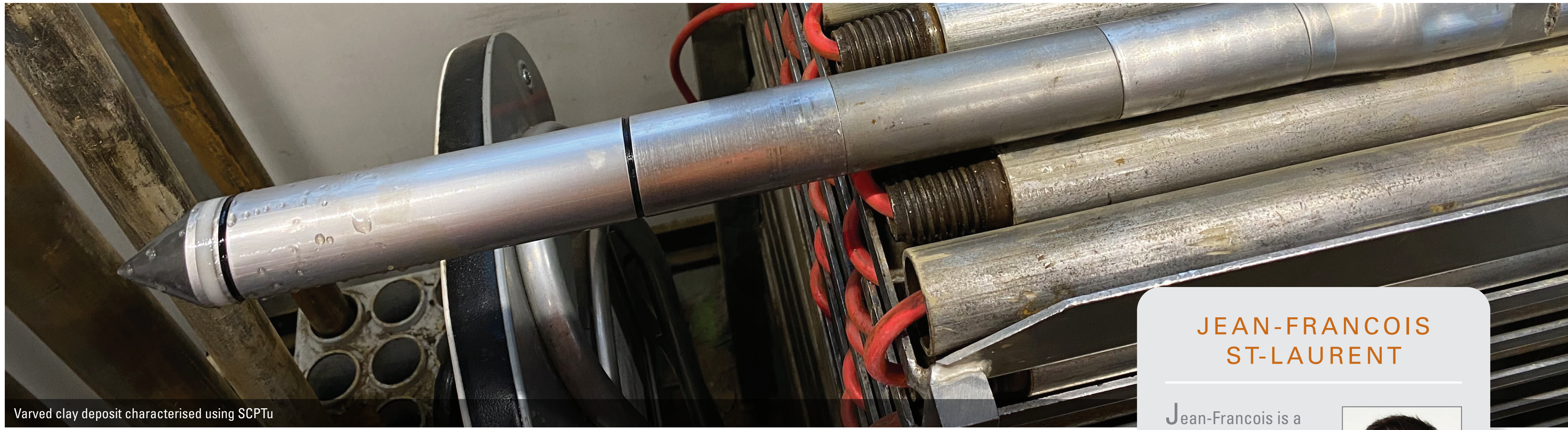


Reducing water usage and risks at the same time: an aspirational target

Tailings embankments on soft sensitive glacio-lacustrine clay



Varved clay deposit characterised using SCPTu

Following recent failures of tailings dams, dramatic change in the global mining industry has been initiated. Numerous technical publications or guidelines for safer management of TSFs have been released. A key objective of these publications is to ensure mining companies raise the performance bar for designing, constructing, operating, maintaining, monitoring, and closing tailings facilities to minimise the risk of failure.

In addition to implementing comprehensive monitoring systems, developing and maintaining an interdisciplinary knowledge base and implementing a performance-based approach during the design, construction, and operation phases of TSFs are strongly recommended. Using a deterministic approach, with fixed and defined load and resistance input parameters to provide a factor of safety (FOS) does not constitute a performance-based approach.

One can argue that performing a probabilistic analysis is not an easy task and to estimate the probability of failure of a system requires distributions describing both the load and the resistance. It is recognised that the distribution describing the resistance of geotechnical material is either unknown or could be largely scattered. As more test results become available, the accuracy of the resistance distribution increases. On the other hand, the distribution describing the load could be defined early in the project and should not vary much as the project advances. In addition, the performance criteria or performance objectives applicable to facilities/embankments are known and established at an early stage in the engineering process. Similar to load distribution, these performance objectives are not expected to fluctuate substantially during the engineering process.

The methodology typically used in the industry to assess the safety of an embankment is to confirm the FOS under various loading conditions meets the pre-defined FOS criteria. During the early stage of the engineering, it is typically accepted that having a pseudo-static FOS below target is not acceptable and mitigation measures are required. While a pseudo-static FOS below target does not necessarily mean that the embankment will fail, it suggests that permanent deformation should be expected. Therefore, quantifying the load as a function of the targeted performance criteria (also called the acceptable permanent deformation level) that is specific to the project could demonstrate the safety of the embankment.

SRK used a performance-based design approach to assess the pseudo-static safety of an embankment built on Eastern Canadian soft and sensitive Barlow-Ojibway clays. The assessment allowed an acceptable permanent deformation level for the embankment and associated loads to be established, which better determine the safety of the embankment.

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JEAN-FRANCOIS ST-LAURENT

Jean-Francois is a senior geotechnical engineer with 16 years of experience in soils geotechnics, mine waste management and site reclamation. He is currently the engineer of record for two closed sites in Québec and identified as potential EOR for two additional mining operations. His experience includes modelling embankment behaviour under various loading conditions, performing risk assessments, statutory inspections and safety reviews of tailings storage facilities. He's been involved in the preparation of detailed engineering designs with drawings and technical specifications for numerous embankment and tailings storage facilities.

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Optimizing operations of a tailings storage facility using statistical analysis of historical monitoring records

Tailings storage facility in Argentina

Operational control and trigger action response plans for TSFs routinely measure several operational aspects to assess risk and ensure the TSF complies with design considerations.

Cerro Vanguardia is an AngloGold Ashanti-owned gold-silver mine in Santa Cruz, Argentina. The mine has a single TSF that has been in operation for over 20 years.

During the development and design of the seventh wall raise, the possibility to increase the usable storage capacity within the basin and defer the wall raise was identified. Ignacio Ezama and Santiago Pastine from SRK Argentina and in-house stakeholders concluded that sequential extension of the spigoting system into the TSF basin was the preferred option to take advantage of this storage capacity.

Key aspects affecting the potentially available capacity within the TSF, such as the beach angle, tailings density and water storage, were identified. A statistical analysis of each parameter was undertaken.

A probabilistic reassessment of the depth of rainfall events based on the rainfall dataset over the operating period was undertaken and intensity-frequency curves were obtained. This clarified uncertainties in water storage capacity needs and the associated risks.

A statistical analysis of the beach slope angle provided a better characterisation of the beach shape and its potential variance. The team estimated trendlines for the average beach slope angle and its standard deviations, and developed three theoretical beach profiles for use in the storage capacity assessment.

A statistical analysis of the tailings density was carried out based on available geotechnical samples. Long-term and short-term historical density scenarios were identified. The short-term density range was considered the most realistic for the analysis, while long-term data were considered for sensitivity.

For the capacity assessment, scenarios considering five successive spigot extensions into the tailings facility with varying lengths were developed. Volumetric storage capacity, time availability and the probability for reaching a given date with the available storage capacity were estimated.

Periodic monitoring was implemented to assess the ongoing operation. Potential for changes in the expected end of capacity were tracked and opportunities for adjusting operational conditions and enhancing capacity usage were reviewed. In general, beach profiles resided between the average and best cases, allowing for an enhancement in capacity usage.

The statistical analysis contributed to an operational strategy to defer construction of the seventh wall raise for approximately two years without interrupting tailings deposition. During construction, operating procedures allowed risk to be assessed and ensured the TSF was in compliance with design considerations. The seventh wall raise of the TSF was finalised in February 2022.

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SANTIAGO JULIO PASTINE

Santiago is a senior consultant in SRK's Salta office. He has over five years of experience in geotechnical design and analysis of tailings and mine waste facilities and open pit and underground operations. This experience has given him a broad perspective of the mining process and a strong knowledge base to identify the key aspects and main needs of the project.

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IGNACIO EZAMA

Ignacio is a civil engineer with a solid knowledge of geomechanics and extensive experience in the development of geotechnical solutions in site-based and desktop applications. Ignacio has been involved in the development of numerous major geotechnical structures from scoping through to detailed design and construction, with practical experience in site selection, field investigation and geotechnical characterisation, design of embankments and other geotechnical structures, and assessment of risks related to hydraulics and seismicity.

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Integrating social and engineering aspects of tailings management

A key area identified as needing improvement for compliance with the 2020 Global Industry Standard on Tailings Management (GISTM) is meaningful engagement of project-affected people for all phases of a TSF life cycle. Stakeholder engagement cannot be meaningful and effective unless the process is suitably structured and resourced by adequately trained personnel.

In-depth engagement with project-affected people is typically limited to the regulatory authorisation processes at the start of a project or before changes to existing projects are implemented. Engagement over the life of mine will not necessarily involve the TSF communities unless project-affected people have raised concerns, or an adverse event triggered the need to engage.

Integration of the mine's environmental and social management system(s) with the tailings management system should support structuring for meaningful engagement. Resourcing should be facilitated by tailings engineers suitably trained to engage directly with stakeholders and project-affected people on the technical aspects of the TSF. The training of tailing engineers is crucial in conveying the dam breach analysis to most at-risk groups. Respecting cultural norms and understanding stakeholder expectations are essential for successful and positive relations between the operation and its stakeholders.

Too often, communities feel that consultation only takes place when a regulatory body requires it. When stakeholder engagement is approached in this way, the community views it as a tick-box exercise. Meaningful stakeholder engagements can be facilitated by direct involvement of project-affected communities. Consideration of project-affected people in the operation's monitoring programs is recommended, where suitable.

SRK has a multidisciplinary team assisting numerous clients on the journey towards GISTM compliance.

Key focus areas are capacitation, training and appropriate messaging for meaningful stakeholder engagement that provides assurance rather than concern or panic.

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JACKY BURKE

Jacky is a registered principal scientist with SRK's Johannesburg office. Her 33 years of experience in water and environmental management includes water use authorisation applications and audits, integrated water and waste management for various sectors, surface water quality assessment, pollution source identification and control, training and capacity building. Jacky's most recent experience is in managing a GISTM project focused on meaningful stakeholder engagement and disclosure.

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VIDETTE BESTER

Vidette is a senior social scientist with a background in sociology, development studies and psychology. She completed her PhD in Sociology in 2019 at the University of Johannesburg. Vidette has been working as a social scientist and social researcher since 2011. Projects completed in this capacity include social impact assessments, steering and conducting socio-economic baseline studies and guiding clients on developmental projects for communities. Vidette also advises mining companies on their social and labour plans.

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Considering climate change in tailings dam design

Environmental considerations have always been an integral aspect of how TSFs are designed and operated. However, the growing impact of climate change demands innovative thinking to understand and address the additional risks imposed on these structures.

CHLOE BOLTON

Chloe is a civil and environmental engineer who has been working at SRK since 2019. She has rich and varied experience in all aspects of the design, surveillance and construction of tailings dams. Her current area of focus is the engineering inputs required to bring these facilities in alignment with the GISTM, including dam breach analysis and closure planning and design.

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GRANT MACFARLANE

Grant is a partner and principal Engineering Geologist in SRK's Engeo business unit in Johannesburg. Since starting his career at SRK in April 2017, Grant has gained experience on several platinum and diamond TSFs in South Africa, Zimbabwe and Botswana. The focus of his attention is the project management and project leadership roles related to all aspects of tailings storage facilities, including detailed geotechnical investigations and specialist studies, Engineer of Record and GISTM related roles and activities and conformance assessments, and TSF design and construction.

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Multiday rainfall events, with high intensity over a short duration are becoming more frequent and are not accounted for in the traditional TSF design criteria. Repeated spills at dams servicing TSFs have occurred at several mining operations in the southern African region during the rainy season. Even though there was no single rainfall event greater than the 1:2-year return interval 24-hour event, two to three of these rainfall events were occurring every few days, with low but continuous rainfall in between.

Some mines have implemented daily inspections of TSFs to detect early warning signs like sloughing or potential instability. Such inspections also detect damage of revegetated areas or signs of seepage and ponding of surface water. Although many of the early warning systems, monitoring, and response plans in place today pre-date the GISTM, many of the elements being monitored have climate-related triggers.

Higher rainfall events have also been addressed with redundancy, such as allowing for double the required decanting capacity of the penstock towers and outfall pipelines. Pools can therefore still be responsibly decanted in the event of heavy rainfall. The application of probabilistic analysis presents an opportunity to incorporate climate change models into various dam breach scenarios.

Water management has always been central to the responsible design and operation of TSFs. Rainfall variability is leading mine operations to consider reducing and optimising water consumption in plants and tailings production. Climate change has become an important variable, and new approaches must be implemented to account for these unprecedented changes. Climate change-related interventions enhance the adaptive capacity of mines and improve the overall resilience of TSFs.

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Influence of acidity on closure costs of mine tailings dams

Closure engineering San Sebastián project, Peru.

OSVALDO ADUVIRE

Osvaldo is a consultant with over 30 years of experience in mining operations design, technical-economic evaluation of mining projects, environmental impact assessments, evaluation of occupational and environmental risks, geomechanical characterisation of rock masses, characterisation of the acid/base generation potential of mine waste, design and reclamation of waste dumps and landfills, geochemical characterisation of mine effluents and pit lakes, passive treatment of acidic waters, and mine closure plans.

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LIZARDO CAHUANA

Lizardo specialises in environmental and soil sciences. He has over seven years of experience in the restoration of contaminated mine sites and soil and vegetational covers. He develops mine closure plans, undertakes environmental and soils studies and prepares technical reports, including schedules and budgets.

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Minerals processed with a concentration technique generate tailings that must be stored in facilities designed according to specific technical, economic, legal, environmental and social requirements. During the operational life of tailings dams, the impact on the environment and on the surrounding communities is monitored through programs included in the mandatory environmental certifications. Once the mining operation is completed, the closure stage during which the tailings storage facility is rehabilitated, is launched.

When closing a tailings dam, consideration is given to factors such as the location, physical and chemical properties of the tailings, method of construction of the reservoir, and the behaviour of the tailings in the long term. For this, it is important to predict the reaction of the tailings when in contact with oxygen and water, as well as its capacity to generate acidity and leach metals.

The closure plan of the tailings dam must ensure physical, chemical, hydrological and biological stability in the post-closure period. One of the most significant challenges in achieving stability of mining waste with potential for acidity generation is contact with oxygen and water; therefore, to achieve chemical stability, the use of impermeable or semi-permeable barriers may be necessary. Each alternative comprises a series of closure activities which generate different direct and indirect costs.

In mining operations that use ore concentration, the cost of the tailings facility closure typically represents 21% of the total closure budget. The proposed solution to assure the chemical stability in the closure of the TSF is to add impermeable covers. These consist of a clay or geosynthetic clay liner placed over the tailings, on top of which a layer of drainage material is placed to direct water to an organic soil cover that sustains vegetation.

The main closure considerations within the budget to rehabilitate the tailing dams are physical, chemical and hydrological stability as well as revegetation. In the case of TSFs with the potential to generate acidity, the chemical stability typically accounts for 75% of the direct cost of dam closure.

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Applying the GISTM to legacy facilities

EMILY HARRIS

Emily is a chartered environmental professional with over 15 years' international experience in the mining industry. She specialises in environmental, social and governance (ESG) risk management aligned with regulatory requirements, global industry standards, including the GISTM, and expectations of project financiers and other stakeholders. Emily frequently collaborates with engineering colleagues to embed ESG concepts into project engineering studies, due diligence reviews and mine closure planning projects.

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ALICE EVANS

Alice is a senior consultant, Practitioner Member of IEMA, a qualified project manager (PMQ) and has over 10 years' experience in the mining industry. She specialises in risk management and has successfully managed numerous environmental and social impact assessments for large-scale mining projects. Alice has recently completed a two-year secondment to the ICMM as the responsible mine closure and tailings manager, contributing to the publication of both the Closure Maturity Framework and Conformance Protocols for the GISTM.

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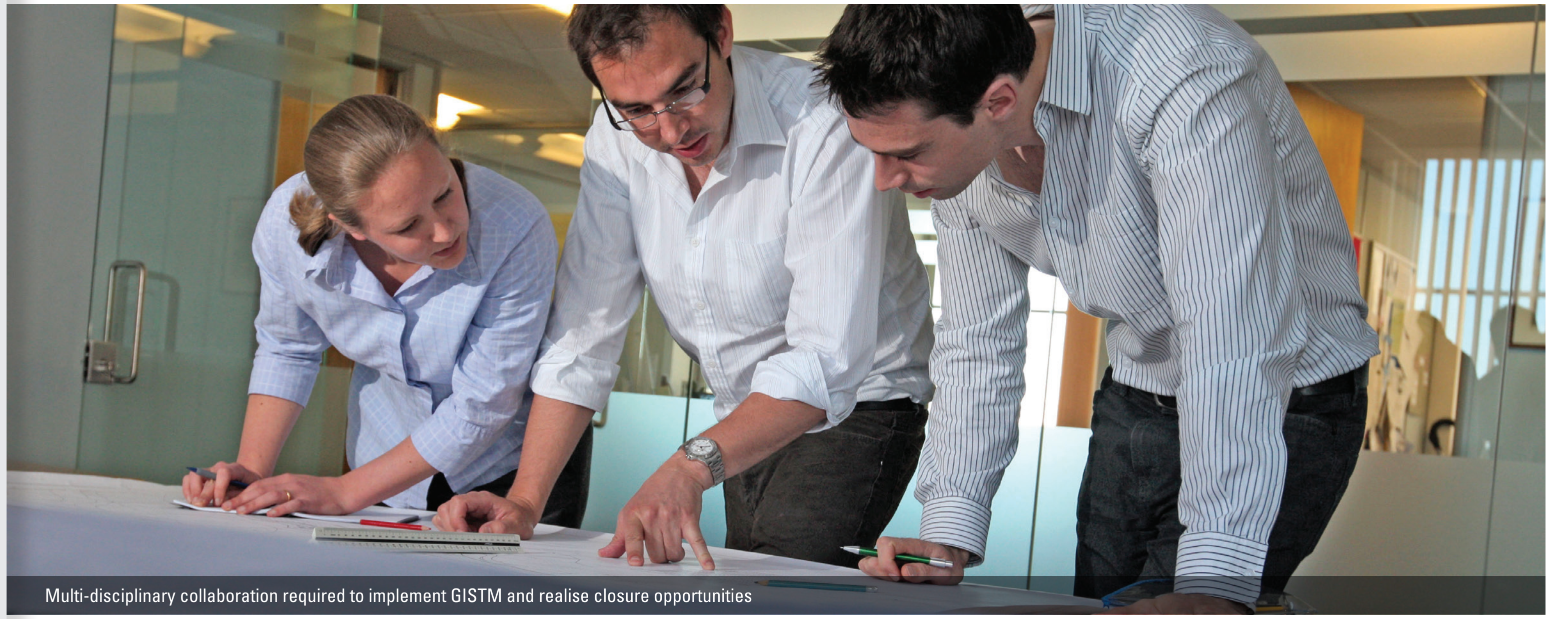

Multi-disciplinary collaboration required to implement GISTM and realise closure opportunities

Since its launch in 2020, the GISTM has been widely adopted, with investors actively voting against company chairs who have not confirmed their intention to meet the GISTM and many mining companies setting ambitious deadlines for compliance with the rigorous criteria. The target for operators that are electing to be GISTM compliant is to achieve it within five years (by mid-2025).

While the immediate focus has rightly been on the highest risk and predominantly operational TSFs, requirements will be equally applied to inactive, remediated or closed TSFs. These latter groups can often represent a substantial part of a mining company's TSF inventory. For example, as of 2021, BHP's portfolio of 73 TSFs included 59 inactive or closed facilities, Newmont's portfolio of 90 TSFs included 69 inactive or reclaimed/closed facilities and Barrick's portfolio of 70 TSFs included 50 inactive or closed facilities. This means over 70% of the TSFs within large mining company portfolios are non-operational.

Similar to operating TSFs, the risks posed by inactive and closed TSFs are site-specific, based on the environmental and social setting, original design of the TSF, nature of material stored, operating history, status of documentation, rehabilitation and closure activities completed. For those inactive and closed TSFs, the application of GISTM requirements will focus on moving the TSF towards a state of 'safe closure' at which point GISTM requirements no longer apply. TSFs in 'safe closure' do not pose ongoing material risks to people or the environment, as confirmed by an ITRB or senior independent technical reviewer and signed off by the Accountable Executive.

The transition through closure to 'safe closure' as defined by the GISTM is focused on achieving zero harm to people and the environment. However, closure doesn't just need to be thought about in the language of risk. Closure can also present opportunities for legacy TSFs to become valuable assets for mining companies. This could include repurposing the closed mine to fulfil a new land use, like conversion into renewable energy sites. It could also involve avoiding the implementation of closure activities altogether by reprocessing the tailings material to extract economic minerals or to provide an alternative supply of sand for the global construction industry. In the same way adherence to GISTM requirements requires a multi-disciplinary team, identifying and realising these opportunities will require tailings engineers, social performance practitioners, mine planners, environmental scientists and closure specialists to share a common vision and collaborate effectively.

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A review of the hydro-mechanical behaviour of tailings

Seepage through TSFs is commonly assumed to occur under gravity flow and is usually determined only under steady-state conditions. However, seepage is also highly influenced by the degree of saturation of the materials involved in these structures and can influence the stability of TSFs. TSFs in areas of alternating dry and wet seasons present additional challenges for the evaluation of soil-asmospheric interations.

The objective of this research was a comprehensive review of the parameters that influence the phreatic surface within the TSF under steady-state conditions and to assess how this behaviour changes under transient conditions. The soil-water characteristic curve (SWCC) and shrinkage curve were analysed to determine their responses to transient conditions.

For the numerical modelling stage, a generic upstream TSF was analysed with a finite element model to determine the location of the phreatic surface under steady-state conditions. Then, a transient seepage analysis was employed to assess the most influential parameters on the TSF stability considering an extremely rainy season. In the model, the effect of the hydraulic boundary conditions of the drain, the beach length, the hydraulic anisotropy of tailings, the segregation of the beach and the influence of the hysteresis of the SWCC were considered as part of assessing the stability of the upstream dam.

The results suggest that the most influential parameter on dam stability is the pond's position on the impoundment, indicating a relationship between the height of the TSF and the beach length. The efficiency and sound design of the drainage system are also essential to prevent the phreatic surface from rising to the top of the dam and are key to increasing the factor of safety. On the other hand, tailings anisotropy, beach segregation and the SWCC hysteresis only have a secondary role, and their impact on the factor of safety is minimal.

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CAMILO MORALES

Camilo is a geotechnical engineer in SRK's Chile office. He has over six years of consulting, research, and teaching experience, focusing on site characterisation for engineering design and numerical analyses. Camilo holds two MSc degrees, in geotechnical earthquake engineering and in soil mechanics and engineering seismology. His experience includes static and dynamic finite element analyses for tailings dams, heap leach pads, piers, deep excavations, and buried structures.

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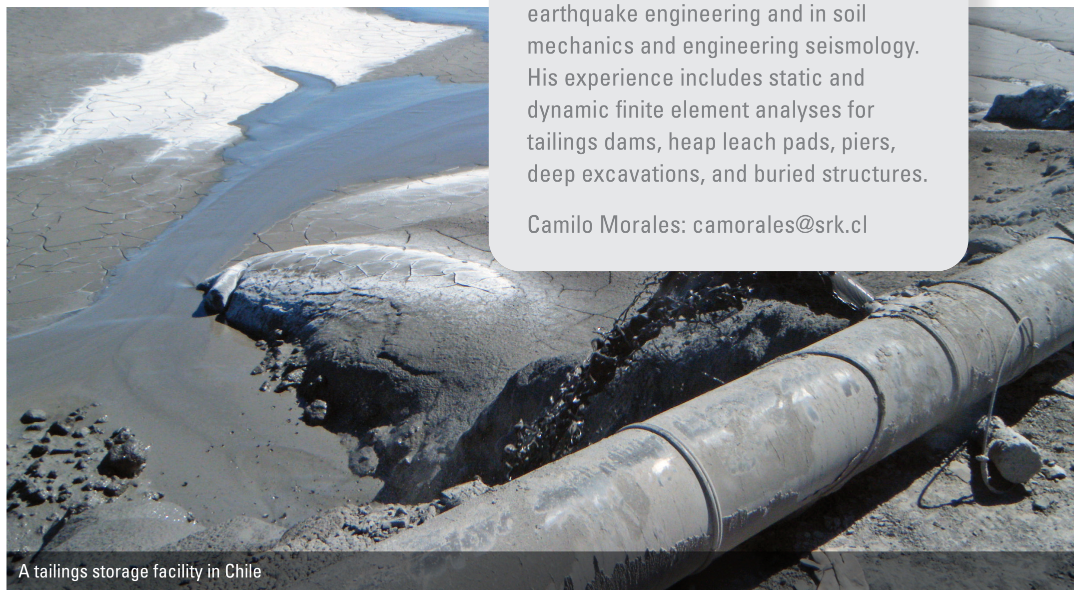

A tailings storage facility in Chile

Are there parallels between tailings risk and flood risk assessments?

SRK has been involved in flood risk reduction research for more than a decade. The principles and knowledge gained from this research were adapted for disaster risk assessment as well as the development of disaster risk reduction measures. The question now is if the methodologies developed for flood risk assessment and reduction measures can be applied to the management of the risk related to tailings.

The Disaster Management Act 57 of 2002 focuses on prevention of disaster risk, including mitigation and preparedness. Disaster risk is the expected loss when a hazardous event occurs, including lost lives, people injured, property damaged, and community livelihoods disrupted. Flood risk can be classified as the probability of occurrence, the extent of a possible incident, and the vulnerability of people, environment, infrastructure and economy.

HERMAN BOOYSEN

Herman has over 20 years' experience with geographic information systems (GIS). He has managed the development of GIS for district and local authorities and developed GIS techniques and disaster management plans used in disaster risk assessment. Herman obtained a PhD in Geography from the University of the Free State, South Africa. He is registered with the Geo-Information Society of South Africa and the South African Geomatics Council and is a member of the Disaster Management Institute of South Africa.

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A flood plain management plan includes a flood study and a flood plain management study that form the basis of flood risk reduction measures. Activities for flood plain management studies include cost-benefit analysis or multi-criteria decision assessment to determine the most cost-effective and appropriate combination of flood risk reduction measures.

The similarities in assessing TSF failure and flood risk include determining areas of inundation, assessing probabilities of various levels of inundation, identifying vulnerabilities, developing risk reduction measures and implementing measures with limited resources.

To prepare for an emergency response to TSF failures described in Principle 13 of GISTM include the principles of flood and disaster risk management. These principles include prevention and mitigation strategies that must form part of the Emergency Preparedness and Response Plan (EPRP). A similar methodology is used to develop these strategies as for flood risk reduction.

Based on the discussion regarding disaster risk assessment, a flood plain management plan and the similarities between tailing failure and flood risk, we can suggest the following for tailing risk reduction:

- determine an inundation area.
- identify communities, environment, infrastructure and economies at risk in the tailings inundation area.
- establish hazard zones created by velocity, depth of inundation and duration for each probability of inundation.
- link these hazard zones with vulnerability and capacity to cope to identify tailings risk zones.
- develop risk reduction plans for each identified risk zone.
- use multi-criteria decision methods to select the appropriate combination of risk reduction measures.

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GISTM requirements to address climate change

Table 1:
GISTM Climate Change requirements

REQUIREMENT	CLIMATE CHANGE RISK IDENTIFICATION	MODELLING OF CLIMATIC CHANGES	MONITORING AND ADAPTATION
TOPIC I – Resource rights and risks to public safety	X		
TOPIC II – Site climate and breach analysis		X	X
TOPIC II – Enhance resilience to climate change	X	X	X
TOPIC II – Include climate change uncertainties in design	X	X	
TOPIC II – Updates required for changing conditions		X	X
TOPIC III – Water Management including CC impacts		X	X
TOPIC V – Requirement 6.5: Change Management System			X

Climate change mitigation has traditionally focused on the reduction of greenhouse gases. However, it is now accepted that a change in climate is inevitable and that mitigation will be insufficient. Now, the focus has shifted to include climate change adaptation: measures required to adjust to the changing climate to avoid significant risks. These risks may include increased or decreased rainfall and increased temperatures with resulting increased prevalence in disasters such as floods, drought, heat waves and fires, competition for resources, changes in disease vectors, greater demands on infrastructure, and associated social impacts.

The risks and associated impacts of climate change are far reaching and cross sector. The GISTM has included requirements for addressing climate change risks as they apply to tailings. These include several topics and are detailed in Table 1. The requirements include three main responses: identifying the risks, modelling the changes, and monitoring and adaptation. The first two relate to planning and operation; monitoring and adaptation requirements will include operation, but extend for the life of the tailings facility through to closure and post-closure.

The sixth assessment report released by the United Nations Intergovernmental Panel on Climate Change provides global models that can inform the identification of risks. The GISTM, however, requires site-specific modelling to inform TSF design. It is further recommended that site-specific models be used to inform the water balance, assessment of impacts and enhancement of resilience.

The GISTM does not provide a standard for site-specific modelling, but there are some best practice guidelines that can inform the approach. Because these models have limitations, monitoring and ongoing adaptation are essential to ensure that risks are addressed. It is critical that monitored information is analysed to ensure trends are highlighted to inform required adaptation. The table illustrates how this will be implemented through the requirements of the GISTM.

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Ashleigh is a principal scientist in SRK's Johannesburg office. She has an MSc in Biochemistry and 13 years of experience in the mining, water, climate change, energy and infrastructure sectors. She focuses on the integration of climate change into mine and infrastructure design to ensure that related risks are addressed in the early planning phases.

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PHILIPPA BURMEISTER

Philippa is an associate partner and principal scientist in SRK's Durban office. She holds a BSc Hons in Environmental Science and many oqualifications in climate change. She has 19 years of experience in integrated environmental management with more recent specialisation in air quality and climate change. She focuses on the identification of risks and opportunities in the project life cycle to inform design and operational optimisation to achieve clients' sustainability goals.

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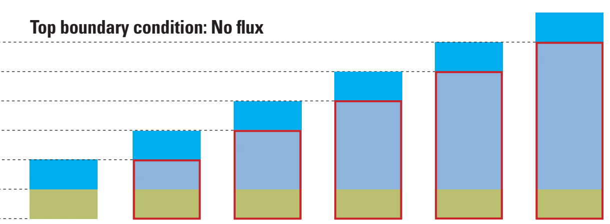
Coupling tailings deposition modelling with Hydrus-1D

FIGURE 1

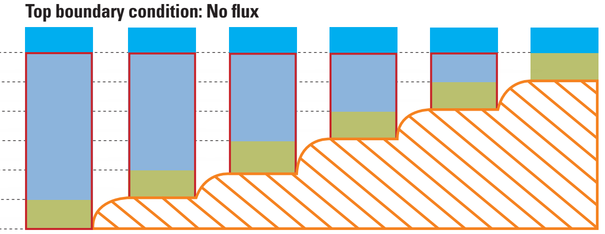
Step	Indiv. Thickness (m)	Cumul. Thickness (m)
6	2.6	40.8
5	3.0	38.2
4	3.6	35.2
3	4.3	31.6
2	6.3	27.3
1	21.0	21.0
	4.0	4.0



Simulation no.:	1	2	3	4	5	6
Time Start (days):	0	120	240	360	480	600
Time End (days):	120	240	360	480	600	720
Bottom boundary condition:	Drained					

FIGURE 2

Step	Indiv. Thickness (m)	Cumul. Thickness (m)
6	2.6	40.8
5	3.0	38.2
4	3.6	35.2
3	4.3	31.6
2	6.3	27.3
1	21.0	21.0
	4.0	4.0



Area n°:	1	2	3	4	5	6
Area (m²):	38500	21633	17407	14462	13851	13622
Time Start (days):	0	120	240	360	480	600
Time End (days):	7730	7730	7730	7730	7730	7730
Bottom boundary condition:	Drained					

Legend

- Foundation material (natural ground); Ksat = $5x10^{-6}$ to $5x10^{-11}$ m/s
- Fresh saturated tailings added to the profile; Ksat = $5x10^{-6}$ m/s
- Tailings from previous simulation; Ksat = $5x10^{-6}$ m/s
- Profile from previous simulation used for initial condition

***Foundation thickness is the same for all areas**

Seepage modelling for a TSF is typically performed to predict seepage into the groundwater system, which is then used to determine the need for geosynthetic liners. An automated computing tool using Hydrus-1D and Python was developed to model seepage through an entire TSF. The model enables pseudo-3D seepage modelling of the TSF that predicts seepage over time.

The seepage modelling portion of this tool is performed with Hydrus-1D, an industry standard one-dimensional time-dependent code that can simulate water and solute transport in a variably saturated porous medium. The coupling enables the computing tool to accommodate all tailings types. It can also use climatic data according to the site conditions and will model foundation conditions. The TSF is first discretised over time using the mill production and the topography (TSF storage curve). Each discretised block is modelled sequentially based on the rate of rise for each individual block. The outflow from each block is then summed to generate a curve to show the seepage variation as a function of time. The timescale can extend beyond the life of mine to include post-closure. The modelling tools can also accommodate geochemical processes and contaminant transport.

The programming uses Python with basic libraries. The Python code reads the input data, discretises the TSF as sequential blocks, prepares the Hydrus input files, runs the Hydrus-1D simulations, and then processes the outputs. The input is provided via a text or Microsoft Excel® file that contains tailings properties, climate data, mill production and storage curve.

The discretisation and the stacking sequence assembled by the Python code and modelled by Hydrus-1D are illustrated in Figures 1 and 2. Figure 1 shows the evolution of a given block over six time steps and Figure 2 shows the state of six blocks at a given time. Visualisation of the output is achieved using either Python or other software with graphical capabilities.

Given the automatic capability of this computing tool, sensitivity analyses are easy to perform by varying conditions such as hydraulic conductivities, foundation thicknesses, deposition rate and climatic conditions. It can accommodate Monte Carlo or point estimated method analyses for assessing the variability of the seepage released by a TSF.

The model has been used for several projects where the bottom seepage of the TSF was predicted over time over the duration of the life of mine or to post-closure. The modelling results were used to determine whether the overall seepage below the TSF was within acceptable limits or whether a liner was required.

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Ariel has over 9 years of experience in solid and fluid computational mechanics in the oil industry, aerospace industry, geotechnics, and structures. As a consultant, Ariel has been involved in tailings deformation modelling using the finite element method, including static and dynamic liquefaction and undertaken unsaturated porous media analysis using an in-house Python code.

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Michel is a Principal geotechnical engineer with SRK with more than 35 years of experience in consulting and research. He has been involved in a wide range of international projects and his experience includes mine closure, tailings and waste rock management, hydrogeology, water management, numerical modelling, data processing, programming, and construction supervision. His skills include the development of computational tools for cover design, gas transport and oxidation of sulphidic rock.

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GISTM and why you should 'breach' your facility

The Global Industry Standard on Tailings Management (GISTM), released in 2020 requires responsible TSF owners to have an integrated knowledge base comprised of all aspects ranging from affected communities and previous stakeholder engagements to full facility closure. An integral part of this knowledge base is being able to assess and record the potential downstream impacts of a hypothetical catastrophic failure and plan accordingly.

The GISTM requires that a TSF breach analysis be conducted that considers all credible failure modes, regardless of their probability of occurrence. Furthermore, the GISTM requires the breach analyses of TSFs with consequence classifications of 'high', 'very high' or 'extreme' to include estimates of the physical area impacted by a potential failure, flow arrival times, flow depths and flow velocities and the depth of material deposition in the results.

The results of a breach analysis are primarily used to inform the consequence of failure classification, which, in turn, informs the external loading component of the TSF design criteria. Identifying the groups most at risk with regard to a potential TSF failure and the drafting of emergency preparedness and response plans are also reliant on the results of the breach analysis.

These parameters are imperative to the robust design, operation and closure of a TSF to ensure zero harm to people and the environment. Zero tolerance for human fatalities is a key consideration in modern TSF management. Enhanced risk awareness translates to better risk preparedness. During a time of intense scrutiny on mine waste storage, this has never been more important.

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Francois is a geotechnical engineer in the Tailings/ Soils Department. He specialises in developing and executing site investigation programs to internationally recognised standards (ASTM, BS) for the development of tailings storage facilities and applying internationally recognised standards and guidelines (ANCOLD, ICOLD, CDA, GISTM) to the design phase of tailings storage facilities. Francois is experienced in conducting limit equilibrium and finite element modelling to assess the stability of geotechnical structures and has been involved in feasibility studies and audits in Kazakhstan, Russia, Uzbekistan, Botswana and Zimbabwe.

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Niel is a geotechnical engineer specialising in mine waste/ tailings management, design of tailings storage facilities and applying internationally recognised standards and guidelines (ANCOLD, ICOLD, CDA, GISTM) to all phases of the facility lifecycle. Niel is experienced in coordinating and executing geotechnical site investigations for programs for tailings storage facilities in compliance with internationally recognised standards (ASTM, BS) and has been engaged in feasibility studies and audits with regard to tailings storage facilities in Kazakhstan, Russia, Uzbekistan and Botswana.

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Leakage collection and recovery from double-lined process water ponds and tailings impoundments

A leakage collection and recovery system (LCRS) for process water ponds and some tailings impoundments typically incorporates a two-layered synthetic liner with drainage media between the layers to drain and dissipate any leakage through primary liner, preventing leakage through the secondary liner. If a vibrating wire piezometer (VWP) at the base of the sump indicates a head higher than the elevation of the primary liner, the secondary liner could leak from the base of the sump.

SRK have designed options (alternative LCRS options) that include:

- pumping from the LCRS sump to measure the rate of leakage through the primary liner into the sump
- gravitating from the LCRS sump via an outlet through the secondary liner to an external sump at a low elevation
- constructing a low-permeability layer under the LCRS base that considers the full life of the facility, including closure.

Pumping from LCRS Sump

In Nevada, sump inflows of greater than 150 gpd are considered a violation. Typical sump construction includes drainage media that can limit the potential for such a high flow rate pump to dissipate the full volume of water stored in the sump. A high pump flow capacity and a low-permeability drainage media can cause underestimation of actual leakage rates through the secondary liner. Additionally, if the sump is operated without a VWP, it cannot be demonstrated that there is no hydrostatic head transfer from the primary to the secondary liner.

Gravitating from the LCRS Sump

This design includes a prefabricated LCRS drain outlet installed in a prepared foundation, a pipe-in-pipe connection to an external sump/pond and methods of operation that will eliminate transference of hydrostatic head from the primary to the secondary liner.

The prepared foundation grading is steeper in the immediate vicinity of the LCRS drain outlet to facilitate gravity drainage toward the low-point inlet of the pipe-in-pipe system. The foundation consists of a prepared soil subgrade underlying a mass concrete foundation slab housing the prefabricated LCRS outlet, which has a smooth finish to allow wrinkle-free installation of the HDPE apron welded to the outlet.

Constructing a Low-Permeability Barrier Under the LCRS Base

The thickness of the foundation depends on how long the system will require LCRS operation and the compacted hydraulic conductivity of the foundation soil. For example, if the timeframe for facility operation and closure is 20 years, and the compacted hydraulic conductivity of the foundation soil is approximately one foot in 10 years, a two-foot-thick layer of foundation soils would provide adequate mitigation against leakage.

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Dave has 45 years of experience in the provision of engineering, environmental permitting, and mine closure services for mining facilities, including tailings disposal, process fluid and stormwater management, tailings recovery and re-treatment, heap leach, waste rock disposal and open pit facilities.

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Dam safety review audits

Ngezi TSF penstock towers

Assessing the safety and security of operational TSFs has been a significant proportion of the SRK UK Mine Waste Engineering team's workload since catastrophic failures at Brumadinho and Mariana, Brazil, and Mount Polley, Canada. Investigations are undertaken in general accordance with the approach for dam safety and operational reviews (DSORs) as recommended by the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) and the Canadian Dam Association (CDA).

The minimum scope of a DSOR should aim to understand the key risks that affect the TSF; It should include the identification of potential shortcomings of the design and operation, with a focus on stability, security and/or safety of the TSF.

SRK recently completed a DSOR audit of two TSFs at the Sukari gold mine in southern Egypt, which is owned by Centamin Plc.

The work followed a standard approach which includes:

1. Issue an information request.
2. Collate available data and identify any data gaps
3. Undertake a 4-day site inspection.
4. Hold discussions with the engineer of record (EOR) and the responsible tailings facility engineer (RTFE)
5. Present preliminary findings and major issues.
6. Issue a DSOR audit report
7. Present findings and recommendations to Centamin's Sustainability Committee

The outcomes of the DSOR audit were positive. The report lists a significant number of positive observations and recent improvements that have been completed since Centamin acquired the project. In reviewed condition, SRK considered both the historical TSF and the recently constructed operational TSF to be safe. This opinion was supported by evidence from site observations and review of the performance monitoring data. Recommendations were separated into those for improvement of safety (mainly related to return water management) and those for improvement in management practices and documentation (mainly related to following consistent monitoring procedures and to updating documentation).

The conclusions and recommendations of the DSOR audit have been accepted and endorsed by the EOR and the RTFE. They have been used to develop a technical action plan which will guide further improvement in safety and performance.

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Richard is a Chartered Engineer and principal consultant (Geotechnical and Tailings Engineering) with over 17 years' experience. Richard specialises in assessment and design of rock and soil slopes; numerical modelling; design and management of ground investigations and performance monitoring schemes; and, audits of slopes and waste storage facilities. Richard has worked on base and precious metal, coal and industrial mineral projects throughout the UK, Europe, Africa and the Americas.

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Jamie is a Chartered Engineer and senior consultant (Tailings Engineering) with over 15 years of experience in tailings and mine waste engineering, geotechnical engineering and environmental studies. Jamie has managed a broad range of projects involving foundations investigation and design, tailings storage facility and waste rock dump design, dam safety audits and closure design.

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Evaporation and infiltration on platinum tailings beaches

Surface renewal

The water balance and position of the phreatic surface in a tailings dam are significantly controlled by infiltration and evaporation in the near-surface layers. Deposition onto tailings beaches provides an excess of water, which is also subject to evaporation losses, both during and after deposition. However, the fate of the deposited water is difficult to assess, particularly at high rates of rise, due to the partition of fluxes, comprising surface runoff to the pool, infiltration during deposition, percolation from the deposited layer after deposition, entrainment of interstitial water and evaporation from wetted and drying surfaces. Understanding these concurrent processes is difficult and practitioners have often resorted to empirical approaches, where evaporation from wet and dry beaches is considered a fraction of the potential evaporation (PET). This can result in significant error to the overall water budget, poor estimates of recharge to the phreatic surface and complex conditions for water management.

Accordingly, a series of physical observations were conducted on a TSF that stores platinum tailings. The purpose of these observations was to quantify evaporation losses and rates of infiltration so that critical elements of the water balance could be refined.

In comparison to normally wetted agricultural soil, expectedly, tailings material behaves differently. Most notable findings were the behavior of actual evaporation (ET) at the various stages of deposition. ET losses were found to be lower than PET demand during the early stages of deposition, most likely due to the turbidity of the slurry. Once settling of the particles commences, ET equals PET, which can continue for 4-10 days after cessation of deposition. Further drying of the tailings surface generally occurs for two weeks, after which evaporation losses are practically nil, unless further wetting of the surface occurs during rainfall. ET may drop well below PET during the drying cycle when demand is high, but may subsequently continue to evaporate at PET, should PET drop.

The observations and understanding gained should be used to provide guidelines for future estimation of evaporation, infiltration and percolation fluxes during tailings dam operation and closure. Typical estimates of 80% of PET over wetted beaches and 20% over dry beach areas need to be revised based on these observations. Continued observations should be made in different tailings materials and different climatic periods. Local meteorological observations or proper A-Pan measurements should be made to allow continued comparisons of responses to the atmospheric demand to be made.

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Simon is a principal hydrologist in SRK's Pietermaritzburg office. He has 40 years' experience in hydrology with a specialisation in vadose zone hydrology. During 30 years in academia, he researched hydraulic and contaminant transport processes in numerous mining and industrial waste materials and contributed to the development of hydropedology in Southern Africa. Currently, he is involved in near-surface contaminant mobility and water quality studies for mining and industrial clients.

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James has been involved in the field of environmental science for 26 years, mainly having worked in the mining sector in Africa across a broad range of resources. He is a professionally registered natural scientist and has extensive experience in mine closure planning and mine closure liability estimation, including financial assurance, asset retirement obligation and life of mine assessments, land contamination, environmental geochemistry, industrial waste and mine residue characterisation and management, water, waste and wastewater management, water quality assessment and environmental auditing.

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The GISTM and how it influences facility closure

The GISTM has a strong focus on closure. One of the objectives of the GISTM with regards to sustainability is that TSFs must be capable of being closed with limited management and maintenance and physically and chemically stable for the long term. This leads to the requirement that a TSF should be planned, designed, constructed, operated and closed on the assumption that it will be a permanent landform that cannot develop credible catastrophic failure scenarios.

The closure of a TSF should be considered at the conceptual phase of the design to ensure that there are no impediments to safely closing the facility at any point of its life, including at the end life of the mine. This requires the development of a preliminary closure plan that will be used to inform the design, with the preliminary plan including at least closure performance objectives and being used to inform a multi-criteria alternatives analysis.

Closure principles are also applicable to operational facilities that are not in a safe state for closure and require that a closure plan be developed for existing facilities. The plan can be iterative and develop as the end of facility life approaches. The GISTM acknowledges that TSFs are subject to change as they develop. Principle 2 requires that an integrated knowledge base be developed to inform safe management throughout the life cycle. Changes to the closure plan for new and existing TSFs through the operating period must be included in the Operation, Maintenance and Surveillance manual so that activities during operations support the closure plan and objectives.

Closure planning for a GISTM-compliant facility is an iterative process starting at concept phase and continually improving as more knowledge is generated through the TSF life.

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Historical TSF for gold plant tailings in South Africa, not yet closed

Implementing water stewardship throughout the life cycle of a TSF

Tailings disposal uses substantial quantities of water. Many TSF failures have resulted from inadequate water management and/or a lack of understanding of the dynamics of water movement on and within a TSF. These facilities conventionally have a return water dam (RWD) system to recover runoff, decant and seepage from the TSF back into the process, thereby reducing the concentrator demand for fresh water. Uncontrolled RWD or TSF discharge results in degradation of downstream water resources.

Construction, operation and closure of a TSF poses a serious risk to water resource quality and quantity. Water stewardship provides a mechanism to contextualise a TSF within a catchment, encouraging appropriate water use management, and water resources impact mitigation throughout the life of a TSF.

The International Council on Mining and Metals endorses water stewardship, requiring strong and transparent water governance, effective operational water management and collaboration to achieve responsible water use.

With appropriate water stewardship practices, it is possible to ensure that:

- TSF operations do not deprive water users (and environment) of good water quantity and quality
- TSF water use requires appropriate catchment mitigation, management and monitoring
- TSF operational emergency situations are appropriately mitigated and managed to prevent catastrophic incidents
- Incidents that can cause environmental or human health risks are appropriately mitigated and managed to minimise long-term adverse impacts.

The GISTM supports water stewardship at TSFs as an appropriate mechanism for the development of TSF water management plans (WMPs). Plausible changes and challenges considering TSF operational and natural system variability and uncertainties throughout a TSF's life cycle need to be identified in the development of a WMP.

The development of a WMP as part of the implementation of a strong water stewardship at TSFs encourages appropriate water use management, and water resources impact mitigation throughout the life of a TSF.

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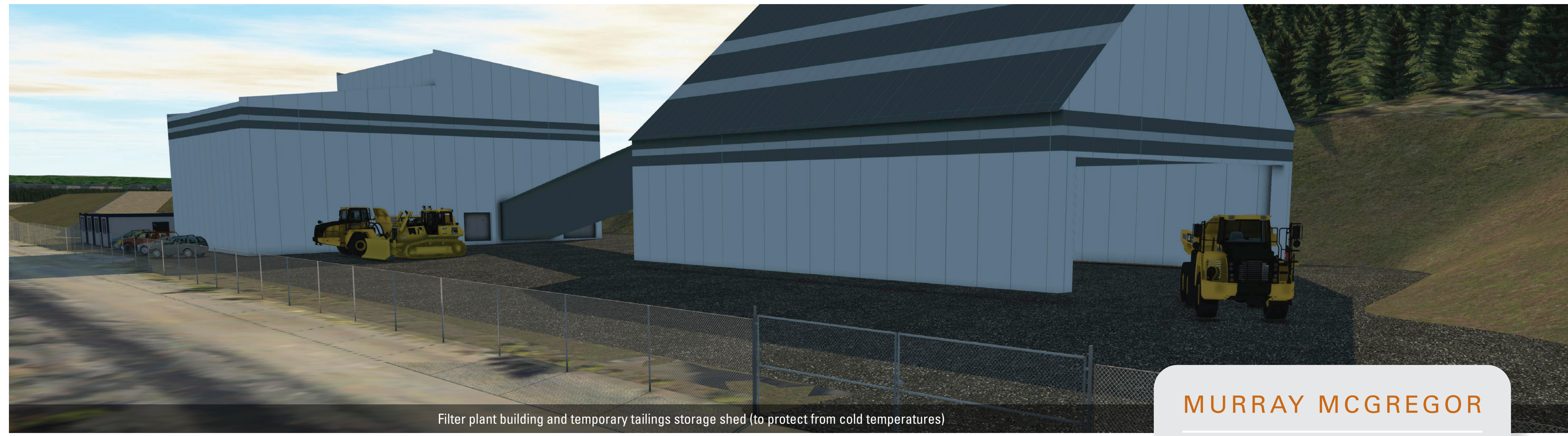
Aksu tailings dam, 2019

Dewatered tailings stacks in northern Europe



Filter plant building and temporary tailings storage shed (to protect from cold temperatures)

SRK has been involved with several studies that are considering the use of dewatered tailings stacks in northern Europe. Tailings dewatering has become a popular option for mining projects in recent studies due to the increased pressure for tailings facilities to minimise the likelihood and consequences of failure. The main advantages of the dewatered stack include:

- improved landform stability
- enhanced water recovery
- reduced infiltration to tailings
- improved access to tailings surface
- progressive reclamation
- blending into existing natural landforms

Although dewatered tailings has significant advantages over traditional slurry tailings, there are only a few dewatered tailings stacks in northern Europe. One key challenge is the operation of facilities in cold climates. SRK draws on experience from Arctic projects in North America to identify appropriate measures for these conditions: operating plans must consider protecting tailings and return water infrastructure against cold climate/freezing conditions.

The permitting process in many countries in northern Europe is rigorous, and the permitting process often begins at the pre-feasibility study (PFS) level of design rather than feasibility or detailed design phase (as is the case in other jurisdictions). It is therefore critical to identify high quality solutions that are practical and achievable at an early stage of design. Critical independent review (i.e. from another practice or entity), typically reserved for feasibility-level studies, can greatly improve identification of potential gaps in scoping and PFS-level studies.

Since there are few examples of dewatered tailings stacks in northern Europe, regulators have a limited dataset for evaluating new projects. However, SRK considers that there are no significant barriers to permitting since dewatered tailings stacks have fewer risks, lower consequences of failure, improved water stewardship, and smaller footprints when compared to traditional slurry tailings strategies.

SRK has been working to provide confidence in switching to new tailings strategies that incorporate dewatered tailings in northern Europe where appropriate. An example of this is the construction of 3D renders showing various stages of dewatered tailings stack designs in support of PFS-level studies. These images help illustrate the life cycle of dewatered tailings facilities from early construction through to the post-closure phase. The aim is to provide clarity to regulators and other stakeholder groups on how the tailings will be managed and what the visibility and appearance of the final landform will be.

SRK has successfully delivered PFS-level designs that give clients a route to permitting their projects and hopes to see more dewatered tailings projects in northern Europe in the coming years.

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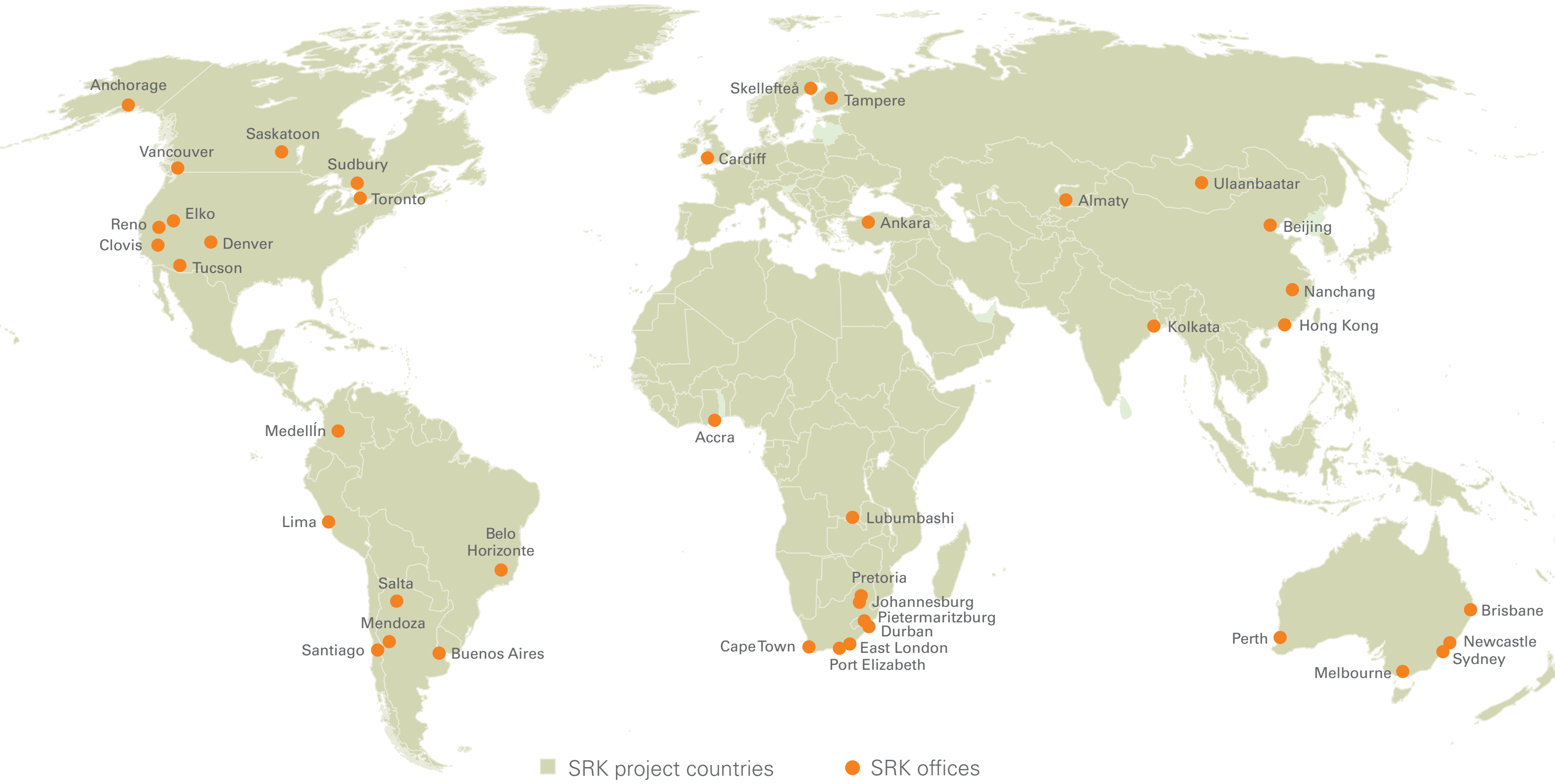

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