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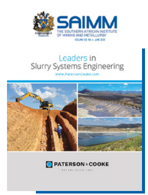


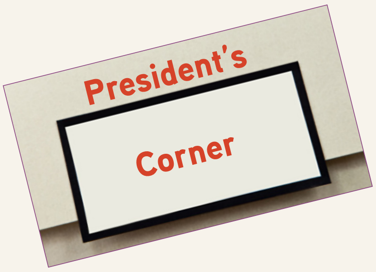
TAILINGS EDITION *(continued)*

PROFESSIONAL TECHNICAL AND SCIENTIFIC PAPERS

Tailings management for a sustainable future

The prominence of the role that tailings management plays in mining company agendas has risen to a new level in the aftermath of the failure of the Feijoa tailings facility at Brumadinho in Brazil in early 2019. The mining industry now understands that if it to be allowed to co-exist with other human activity it must regain public trust that it will no longer have a right to place lives of people living within the zone of influence of its facilities at risk. To the credit of the industry, it has taken broad-ranging action to impose self-regulation, which will improve safety. Risk will, however, always be present where there are unknowns that influence safety margins. These unknows are related to weaknesses in the engineering of tailings facilities, which arise from poor understanding of the characteristics and behaviour of the foundations of the facilities and of the tailings itself. It is therefore appropriate that research and development interest in tailings has surged. The output of this R&D will contribute towards improvements in the practise of tailings management. This edition of the Journal serves to make a significant contribution to the dissemination of information that will contribute significantly to improving the safety of tailings facilities around the world.

John Wates
Geotechnical and Tailings Engineer | John Wates Consulting



Hydrogen-fuelled trucks and inspiration

In 1874, science fiction author Jules Verne set out a remarkably insightful vision that has inspired innovators in the 145 years since. In his book *The Mysterious Island*, Verne wrote of a world where 'water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable'. As an avid reader I read all Jules Verne's books in my youth and have a soft spot for the author anyway. But when I recently returned to this book, this insightful remark gave me goosebumps of excitement. In a culture obsessed with measuring talent and ability, we often overlook the importance of being inspired. In my opinion, inspiration is the spark that opens the mind to new possibilities and propels a person from apathy to possibility. Inspiration transforms the way we perceive the possible. Perhaps inspiration is often overlooked because of its elusive nature.

Inspiration recently came for me in the form of the launch of the world's biggest hydrogen-powered truck. Anglo American unveiled their retrofitted haulage vehicle at the Mogalakwena platinum mine in Limpopo Province amidst a lot of fanfare and excitement in early May 2022. The hydrogen-powered retrofitted diesel truck is a result of many years of work and commitment. The vehicle is a tangible outcome of Anglo American's committed strategy to reduce their carbon footprint, thus also tangibly playing a role in the South African and global energy transition in mining. Anglo's hydrogen-powered truck is an inspirational game-changer and a remarkable milestone for the mining sector in general. This massive truck weighs 220 t with a load capacity of 290 t, giving it a total weight of a mindboggling 510 t.

Known as the nuGen Zero Emission Haulage system, the hydrogen-powered truck is retrofitted from a diesel-powered vehicle, employing a hybrid hydrogen fuel cell providing roughly half of the power and a battery pack the other half, to allow energy recovery from braking. The 2 MW hybrid power system, which replaces the diesel engine, was designed by Anglo American and First Mode in Seattle, USA. A conventional diesel truck of this size would use around 3 000 litres of diesel per day, generating 8 t of carbon dioxide. Anglo American also intends to use South Africa to prove up its hydrogen truck technology for global implementation. The plan is to retrofit 40 diesel trucks at Mogalakwena platinum mine, the largest open-pit platinum mine in the world, and later roll out the concept to all 400 haulage trucks in the fleet. Haul trucks account for 80% of diesel emissions at Anglo's mining sites globally, so a conversion to hydrogen and battery power will make a substantial contribution towards carbon neutrality for the company. Hydrogen enters the fuel cell from the tank and mixes with oxygen to form water in a chemical reaction catalysed by platinum. This reaction generates electricity that is used to power the motors that drive the wheels. The only emission from the vehicle is water vapour. To facilitate the piloting phase at Mogalakwena, Anglo has built a zero-emission hydrogen production, storage, and refuelling complex, which includes the largest electrolyser in Africa, tied to a captive solar photovoltaic field.

President's Corner *(Continued)*

Given the importance of platinum group metals (PGMs) in the production of electrolysers used to produce green hydrogen, it is fitting that Anglo Platinum has been chosen as the hub of the nuGen programme. The end-to-end integrated green hydrogen production, fuelling, and haulage system implemented at Mogalakwena has the potential to cut up to 80% of the diesel emissions generated in the opencast mine environment. The launch of Anglo's nuGen truck provides a real-world example of the potential of hydrogen to shift mining towards a wider adoption and use of hydrogen across the heaviest duty forms of transport, for which hydrogen carries numerous advantages over battery technology. Moving away from diesel-guzzling trucking can substantially shift the carbon footprint of mining and transport in general. The nuGen project is, however, not an isolated breakthrough or milestone. For about 20 years, various research and academic institutions locally and globally have been part of a network focused on building capacity and technology associated with a future hydrogen economy.

Recently a joint feasibility study, coordinated by the Department of Science and Innovation (*Hydrogen Valley Feasibility Study Report*[1], dated October 2021), identified three hubs with a fundamental role to play in integrating hydrogen into South Africa's economy with the intent of establishing the country as a strategically important centre for green hydrogen production. The study evaluated the potential for a 'hydrogen valley' to be developed in the Bushveld Complex geological area and beyond, based on nine key pilot projects centred on the three main hubs. The hubs include Johannesburg, extending to Rustenburg and Pretoria; Durban, encompassing the city itself and Richards Bay; and Limpopo Province, centred on Anglo American's Mogalakwena PGMs mine. The study identified the adoption of fuel cells for forklifts in Durban and Richards Bay ports for large mining haul trucks across the country, for buses in Johannesburg, and to power data supply centres in Limpopo and for offices in Johannesburg and Pretoria.

Therefore, the successful piloting of the nuGen truck has elicited such excitement and inspiration for me. The pathway towards a hydrogen economy has been a long and winding one to date, but finally we are seeing a real-world, commercial example of what can be done. The nuGen truck is a symbol of sorts of a new generation of clean technologies in large mining haul trucks , and opens up a much larger scope for the economy that can accelerate the goal of carbon neutrality while creating commercial opportunities and jobs where they are most needed. And Jules Verne's prediction is increasing becoming our reality, a reality that has the potential to make a real change.

'If you always do what you've always done, you'll always get what you've always got.' - Henry Ford, founder of the Ford Motor Company.

I.J. Geldenhuys
President, SAIMM

[1]https://www.dst.gov.za/images/2021/Hydrogen_Valley_Feasibility_Study_Report_Final_Version.pdf

Field and laboratory research into the undrained behaviour of tailings at the University of Pretoria

by S.W. Jacobsz[1] and Y. Narainsamy[1]

Affiliation:
[1]University of Pretoria, Pretoria, South Africa.

Correspondence to:
Y. Narainsamy

Email:
yashay.narainsamy@tuks.co.za

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ORCID:
Y. Narainsamy
https://orcid.org/ 0000-0002-1864-3317

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Synopsis

Several high-impact tailings dam failures around the world in recent years have placed a renewed focus on the stability of tailings dams and pointed to potential shortcomings in traditional drained design and safety evaluation procedures. A need to consider undrained shear strength in the design of tailings facilities has become apparent. However, there are specific requirements that need to be met before undrained shearing occurs. In South Africa, the last major failure was likely the Merriespruit disaster in 1994, which leads to the question of whether the conditions required for undrained shearing are readily applicable to South African tailings dams. This paper describes research at the University of Pretoria that has recently commenced to further investigate the conditions required for undrained failure to occur. The research includes laboratory and field testing to replicate these conditions in the laboratory and relate them to those found in an active tailings dam.

Keywords

tailings, liquefaction, centrifuge modelling.

Introduction

Several high-impact tailings dam failures around the world in recent years have placed a renewed focus on the stability of tailings dams and pointed to potential shortcomings in traditional drained design and safely evaluation procedures. The phenomenon of static liquefaction has been cited as a contributor to several of the recent failures. A need to consider undrained shear strength in the design of tailings facilities has become apparent (Morgenstern, 2018). This is thought to be especially applicable to upstream tailings dams where the walls containing the tailings are themselves constructed from initially saturated silty/sandy slurries and the material is deemed to be in a state susceptible to undrained shearing. Over the years, this has led to the construction and operation of tailings dams using the upstream deposition method being banned in Brazil and Chile (Ministerio de Minería de Chile, 1970; Agência Nacional de Mineração, 2019).

Several experts suggest that for tailings dams where the tailings material is found to be in a state where it is susceptible to undrained shearing, and where the consequences of failure are severe, it must be assumed that undrained conditions can occur. However, under the same effective stress, peak undrained shear strengths are typically only half of the peak drained strengths (*e.g.* Olson and Stark, 2003). Therefore, when undrained shear strengths are applied, stability analyses of many existing South African tailings dams indicate unsatisfactory factors of safety. To provide adequate factors of safety, expensive remedial works, generally the construction of stability buttresses, are required. For many mine owners, the associated costs can be unaffordable.

In the field, in addition to potentially unstable geometry, three conditions are necessary for undrained failure to occur, namely:

1. The material must be loose and of a contractive nature
2. The material must be saturated
3. A trigger initiating undrained shearing must occur.

When evaluating whether these conditions occur in South African tailings dams, the authors must, without doubt, answer in the affirmative in the case of the first two requirements. However, large-scale flow failure of tailings dams is rare in South Africa, with the last major event probably being Merriespruit in 1994, despite the presence of hundreds of upstream tailings dams in the country, some of which are older than 100 years. It therefore appears that flow failures are rare because the triggers do not commonly occur.

What would constitute a trigger event resulting in a tailings flow failure? The first that comes to mind is a seismic event. Despite being in an area of low seismic hazard, mining-related seismicity is common in South Africa, with the most severe event being of magnitude 5.5 on the Richter scale in Orkney in 2014 (Midzi *et al.*, 2015). However, the authors are not aware of any seismic event that resulted in damage to a tailings dam in the country. In neighbouring Botswana, a magnitude 6.5 earthquake took place in 2017 (Midzi *et al.*, 2018). No damage was reported at the three nearest tailings dams at Ghaghoo mine (25 km), Orapa mine (160 km), and Jwaneng mine (210 km) (Anglo American, 2017; Gem Diamonds, 2017), all three of which were constructed using the upstream method. More intense seismic events may possibly provide a sufficient trigger and their likelihood of occurrence can be probabilistically expressed.

This paper describes research under way at the University of Pretoria to further investigate the three conditions for undrained failure. The potential contractive nature of a soil depends on its void ratio and stress history, including the current stress state. These elements will be investigated using high-quality sampling, advanced laboratory testing, and *in-situ* measurement of the stress state. In addition, the effect of trigger events such as a gradually rising water table is being studied using physical modelling in the geotechnical centrifuge. The paper presents work planned in terms of the determination of *in-situ* void ratio and the associated behaviour of tailings under shear using laboratory testing. The measurement of negative pore water pressures in an active tailings dam, providing insight into the stress history that the tailings is subjected to, is presented. This is followed by a description of a centrifuge model investigating a rising water table as a trigger mechanism for a flow failure.

Research undertaken

The University of Pretoria has been conducting research into tailings dams safety for several decades and this is planned to continue. The current research is focused on understanding undrained shearing in the context of South African tailings dams and is presented in three aspects.

- The first aspect entails high-quality sampling of tailings material *in situ*. This is important as the first two requirements for undrained shearing relate to the state of the material. The intent is to design and construct a sampling device and to develop a repeatable sampling procedure with the aim of reducing sample disturbance associated with sampling, transportation, and storage.
- The second aspect concerns field monitoring of active tailings dams. Although sampling provides an indication of the current state of the material, the development of the material state is also of importance. As it is difficult and costly to obtain undisturbed samples, in many instances reliance is placed on laboratory testing of disturbed samples to obtain relevant geotechnical soil parameters. Understanding the stress paths imposed on active tailings dams may assist in the development of improved methods of preparing samples in the laboratory for testing. Current field monitoring systems are discussed as well as plans for future systems.
- The third aspect is laboratory testing. The third requirement for undrained shearing to occur is that a trigger must initiate undrained shearing. The University is in the unique position of having a geotechnical centrifuge. This enables physical modelling of geotechnical structures at a small scale while maintaining appropriate prototype (full-scale) stress conditions (Jacobsz *et al.*, 2014). The current research involves the investigation of likely trigger mechanisms in a South African context and observation and analysis of the subsequent instability. Results from recent testing are discussed.

Research aspect 1: High-quality sampling

On upstream tailings dams, tailings are typically pumped as a slurry from the beneficiation plant to the tailings dam, where the material is deposited. When using paddock deposition, a layer of slurry, typically 100 mm thick, is deposited. The coarse material in the slurry will settle out first, forming a coarser more permeable layer at the base of the newly depositedmaterial, while the upper part will be more fine-grained and impervious. This separation into coarse and fine fractions results in an intensely layered profile as demonstrated by the sample shown in Figure 1. CPTu soil identification charts from tailings profiles typically also demonstrate extreme heterogeneity, with material over short depth intervals ranging across much of the soil type spectrum, from very soft clays to dense sands.

In upstream tailings dams where deposition occurs by means of spigoting and cycloning, an effort is made to separate the coarse and fine fractions. The coarse fraction is then used for the construction of the outer walls, while the fine fraction is discharged on the beach, with excess water flowing towards the pond. These methods of deposition are likely to result in a less heterogeneous soil profile.

The question arises how significant the differences in the behaviour of the various layers comprising the tailings profile will be upon shearing and how this would affect the behaviour of the profile as a whole. In order to begin to assess this, it is of interest to know the variation in the *in-situ* void ratio and also the variation in the critical state line applicable to the various soil layers. Vermeulen (2001) presented data illustrating how tailings samples from different strata can have significantly different critical state lines.

A major challenge with the assessment of the behaviour of tailings samples is that of sample disturbance. The relatively high permeability of tailings means that negative pore pressures generated during the extraction of samples rapidly dissipate, so that the effective stress is not preserved to the same degree as in the case of clays. Recovering high-quality samples from a tailings dam is therefore challenging, especially below the water

Figure 1—Tailings sample demonstrating layering

table. As a consequence, engineers often resort to the testing of reconstituted samples. However, reconstituting destroys the *in-situ* sample fabric and results in behaviour during shearing that can differ very significantly from the response of tailings in the undisturbed state (Chang *et al*., 2011). The response of reconstituted samples is highly dependent on the method of sample preparation (Zlatovic and Ishihara, 1997). Moist tamping, the easiest and most popular means of sample preparation, results in samples showing a tendency to contract and potentially liquefy, while samples prepared from a slurry tend to initially contract somewhat and then dilate strongly. It is not clear how samples should be prepared to replicate *in-situ* material behaviour in the field (Reid and Fanni, 2020). In addition, uncertainties exist about the behaviour of samples in the field due to the difficulties associated with recovering high-quality undisturbed samples.

The questions raised above are not easily answered. However, a sampling study is planned to recover high-quality undisturbed samples from above the water table in tailings dams. It is proposed to use hand augering to drill to the required depth to minimize vibration-related disturbance during sampling. Large-diameter (100 mm) Shelby tube samples will be taken. The angle of the cutting edge of the samplers will be 5°. A vacuum will be applied to the sample as it is being extracted. It is well established that, aside from disturbance during sampling, sample disturbance also occurs during transportation and storage before testing is conducted (Amundsen *et al*., 2016). To address this, a unique feature of the sampling programme is that arrangements are being made to extrude the sample while still on the tailings dam, immediately upon recovery. The sample will be placed in a triaxial cell and pressurized before being transported off the dam for testing. It is hoped that in this way sample disturbance during sampling, transportation, and storage can be minimized.

Research aspect 2: Field monitoring

Stress history and state in an active tailings dam

It is often useful to perform tests in the laboratory to observe soil behaviour in a controlled environment. However, these controlled conditions rarely present themselves in the field. An example of this is the stress conditions during the consolidation phase of a triaxial test, where it is common to consolidate the soil specimen isotropically (*i.e.* under zero shear stress). However, this will be representative of field conditions only if the horizontal and vertical stresses are the same, which is unlikely to be the case. The result is that in q-p' space, the stress state does not find itself on the p' axis (q = 0) after completion of consolidation, but at a shear stress offset above the p' axis, which is dependent on the coefficient of lateral earth pressure, K_o. This potentially locates the stress state much closer to the critical state line compared to isotropic conditions.

After deposition, the solids in a tailings slurry settle out and excess water is decanted. During deposition, a small amount of excess pore pressure is generated which, in silty tailings such as gold tailings commonly found in South Africa, dissipates very soon after deposition (Lebitsa *et al*., 2020). Consolidation is associated with the dissipation of excess pore pressure, matched by an equal increase in effective stress, and is therefore associated with a small gain in strength. This, however, is not the only mechanism of strength gain active in tailings after deposition.

As excess water is decanted and the tailings begin to dry out, negative pore water pressures rapidly develop due to menisci receding into the drying tailings as evaporation takes place. The magnitude of the negative pore pressures (or suctions) depends on the soil water retention curve (pore water suction *vs* water content). In a saturated state the suction generated will be matched by an equal increase in effective stress. As the degree of saturation reduces during drying, reduced continuity develops in the pore water, accompanied by an increase in suction. The suction component contributing to the effective stress, and hence shear strength, can be expressed using the suction stress characteristic curve (Lu *et al*., 2010). The increase in effective stress may result in a volume reduction if the settled tailings is compressible, resulting in cracking and desiccation.

When a new layer of tailings is placed, the pore water suctions will dissipate, reducing the effective stress. However, due to the effects of over-consolidation contributing to phenomena such as interlock and fabric, dissipation of suction during a new deposition event only results in a relatively small reduction in the shear strength gained during desiccation (Daliri *et al*., 2014). As new layers are deposited, consolidated, allowed to dry out, and become desiccated, complex effective stress cycles are imposed on the drying tailings, resulting in a complex stress history and an uncertain current stress state. Critical state theory demonstrates how the stress history and current state, in combination with void ratio, influence undrained soil behaviour. The stress history and state in actual tailings dams are topics that have not been researched in depth.

As knowledge about the actual stress path associated with normal deposition cycles becomes available, stress path testing can be carried out to assess material behaviour in terms of stress path dependence. Given the changes that tailings deposited on a tailings dam are subjected to, it will be necessary to model unsaturated behaviour. Testing equipment with unsaturated capability is therefore required.

High-capacity tensiometers

Harrison and Blight (2000) mentioned that simple and reliable measurement of *in-situ* pore water suction is challenging. Various indirect means of suction measurement are available. However, these methods typically suffer from lagged response times. High-capacity tensiometers provide a direct measurement of pore water suction with minimal response time lag. However, these instruments are difficult and costly to source.

A low-cost high-capacity tensiometer was developed at the University of Pretoria (Jacobsz, 2018). The tensiometer has been demonstrated measuring suctions as high as 1 700 kPa (Jacobsz, 2019). The tensiometer comprises a commercial pressure sensor to which a high-air-entry ceramic filter is glued. The first tensiometers were encapsulated in a structural epoxy adhesive, but current versions are potted in a stainless steel housing using a structural epoxy adhesive. These tensiometers have been installed in trials in active tailings dams, with the first installed now operating for a period of 2.5 years.

Pore water suction monitoring

Figure 2 shows a cross-section of a gold tailings dam where pore water suctions have been monitored since April 2019. The tensiometers were installed in the daywall at the locations shown shortly after stepping in of the wall. The new daywall was at a height of 5 m in July 2021, implying a rate of rise of approximately 2.5 m per year.

The tensiometers were installed at depths of 150 mm and 300 mm below the tailings surface in shallow holes which were backfilled with loose tailings. The sensors were saturated in the

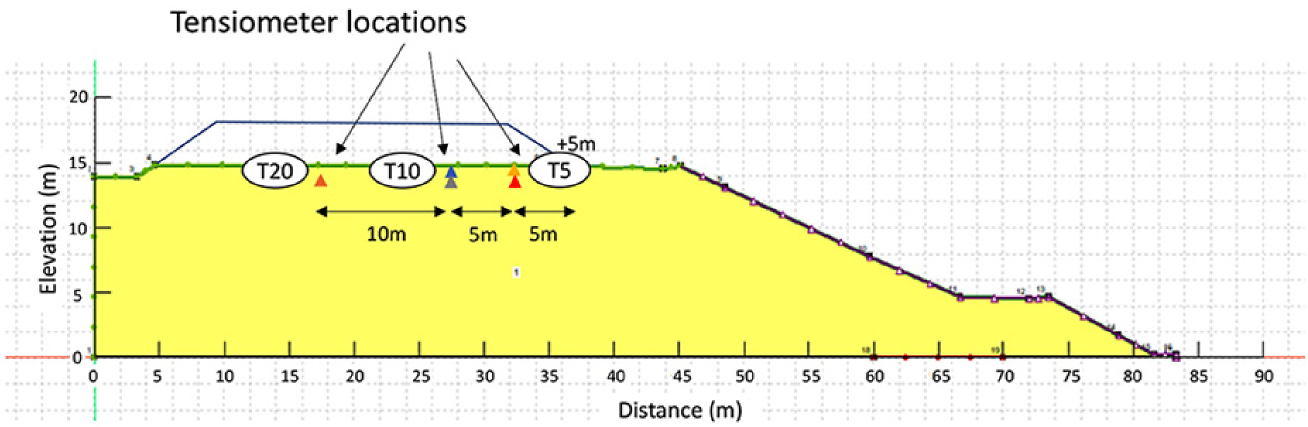

Figure 2—Tensiometer locations

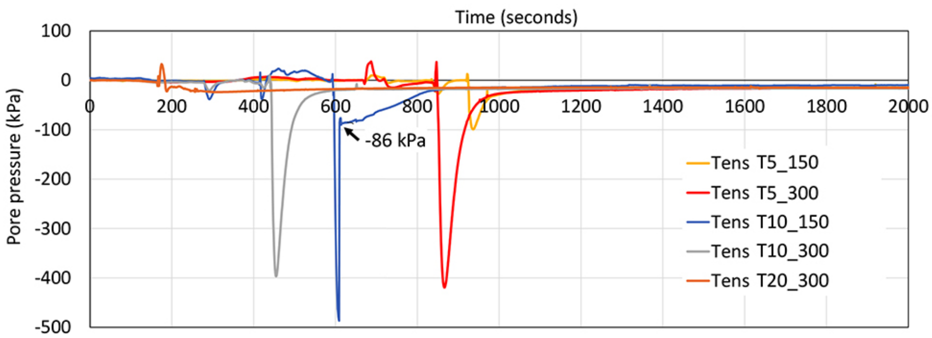

Figure 3—Pore pressure measurements during tensiometer installation

laboratory and transported to site in de-aired water. Readings were zeroed shortly before installation. The sensors were logged during installation, with the data displayed in Figure 3. The colours correspond with the sensor locations in Figure 2. The tensiometers were installed by excavating shallow holes, adding water to cover the base of the hole, and initially gently pushing the tensiometer into the underlying tailings. Figure 3 shows that pushing of the tensiometers resulted in large negative pore pressures caused by dilation, which could cause the tensiometers to cavitate. Cavitation was in fact observed on tensiometer Tens T10_150, with pore pressure rapidly increasing to –86 kPa (absolute zero for the site elevation). Cavitation is an essentially irreversible process under field conditions and renders the tensiometer useless. This behaviour is distinctly different to the other tensiometers which were pushed in. These tensiometers show a smooth return to the ambient pore pressure, indicating normal operation. An improved installation procedure is to simply bury the tensiometers in saturated tailings, adding additional water to ensure thorough saturation of the surrounding material when the sensors are covered. It can be seen that the pore pressure rapidly equilibrated after installation to an ambient pressure of approximately 15 kPa.

Figure 4 presents pore water pressures recorded over a period of four months. It also shows temperatures recorded using thermistors installed with the tensiometers at 5 m and 10 m from the edge of the stepped-in daywall. Deposition events and the daily rainfall record are indicated. Daily tailings temperatures generally fluctuated between 12°C and 20°C, with temperatures falling during the winter months and beginning to rise in August. The daily temperature fluctuation is evident, reducing with time as the tailings thickness increased above the instrumentation as deposition took place.

The gravimetric Soil Water Retention Curve (SWRC) for the gold tailings, as measured with the tensiometer method (le Roux and Jacobsz, 2021) is presented in Figure 5. This curve shows how moisture content influences the soil suction. The air entry value is shown on this SWRC at about 14 kPa. Due to the flat slope of the SWRC beyond air entry, the application of suction above the air entry value will result in rapidly desaturation.

The tensiometers were installed approximately one week after the last deposition event. The surface was relatively dry. Shortly after installation the suctions equilibrated to between 15 kPa and 20 kPa, with the suction at 20 m from the daywall edge being slightly higher than at the other locatins. During installation, the material here appeared more fine-grained. The suction values gradually increased over the first 10 days, reaching a maximum of 30 kPa and showing daily temperature-related fluctuations and fluctuations due to rainfall. Unfortunately not all the tensiometers provided reliable suction measurements over the study period. For example, tensiometer T20_300 ceased to provide suction measurements around 22 April. However, based on the available suction record, it appears that the suction state in the tailings was on the flat plateau on the SWRC for the entire study period, as presented in Figure 4.

Suction trends matched each other closely for the three of the instruments, with suctions at 150 mm depth slightly exceeding those at 300 mm depth initially, as indicated by the measurement taken at 5 m offset from the daywall edge. The influence of deposition events is clearly evident, with the first event resulting in the complete dissipation of suctions. With subsequent events,

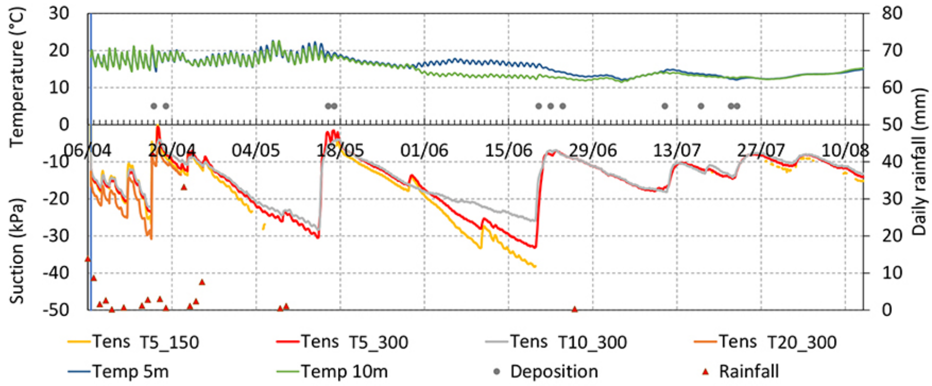

Figure 4—Pore pressure, temperature, rainfall, and deposition events over a four-month period after installation

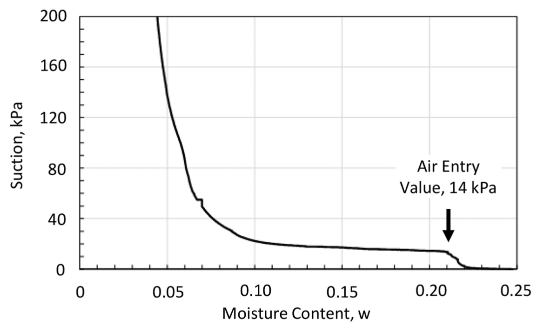

Figure 5—Gravimetric soil water retention curve for gold tailings

suction dissipation became progressively less as the thickness of tailings increased. After the June deposition events, the suction state remained quite constant during the winter months, varying between 8 kPa and 18 kPa.

The suction record shows that an average maximum suction value of approximately 30 kPa developed gradually following deposition-associated dissipation. These cycles would have resulted in some overconsolidation and strength gain of the tailings. The thickness of tailings reached approximately 1 m at the end of the record shown in Figure 4, which would have resulted in about 15 kPa of overburden pressure. The data illustrates how suction measurements can provide insight into the effective stress history imposed on tailings deposited on an active tailings dam as it repeatedly desaturates and becomes resaturated again. To assess whether this process has a temporary or permanent influence, these measurements needs to be coupled with void ratio and saturation measurements.

Future field instrumentation

To gain insight into the stress history of the material in the wall of a paddock-type upstream tailings dam, a new instrumentation programme is planned. Most instrumentation systems installed on tailings dams are only able to measure aspects of the soil state (*e.g.* pore pressure) and assumptions need to be made to fully define the soil state. To improve on this, the University intends to design and install an instrumentation system capable of measuring the complete soil state in an active tailings dam. The system will comprise total stress cells, high-capacity tensiometers, and volumetric water content sensors. The instruments will be placed in clusters at selected locations in the walls of active tailings dams, allowing them to be 'slimed in' during normal deposition to minimize installation conformance errors. Preparatory trials will be carried out in the laboratory, where better control over conditions during experiments is possible, prior to field installations. With both total stresses and pore pressures (measured by the tensiometers) known, the development of the effective stress path in an active dam can be tracked. An important aspect to be gained is an indication of the *in-situ* horizontal effective stress.

Research aspect 3: Laboratory testing

In order for undrained failure of a slope to occur, the material must be contractive (a sufficiently high void ratio), it must be saturated, and subjected to a trigger mechanism to initiate undrained loading (Take and Beddoe, 2014). Perhaps the most obvious trigger mechanism that comes to mind is a seismic event. However, as discussed earlier, South Africa is generally an area of low seismic hazard, and to the authors' knowledge seismic events have not to date resulted in damage to a tailings dam in South Africa. There are, however, other potential triggers. These could include events such as loss of confinement, overtopping, and significantly, static liquefaction. Static liquefaction occurs as a result of a loss of strength of loose contractive soils under undrained conditions (Olson *et al.*, 2000). Also potentially significant is a gradual increase in the water table, which then reaches a 'trigger' pressure, causing failure.

It is difficult to study the impact of trigger events and static liquefaction analytically or numerically, and although case studies are available of major tailings dam failures they provide limited scope to carry out sensitivity studies. Many examples of physical models studying landslides can be found in the literature (*e.g.* Eckersley, 1990) and these may be informative regarding the possible behaviour of tailings slopes. However, we are not aware of centrifuge model studies investigating the liquefaction behaviour of tailings dams. Based on the success of many studies of landslides in the centrifuge, it is likely that physical models may also provide valuable insight into the conditions under which liquefaction-type failure of tailings dams may occur. A physical model study has recently commenced at the University of Pretoria to model tailings slope failures in the geotechnical centrifuge in order to investigate the conditions under which such a failure can occur.

Centrifuge model

Figure 6 shows a model tailings slope constructed from gold tailings at an angle of repose of 34°, compacted using moist tamping in an attempt to create a contractile fabric (Reid and Fanni, 2020). The material was compacted to a void ratio of

0.95 at a gravimetric water content of 6.5%. The model scale was 1:60, implying a test acceleration of 60g. The 300 mm high slope therefore scaled to 18 m.

The intention was to trigger static liquefaction failure of the model slope. A trigger to impose during testing had to be selected. Chu *et al*. (2012) noted that drained failure resulting in monotonic shearing can act as a trigger for undrained instability and that the loss of shear strength during undrained instability may be of short duration. Monotonic loading in the form of a slowly rising fluid level was therefore imposed. A high water table, resulting in seepage at the toe, and toe instability are often causes of stability problems on tailings dams.

A pore fluid comprising a mixture of glycerine and water was used to provide a kinematic viscosity 60 times that of pure water. This is necessary in order to satisfy scaling laws for the latter of the two processes associated with a liquefaction event, namely contractive collapse of loosely packed particles into void spaces and the subsequent dissipation of excess pore pressure (Askarinejad *et al*., 2014). The slope was monitored with six pore pressure transducers, with two displacement transducers monitoring crest settlement. Photogrammetry was used to monitor the model in section.

The upstream side of the model slope was constructed against a well in which a constant fluid level could be maintained throughout the test. The well was separated from the slope using a needle-punched non-woven geotextile. After accelerating the model to 60g, the fluid level in the well was raised to just below the crest of the embankment. The pore fluid was allowed to seep into the model for the pore pressure regime to establish. The development of the pore pressure regime was monitored visually using cameras and pore pressure transducers.

Figure 7 presents pore pressure changes during the course of the centrifuge test. Pore water pressures generally decreased as the model dried out during testing, but then rose as they were influenced by the advancing wetting front. It took approximately 24 hours for the pore pressure regime to fully develop. As the fluid began to emerge at the toe of the slope, sloughing of the toe began to occur, slowly advancing backwards along the slope, with cracks gradually appearing parallel to the strike of the slope. At a certain point in time, the cracks propagated rapidly upwards against the slope and the slope failed suddenly, also illustrated by the spiking pore pressures in Figure 7.

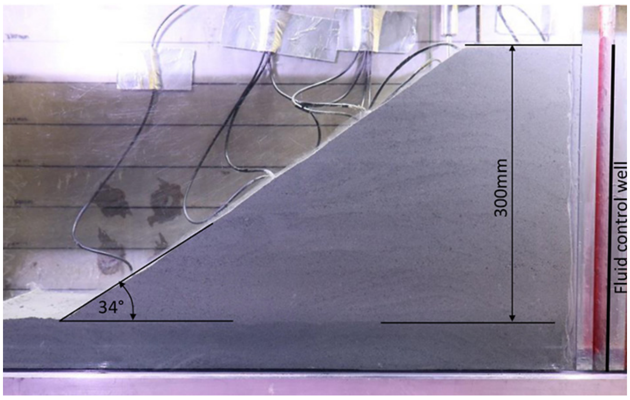

Figure 6—Model tailings slope

The failure surface was located slightly below the fluid level (shown as a dotted yellow line in Figure 8). Examination of the pore pressure response revealed a small increase in pore pressure at the base of the slope at the moment of failure, demonstrating contractive behaviour. Another aspect to note is that sloughing at the toe resulted in a local loss of confinement, often seen to be a factor in major tailings dam failures. The model slope failure demonstrated how drained instability can trigger undrained, or at least partially undrained, failure. The purpose of this discussion is to demonstrate the potential of centrifuge modelling as a means of studying tailings dam slope failures and a detailed analysis of the event falls outside the scope of the present paper. Further modelling is ongoing.

Conclusions

A number of high-impact tailings dam failures around the world in recent years have placed a renewed focus on the stability of tailings dams and pointed to potential shortcomings in traditional drained design and safely evaluation procedures. A need to consider undrained shear strength in the design of tailings facilities has become apparent. In the field, in addition to potentially unstable geometry, a number of conditions are necessary for undrained failure to occur, namely:

1. The material must be loose and of a contractive nature
2. The material must be saturated
3. A trigger initiating undrained shearing must occur.

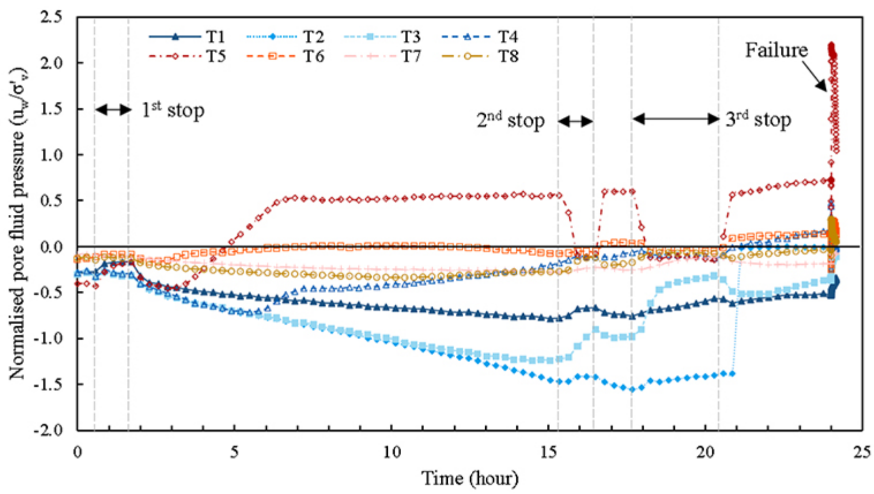

Figure 7—Pore pressure response during saturation and failure of the model slope (Crous, 2022)

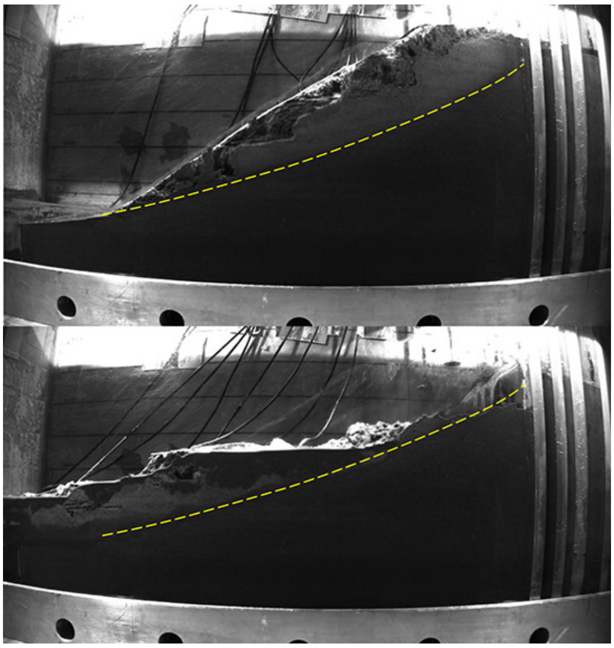

Figure 8—Before and after images illustrating slope failur

Large-scale flow failure of tailings dams is rare in South Africa, with the last major event probably being Merriespruit in 1994, despite hundreds of upstream tailings dams in the country, some of which are older than 100 years. It therefore appears that flow failures are rare because the triggers do not commonly occur.

Three aspects of research being undertaken at the University of Pretoria to investigate the requirements for undrained shearing were presented. These include high-quality sampling of tailings materials so that the *in-situ* state of the tailings can be determined, field monitoring to understand the stress imposed on the tailings during operation, and advanced laboratory testing to simulate undrained trigger mechanisms and observe the subsequent instability. Preliminary results from some of these studies were presented. The intent of this research is to improve the understanding of tailings behaviour, specifically in relation to undrained shearing in South African conditions. It is hoped that this will lead to the continued safe construction and operation of tailings dams in the country and around the world. This research is ongoing and additional results and analysis will be published as they become available.

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ESGS ENVIRONMENTAL SOCIAL GOVERNANCE SUSTAINABILITY

SAIMM COMMITTEE

THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

The Southern African Institute of Mining and Metallurgy (SAIMM), Environmental Social and Governance (ESG) and Sustainability (S)

The concept of 'ESG' although poorly defined, and possibly misunderstood has evolved from a real social need for global sustainability. The focus on ESG creates an awareness of the interlinkages of environmental, social, and governance aspects that are key to sustainable business practice.

Professionals play a significant role in helping society develop and attain a sustainable way of living. Due to their knowledge and skills, they are the potential providers of options and solutions to maximize social value and minimize environmental impact. They should work to enhance the welfare, health, and safety of all while paying due regard to environmental impact, biodiversity, and sustainability of resources. Professionals therefore need to be informed, committed, creative, and play an active role in the responsible management of the planet's ecosystems, and in so doing safeguard the security and prosperity of future generations.

The expertise and attitude of our members is crucial to effective environmental, social and governance engagement with industry, finance providers, government, organized labour, NGOs, other stakeholder groups, and the broader community to deliver sustainable social and economic benefits for the current economic climate and generations to come.

The role of the Southern African Institute of Mining and Metallurgy (SAIMM) in the promotion of ESGS is thus based on the premise that sustainability, and the contribution of the mining and minerals industry to society, is dependent on the professional and ethical conduct of minerals industry professionals – our members.

On this basis, the purpose and focus of the ESGS Committee is to build member capability, influence professional behaviour, and foster industry dialogue on sustainability and responsible mining through Environmental, Social, Governance, and Sustainability-related matters.

Key activities are:

- Building member capability through creating awareness and understanding, providing single-point access to relevant source and support material, and facilitating skills development.
- Thought leadership that adds meaning to the concept of responsible mining and the linkages to ESGS.
- Proactive guidance of Conference and Journal content to ensure that ESGS-related aspects are given sufficient prominence.
- Enabling industry and stakeholder dialogue to build shared understanding of opportunities and challenges and to find the common ground.
- Maintaining and expanding influence in the governance area, specifically minerals industry reporting codes, to ensure effective integration of ESGS aspects.
- Revision of the SAIMM Code of Conduct and associated governance materials to embrace the concept of responsible mining *e.g.* guidelines, responsibility statement, and membership requirements / obligations.
- Expansion of membership to provide a professional home for sustainability practitioners in Southern Africa.

To comment on this article or join the ESGS Committee send an e-mail to sam@saimm.co.za

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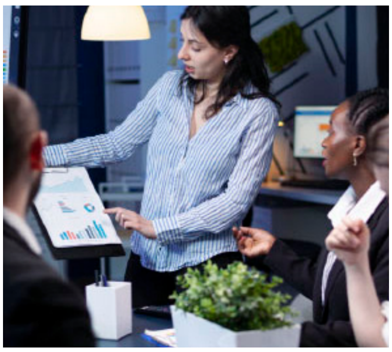

GOVERNANCE

SUSTAINABILITY

Creating Awareness
through statements of professional principles, codes of ethics, and guidance notes

Creating Understanding
of how professionals can contribute to minimising harm and maximising value to communities and broader society

Creating Competency
in environmental, social, governance and sustainability performance areas to mitigate the impact of business acitivity on communities and society.

A limit equilibrium approach to the use of stability bunds in the design of HDPE-lined tailings storage facilities

by J.D. Visagie[1] and T. Bezuidenhout[2]

Affiliation:
[1]SRK Consulting (Pty) Ltd, Johannesburg, South Africa.
[2]SRK Consulting (Pty) Ltd, Cape Town, South Africa.

Correspondence to:
J.D. Visagie

Email:
jvisagie@srk.co.za

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Synopsis

In recent years the requirements for a barrier system between the waste body of tailings storage facilities (TSFs) and the natural ground (NG) has necessitated the use of HDPE-lined TSFs in South Africa and other countries. The addition of an HDPE liner creates an interface between, *inter alia*, the tailings and surrounding soils on the footprint of the TSF. It is known that low-strength materials beneath slopes can cause slope instability. One method which can theoretically mitigate this instability of a lined TSF is the addition of stability bunds along the footprint of the TSF. Altering the profile of the footprint to include slope changes which oppose the direction of the failure creates passive slices in a limit equilibrium analysis. The passive slices actively oppose the movement of active slices, resisting the mobilization of tailings, thus greater active slice forces are required to develop a failure surface running along the liner interface. Two scenarios are presented and compared. The first scenario retains the ground profile unaltered and the second scenario includes stability bunds along the ground profile. An in-depth assessment is made of the interslice forces and the interface shear stresses for each scenario. The theoretical background is discussed in greater detail to determine the mechanisms of reinforcement provided by the bunds.

Keywords

TSF design, HDPE lining, stability bunds, limit equilibrium approach.

Introduction

In recent years the requirements for a barrier system between the waste body of a tailings storage facility (TSF) and the natural ground (NG) has necessitated the use of HDPE-lined TSFs. As specified in Government Notice R636 of the National Norms and Standards for the Assessment of Waste to Landfill, (South Africa, 2013), material classified as a Type 1 to 4 waste requires the inclusion of a Type A to D landfill containment barrier. Landfill containment barrier classes A to C specifically require the inclusion of an HDPE geomembrane in the barrier system.

By introducing a geomembrane along the natural ground surface at the base of a TSF, a weak layer is created at the interface between the geomembrane and the surrounding materials. The failure plane, as determined from stability analyses, is naturally inclined towards the weak layers as these provide less resistance to shear failure. This has major implications for the overall stability of the system.

With the arrival of the Global Industry Standards on Tailings Management (GISTM), more emphasis has been placed on safety with regard to TSFs. In order to conform to the requirements of GISTM, new innovative ways need to be explored to manage the stability and safety of TSFs.

One such method to improve the stability of a TSF is to alter the failure plane by including stability bunds along the interface between the tailings and geomembrane to improve the global factor of safety (FoS). A FoS can simply be defined as the ratio between the shear strength of the soil resisting movement and the shear stress applied to the slip surface by the active slices. This is fundamental in understanding the benefit of stability bunds.

The basic principle behind the stability bund can be thought of conceptually as an asperity between two shearing surfaces, as shown in Figure 1. A planar discontinuity will yield a frictional resistance proportional to the base-normal stress (Figure 1a). With irregularities in the form of an asperity, additional work is required to overcome the interlocking effect, either by sliding over or shearing off the asperity, as shown in Figure 1b. These irregularities control deformation behaviour by either causing

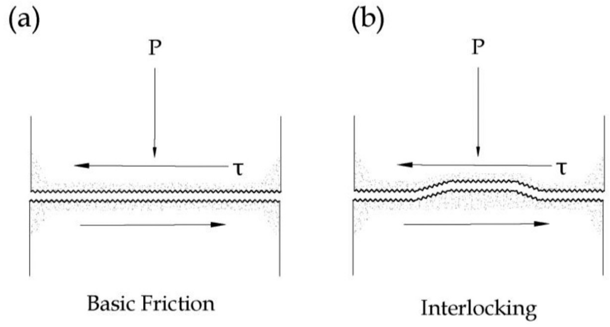

Figure 1—Effect of an asperity between two sliding surfaces

dilation in the adjacent material (riding-over) or shearing horizontally through the asperity along the shear direction (Kwon, Baak, and Cho, 2009).

It should be noted that all symbols are described in the Nomenclature section at the end of the paper. To demonstrate the global improvement to the FoS, two limit equilibrium (LE) analyses are compared using the Morgenstern and Price (1965) method. For the first scenario the basin of the TSF was kept unaltered while in the second scenario stability bunds were included along the interface. To further explain the impact of interslice forces, a comparison is made between the Morgenstern and Price method and the ordinary or Fellenius method, which does not take interslice forces into account. Specific attention is given to the interslice force mechanics from a theoretical and LE perspective. The addition of computer-assisted graphical representation of the slice data allows users to interrogate the results of the LE analyses in more detail.

Theoretical background

Interslice force mechanics

Slope failure, or the downslope movement of soil, rock, or tailings masses, occurs as a result of shear failure at the boundaries of the sliding mass (Eid *et al*., 2006). There are numerous types of failure mode which could occur, of which the most common are either rotational or translational failure modes, or a combination of the two referred to as compound slips. As these are very basic failure modes and are not necessarily representative of actual conditions, it is imperative that all possible modes of failure be checked to avoid over-estimating the FoS of the system.

Translational sliding modes are commonly subdivided into three categories, namely slab-sheet, block, and wedge slide. Residual shear strength is mobilized in soils when sliding through a pre-existing failure surface, as a result of low shear strength at the base. Heterogeneity located beneath the slope surface in the form of a stronger material underlain by a weaker material creates a planar shear surface and predominantly translational slide movement. With the presence of an interface between a geomembrane and the tailings mass, translation along the base with a linear or rotational back-surface failure is most likely (Qian, Koerner, and Gray, 2003). The tensile strength of the geomembrane can be deemed negligible as it is nominal in relation to the shear stress associated with the large failure mass. It is important that designers fundamentally assess the interface effects on the structure. Thus, accurate material-specific interface shear strengths of the various interfaces are necessary.

For translational stability evaluation it is quite appropriate to use block LE techniques employing wedges or a planar configuration in which the weakest layers are known or can be estimated. A two-wedge method was developed by Qian, Koerner, and Gray (2003) as a piecewise linear LE approach to analyse possible block movements along a geomembrane in landfills. This method can be used to analyse translational slope failure in a TSF underlain with a liner. Figure 2 shows a simplified cross-section of a TSF slope, displaying a two-wedge system for analysing translational failure. It should be noted that care must be exercised when using this method with regard to the location of the failure surface during preliminary design.

In Figure 2, zone 1 acts as a passive wedge resisting the downward movement of zone 2, which acts is the active wedge. The lateral movement of the active wedge is a result of gravitational movement of the soil mass. Zone 3 is assumed to act as a stationary wedge and is held in place by force equilibrium. Translational movement is as a result of the active wedge driving the passive wedge laterally along the failure plane. The frictional resistance along the failure plane counteracts the effects of deformation. The free body diagrams of the active and passive wedges are presented in Figure 3.

With the objective of calculating the contribution to shear strength, while maintaining equilibrium, the static force equilibrium equations can be derived from the parameters presented in Figure 3. For brevity, the derivation is not shown; however, the equations for normal forces acting at the base of the passive and active wedge and inter-wedge horizontal forces are shown below in Equations 1 to 4.

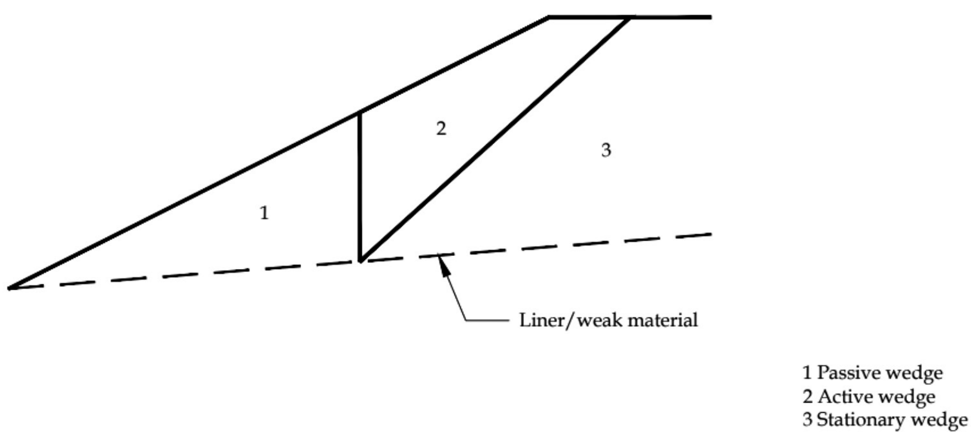

Figure 2—Simplification of a two block wedge system of a TSF slope (Howell and Kirsten, 2016)

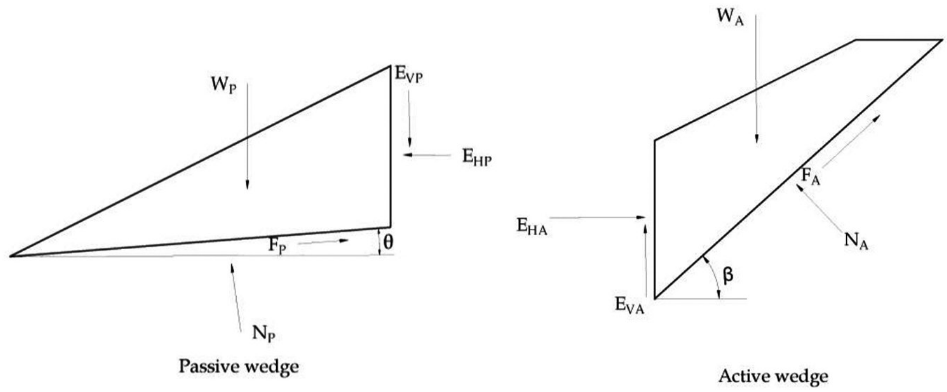

Figure 3—Free body diagram of forces acting on zone 1 and zone 2 (Howell and Kirsten, 2016)

$$N_p = \frac{E_{HP}}{\frac{cos\theta tan\delta_P}{FoS} - sin\theta} \quad [1]$$

$$E_{HP} = \frac{W\left(\frac{cos\theta tan\delta_P}{FoS} - sin\theta\right)}{\left(cos\theta + \frac{sin\theta tan\delta_P}{FoS_P} - \frac{m_{sw}cos\theta tan\delta_P}{FoS_P} + m_{sw}sin\theta\right)} \quad [2]$$

$$N_A = \frac{E_{HA}}{sin\beta - \frac{cos\beta tan\delta_A}{FoS_A}} \quad [3]$$

$$E_{HA} = \frac{W_A(sin\beta - \frac{cos\beta tan\delta}{FoS_A})}{cos\beta + \frac{sin\beta tan\delta_A}{FoS_A} + sin\beta m_{sw} - \frac{cos\beta tan\delta_A m_{sw}}{FoS_A}} \quad [4]$$

Equation [1] to Equation [4], together with the equality $E_{HP} = E_{HA}$, show the net resistance. This expression is best solved with the aid of a spreadsheet to test the parameters. This model is very powerful in promoting understanding of the engineering processes involved. Cohesion and tension in the liner can easily be calculated by adding a term to Equation [4] (Howell and Kirsten, 2016). Design calculations can be carried out quickly and efficiently to evaluate the shear strength gain by introducing a stability bund into the two-slice model, as will be shown later. More sophisticated numerical modelling can be conducted once the fundamental design is understood.

Limit equilibrium

General limit equilibrium (GLE) formulation

The general limit equilibrium (GLE) equations were developed by Fredlund at the University of Saskatchewan in the 1970s (Fredlund and Krahn, 1977; Fredlund, Krahn, and Pufahl, 1981). The GLE equations consist of two FoS equations, with respect to moment equilibrium (F_m) and force equilibrium (F_f), and allow for a range of interslice shear force directions.

Initially, LE equations were developed for base-normal forces primarily influenced by gravity, while disregarding the impact of normal and shear forces acting on the sides of the slices. Methods have since been developed which consider interslice forces. Interslice shear forces in the GLE method are determined through Equation [5], developed by Morgenstern and Price (1965).

$$X = E\lambda f(x) \quad [5]$$

The Morgernstern and Price (1965) method allows for $f(x)$ to be defined by the user, while other methods assume a fixed function to describe the ratio between normal and shear interslice forces. Equations [6] and [7] present the GLE FoS equations with regard to moment equilibrium and force equilibrium, respectively.

$$F_m = \frac{\Sigma[c'\beta R + (N - u\beta)R\ tan\ \phi']}{\Sigma Wx - \Sigma Nf \pm Dd} \quad [6]$$

and

$$F_f = \frac{\Sigma[c'\beta \cos\alpha + (N - u\beta)\tan\phi' \cos\alpha]}{\Sigma N \sin\alpha - D \cos\omega} \quad [7]$$

The key variable in both FoS equations is the normal stress at the base of each of the slices, determined through satisfying vertical force equilibrium. Utilizing GLE formulation, the base-normal force is determined through Equation [8].

$$N = \frac{W + (X_R + X_L) - \frac{c'\beta sin\alpha + u\beta sin\alpha tan\phi'}{FoS}}{cos\alpha + \frac{sin\alpha\ tan\phi'}{FoS}} \quad [8]$$

As can be seen in Equation [8], the base-normal forces are dependent on interslice shear forces. The value of N is therefore sensitive to the method, as well as the function used to define the interslice shear forces. Calculating the base-normal forces is an iterative process as the equation is dependent on the global FoS of the system. The denominator in Equation [8] is often referred to as m_α and will be referred to as such in the remainder of this paper.

Morgenstern and Price (1965) method

A mathematically more rigorous method was selected for this study to account for the interslice shear and normal forces, the complex geometry of the basin, and a composite slip surface. Simpler methods do not all consider the impact of interslice forces and do not satisfy both moment and force equilibrium. The Morgenstern and Price method was used in this study for the following reasons:

- ➤ Both moment equilibrium and force equilibrium are satisfied
- ➤ Both interslice normal and shear forces are considered
- ➤ The interslice force function can utilize user-defined functions to determine the ratio between interslice normal and shear forces.

A constant interslice force function specified in the Morgenstern and Price method corresponds with the Spencer method. For the purposes of this paper a half-sine function was specified to define the ratio between normal and shear interslice forces as it concentrates the interslice shear forces towards the centre of the sliding mass, where the focus of the study lies.

Ordinary or Fellenius method

To define the effect that interslice forces have on the normal and shear stresses of each slice the ordinary or Fellenius method will be used as a baseline comparison against the Morgenstern and Price method, as interslice forces are neglected. The values determined using the ordinary or Fellenius method considers only gravitational forces in determining the normal force at the base of the slices. As a result, the equation for the base-normal forces differs from that of GLE formulation, as shown in Equation [9].

$$N = W\cos\alpha - kW\sin\alpha + [D\cos(\omega + \alpha - 90)] \quad [9]$$

The variation between the normal forces determined by the ordinary/Fellenius method and the GLE formulation can then be ascribed to the presence or absence of interslice forces.

Slip surfaces

For a circular slip surface, moment equilibrium is independent of interslice shear forces while force equilibrium is sensitive to interslice shear forces. For a planar slip surface, force equilibrium is independent of interslice shear forces while moment equilibrium is sensitive to interslice shear forces.

As the problem is defined by the existence of a weak layer or plane, and is in essense considering the stability of a slope, both moment and force equilibrium are sensitive to interslice shear forces. A composite slip surface was considered as it acts as a combination of other standard slip surface shapes. As the Morgenstern-Price method is based on GLE formulation, it is not restricted by the shape of the slip surface.

Limitations

LE analyses are based purely on statics and do not necessarily give an accurate representation of actual stresses and displacements in the system. This is due to the fundamental assumptions which have to be made to provide a reasonable global FoS as stated by Krahn (2003), namely:

- ➤ The forces acting on each slice have to be calculated to ensure that force equilibrium (F_f) is satisfied
- ➤ The forces acting on each slice have to be calculated to provide a single FoS for each of the slices and the global system.

The overall FoS only provides a measure of the average stress mobilized in the slope (Morgenstern and Sangrey, 1978); however, it can still be considered realistic as the local irregularities are smoothed out as the driving forces and base resisting forces are integrated into the analysis (Krahn, 2003).

While LE methods are not capable of providing detailed stress, strain, and deformation outputs, they can be beneficial when used as a tool to understand the nature and mechanisms of failure. Howell and Kirsten (2016) highlighted two key benefits of LE:

- ➤ It forces the user into inductive (as opposed to deductive) reasoning by asking what the mechanism of failure could be
- ➤ It requires the calculation of basic first-principle forces and counter forces.

An added benefit to using LE is that it has been utilized for determining FoS for many years. As a result, it has been calibrated through experience and observations, which cannot be said for newer methods (Krahn, 2003).

Analysis

Limit equilibrium analysis

Initial LE analyses were completed for two scenarios to determine the overall impact of stability bunds along the weak layer. For scenario 1, the basin of the TSF remained unaltered, while in scenario 2, stability bunds were included along the basin of the TSF altering the path of the weak plane so as to run over the stability bunds. An undrained analysis was considered for the LE analyses and was done using Rocscience Slide2 software (Rocscience, 2020). The basic geometries of the models is presented in Figure 4. The material properties used in the analyses are presented in Table I.

The liner interface considered the lower friction angle obtained between the liner and the tailings, and the liner and the foundation material. The results from scenario 1 and scenario 2 are presented in Figure 5 and Figure 6, respectively. Figure 7 shows the path of the failure surface over the bunds in scenario 2.

Table I

Material properties

Material Type	Unit weight (kN/m³)	Saturated unit weight (kN/m³)	Strength type	Cohesion (kPa)	Friction angle (deg)	Vertical strength Ratio	Minimum shear strength (kPa)
Starter wall/stability bunds	19	19.6	Mohr-Coulomb	0	26	-	-
Tailings - underflow	22	22.6	Mohr-Coulomb	0	36	-	-
Tailings -overflow	19	19.5	Mohr-Coulomb	0	34	-	-
Tailings - overflow (undrained)	19	19.5	Vertical stress ratio	-	-	0.22	20
Liner interface	20	-	Mohr-Coulomb	1	12	-	-

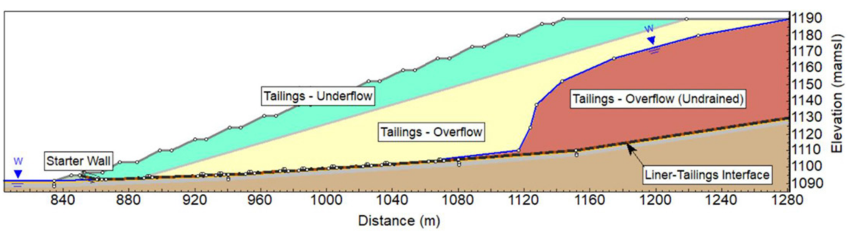

Figure 4—Basic geometry of limit equilibrium analysis scenario 1

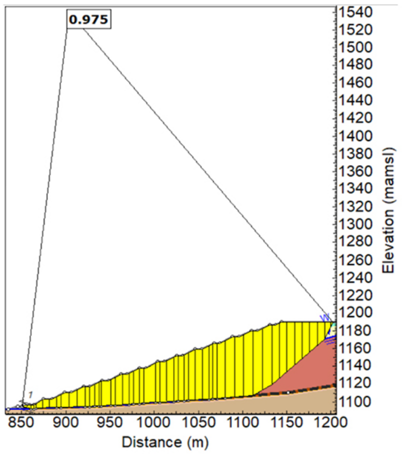

Figure 5—FoS obtained for scenario 1

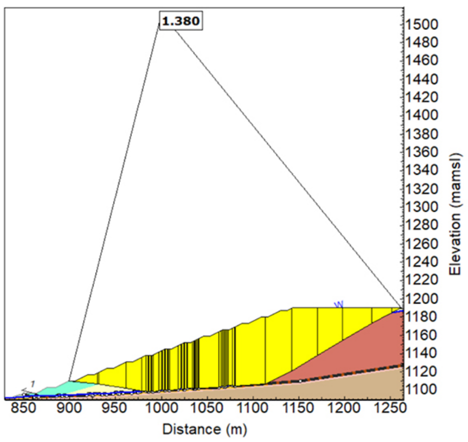

Figure 6—FoS obtained for scenario 2

As can be seen from Figure 5, the slip surface runs along the weak layer at the base of the TSF and exits the TSF near the toe above the starter wall. Scenario 1 resulted in a global FoS of 0.975, which indicates instability. It can be seen in Figure 6 that the slip surface in scenario 2 is also inclined to run along the weak layer, following the geometry of the bunds. The overall FoS for scenario 2 was 1.38. It is clear from these examples that the addition of bunds improves the overall FoS of the slope. The mechanics of why this happens is discussed in following sections.

A significant observation regarding the two scenarios is the difference in the path of the failure surface near the toe of the TSF. Scenario 2 shows how the failure surface diverges from the weak layer and cuts through the stronger tailings material above the toe. This signifies that the resistance to shear, provided by the bunds along the weak plane, is greater than the shear resistance of the tailings material, forcing the failure surface away from the interface.

To understand why the global FoS improves, attention should be given to the slice mechanics of the failure surface. Specific attention should be given to the following:

- The inclination of the slice base
- m_α as previously defined
- The base-normal stress.

Figure 8 plots the change in base topography along with m_α, over the distance where the failure surface intercepts the weak layer in both scenarios 1 and 2.

Figure 8 shows that m_α is consistently lower in scenario 2 than in scenario 1. However, the average variation between the two scenarios can be explained by the iterative nature of Equation [10], with the inclusion of a FoS. What is of significance is the fluctuations of m_α between the sides of the stability bunds. Consider the definition of m_α as defined by Equation [10].

$$m_\alpha = \cos\alpha + \frac{\sin\alpha \tan\phi'}{FoS} \qquad [10]$$

Considering the term 'sin α' in the second part of the equation, it is possible that a negative base inclination, relative to the direction of slippage, will cause the second part of the equation to become negative. This then decreases the value of m_α which, in turn, will increase the base-normal force, increasing the FoS. The negative sign in the numerator of Equation [8] will also change to positive, as a consequence of sin α being negative, further increasing the base-normal force. The opposite applies for slices on the downstream side of the stability bunds where sin α causes base-normal stresses to decrease. This also explains the sudden decrease in the value of m_α on the resisting side of the stability bund. The effect of m_α on the base-normal stresses is demonstrated in Figure 9.

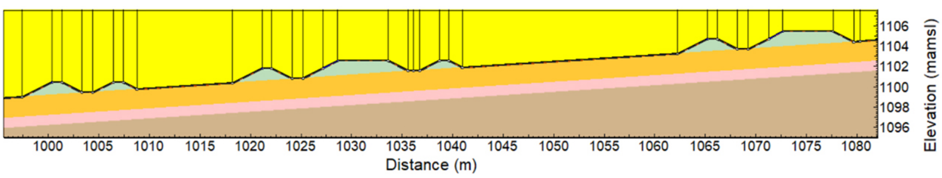

Figure 7—Failure surface over stability bunds

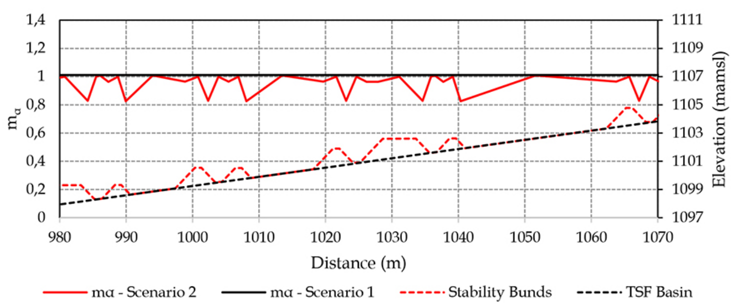

Figure 8—Change in m_α plotted against the change in basin topography

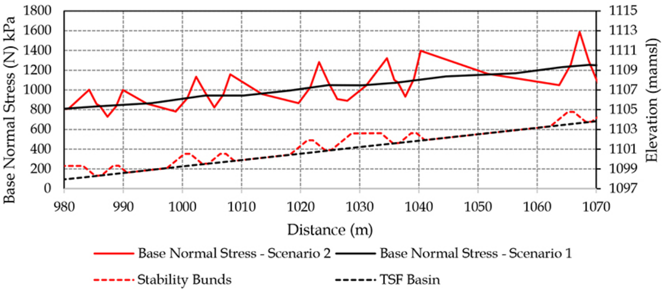

Figure 9—Change in base-normal stresses plotted against change in basin topography

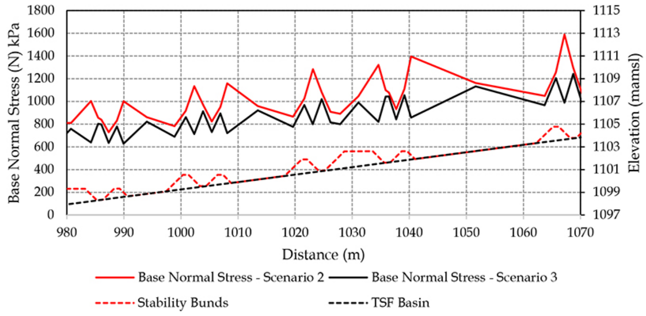

Figure 10—Change in base-normal stresses, between the Morgenstern and Price method and the ordinary or Fellenius method, plotted against change in basin topography

As can be seen in Figure 9, the base-normal stress on the resisting side of the bunds is significantly greater than that on the opposite side of the bund, which is consistent with the values of m_α presented in Figure 8. The higher base-normal forces on the resisting side of the bunds are beneficial in resisting the active mobilization forces of the sliding mass. However, the reason for the higher normal forces has only been defined from LE formulation. To define this occurrence from a force equilibrium point of view it would be beneficial to compare the base-normal stresses obtained with the Morgenstern and Price (1965) method to that of the ordinary or Fellenius (1936) method.

For scenario 3 the same conditions were applied to the LE model as in scenario 2, however, the overall FoS was determined using the ordinary or Fellenius (1936) method. Figure 10 shows the base-normal stresses for both scenarios 2 and 3 over the distance where the slip surface intercepts the weak layer.

It is clear from Figure 10 that the base-normal stresses in scenario 3 do not show such significant fluctuations as in scenario 2. The change in base inclination decreases the base-normal stress on the resisting sides of the bund, the opposite of what was observed for scenario 2. The ordinary or Fellenius (1936) method considers only gravitational forces to determine the base-normal force while neglecting interslice shear forces. The variance between the base-normal forces in scenarios 2 and 3 can therefore be attributed to the presence or absence of interslice shear forces in the formulation. The FoS obtained using the ordinary or Fellenius (1936) method was 1.217, which is lower than that obtained using the Morgenstern and Price (1965) method which gives a FoS of 1.38.

Interslice force mechanics

With the inclusion of the stability bund in the passive wedge, the passive wedge in the two-block method is subdivided into slices as shown in Figure 11.

When analysing interslice force mechanics using block LE techniques the resultant forces thus act against E_{HA} so that E_{HP} (wedge 1) + E_{HP} (slice 6) + E_{HP} (slice 5) + E_{HP} (slice 4) = E_{HPA} to maintain static equilibrium. The free body diagrams of wedge 4 and 2 are shown in Figure 12. It is assumed that the normal and shear forces on the base and the inclined interfaces all obey the Mohr–Coulomb criterion.

The resultant interslice shear force thus works in the resisting direction against the active wedge and E_{HP4} and E_{V4} are included in E_{VP5} and E_{HP5} so that $E_{HP5} < E_{HP}$ and $E_{VP5} < E_{VP}$. The derivation of Equation [1] and [2] thus holds true for E_{HP5} and N_{VP4}. From wedge 4, a change in the base inclination results from the upstream slope of the stability bund. From Equation [1] and [2], reversing the base inclination results in the following:

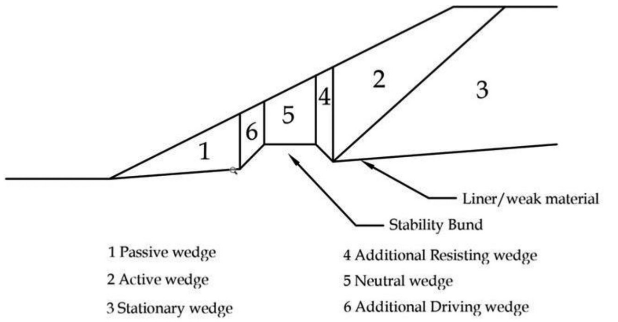

Figure 11—Simplification of a block wedge system of a TSF slope with the inclusion of stability bunds

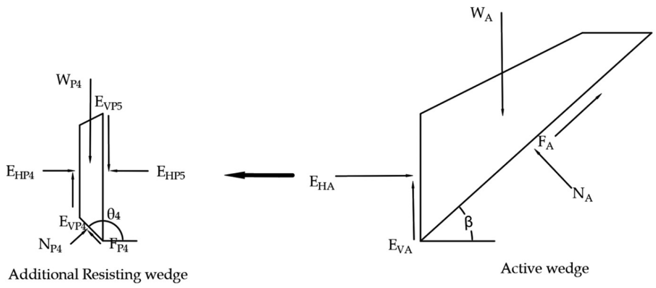

Figure 12—Free body diagrams of forces acting on wedge 2 and wedge 4

- ➤ The horizontal component of the base-normal force changes direction, acting against the active movement of wedge 2
- ➤ The negative base inclination will cause a sign convention change for all terms containing sin θ. The change in sign convention will decrease the value of the denominator in Equation [2] while increasing the numerator, thus increasing E_{HP} (the resistance against the active wedge)
- ➤ As E_{HP} is a parameter in Equation [1], N_P will also increase as a result of an increase in E_{HP}.

Implementation

To promote maximum shear strength in resisting slope movement, stability bunds should be placed where translation takes place at the base of the slope failure (a Active wedge). It is up to the designer to scrutinise the model and find the maximum FoS, by including stability bunds within the known failure plane. Stability bunds could shift the failure plane either through the sliding mass or through the foundation material below the liner. The stability bunds will add complexity to the construction and practical considerations should be taken with regard to constructability.

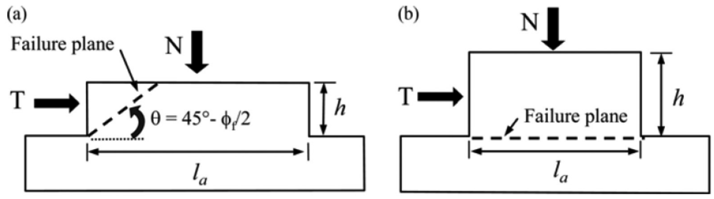

Figure 13—Shear failure modes of rectangular-shaped asperities (a) Dilative failure, and (b) Non-dilative failure (Kwon, Hong, and Cho, 2009)

Kwon, Hong, and Cho (2010) defined a calculation procedure for shear behaviour of rectangular-shaped asperities using rigid body force equilibrium. Kwon, Baak, and Cho(2004) showed that, contrary to triangular asperities, rectangular asperities will break with a dilative failure mode. This is shown by the shear behaviour of a rectangular-shaped asperity (Figure 13).

An aspect ratio for the asperity in the form of height (h) to length (l_a) can be used to determine the mode of failure. Thus, the critical aspect ratio depends on the normal stress, the cohesion, and the peak friction angle (Kwon, Hong, and Cho, 2010). To promote dilative failure (Figure 13a), stability bunds should be constructed at low aspect ratios. High aspect ratios will cause failure horizontally along the shear direction (Figure 13b). The critical aspect ratio is most sensitive to the peak friction angle, proportional to the cohesion, and inversely proportional to the normal stress. The shape of a stability bund is governed by the internal friction angle of the material used in the construction. Thus, the most practical form for a stability bund would be trapezoidal (Kwon, Hong, and Cho, 2010).

The slope angles of the stability bund can be determined by a dilatant angle equal to Rankine's passive pressure 45^{o}-$\phi_f/2$. The angle of a failure plane to shear direction is dependent only upon the peak friction angle (Kwon, Baak, and Cho 2004).

Convergence of the FoS is sensitive to the slice base inclination. As the inclination increases, the denominator of Equation [5], also defined as m_α, either increases or decreases, which can eventually lead to a value of m_α computing a base-normal stress which does not satisfy the force equilibrium of the slice. This will lead to nonconvergence of the FoS, which is solved through iterative techniques. This will occur as the sides of the bunds are near vertical.

Conclusions and recommendations

Providing stability bunds along an expected weak plane will improve the FoS along that plane, when considering LE techniques. However, it is not recommended that stability be completely reliant on the provision of stability bunds, as LE techniques do not accurately define the stress state of the bunds.

Considering interslice shear mechanics, the following conclusions can be drawn.

- ➤ The horizontal component of the base-normal force on the resisting side of the stability bunds changes direction, acting against the active movement of the sliding mass.
- ➤ The negative base inclination will cause a sign convention change for all terms containing sin θ in Equation [2]. The change in sign convention will decrease the value of the denominator in Equation [2] while increasing the numerator, thus increasing resistance against the active movement of the sliding mass.
- ➤ As E_{HP} is a parameter in Equation [1], the base-normal force on the resisting side of the stability bunds will also increase as a result of an increase in E_{HP}.

Considering LE techniques, the following conclusions can be drawn:

- ➤ Considering Figures 5 and 6, a general improvement in the global FoS of a slope was observed with the inclusion of stability bunds along the interface between a geomembrane and the surrounding materials.
- ➤ As can be seen in Figure 8, a change in base inclination on the resisting side of the stability bunds decreases the value of m_α, which essentially increases the base-normal stress, as demonstrated in Figure 9.
- ➤ Comparing the base-normal stresses acting on the stability bunds between the ordinary or Fellenius (1936) method and the Morgenstern and Price (1965) method (Figure 10) it is clear that the inclusion of interslice forces in, specifically, the Morgenstern and Price (1965) LE formulation results in a greater base-normal stress acting on the resisting side of a stability bund than on the active side.

It is recommended that in order to accurately define the stress, strain, and deformation characteristics of stability bunds, that analysis methods that consider the stress-strain relationship of the materials present be considered. Such methods would include finite element analyses or using finite element based stresses in a LE analysis.

Nomenclature

$f(x)$	-	User defined function for the distribution of interslice shear forces
λ	-	Percentage of the specified function used in the analysis
E	-	Interslice normal forces
X	-	Interslice shear forces
c'	-	Effective cohesion
φ'	-	Effective friction angle
u	-	Pore -water pressure
W	-	Slice weight
D	-	Applied line load
$\beta, R, x, f, d, \omega$	-	Geometric parameters
α	-	Inclination of the slice base
N, P	-	Base-normal force
T	-	Shear force
H	-	Height of rectangular asperity
l_a	-	Length of rectangular asperity

Θ	-	Base angle of passive wedge measured from horizontal
Θ_4	-	Base angle of passive wedge 4 measured from horizontal
β	-	Base angle of active wedge measured from horizontal
δP	-	Interface friction angle of liner components beneath passive wedge
δ_A	-	Interface friction angle of liner components beneath active wedge
W_P	-	Weight of passive wedge
W_{P4}	-	Weight of resisting wedge 4
W_A	-	Weight of active wedge
N_P	-	Normal force acting on the bottom of passive wedge
NP_4	-	Normal force acting on the bottom of resisting wedge 4
N_A	-	Normal force acting on the bottom of active wedge
F_P	-	Frictional force acting on the bottom of passive wedge
F_{P4}	-	Frictional force acting on the bottom of resisting wedge 4
F_A	-	Frictional force acting on the bottom of active wedge
E_{VP}	-	Frictional force acting on side of passive wedge
E_{VP4}	-	Frictional force acting on side of resisting wedge 4
E_{VP5}	-	Frictional force acting on side of resisting wedge 4
E_{VA}	-	Frictional force acting on side of active wedge
E_{HP}	-	Normal force from active wedge acting on passive wedge
E_{HP4}	-	Normal force from resisting wedge 5 acting on passive wedge
E_{HP5}	-	Normal force from active wedge acting on resisting wedge 4
ϕ_{sw}	-	Internal friction angle of solid waste
m_{sw}	-	Tan ϕ_{sw} /FoS
FoS_P	-	Factor or safety for the passive wedge
FoS_A	-	Factor or safety for the active wedge
φ_f	-	Rankine's strength paramter
X_R	-	Interslice shear force on the right of the slice
X_L	-	Interslice shear force on the left of the slice

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Practical steps to Global Industry Standard on Tailings Management (GISTM) compliance for operational tailings storage facilities in South Africa

by S.D. Dladla[1] and S. Ramsamy[1]

Affiliation:
[1]Fraser Alexander, Johannesburg, South Africa.

Correspondence to:
S. Ramsamy

Email:
shaunr@fraseralexander.co.za

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Synopsis

The majority of the tailings dam operations in South Africa will be required to comply with the new Global Industry Standard on Tailings Management (GISTM) within the next one to three years, depending on the dam classification and the requirements of the respective investors and insurers. With up to 72 auditable requirements, the implementation of the Standard needs careful planning and prioritization. This paper focuses on the practical steps to GISTM compliance for tailings facilities in operation in South Africa. The discussions are based on current practices, South African regulations, and industry standards requirements. The possible changes in dam classifications and the associated requirements are presented.

Keywords

tailings management, GISTM, ICMM, SANS, standards.

Introduction

All International Council on Mining and Metals (ICMM) members have committed to implement the Global Industry Standard on Tailings Management (GISTM) on their tailings dam operations. The commitment compliance date for facilities with 'Extreme' or 'Very high' potential consequences is 5 August 2023, and all other tailings facilities in operation must be in conformance with the Standard by 5 August 2025. Given how close these dates are and considering that there are as many as 77 auditable requirements, the implementation of the Standard needs careful planning and prioritization.

In this paper we focus on the practical steps to GISTM compliance for tailings facilities in operation in South Africa, based on the current practices, South African regulations, and industry standards requirements.

In order to identify areas that are already sufficiently covered within the South African context, and areas that will need more attention during the GISTM compliance journey, we first give a high-level comparison between the requirements of the GISTM and those of the South African regulations and standards.

We also briefly look at the conformance protocol document, which gives guidance on levels of conformance with the Standard.

The proposed GISTM compliance process is presented, together with suggestions on the initial GISTM project set-up and critical appointments.

The dam classification method based on the South African Code of Practice for Mine Residue Deposits, SANS 10286 (SABS, 1998), is compared with the method described in the GISTM, and the major differences are highlighted together with the likely factors affecting the final new dam classifications.

The potential changes to the operations based on the GISTM are discussed.

Other related topics that are covered in this paper include the addressing of the brittle failure requirement, upgrading of dam monitoring instrumentation, implementation of information systems, and the required communication with interested and affected parties during the implementation process.

The Global Industry Standard on Tailings Management

Following the catastrophic tailings dam collapse at Vale's Córrego de Feijão mine in Brumadinho, Brazil on 25 January 2019, the need for a global tailings management standard to prevent similar failures in the future and to seek transparency regarding the management and executive oversight of the residue facilities was identified.

The Global Tailings Review initiative was co-convened with a multidisciplinary expert panel, which included the ICMM, the United Nations Environment Programme (UNEP), and Principles for Responsible Investment (PRI), who headed up the review. The GISTM (ICMM, 2020), which was launched in August 2020, was developed with input from a multi-stakeholder advisory group. The review involved extensive public consultation with affected communities, government representatives, investors, multilateral organizations, and mining industry stakeholders and is informed by existing best practice and findings from past tailings facility failures.

The GISTM is organized around six Topic areas and covers 15 main Principles, and has 77 auditable Requirements.

The GISTM is supported by the Conformance Protocols and Good Practice and Documents, both released by the ICMM in May 2021 (ICMM 2021a, 2021b)

The GISTM Requirements *vs* the South African regulations

South Africa is considered as one of the leading countries when it comes to the tailing-related regulations and standards which are aimed at preventing tailings dam failures.

SANS 10286 is based on the ISO management principles and provides a good base for tailings management in general. The mining and engineering companies were the key contributors in the establishment of these standards.

The South African legislation and standards were included in the comparative analysis of tailings-related legislation of key mining jurisdictions by Campbell *et al.* (2019), who looked at how various countries' regulations address the requirements of the GISTM principles. The scoring criteria are shown in Table I and the results are shown in Table II.

Table I

Comparative analysis scoring criteria

Score	Scope of legislation in key jurisdictions compared with the Standard
1	'*Not Addressed*' (*i.e.*, there is no applicable legislation addressing the Principle)
2	'*Minimally Addressed*' (*i.e.*, the elements of the Principle are marginally or peripherally addressed in regulation)
3	'*Partially Addressed*' (*i.e.*, most but not all elements of the Principle are addressed in the legislation, or all elements of the Principle are addressed but to a lesser standard)
4	'*Comprehensively Addressed*' (*i.e.*, the elements of the Principle are addressed in legislation to about the same level as the Standard)
5	'*Higher Standard*' (*i.e.*, all elements of the Principle are addressed more comprehensively and/or more strictly in the legislation than the Standard)

Table II

The South African tailings-related regulation scores against the Standard by Principle

The 15 GISTM Principles	Score
Principle 1: Respect the rights of project-affected people and meaningfully engage them at all phases of the tailings facility lifecycle, including closure.	3
Principle 2: Develop and maintain an interdisciplinary knowledge base to support safe tailings management throughout the tailings facility lifecycle, including closure.	4
Principle 3: Use all elements of the knowledge base – social, environmental, local economic and technical – to inform decisions throughout the tailings facility lifecycle, including closure.	3
Principle 4: Develop plans and design criteria for the tailings facility to minimise risk for all phases of its lifecycle, including closure and post-closure.	5
Principle 5: Develop a robust design that integrates the knowledge base and minimises the risk of failure to people and the environment for all phases of the tailings facility lifecycle, including closure and post-closure.	4
Principle 6: Plan, build and operate the tailings facility to manage risk at all phases of the tailings facility lifecycle, including closure and post-closure	4
Principle 7: Design, implement and operate monitoring systems to manage risk at all phases of the facility lifecycle, including closure	4
Principle 8: Establish policies, systems and accountabilities to support the safety and integrity of the tailings facility	3
Principle 9: Appoint and empower an Engineer of Record	2
Principle 10: Establish and implement levels of review as part of a strong quality and risk management system for all phases of the tailings facility lifecycle, including closure	4
Principle 11: Develop an organisational culture that promotes learning, communication and early problem recognition	4
Principle 12: Establish a process for reporting and addressing concerns and implement whistle blower protections	4
Principle 13: Prepare for emergency response to tailings facility failures	2
Principle 14: Prepare for long term recovery in the event of catastrophic failure	3
Principle 15: Publicly disclose and provide access to information about the tailings facility to support public accountability	3

The results showed that the current South African requirements meet or exceed the requirements of the GISTM in most areas. The two areas where the scores were low, Principle 9 (appointment and empower an EOR) and Principle 13 (prepare for emergency response of tailings facility failures), are covered in SANS 10286 and the Mine Health and Safety Act No. 29 of 1996 (MHSA).

The current scope of the MSHA Reg. 2.6.1 technical appointment has similar objectives to that of the Engineer of Record (EOR). The term EOR was coined in North America and has therefore only recently been adopted by the industry in South Africa.

The Emergency Preparedness Plan is required by the MHSA as part of the Mandatory Code of Practice (required as per Section 9(2) of the MHSA and the Chief Mine Inspector directive reference number: DME 16/3/2/5_A1). However, the GISTM requires a more comprehensive plan, including a recovery plan after failure.

Based on these results, it is therefore expected that a tailings dam that is currently fully compliant with the requirements of the South Africa regulations and standards should conform with most of the GISTM requirements by the specified deadlines.

It is worth noting that the compliance of tailings dams that currently fall under the industrial sector (*e.g.*, Eskom, Sasol, and smelters) is not included in the discussions of this paper as they generally do not follow most of the mine-related regulations and SANS standards. Some international insurers and investors may not treat these facilities differently to mine tailings (even though they may be ash or slag facilities) and will require compliance to the GISTM.

The conformance protocols

A specific conformance protocol document was release by the ICMM in May 2021 (ICMM, 2021a). This document gives guidance on how to evaluate compliance with the Standard.

The basic principle when it comes to compliance with the GISTM requirements is that reasonable evidence must be produced to prove the level of conformance. The levels of conformance are shown in Table III (Table I, page 6 of the Protocol document).

The examples of compliance are given within the Protocol together with guidance where necessary. The good practice guidelines were also released with these protocols (ICMM, 2021b).

The mines are allowed to carry out the initial self-assessment and associated reporting as part of meeting the initial compliance dates. It is important to note that the committed compliance dates do not mean that all the requirements should be fully met by then, but it is required that at least the gaps and weaknesses in the system will have been identified and that plans will be in place to address these.

Proposed initial GISTM compliance process for existing South African operations

Different mines are likely to follow different paths to compliance based on their current level of conformance to the South African requirements, the available information, and their previous initiatives in anticipation of the new Standard. The suggested GISTM initial compliance process is as follows.

(i) Project set-up – This phase includes the appointment of the internal project team, defining roles and responsibilities within the compliance project, and the appointment of the external resources where required.
(ii) Information gathering – This phase includes gathering of the information that is required for the GISTM dam classification process.
(iii) Dam classification process.
(iv) Assessment of changes required based on the outcome of the initial dam classification process.
(v) Implementation –Involves the completion of self-assessments, creation of a strategy of closing the gaps, and documentation.
(vi) Final self-assessment and documentation, and possible third-party audit.

The rest of the paper discusses the common issues that may be encountered during the initial implementation of the GISTM compliance process and the approach that can be adopted to address some of the issues that are applicable to the majority of the tailings operations in South Africa.

Appointments and training

With the compliance dates looming, especially for the High and Extremely High classified dams as per the GISTM, it is important for mines to treat the compliance process as a project on its own, and the appointment of experienced persons is crucial for the success of this project.

Some of the mines anticipated the changes a while back, and as part of their compliance initiatives have already appointed personnel that can fulfil some of the roles as stipulated in the Standard. However, other mines are well behind in this regard.

It is important to note that most of the required skills and appointments may already exist within the mines or their external suppliers. What will need to happen in most of the cases will be to change the titles or appointments so as to be in line with

Table III

Description of conformance levels

Conformance level	Description of outcome
Meets	Systems and/or practices related to the Requirement have been implemented and there is sufficient evidence to demonstrate that the Requirement is being met.
Partially meets	Systems and/or practices related to meeting the Requirement have been only partially implemented. Gaps or weaknesses persist that may contribute to an inability to meet the Requirement, or insufficient verifiable evidence has been provided to demonstrate that the activity is aligned to the Requirement.
Does not meet	Systems and/or practices required to support implementation of the Requirement are not in place, or are not being implemented, or cannot be evidenced.
Not applicable	The specific Requirement is not applicable to the context of the asset.

those in the Standard. It will also be important to assess whether the appointed persons have the right qualifications, experience, required resources, and authority to fulfil the associated roles (refer to Annex 3, Table IV of the Standard).

A project champion must be appointed to manage and drive the GISTM compliance process. This person can be internally appointed, *e.g.*, Responsible Tailings Facility Engineers or civil departmental engineers where available; or externally appointed, *e.g.*, consulting engineers, independent engineers, or the technical staff of the appointed dam operator. The project champion must keep a detailed conformance table and record of the overall project timelines.

The standards are fairly new, and there are still a lot of developments taking place, therefore the appointed champion must be provided with adequate resources (support, budget, and time) to enable him or her to attend learning sessions and to consult with the field experts when required.

The next crucial internal appointment will be the Responsible Tailings Facility Engineer (RTFE), who must be well experienced and qualified for the specific classification of the dam. The current limited pool of engineers in the country may cause some delays in the appointment of the RTFE and possibly the appointment of the EOR where required. Due to the potential delays, the recruitment of potential RTFEs might have to include appointments of civil engineering graduates that can be seconded to consulting engineering companies and tailings operating companies to gain adequate technical and practical experience. The recruitment process might also include the offering of bursaries to undergraduate students. It is expected that the RTFE, with assistance from various departments and external consultants, should be able to complete the self-assessment as required by the Protocols before the compliance dates.

The current dam designers and Responsible Professional Engineer (appointment MHSA Reg, 2.6.1 – Technical) should be suitable to hold the EOR appointment, therefore the EOR appointment must be finalized in writing, and the role must include all requirements as listed in Table 4 of the GISTM.

It is important to note that the appointment of the current responsible professional engineer as an EOR does not relieve them of their duties under the MHSA, and due consideration must be given to the amendment of the letters of appointment of the professional engineers (2.6.1 Technical Appointment) to include the duties of the EOR as stated in the GISTM to streamline the process.

The field of tailings engineering is highly specialized, with only a handful of internationally recognized engineering consulting firms practicing in South Africa with sufficient expertise as envisaged in Requirement 9 in the GISTM

The current MHSA Reg 3.1 appointment (Mine Manager) can be appointed as the Accountable Executive. It is critical for the Accountable Executive to be part of the implementation team as key decisions will need to be taken at this phase of the project. Some of the current positions within the mine that can be considered for this appointment, depending on the size and organizational structure, include the Vice-President, Chief Operational Officer, General Manager, Chief Engineer, Departmental Manager *etc.*

Information required for dam classification purposes

Sufficient time and resources must be provided for the information gathering process. The information that is required for dam classification purposes can be obtained from the following documents, which are mandatory for all tailings operations in South Africa:

- ➤ Tailings storage facility design report (most important, often non-existent)
- ➤ The DMR Mandatory Code of Practice
- ➤ Environmental authorizations (EMPR)
- ➤ Integrated water use licence (IWUL)
- ➤ Waste management facility licence (WMFL)
- ➤ Air emissions licence (AEL)

Most of the information that is required for the consequence classification should be residing with the mine or their appointed design engineers and EORs. However, as per our recent experience, when developing our internal risk management system, which required gathering of this information from our clients, most of this information was not readily available. This can be attributed to inadequate change management processes, *e.g.* during changes of the operating and client personnel and/or changes of responsible engineers. As some of the operations have been continuing for extended periods of time, some of the data is stored in outdated formats and is difficult to retrieve or read.

Typical places to get the historical information include old office/drawing cabinets, storage containers, mine libraries, consultants and external operator offices or servers, and external storage warehouses.

Where insufficient information exists, 'Continuation Reports' need to be compiled as per the guidance in SANS 10286, and this might need additional investigations and test work, including some design work. This process is likely to take significant time and the reports might not be ready by the target compliance dates.

Dam classification assessment

The dam classification process should commence with the review of the current safety classification based on SANS 10286. The SANS-based classification should contain some of the information that is required for the GISTM dam classification; a quick comparison is shown in Table IV.

The dam classification is carried out by first approximating the physical area impacted by the potential failure due to flowable materials and pool water. In South Africa this is conducted based on a prescriptive method that only considers the final height of the dam, with the zone of influence determined as follows: upstream 5 × final height, sides 10 × final height, downstream 100 × final height with a limit of 6500 m.

The GISTM requires that a dam breach analysis takes into consideration the actual credible failure modes and scenarios as well as site conditions. Therefore, it is possible for a dam that is operated by skilled individuals with a well-controlled pool and a phreatic surface that is kept away from the liquifiable zone to return a lower classification than a dam that is not well operated.

In South Africa, dam breach assessments have been conducted primarily on water dams, therefore these skills reside predominantly with water dam engineers. However, a tailings dam breach analysis requires additional understanding of the behaviour of the tailings material, therefore the need for the reskilling and integration of water and tailings dam engineers with evolving software is required.

The GISTM dam classification has five classes of potential consequences (Low, Significant, High, Very High, and Extreme) while SANS 10286 has three classes (Low, Medium, and High).

Table IV

General comparison between GISTM and SANS 10286 consequence/safety classification

Criteria	Comment
1. Potential population at risk	• Considered in SANS.
	• The uncontrolled influx of people within the zone of influence is likely to push some of the facilities to the Extreme category (*i.e.* >1000 population at risk).
2. Potential loss of life	• SANS exclude the workers, while the GISTM includes everyone.
	• Potential to move current SANS Medium and High hazard dams to High and Very High classification respectively based on the GISTM (*i.e.* on some dams the number of workers is more than 10 at any given period, with the site offices within the zone of influence).
3. Environment	• Considered in SANS 10286, but does not contribute to the safety classification of the dam.
4. Health, social, and cultural	• Not considered in SANS 10286 but covered in the MHSA and regulations governing EIA and social impact studies.
	• Currently difficult to monitor the health and social impacts of the general public.
	• Often a number of operations are clustered together, and it will be difficult to separate the impacts of each operation.
5. Infrastructure and economic	• Considered in SANS 10286 but does not include the mine's own infrastructure (note: 1996 rand values) • The provided monetary values for different GISTM classifications are significantly higher than those of SANS 10286, therefore these are unlikely to have a major influence on the final classification.

SANS 10286 requires significant input and involvement from the Professional Engineer for dams with Medium and High hazard classifications. Therefore, there is a strong likelihood that if the current facilities are classified as either Medium or High they will satisfy most of the GISTM requirements.

It should be noted that most of the dams currently classified as Medium to High hazard (based on SANS 10286) will mostly likely fall within the High to Very High classification based on the GISTM. The significant contributors are noted in Table IV.

Investigations are ongoing around the world on tailings dam breach analysis, for example the work by Martin, Al-Mamun, and Small (2019), which might be adopted widely in the future.

One of the main contributors to the final dam classification is the number of people residing within the zone of influence. The illegal and sometimes legal occupation of the land within the zone of influence is a common occurrence in South Africa, and it is not always easy to execute eviction orders even on land owned by the mines themselves. The classification of the dam is likely to change with time if the influx of residents within the zone of influence is not controlled.

A high influx of people may also complicate the implementation of the Emergency Preparedness and Response plans, as per Requirement 13.2.

The mines will have to find creative ways of addressing this issue and must engage the services of experienced social specialists.

The mines, regulators, communities, and all other affected and interested parties must agree on acceptable levels of compliance on requirements related to the communities.

The zone of influence must be frequently monitored using technology and regular patrols to ensure that the mine is able to act in time to prevent the influx of people within the zone of influence.

Operational changes based on the GISTM consequence classification

The two design criteria affected by the GISTM consequence classification are:

- ➤ The flood design criteria
- ➤ The seismic design criteria.

The changes in the two design criteria have the potential to change the current freeboard requirements and may have other implications for the general factors of safety. These are discussed below.

Freeboard compliance

The current value used for flood design in South Africa is a 1:50-year, 24-hour storm event (2% annual exceedance probability) for all dam classifications. This storm event plus 800 mm of freeboard is used to determine the ongoing freeboard requirements during operations. The freeboard requirements are normally revised by the consulting engineers on a quarterly to yearly basis on most of the operations and are tracked monthly by the dam operator.

The GISTM requirements are shown in Table V. They are significantly stricter than the South African requirements and are based on the consequence classification of the individual dams.

On a few of our operations where the new requirements have been adopted, the general freeboard requirements as provided by the EORs have increased typically by 150 mm to 300 mm above the South African legal requirements. Although marginal, this has resulted in non-compliance on some facilities that are borderline with respect to freeboard.

Table V

Annual exceedance probabilities for flood and seismic design parameters

Consequence classification	Operational and closure (active care)	Passive closure (passive care)
Low	1/200	1/10 000
Significant	1/1 000	1/10 000
High	1/2 475	1/10 000
Very High	1/5 000	1/10 000
Extreme	1/10 000	1/10 000

Figure 1 shows the distribution of the classification of the freeboard over the past year for the operations we are currently monitoring (90 dams) using our internal risk monitoring system (TORAS). Approximately 47% of the dams, which comply with the legal requirement plus our own additional 30% requirement, are not expected to experience any operational challenges with the new requirements.

However, it is expected that for some of the dams that fall within the TORAS legal freeboard status, the original deposition method may have to be revised in order to accommodate the new freeboard requirements, and this will affect most of the dams with the current low freeboard requirement, between 1 m and 1.5 m. On most of our cyclone operations, no changes will be required as they normally have a high freeboard.

Due to improvements in grinding technology and the reprocessing of tailings, most of the deposited tailings material is now finer and uniformly graded (*i.e.* comprises mainly particles of one size, as opposed to the original design assumption of 'well graded' with an even proportion of all size particles) This will result in flatter beaches, which affects the available freeboard.

The conversion of the deposition method will be required on some of the facilities. A few operations have already been converted from spigot dams to hybrid systems. The common hybrid system consists of mechanically built paddocks on the outside, which are filled with the tailings material using spigots. These operations are similar to a 'daywall' system. Deposition trials must be conducted before the conversion to determine feasibility, drying times, and deposition cycles.

Seismic loading

In South Africa there is no legislated minimum Operating Basis Earthquake (OBE) for tailings dam design because of the low seismic activity in the region. Most of the tailings dams in South Africa are located within the regions with a peak ground acceleration (PGA) of between 0.2 and 0.4 m^2/s with a 10% chance of exceedance in 50 years (1 in 475 years return period). A PGA value of 0.05 × gravitational acceleration, as proposed in the Chamber of Mines of Guidelines (1996), is often adopted for earthquake loading analysis. The application of the full PGA when conducting pseudo-static stability analysis often returns acceptable factors of safety.

With the new higher values stipulated by the GISTM, also shown in Table V, it is likely that when more detailed slope stability analyses are conducted (*e.g.*, coupled stress-deformation stability analysis), some materials that are currently assumed to have drained shear strength may show weaker undrained shear strengths or potential liquefaction behaviour. The results of such analyses may require the mines to construct large buttresses around their tailings dams, which is extremely expensive. Therefore, it is important for the industry to understand how the new values are derived and what the impact of these values will have on the tailings dams. Detailed earthquake analyses for the tailings dams in South Africa have not been widely undertaken, and thus upskilling of the current consultants will be required in order to fulfil the Standard requirements.

It is important to note that with regard to existing tailings facilities, the Standard allows for the review of the applicability of these requirements. This review is to be completed by the EOR and the independent technical reviewers. The Accountable Executive must understand and accept the risks, if any, associated with not implementing or delaying the required changes.

It will be critical for the tailings industry to hold frequent workshops to share knowledge and tips with regard to handling and implementing these design criteria as these will be fairly new to most players. Knowledge must also be obtained from the mines and consulting engineers who have already implemented some of these criteria on their operations.

Addressing the GISTM brittle failure mode requirements

The GISTM requires that brittle failure modes be identified and addressed with conservative design criteria during the design phase of the tailings dam (Requirements 4.6. and 7.2; refer also to the definition of 'Robust design' in Annex 1 of the Standard).

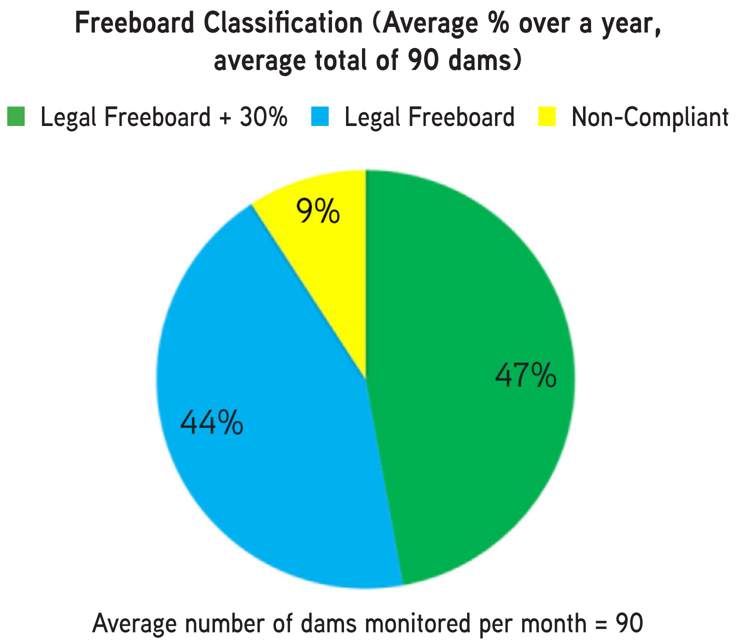

Figure 1—Freeboard classification

For most of the operational dams in South Africa, the site and tailings characterization undertaken during the design did not include the identification of brittle materials within the foundation materials and the dam. There is little or no reference to potential liquefiable materials in the reports. This is changing rapidly as cone penetration testing with pore pressure dissipation (CPTu) testing is being carried out more often.

Although brittle failure is not explicitly addressed in most of the design reports, the generally conservative design approach adopted by South African engineers limits the rate of rise (ROR) of the daywall and spigot tailings dams to around 2 m/a, which ensures sufficient compaction and drying, thus increasing the strength of the outer wall.

The cyclone dams are able to accommodate a higher ROR as the consolidation of the underflow material takes place rapidly, provided the correct grading is achieved. The maximum ROR for these dams is limited to between 4 and 6 m/a.

This low ROR affords sufficient time for the tailings material to desiccate, consolidate, and remain at a dense state, which allows for dilation during shear, which in turn reduces pore pressures. Importantly this allows more material to be placed while still achieving the required factor of safety (FOS).

In addition to the low ROR, the designs include careful sizing and placing of the underdrains, especially the blanket and the toe drain, with the optimal positions and sizes generally 'understood' by the engineers. This, in combination with keeping the operational pool relatively small (usually less than 30% of the top surface), has ensured that the outer zone of the tailings dam remains in a drained state .

The introduction of stricter barrier system requirements in 2013 has meant that, for the newer dams, the brittle failure mode must be carefully considered, as the drainage regime is significantly different to the older dams. The regulation that required plastic lining of almost all tailings dams was withdrawn in 2018, and a risk-based approach was adopted instead.

In the context of South African operational facilities, it is possible to prove compliance to the GISTM requirement for reducing the probability of brittle failure by presenting evidence of the following:

- ➤ The low ROR, within the design limits, and the deposition plans that show sufficient time for material drying and consolidation
- ➤ Pool location, depth, and size
- ➤ The original design or as-built drawings showing the positions of the drains
- ➤ The drain flow readings, and associated maintenance (jet-rodding).
- ➤ Piezometer readings and associated maintenance (upset tests). Installation of the more accurate vibrating wire piezometers may be required for some facilities where issues already exist
- ➤ The tailings material testing results (CPTu testing is highly recommended), which indicate a dilatant rather than contractive response during shearing
- ➤ Installation of an appropriately designed buttress, where the FOS is below the new requirements
- ➤ The annual slope stability analysis, which takes into consideration all of the available information. These analyses require specialized skills, therefore third-party review (ITRB or a Senior Technical Reviewer) is required.

It is then critical for the operations to be run as per the design intent, and the documentation of the operations and associated investigations must be accurate and up to date. The critical elements from this report must be included into a Trigger Action Response Plan (TARP) and any deviation fromthe requirements must be attended to as soon as practically possible.

Updating of dam monitoring instrumentation

The monitoring instrumentation on most of the dams in South Africa is limited to standpipe piezometers, with the freeboard monitoring conducted using freeboard poles and occasional aerial survey, and drain flows measured manually once a month. The current dam instrumentation is not robust enough to satisfy the requirement of the Standard. With the new classifications and the need to increase transparency, it will be necessary to install electronic monitoring systems and, in some cases, real-time monitoring. It must be noted that with generally low RORs, the changes in the measurements do not vary rapidly, therefore the frequency of readings will have to be adjusted accordingly.

The general challenge globally is the availability of integrated platforms that are able to accommodate various instrument types, makes, and models. The selection of the platform must take this into consideration, and also the potential for integration with other systems at the mine.

There is a drive internationally to develop and introduce these systems specifically to the mining industry. Prices are expected to decrease as more mines adopt these systems, and the ICMM is looking at common systems that can be used by their member companies, as mentioned during the launch of the Protocols in May 21.

The integration of the various instruments is important to enable quicker analysis and correlations, to make decision-making quicker, and enable potential issues to be identified much earlier and more efficiently.

The instrumentation installation needs may differ from mine to mine, and the most practical implementation strategy must include the following:

- ➤ Completion of slope stability assessment to identify critical sections that will need immediate attention
- ➤ Installation of vibrating wire piezometers at critical areas, possibly followed by retrofitted piezometer probes (pressure transducers) on the rest of the standpipes (the annual upset tests will still be required to ensure continued satisfactory performance)
- ➤ The use of suitable slope movement technology, with InSAR used to track the movements for at least the previous two years.

Theft and vandalism is one of the biggest challenges on the tailings sites, therefore the design and installation must take this into consideration.

On most of the dams the information is currently dispersed, and environmental monitoring information has mostly been left out of the annual audits and quarterly reports. With the introduction of the GISTM this should form part of the normal reporting.

Information system implementation

The collection, storage, and transparency of information is critical and as such, information should be stored in a central database, which is easily accessible. This information should include life of facility documentation, records of meetings, policies, dam safety reports, ITRB reports, deviations reports, and emergency and preparedness plans. The transparency of information, to all key stakeholder and affected persons, is a fundamental process. Regular engagement must be conducted with parties that are impacted by the tailings facility and recorded. In the case of Very High or Extreme consequence facilities it is suggested that a representative of the relevant regulatory authority attends these engagements.

The information must be dealt with in accordance with the Protection of Personal Information Act (POPIA) or General Data Protection Act (GDPA).

The systems must be flexible to cater for the requirements of other standards and regulations that the facility still needs to comply with, *e.g.*, the Cyanide Code.

Communication with interested and affected parties

It is unlikely that tailings facilities will be able to satisfy all the GISTM requirements within a short space of time, therefore it is important to prioritize the most important criteria, especially those related directly to the stability of the dam. The ultimate strategy and timelines for full compliance must be communicated to all interested and affected parties, *e.g.*, insurers, financiers, and the local communities.

Conclusion

It is expected that most of the dams that currently comply with the South African regulations and standards will likely comply or partially comply with most of the GISTM requirements. In instances where they do not comply, with minimum FOS requirements, the construction of an appropriately designed buttress may be needed.

To ensure the success of the compliance process it is critical that a project be set up and appropriately qualified people be appointed. The Accountable Executive must be part of this team. The Accountable Executive is responsible for ensuring that the operations and designs conform to the principles of As Low As Responsibly Practicable (ALARP)

One of the main challenges in the South African context is the encroachment of residents within the zone of influence. Mines need to understand the impact of this on the overall consequence classification and need to carefully manage it.

Furthermore, the site laydown areas and offices are usually within the zone of influence, and the relocation of these facilities should be considered in order to lower the consequence classification and to minimize the number of potential casualties in the event of a failure.

The necessary EOR skills are available within South Africa, although due to the limited number of engineers they may be fulfilling the role of third-party reviewers. Additional training and upskilling might be needed for engineers to take on the role of RTFE.

There is sufficient technology available, although the gap between tailings engineers and software developers must still be bridged to enable the development of suitable tailings monitoring software. Relevant training must be obtained, or a co-creation methodology should be adopted.

We believe the new GISTM standards will greatly improve accountability and transparency between all key stakeholders and further minimize risk, although funds, resources, training, and software development must be considered.

Nomenclature

ALARP	- As Low As Reasonably Practicable
CPTu	- Cone penetrometer test (with pore pressure measurement)
DSR	- Dam Safety Report
EOR	- Engineer of Record
FOS	- Factor of safety
GDPA	- General Data Protection Act
GISTM	- Global Industry Standard on Tailings Management
ICMM	- International Council on Mining and Metals
InSAR	- Interferometric synthetic aperture radar
ITRB	- Independent Technical Review Board
MHSA	- Mine Health and Safety Act
POPI	- Protection of Personal Information Act
PRI	- Principles for Responsible Investment
ROR	- Rate of rise
RTFE	- Responsible Tailings Facility Engineer
TARP	- Trigger Action Response Plan
TMS	- Total Management System
TORAS	- Technical and Operations Risk Assessment System
UNEP	- United Nations Environment Programme

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A review of EN 16907 on earthworks (extractive waste) in the context of South African mine residues

by F. Hörtkorn[1] and Y. Narainsamy[2]

Affiliation:
[1]Karlsruhe University of Applied Sciences, Karlsruhe, Germany.
[2]University of Pretoria, Pretoria, South Africa.

Correspondence to:
Y. Narainsamy

Email:
yashay.narainsamy@tuks.co.za

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Synopsis

Rather quietly, a new generation of European norms dealing with earthworks has been developed over the past few years, in particular a part of EN 16907 pertaining to extractive waste. Whereas the majority of the parts deal with routine geotechnical aspects, one part deals specifically with tailings dams. The standard is currently in draft form but if this becomes a European Standard, members of the European Union are bound to comply with the regulations. As such, the standard has the capacity to influence mining in Europe and potentially in South Africa. In this paper we review the standard and compare it to the South African standard on mine residues and the recently published Global Industry Standard on Tailings Management (GISTM). We conclude found that although the European norm makes great strides towards increasing tailings dam safety, there is room for improvement. The current South African standard has served well since its inception, but can be improved by using concepts from the European and global tailings standards.

Keywords

tailings, tailings management, EN 16907, SANS 10286, GISTM.

Introduction

Recent tailings dam failures around the world have resulted in increased scrutiny of the safety of these structures. The failures have highlighted the real social, environmental, and reputational risk that tailings dams can pose if not managed correctly. For example, the failure of the Fundão tailings dam in 2015 resulted in the pollution of 668 km of watercourses from the Doce River Basin to the Atlantic Ocean (do Carmo *et al*., 2017). In 2019, as a result of the Feijão tailings dam failure, 259 people were reported to have died (Vale, 2019). These events have prompted many regulators to review the statutory framework within which tailings dams are designed, licenced, and operated. The intent of this paper is to review the recently published draft European Standard on hydraulic placement of extractive waste. This standard is discussed within a context of the South African legislative framework and comparisons are drawn with the recently published Global Tailings Standard on Tailings Management (GISTM). Similar types of reviews and comparisons have been undertaken by others (*e.g*. Poswa and Davies, 2017; Wates and Lyell, 2018).

National standards

One method to regulate the practice of tailings dam design, construction, and operation is the development and promulgation of national standards. As these documents take time to be developed and published, several large mining houses have developed their own internal standards on tailings management (*e.g*. Anglo American, 2019; Rio Tinto, 2020). With all these standards being published, it remains the responsibility of the dam owner to ensure that the internal and local and/or regional standards are met. This typically means the planning, design, construction, operation, and closure will be done according to a combination of standards. It is important to note that the different standards must be consistent and must not contradict each other. This is particularly relevant when local requirements are compared to international best practice.

An interesting case history where multiple standards were involved is the issue of mercury levels in the rivers downstream of the now closed Victor Diamond Mine. As the mine is located in Canada, monitoring was done according to the Canadian Environmental Quality Guidelines (CEQG). De Beers Canada Incorporated (De Beers), the owners of the mine, published annual mercury reports as part of the monitoring programme. In their 2013 report, De Beers acknowledged that although the observed mercury levels were well below those required by the CEQG, they were above those recommended by the US Environmental Protection Agency (US EPA). A few years later, it was alleged that De Beers was not publicly disclosing all the results of the mercury levels recorded at the monitoring points as mandated. This case went to court, and it was found that, despite the mercury levels being within the CEQG requirements, De Beers did not disclose the results as mandated (Ecojustice, 2021). Although De Beers was not found guilty of not using the US EPA standard, it was this initial disclosure that led to the court case by concerned activists. This case therefore highlights some of the potential complexities that arise when multiple standards are used.

Risk in the context of tailings dams

In the development of national standards, a fine balance needs to be found between efficient engineering and adequate safety, especially where the public and the environment are involved. Broadly speaking, incidents relating to tailings dam safety can be placed in one of three categories: engineering-related, operations-related, and regulatory-related (*e.g.* Morgenstern, 2018). Engineering-related refers to incidents caused by deficiencies in the design, construction, and associated quality control and quality assurance of tailings dams. Operations-related refers to incidents that are due to deviations from activities described in the Operations, Maintenance and Surveillance (OMS) manual. Regulatory-related refers to decisions taken (or not taken) by regulatory authorities that contributed to the incident. A comprehensive standard must therefore address each of these three aspects to achieve the target of zero harm to people and the environment.

In the following sections, three standards which address these aspects are discussed. The first is the draft European Standard on Extractive Waste (EN 16907). The second is the South African National Standard on Mine Residue (SANS 10286), and the third is the GISTM. We then present a discussion of these standards and their implications in a South African context.

Technical analysis

Although standards by nature are wide-ranging and consider the entire life-cycle of a tailings dam, the key aspect relating to the safety of tailings dams is the assessment of their stability. Traditionally, earthen slopes and embankments have been assessed by means of limit equilibrium analysis using effective stress parameters such as the friction angle and cohesion intercept. However, there are limitations to this approach in the sense that undrained shearing cannot be appropriately assessed, especially for loose, saturated contractive material. The use of undrained strengths has become more prevalent as it has been shown that undrained failure mechanisms may have led to recent failures (*e.g.* Morgenstern *et al.*, 2016; Robertson *et al.*, 2019). It is important to consider undrained failure mechanisms since under the same effective stress, peak undrained strengths are typically only half that of peak drained strength (*e.g.* Olson and Stark, 2003). Furthermore, it is becoming popular to regard these mechanisms as brittle behaviour. During the review, specific attention was paid to the handling of the slope stability assessment of tailings dams.

European Standard EN 16907 – Earthworks

A specific series of documents, the EN 16907 series, deals with earthworks and comprises seven parts (CEN, 2021). Whereas the majority of the parts deal with routine geotechnical aspects such as material classification, soil treatment with lime, and quality control, there is one part that deals with tailings material and tailings dams. This part of the code is referred to as 'Earthworks – Part 7: Hydraulic placement of extractive waste'.

Brief history of the Eurocodes

The European Commission decided in 1975 to develop a programme to reduce trade barriers as much as possible. Part of the programme was devoted to developing a new generation of standards that are applicable to all member countries of the European Union (EU). The new generation of standards was meant to:

- ➤ Ensure standardized design approaches throughout Europe
- ➤ Ensure a common base for research and development
- ➤ Harmonize different national approaches
- ➤ Simplify tendering processes within Europe.

The body tasked with developing these standards is known as European Committee for Standardization (CEN), comprising countries that are members of the EU. If a common European standard is agreed upon, this standard will have to implemented – within a transition period - replacing a national code without any alteration. As such, the numbering of the code and the title remain the same; the only indication that one is dealing with a European Code is the prefix. For instance, the German prefix is DIN and German standards therefore start with DIN EN. For individual members there is, however, the opportunity to amend the code by a national annex. It is important to note that separate national codes may only exist if the topic is not regulated in any form by a European Code. Further some codes are introduced by regulating authorities and hence must be considered, others are more indicative in nature. Although one is, strictly speaking, not forced to apply the code, the code is seen as best practice and therefore has relevance.

With regard to the building and construction environment the first Eurocodes were published in the 1980s. They were official introduced in Germany in 2012. The biggest change with the new generation of Eurocodes was the move away from the global factor-of-safety concept to the partial safety factor concept, together with the introduction of partial safety factors. This makes a direct comparison of specific values to codes that incorporate the global factor-of-safety concept very difficult or nearly impossible.

Components of EN 16907

The EN 16907 series has been developed by a technical committee consisting of members of the EU (CEN/TC 396 'Earthworks'). Some parts of the Code have been formally adopted – some parts, for instance Part 7, are currently submitted to the formal vote of the member countries and will most likely be introduced shortly. To provide an overview of the whole series of EN 16907, the individual parts are listed below.

- EN 16907-1:2018: Earthworks - Part 1: Principles and general rules
- EN 16907-2:2018: Earthworks - Part 2: Classification of materials
- EN 16907-3:2018: Earthworks - Part 3: Construction procedures
- EN 16907-4:2018: Earthworks - Part 4: Soil treatment with lime and/or hydraulic binders
- EN 16907-5:2018: Earthworks - Part 5: Quality control
- EN 16907-6:2018: Earthworks - Part 6: Land reclamation earthworks using dredged hydraulic fill
- EN 16907-7:2018: Earthworks - Part 7: Hydraulic placement of extractive waste.

When comparing the individual parts, it becomes clear that parts 1 to 6 are related to construction activities that are related to infrastructure aspects such as road construction. This becomes particularly obvious in Part 2, which refers to other European Standards describing classical geotechnical tests, such as the various parts of EN 14688: Geotechnical investigation and testing - Identification and classification of soil, or EN ISO 14689: Geotechnical investigation and testing - Identification and classification of rock.

Part 7 of EN 16907 however, deals, with 'extractive waste', or what is also referred to as 'tailings material'. From a geotechnical aspect these materials are a very specific subset of natural soils and rocks but are used in a different environment (mining). To a certain extent this is acknowledged and accounted for in Part 7, which is described below in more detail.

EN 16907-7: 2018 Hydraulic placement of extractive waste

Overview

Part 7 of EN 16907 consists of 12 chapters plus Annexes A–N, totalling 101 pages and describes various aspects from the design phase to closure which are applicable to the various forms of 'waste facilities', *e.g.* dams, confining embankments. As the authors are of the opinion that the term 'waste' might be misleading and could lead – subject to local legislation – to misunderstandings or even trigger approval processes that might be not relevant to such a facility, the term 'tailings dam' will be used instead. It is important to note that Part 7 of EN 16907 does not define, establish, or specify detailed elements of the design of a tailings dam but provides overall recommendations to follow in order to comply with 'good regulatory and engineering practice'. Instead, it refers to the design principles as described in Eurocode 7 plus the relevant National Annexes. A key objective of this part of the standard is to ensure both short-term and long-term safe disposal of extractive waste.

Content

It is not necessary to describe Chapters 1 to 6 in detail as these chapter are similar to most standards and deal with topics such as the scope, references, terms, and definitions and abbreviations (Chapters 1 to 4), provide a brief and basic overview of the phases of mining projects (Chapter 5), or information with regard to the characterization of mine waste facilities according to European legislation, which subsequently defines what management documentation is required in detail (Chapter 6). Chapters 7 to 12, however, provide more information for the owner, operator and designer and are therefore described below.

- *Chapter 7: Site and Material Characterization:*
  This chapter suggests that tailings dams be classified as Category 3 structures unless there is sufficient evidence that the structure does not pose a lower risk. Classification as a Category 3 structure defines the minimum required extent of geotechnical investigation according to Eurocode EC7-1. Additional information is provided to account for tailings-specific circumstances (*e.g.* sampling during operational phases, location of sampling points). Detailed suggestions are provided; however, the exact geotechnical parameters that should be obtained and the tests required to establish these parameters are referenced to the relevant officially-introduced standards. As far as unusual tests are suggested, reference is made to Annex A (Non-standardized geotechnical tests on hydraulic fill). However, it must be noted that some of the parameters in Annex A are already described in other standards. For instance, the approach to determine the coefficient of consolidation (cv), the coefficient of compressibility, (mv) or the compression index (cc). Chapter 7 also deals with geochemical assessment, acid mine drainage, and sampling.
- *Chapter 8: Extractive Waste Management Plan:*
  This is the shortest chapter of EN 16907. It makes reference to a specific European Legislation (Directive 2006/21/EC, see also Chapter 6) which was officially introduced and promulgated in Germany as national law in 2006.
- *Chapter 9: Mine Waste Facility (MWF) Design, Construction, Operation and Closure*:
  Comprising 17 pages, this is the largest chapter in the Code and covers the whole life-cycle of an MWF. The chapter starts with basic comments with regard to questions such as site selection, selection of the type of embankment, or the seepage management system. It further addresses the design of the hydraulic deposition system as well as water management, and ends with a section discussing closure. In terms of slope stability, EN 16907 refers to Eurocode EC7-1, which follows the partial safety concept. Partial safety factors are introduced subject to the nature of the structure (permanent or transient). As such the values can be compared and are in the region between 1.35 and 1.50. It is important to note that in the development of EC7-1, tailings dams were not specifically considered.
- *Chapter 10: Construction Quality Control:*
  This is a short chapter comprising two pages. It raises the need for a construction management plan and a Construction Quality Assurance (CQA) plan. For further details the Code refers to national legislation. This chapter needs to be read in conjunction with the Annexes as these contain suggestions made, for instance, regarding the frequencies of specific tests during construction.
- *Chapter 11: Instrumentation and Monitoring:*
  Similar to Chapter 10, this is a rather short chapter comprising four pages. It raises the need for an overarching monitoring plan and lists some of the principal monitoring requirements.

- *Chapter 12: Inspection Regimes:*
  This chapter addresses technical inspections performed by the owner/operator and regulatory inspections by or on behalf of the competent authority. With regard to the minimum requirements of technical inspections; a scheme of daily, weekly, monthly, quarterly, and annual inspections is suggested, and reference is made to Annexes J to N of the document.
- *Annex A: Non-Standardized Geotechnical Tests on Hydraulic Fil:*
  This is a very informative annex and describes geotechnical tests which are required to characterize and describe the physical and mechanical properties of tailings. These tests are in addition to the geotechnical tests described in the series EN ISO 17982. The following tests are described in detail.
  - Solids content
  - Particle settling velocity
  - Undrained settling
  - Drained settling te,
  - Air drying test
  - Slurry consolidation.
- *Annex B: MWF Phases:*
  This annex consists of one table (Table B.1) listing the MWF regulatory phases and comparing them to the design stage of the project. Suggested investigations and reviews for the specific design phases are listed.
- *Annex C: Procedures for the Construction of a MWF Embankment:*
  Similar to Annex B, this annex consists of a single table (Table C.1) listing required steps for the various phases (*e.g.* pre-deposition, operation/raises) and separately lists subjects related to the phases (*e.g.* design, construction, review).
- *Annex D: Earth Structure Design Considerations:*
  This annex again refers to EN 1997/EC7-1 as a design guideline (all parts) and EN 1998 with reference to seismic loading on structures (all parts) and addresses aspects such as overall stability for static and seismic conditions, hydraulic failure, and liquefaction.
- *Annex E: Water Reclaim Options:*
  Similar to Annexes B or C this annex consists of a single table (Table E.1) listing different water reclamation options.
- *Annex F: Contents of Typical OMS Manual:*
  This annex lists points that should form part of a typical OMS manual.
- *Annex G: Confining Embankment CQA – Recommended Testing Frequencies:*
  This annex tabulates the recommended testing frequencies for standard geotechnical tests (*e.g.* tests to determine particle size distribution, water content, Atterberg limits, *in-situ* density, Proctor optimum moisture content, and maximum dry density, and *in-situ* permeability). Tests for embankment fills and natural and engineered barriers are provided in the form of a table.
- *Annex H: Confining Embankment CQA – Monitoring of Hydraulic Fill Deposits:*
  Annex H provides a table indicating which tests should be conducted and makes reference to Annex A if the tests referred to are non-standard.
- *Annex I: Instrumentation on a MWF:*
  Annex I lists various parameters such as surface movement, pore pressure, and seepage. The annex provides suggestions on what kind of instruments should be considered and partially describes these in more detail. The overview is presented in the form of a table (Table I.1).
- *Annex J: Typical Inspection Frequency for a MWF:*
  This annex provides a table showing the phases of a dam and lists the minimum types of inspections that need to be conducted, their frequency, and which responsible parties need to carry them out (Table J.1).
- *Annex K/L: Daily/Weekly Technical Inspections:*
  This annex provides a table showing different monitoring parameters and provides comments with regard to the methods of monitoring as well as recording and assessing the monitoring data (Table K.1 and Table L.1).
- *Annex M: Programme for Technical Inspection and Reporting:*
  Annex M lists a programme for inspections and reporting (Table M.1).
- *Annex N: Content of a Technical Inspection Report:*
  Annex N list the typical content of a technical inspection report that needs to be routinely compiled by the independent qualified engineer at intervals discussed in Chapter 12.

South African National Standard on Mine Residue (SANS 10286)

In 1994, the Merriespruit tailings dam failed and 600 000 m^3 of tailings flowed into the town of Merriespruit killing 17 people (Wagener, 1997). It remains one of the worst tailings dam failures in South Africa in terms of environmental and social impact. It was also the last serious tailings incident to occur in South Africa. Following the failure, it was decided that a national standard would be developed to specify minimum requirements in terms of planning, design, operations, monitoring, review, and non-conformance follow-up in relation to mine residue facilities. In 1998, the South African National Standard on Mine Residue (later renamed SANS 10286) was published (SABS, 1998). Note that this document was developed to include all mine residue deposits, such as waste rock dumps, and is not limited to tailings dams.

Although South African National Standards by nature are not legally mandatory, they often become legally binding when referenced in legislation. This is the case for SANS 10286. Section 9 of the Mine Health and Safety Act (MHSA) specifies that a Code of Practice (CoP) must be prepared and implemented on any matter affecting the health and safety of employees and other persons who may be directly affected by activities at a mine (MHSA South Africa, 1996). It further states that the Code of Practice must comply with guidelines issued by the Chief Inspector of Mines. This guideline (the Guideline for the Compilation of a Mandatory Code of Practice on Mine Residue Deposits) was published in 2000 and states that the SANS 10286 code must generally be regarded as providing the minimum requirements for good practice on which to base the relevant sections of the CoP (DME, 2000). In this way, SANS 10286 must be legally complied with when dealing with mine residue deposits.

Although there is a design code for the basis of geotechnical design and actions (SANS 10610-5), it specifically excludes the design of geotechnical structures such as slopes, embankments, or free-standing retaining structures (SABS, 2010). Rather, the standard focuses on the determination of geotechnical actions on buildings and industrial structures, including vertical earth loading, earth pressure, groundwater and free water pressure, and actions caused by ground movement.

The management of supernatant water is generally dealt with using the SANCOLD guidelines on freeboard requirements as well as the regulations published under the National Water Act and Mineral and Petroleum Resources Development Act (South Africa, 1999, 2004; Bosman *et al*., 2011). This aspect is complex in itself and has been dealt with in a separate publication (Narainsamy, 2018). The stability of tailings dams is conventionally managed in accordance with the South African Institution of Civil Engineering's code of conduct on lateral support (SAICE, 1989), specifying a global factor of safety (FoS) of 1.5 and using effective stress parameters. In addition to SANS 10286 and the documents mentioned above, tailings dams in South Africa are governed by a complex combination of several pieces of legislation. These include licence requirements for water and waste usage as well as adherence to approved environmental management programmes during operation and post closure of mine residue deposits.

Global Industry Standard on Tailings Management (GISTM)

The International Council on Mining and Metals (ICMM) is an international organization dedicated to a safe, fair, and sustainable mining and metals industry. After the Feijão tailings dam failure in 2019, the ICMM, the United Nations Environment Programme (UNEP), and the Principles for Responsible Investment (PRI) co-convened the Global Tailings Review to establish an international standard on tailings management. This initiative was led by Dr Bruno Oberle, and in 2020 the GISTM was published (Oberle, 2020). The GISTM contained 77 requirements over six categories, namely: affected communities; integrated knowledge base; design, construction, operation and monitoring of tailings facilities; management and governance; emergency response and long-term recovery; and public disclosure and access to information.

Following the publication of the GISTM, the ICMM members committed in August 2020 to implement the GISTM within three years for all facilities with an 'Extreme' or 'Very High' classification (as per Annexure 2 of the GISTM), and all other facilities within five years. To support this initiative, the ICMM published two documents in 2021. The first document, the Tailings Management Good Practice Guide (GISTM Guideline) was developed to support the interpretation of many of the requirements within the GISTM and promote good engineering practices for tailings management (ICMM, 2021a). The second document, the Conformance Protocols for the Global Industry Standard on Tailings Management (GISTM Conformance Protocols) was developed to help operators and independent third parties to assess implementation of the GISTM and to demonstrate conformance (ICMM, 2021b).

Some emphasis is given to the design of tailings dams, specifically in terms of slope stability analysis. Requirement 4.6 of the GISTM states that brittle failure modes must be identified and addressed, independent of the trigger mechanism. Interestingly,

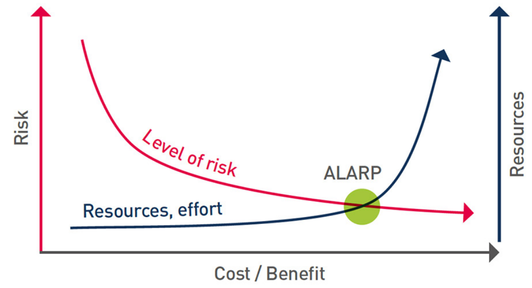

Figure 1—Visual representation of a typical risk and resource trade-off (ICMM, 2021a)

design FoS values are not prescribed. Rather it is stated that these should be determined by the Engineer of Record (EoR) and endorsed by independent review. There is an exception to Requirement 4.6 and this is detailed in Requirement 4.7 of the GISTM. This clause introduces the idea of considering not just the risk involved, but also the associated resources required to achieve that risk level.

In the associated guideline, it is explained that the goal is to achieve the desired outcomes by reducing risk to levels as low as reasonable possible (ALARP). A visual representation of the ALARP concept is shown in Figure 1. In this approach, measures are taken to reduce the risk to a state where the cost and other impacts of additional risk reduction are grossly disproportionate to the benefit. As this clause could be used out of context, it is followed by a statement that this approach is acceptable only when proposed by the EoR, reviewed by the Independent Technical Review Board (ITRB), and documented and approved by the Accountable Executive. It should be noted that this approach is aimed at existing tailings dams that cannot meet the new requirements, and not for new tailings dams.

Comparison of standards

As the three different standards were developed at different points in time and for different regions, it can be expected that different terminology is used. A summary of the key terms is provided in Table I. A few key points with regard to technical aspects are discussed in Table II. A deficiency in the South African standard is that there is no mandatory requirement for an independent review of the operation. However, as discussed earlier, it is common practice for independent reviews to be conducted even though this is not mandatory. It is also interesting to note that the while the South African and European standards are applicable to all tailings storage facilities, the GISTM is applicable to only those facilities that have a wall height greater than 2.5 m and/or combined storage capacity of more than 30 000 m^3. This approach is similar to that taken by the Dam Safety Office in South Africa in regard to water dams that could pose a safety risk and need to be registered. In this case, only dams with a wall height greater than 5 m and which store more than 50 000 m^3 of water need to be registered. This is less conservative than the GISTM standard which, aside from the more stringent values, only requires that one of the criteria to be met.

What becomes obvious as well is that SANS 10286 explicitly introduces legally responsible persons as per the MHSA (for instance, the 2.6.1 Appointment for competent owner-managers). This explicit legal responsibility appears to be missing in the other documents or is subject to local legislation, which is not uniform within the member countries of the EU.

Table I

Terminology used*

Description	SANS 10286	EN 16907	GISTM
Fine waste material produced as part of the mining process.	Mine residue	Extractive waste	Tailings
Scope of the standard.	All residue deposits that contain waste as defined in terms of the Minerals Act	All aspects of a dam serving to contain extractive waste in a terrestrial environment	Wall height greater than 2.5 m or combined storage of water and solids of more than 30 000 m³
Person accountable for the safety of the tailings dams.	Mine Manager (3.1)*	Owner	Accountable Executive
An independent engineer that provides independent technical review of the design, construction, operation, closure, and management of tailings dams.	N/A	Independent engineer	Independent Tailings Review Board
A periodic review carried out by an independent engineer to assess and evaluate the safety of a dam.	N/A	Independent technical review	Dam Safety Review
The qualified engineering firm responsible for the design, construction, and decommissioning of tailings dams.	Professional Engineer	Designer	Engineer of Record
A person responsible for the tailings dams.	Sub-ordinate Manager (2.6.1)*	Operator	Responsible Tailings Facility Engineer
An entity that exercises ultimate control of a tailings dam.	Owner	Operator	Operator

*Typical appointments as per the MHSA

Table II

Technical guidance provided by the standards

Description	SANS 10286	EN 16907	GISTM
Consequence classification	Yes	Yes	Yes
Probability considered in classification?	No	Unclear	No
Factor of safety	1.5*	1.35-1.5+	EoR to recommend
Consider brittle behaviour?	-	Yes	Yes
Consider trigger mechanism for brittle behaviour?	-		Assume exists^
Flood management	Up to PMP**	Up to PMP	Up to PMP
Seismic loading	-	Up to MCE++	Up to MCE

* Based on locally accepted code of practice and legislation (SAICE, 1989; NEMWA South Africa, 2015).
** Based on locally accepted guideline (Bosman *et al*., 2011).
+ EN 16907 refers to Eurocode EC7-1, which follow the partial safety concept. In this concept partial safety factors are introduced subject to the nature of the structure (permanent or transient). As such the values can be compared and are in the region between 1.35 and 1.50. It is important to note in the development of EC7-1, tailings dams were not specifically considered.
++ EN 16907 refers to ICOLD Bulletin 184, which references the Safety Evaluation Earthquake (SEE) which considers the MCE (ICOLD, 2016).
^ Based on GISTM Guideline (ICMM, 2021a).

A summary of the technical guidance provided in the three standards is shown in Table II. For flood management, storm events up to the Probable Maximum Precipitation (PMP) are considered depending on the classification of the tailings dam. Similarly, seismic events up to the Maximum Credible Earthquake (MCE) are considered. No FoS is specified in the South African standard, although there was a locally accepted value of 1.3 using effective stress parameters until legislation under the National Environmental Management: Waste Act was promulgated in 2015 (NEMWA South Africa, 2015). This regulation specifies a minimum FoS of 1.5 but does not specify a method of determining this. Interestingly, no FoS is prescribed in the GISTM. Rather, it is recommended that the EoR proposes a FoS and that this is reviewed independently and accepted by the Accountable Executive.

An important point to note is that the GISTM clearly states that brittle failure modes must be identified and addressed, independent of trigger mechanisms. This is in line with comments by other researchers, *e.g.* Robertson (2021), who notes that for structures where the consequences of failure are high (*e.g.* loss of life and/or significant environmental and reputational damage), it is prudent to assume that strength loss will be triggered since it is often impossible to design with confidence based on an assumption that strength loss will not be triggered at some time in the life of the structure.

Discussion and conclusion

We have described and compared various standards, particularly with regard to how slope stability assessments were incorporated into these standards. EN 16907-7 is not very concise and appears to be almost a textbook. It mentions a FoS only indirectly when it remarks on the requirement to use Eurocode 7-1 for any geotechnical design. Using this document, one would expect a FoS between 1.35 and 1.50 subject to the loading conditions (permanent or transient). In this context it is, however, important to note, that EC7-1 was not developed with tailings dams in mind. A point for discussion is, for instance, the fact, that a tailings dam only reaches its final shape at the end of its life – would this indirectly allow a lower FoS during the operational phase (loading case transient)? EC7-1 also does also not specifically address the issue of liquefaction. This topic is addressed in EN 16907-7, but in a very general manner.

The South African Standard, does not specify a FoS. There is, however, a locally accepted value of 1.5 using effective stress parameters, although the method of establishing this is not specified.

Interestingly, no FoS is prescribed in the GISTM either. Rather, it is recommended that the EoR proposes a FoS and that this is reviewed independently and accepted by the Accountable Executive. The initial rigorous striving for safety at all costs ('zero harm') committed to after the recent catastrophic failures is already softened by an approach called ALARP (see Figure 1).

The intent of national codes and standards in the context of tailings dams is to promote good engineering practice to ensure the safe planning, design, construction, operation, and closure of tailings dams with the ultimate goal of zero harm to people and the environment. The three standards described make great strides towards achieving this goal. However, during the review, several areas for potential improvement were noted, specifically in terms of technical aspects and clear guidance required for the slope stability assessment of tailings dams. These can broadly be described as follows.

1. Standards should be as short and concise as possible and written in plain, simple terms.
2. Guideline documents should be developed to assist in the interpretation of the standards. These guideline documents should clearly and objectively describe how compliance to the standard can be achieved and verified.
3. This clarity is especially important with respect to methods of assessing the stability of tailings dam. As the intent is to provide minimum standards, the authors are of the opinion that minimum FoS values and minimum scenarios should be specified. For example, a standard or guideline could state that limit equilibrium slope stability analysis must be conducted using effective strength parameters and a minimum FoS of 1.5 must be achieved. In addition, limit equilibrium slope stability analysis must be conducted using peak undrained strength parameter and a minimum FoS of 1.3 must be achieved.

It is suggested that in the future, standards for the planning, design, construction, operation, and closure of tailings dams provide clear, concise requirements for slope stability assessment. Standards should also make reference to scientifically well-researched design approaches which can be introduced in daily engineering by all stakeholders involved, such as designers, operators, and regulators. An example is the topic of 'liquefaction'. Even EN 16907-7 acknowledges that this topic is the 'subject of advanced geotechnical research' (EN 16907-7, D.2.3.5). Also, the authors are of the opinion that there is currently uncertainty regarding generally accepted methods on how to test for liquefaction or how to incorporate this into a design with confidence. Until a clear approach on how to incorporate this aspect is available, one would have to make extremely conservative assumption to achieve the goal of 'zero harm'. This, however, leads to a very expensive design solution. With reference to Figure 1 the authors fear that this noble goal will be bypassed due to economic considerations.

Significant resources are currently being spent on enhancing the safety of tailings dams as regards liquefaction. As indicated above, the question must be raised if this is not premature in some cases. We hope that some of these resources can be made available for research purposes as this will allow the topic of liquefaction to be addressed and incorporated into design approaches with confidence.

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GISTM: Who are the responsible individuals?

by C.J. MacRobert[1], J. Wates[2], A. Coetzee[3], and G. Howell[4]

Affiliation:
[1]Stellenbosch University, South Africa.
[2]John Wates Consulting, South Africa.
[3]Impala Platinum Holdings Ltd, South Africa.
[4]SRK Consulting, South Africa.

Correspondence to:
C.J. MacRobert

Email:
macrobert@sun.ac.za

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ORCID:
C.J. MacRobert
https://orcid.org/ 0000-0002-7141-1339

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Synopsis

The Global Industry Standard on Tailings Management (GISTM) requires mining companies to make four key appointments as part of their tailings management structure. These four positions are an Accountable Executive with policymaking responsibilities, a Responsible Tailings Facility Engineer with operational responsibility, an Engineer of Record to ensure facilities are designed, operated, and closed safely, and an Independent Tailings Review Board to assess safety drivers regularly. Little guidance on the traits of these individuals is available in a South African context. Consequently, the tailings community of practice was surveyed to develop a table of ideal competencies and establish the flexibility in meeting these traits.

Keywords

tailings, safety, GISTM, management structure, responsible individuals.

Introduction

The safe operation of tailings dams revolves around having the correct management structure in place. Tailings dams are 'living structures' in that they are constantly growing and changing. This growth needs to be managed and decisions taken to ensure the facility conforms to the original design intent. The management need becomes even more acute if the original design is no longer fit for purpose and changes need to be made to ensure the facility remains safe.

In South Africa, SANS 10286 (SABS, 1998) has been adopted by many mining companies (Wates and Lyell 2018). Since the adoption of SANS has been so pervasive it likely that the courts would refer to it as a benchmark in the absence of other legislation. At its core this standard defines a management structure, where the key roles are a 'Manager', an 'Operator', and a 'Professional Engineer'. The Manager's main role is appointing the individuals to the key roles, the Operator's main role is to manage and operate the facility, whereas the Professional Engineer is required to design and carry out inspections that provide assurance of conformance.

A typical implementation of this structure in South Africa is shown in Figure 1. The Board of Directors appoints a Chief Executive Officer who in turn appoints a Mine Manager. The Mine Manager could fulfil the SANS 10286 'Manager' role, but this is typically subordinated to an engineering manager (often the metallurgical/plant manager). The 'Operator' role is often outsourced to a contractor, although this could be fulfilled by a mine employee. A 'Professional Engineer' is also required (but not for low hazard facilities) and is typically an outsourced consultant although some mining companies have internal technical divisions that fulfil this role. It is largely expected that the 'Operator' and 'Professional Engineer' are supported by others in carrying out their duties.

These different role players can also hold legal appointments. For instance, the Mine Manager usually holds the 3.1 appointment stipulated in the Mine Health and Safety Act No. 29 of 1996. The subordinate/engineering manager usually holds either a 2.13.1 or 2.6.1 appointment as stipulated in the Mine Health and Safety Regulations. Mines often also require the Operator and Professional Engineer to be 2.6.1 appointees, although the necessity of this is disputed. For the Engineer, this appointment would be limited to off-site, consulting, or technical responsibilities only.

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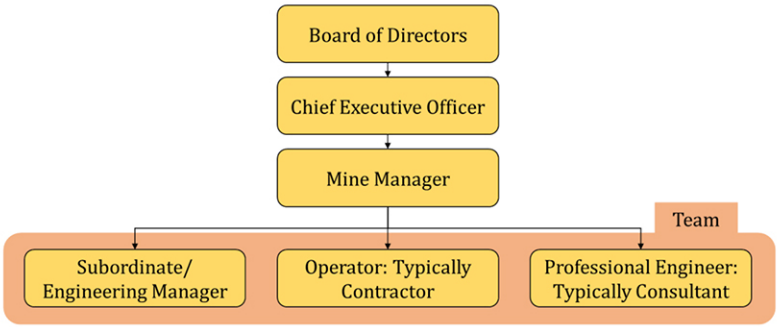

Figure 1—Typical SANS 10286 management structure

Table I

Summary of GISTM appointees

Role	Functions
Accountable Executive (AE) *Appointed by the CEO or Board of Directors*	• Executive accountable and responsible for ensuring adequate management structures are in place and functioning at each mine. • Responsibility can be delegated (*e.g.*, to a corporate tailings expert) but not accountability. • Appointing the ITRB (or a Senior Independent Technical Reviewer). • Assist operations in selecting RTFE and EOR. • Accepting lower design criteria when appropriate.
Responsible Tailings Facility Engineer (RTFE) *Appointed by the Operation (Mine Manager) with input from the AE. In some cases the AE may appoint an RTFE if duties are shared.*	• Accountable for the integrity of a tailings facility. • Facilitate communication between parties. • Scope and budget required work. • Ensures the tailings facility is designed, constructed, and decommissioned appropriately (jointly with EOR).
Engineer of Record (EOR) *Appointed by the Operation (Mine Manager) with input from the AE.*	• Ensures the tailings facility is designed, constructed, and decommissioned appropriately. • Carry out inspections on a regular basis. • Supported by a multi-disciplinary Design Team (either working alongside the EOR or sub-contracted out).
Independent Tailings Review Board (ITRB) or a Senior Independent Technical Reviewer *Appointed by the Operation (Mine Manager) with input from the AE. The AE may also appoint the ITRB.*	• Do not have decision-making authority. • Assess the underlying drivers of tailings safety throughout the tailings facilities life cycle.

While this standard has been successfully used over many years it has some shortcomings. For instance, the term 'Manager' is used generically so its meaning is sometimes not clear, for example, it can refer to the owner, a representative of the owner, the mine manager, and specific tailings appointees of the mine manager. Further, the management structure largely pertains to a given facility and it is not clear how this integrates into the wider structure of a mining company.

Largely in response to disparate management structures globally, the Global Industry Standard on Tailings Management (GISTM) was recently published (GTR, 2020). This attempts to remove ambiguity by expanding and better defining the management structure. The standard also assigns explicit responsibilities and accountabilities to individuals with standardized titles. The stated objective of this management structure is to ensure 'the safety of tailings facilities and for minimising the social and environmental consequences of a potential tailings facility failure' (GTR, 2020, p. 25).

GISTM defines four roles, an Accountable Executive (AE), a Responsible Tailings Facility Engineer (RTFE), an Engineer of Record (EOR) and an Independent Tailings Review Board (ITRB). Important functions of these four appointments are summarized from the Tailings Management Good Practice Guideline (ICMM, 2021) in Table 1. The main function of the AE is to be accountable and responsible for ensuring management structures are in place at all facilities within a mining company. The RTFE is accountable for the integrity of one or more named facilities. An EOR, working with the RTFE, ensures that a facility is designed, constructed, and decommissioned safely. On a regular basis, the underlying drivers of safety need to be assessed by an ITRB (or a single senior reviewer). Importantly, the ITRB does not have decision-making authority. The AE remains responsible for setting safety criteria, which the EOR in collaboration with the RTFE makes design decisions to achieve.

Figure 2 illustrates a possible way to implement the GISTM management structure in a South African context. The 'core team' shown in Figure 2 has similarities to the SANS 10286 'team' highlighted in Figure 1. Differences include the RTFE being a more dedicated role filled by an individual trained in aspects relating to tailings engineering, rather than being a manager with tailings responsibilities. Another difference is that the term 'Operator' refers to the entire mining operation in GISTM. To avoid potential confusion in the South African context, the 'Operator' shown in the core team, retains its original meaning and is the entity responsible for operating the tailings facility. The final member of this core team is the EOR who fulfils largely the same function as the Professional Engineer required in SANS 10286. Copeland (2018) provides an overview of the EOR role in a South African context. As with SANS 10286, GISTM expects the Operator and EOR to be assisted by others in performing their duties.

GISTM: Who are the responsible individuals?

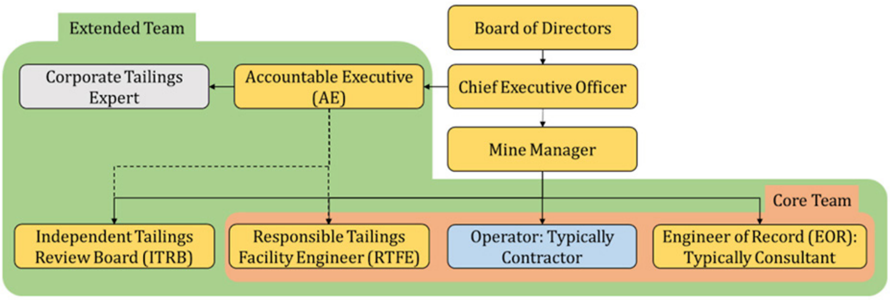

Figure 2—Typical GISTM management structure (**solid lines indicate typical appointments, however, appointments may also follow the dotted lines**)

GISTM's main addition is the 'extended team' shown in Figure 2, which clearly integrates a facilities management structure into that of the mining company and introduces independent review. The AE is a senior executive reporting directly to the Board or CEO to ensure the risks associated with tailings facilities receive necessary oversight. While the link between the RTFE and AE is explicitly shown, the AE will necessarily interact with the Mine Manager, and in some cases the AE is positioned directly between the CEO and Mine Manager. A corporate tailings expert may also be appointed to provide technical advice to the AE in larger mining companies. Additionally, larger mining companies may appoint executives below the AE for specific regions or commodities. The ITRB is introduced to provide regular reviews of underlying safety drivers. The makeup of the ITRB will vary depending on the issues of concern and need only be a single person for low and significant consequence facilities.

As mines adopt GISTM, the question arises as to who these individuals should be within the South African context. This has implications both in the short term (as supply of skills is limited) and in the long term (to guide training requirements). To try and answer these questions a review of international practices and a survey of the tailings community of practice was undertaken.

Survey

The Southern African Institute of Mining and Metallurgy (SAIMM) carried out a survey of industry to obtain views relating to qualifications, experiences, and competencies of the various appointees envisaged in GISTM. An online survey was distributed to SAIMM members, selected individuals active in the tailings community of practice and on social media platforms.

As GISTM is relatively new, the first survey page included a brief explanation of the intentions of the survey and GISTM definitions of the four main appointees (AE, RTFE, EOR, and ITRP). Participants were asked to familiarize themselves with the appointees and then indicate if they were familiar with them before proceeding. The survey ended if participants responded 'No'.

Following this orientation page, a series of questions were asked to establish participant's backgrounds. This included which sector they currently worked in, what their level of responsibility was, what professional/vocational background they came from, when they obtained their undergraduate qualification, and finally in which geographical region they predominantly work in.

Four sections followed, dealing sequentially with the RTFE, AE, EOR, and the ITRB roles (definitions for each were restated). At the start of each section, potential requirements for each role were given and participants were asked to rank appropriateness according to consequence classification.

Each section also contained specific questions regarding each role. With respect to the RTFE, participants indicated whether the role should be dedicated (*i.e.*, a sole responsibility) and whether the role can be shared between mines. Participants were also asked whether the AE role should be dedicated. Guidance was also requested on the number of appointments an EOR can hold.

The penultimate question asked participants to indicate the flexibility in meeting minimum requirements associated with each role. An open question for additional comments closed out the survey. A copy of the survey is available from the lead author.

Results

Participants

A total of 56 complete responses were received, with 50 indicating they were familiar with the GISTM appointees. Most participants came from mining companies (42%) and tailings consultancies (28%), the remainder indicated they were academics, contractors, or in allied fields. No regulators participated. Twenty-four per cent (24%) of respondents identified themselves as senior executives. Just under half (48%) identified themselves as filling at least one of the GISTM roles.

Twenty-six per cent (26%) came from a chemical (including process and metallurgical) engineering background, 34% from a civil (including geotechnical and geoenvironmental) engineering background, and 20% from a mining engineering background. Three participants had a mechanical/electrical engineering background, three an earth science (geological/environmental) background and one a commercial (law/business/accounting) background. Most of the participants (94%) worked in Africa.

A quarter of participants had at least 35 years of work experience following the completion of their undergraduate studies. On average participants had 26 years of experience and 92% of participants had at least 10 years of working experience. Considering the responses to these background questions, the participants are considered representative of the tailings community of practice in southern Africa.

Survey interpretation

One shortcoming of the survey was the interpretation of the 'Not appropriate for any consequence classification facility' response. This could be interpreted as either 'Not required' or 'Not suitable'. The authors, therefore, exercised their judgement in distinguishing between these responses based on the context of each potential requirement.

Qualifications

Figure 3, shows that many considered an engineering degree in

Appropriateness of qualification per role considering consequence class:

	RTFE				AE				EOR				ITRB			
	Not	Low risk	All	High risk	Not	Low risk	All	High risk	Not	Low risk	All	High risk	Not	Low risk	All	High risk
BTech Civil Eng	4	26	12	8					8	23	16	3	9	16	23	2
BEng/BSc Civil Eng	2	8	19	21	10	4	27	9	2	6	25	17	3	6	27	14
BEng/BSc Chem. Eng	14	17	11	8												
BEng/BSc Mining Eng	17	19	7	7												
BSc Earth Sciences	17	15	10	8					13	14	18	5	9	10	27	4
BEng/BSc mine related					6	7	30	7					11	15	19	5

Number indicates responses per choice

Figure 3—Qualifications appropriate to each role (50 responses in total per row)

Appropriateness of experience per role considering consequence class:

	RTFE				AE				EOR				ITRB			
	Not	Low risk	All	High risk	Not	Low risk	All	High risk	Not	Low risk	All	High risk	Not	Low risk	All	High risk
5 years	10	26	10	4												
10 years	1	7	17	25	6	23	17	4								
15 years					3	7	15	25	3	21	20	6	7	20	19	4
20 years									3	2	21	24	3	4	25	18
CPD training	10	8	26	6	12	7	26	5	8	8	30	4	8	7	29	6
PG training	7	8	23	12	13	8	23	6	7	8	27	8	9	8	25	8
Pr Eng	2	5	16	27	12	8	20	10	3	3	28	16	1	3	32	14
Pr Tech Eng	3	24	15	8					8	17	21	4	7	11	26	6
Pr Sci Nat	17	14	12	7					18	12	16	4	11	11	24	4

Number indicates responses per choice

Figure 4—Experience appropriate to each role (50 responses in total per row)

civil engineering an appropriate qualification for the RTFE for all to high-risk facilities. Many considered a Bachelor of Technology in civil engineering appropriate for lower risk facilities. Very few considered a background in civil engineering inappropriate (*i.e.* not required) for the RTFE. Chemical engineering, mining engineering, and earth sciences backgrounds were considered less appropriate with many seeing these as not suitable. In the context of SANS 10286, the mine engineer responsible for tailings was typically the metallurgical/plant manager. Given that many tailings facility failures can be related to the plant (*e.g.* slurry density, split between coarse and fine materials, and water balance) it is perhaps wise for the RTFE to have a thorough understanding of these aspects.

Fewer qualifications were suggested for the EOR, with a Bachelor of Technology in civil engineering deemed more appropriate for all to low-risk facilities, and an engineering degree in civil engineering for all to high-risk facilities (Figure 3). A background in earth sciences was also seen as appropriate for all to low-risk facilities, however, a large group saw this qualification as inappropriate (*i.e.*, not suitable).

For the AE role, many considered any mining-related engineering degree appropriate (Figure 3). A civil engineering background was also deemed appropriate, although several participants indicated not appropriate (*i.e.* not required). For the ITRB the modal answers suggested the proposed qualifications were deemed appropriate for all facilities, although degrees in civil engineering trended higher, with Bachelor of Technology in civil engineering, earth sciences degrees, and mine-related degrees trending lower.

Experience

For the RTFE, it is evident that less than 5 years of experience is considered less suitable but that 10 years is largely considered appropriate in more extreme cases (Figure 4). This range for the AE was 10 to 15 years, for both the EOR and ITRB this was 15 to 20 years. The distribution of responses across roles for continuous professional development (CPD) and postgraduate (PG) training was very similar, although need for training was marginally higher for the EOR and ITRB. This result, particularly the appropriateness of PG training, was interesting. It is most likely that 'appropriate' was being interpreted as 'suitable' rather than 'required' in this case.

For the RTFE, professional registration as an Engineer (Pr Eng) was largely considered appropriate for high-risk facilities, with registration as a Professional Engineering Technologist (Pr Tech Eng) appropriate for lower risk facilities (Figure 4). Registration as a Professional Natural Scientist (Pr Sci Nat) was not considered appropriate for the RTFE by many, but others saw it appropriate for low-risk facilities. The need for the AE to be a Pr Eng was less explicit compared to other roles with a larger number of respondents seeing it as not appropriate (*i.e.*, not required).

For the EOR, Pr Eng was considered most appropriate, especially for high-risk facilities, a Pr Tech Eng was also considered appropriate but more so for low-risk facilities, a Pr Sci Nat was not considered appropriate by many, but others saw it appropriate for low-risk facilities. The appropriateness of the three types of professional registration for the ITRB showed similar trends to the EOR, except that a Pr Sci Nat was considered more appropriate.

Competencies

For the suggested competencies for each role, there was little in the distribution of responses to suggest a stated competency was not considered appropriate for a given role (Figure 5). Attention is drawn to two aspects: first is the divided opinion for the EOR to be a technical executive ('Executive experience in a technical discipline'). This reflects practice in that the EOR does not need to be an executive within a consultancy. The second aspect we wish to highlight is that many saw the suggested competencies for the AE being considered highly appropriate for 'All' facilities. This reflects how GISTM necessitates considerable stakeholder engagement to be driven by the AE. The AE, therefore, needs a wide range of competencies with soft-skills being foremost.

Division of labour

A minority of respondents indicated that the RTFE role should be a dedicated role on a mine (Table II). The necessity of a dedicated role was linked more to the consequence classification of the facility rather than the stage or performance of the facility. Comments received suggested a dedicated role is ideal but often not practical. Time and support were also identified as important deciding factors. A dedicated role may not be necessary if sufficient group level support is provided. A site may have several low risk facilities requiring considerable oversight justifying a dedicated role, whereas a single well-resourced very high consequence facility may not need a full-time RTFE.

Again, a minority of respondents indicated that the RTFE should not be shared between facilities, with the suitability of sharing linked to lower risk facilities (Table II). Sharing an RTFE was also seen to be dependent on workload and proximity of facilities. An important consideration raised was potential conflicts of interest arising from who the RTFE is employed by. For instance, if the RTFE is employed by a mining company (head office) they may have limited agency to affect decisions on a mine.

Just under half (42%) of respondents did not see the necessity of a mining company having a dedicated AE (Table III). Those that did indicate a necessity of a dedicated role, linked this to the consequence classification of facilities within a mining company's portfolio. Considering the proportion of High to Extreme consequence facilities globally (Franks *et al.* 2021) mining companies may increasingly have dedicated AEs.

On average respondents suggested each EOR should have no more than five appointments, however, this ranged between 3 and 10. Of respondents that provided rationale for the number of appointments, most linked the number of appointments to the consequence classifications associated with the facilities. Other key factors included the experience and capabilities of the individual and team available to the EOR, and the time available for the EOR to visit each facility.

Flexibility

In the short term, there is likely to be a shortage of appropriate personnel to take up these roles. Consequently, participants were asked to rank the required traits for each of the four roles from less to more flexible. Solid round symbols in Figure 6 are the mean

Table III

Division of Accountable Executive responsibilities

In which scenario should the AE be a dedicated role in a mining house (as opposed to the AE having other managerial responsibilities)?	
The AE need not be a dedicated role for mining houses.	42%
A mining house should have a dedicated AE if it has any High to Extreme consequence facilities.	48%
A mining house should have a dedicated AE if it has any Very High to Extreme consequence facilities.	10%

Appropriateness of competency per role considering consequence class:

	RTFE				AE				EOR				ITRB			
	Not	Low risk	All	High risk	Not	Low risk	All	High risk	Not	Low risk	All	High risk	Not	Low risk	All	High risk
Know standards	4	8	25	13	0	5	32	13	3	6	28	13	2	7	31	10
Manage teams	8	6	25	11	7	4	32	7	11	4	23	12				
Know risk management					0	5	36	9								
Technical executive					2	6	31	11	13	3	19	15	5	6	25	14
Governance executive					4	5	30	11								

Number indicates responses per choice

Figure 5—Competencies appropriate to each role (50 responses in total per row)

Table II

Division of Responsible Tailings Facility Engineer responsibilities

In which scenario should the RTFE be a dedicated role on a mine as opposed to the RTFE having other responsibilities (*e.g.* a 2.13.1 or 3.1 appointee)?	
The RTFE should be a dedicated role for all consequence classification facilities.	28%
The RTFE should be a dedicated role for High to Extreme consequence classification facilities.	36%
The RTFE should be a dedicated role for Very High to Extreme consequence classification facilities.	23%
The RTFE should only be a dedicated role for certain situations (*e.g.* during commissioning, when complex construction activities are underway or when a facility is showing distress).	13%
In which scenario should the RTFE be shared with other mines?	
The RTFE should not be shared between mines.	24%
The RTFE can be shared between mines with Low to Significant consequence classification facilities.	42%
The RTFE can be shared between mines with Low to High consequence classification facilities.	33%

responses and the solid lines are the interquartile ranges. This suggests that the AE role is considered the most flexible followed by the ITRB, RTFE and finally the EOR. This ranking likely also reflects the responsibility held by the various roles in ensuring the safety of a tailings facility.

Suggested requirements

Based on the survey results, a review of relevant literature, and the consensus of the authors, Table IV is proposed as a list of minimum or ideal requirements for the various GISTM appointees to which South African mining companies should strive. Given that an ideal candidate is often difficult to find, the authors suggest that greater weight should be placed on demonstrated competencies and years of experience. The required traits of the four appointees are ranked from most flexible to least flexible from left to right.

Summary

Disparate tailings facility management structures globally have resulted in a consolidated effort to define a global standard. The resulting Global Industry Standard on Tailings Management defines four key roles: an Accountable Executive (AE), a Responsible Tailings Facility Engineer (RTFE), an Engineer of Record (EOR), and an Independent Tailings Review Board (ITRB). In a South African context, there is little guidance on the traits required by these individuals. Consequently, this paper explored the management structure proposed in GISTM in relation to the widely adopted SANS 10286 structure. Further, a survey of the local tailings community of practice was undertaken and results were interpreted in light of international practices. From this, a list of minimum or ideal requirements for each role was proposed (see Table IV).

List of notations

AE Accountable Executive
CEO Chief Executive Officer

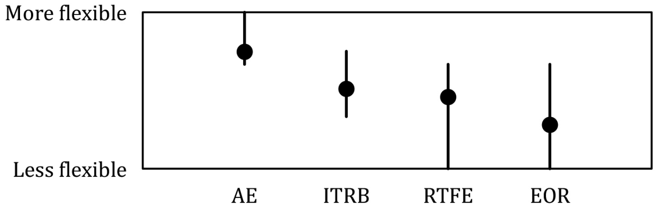

Figure 6—Importance in meeting the minimum requirement

EOR Engineer of Record
ITRB Independent Tailings Review Board
RTFE Responsible Tailings Facility Engineer

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Table IV

Ideal requirements for GISTM appointees

	AE	ITRB	RTFE	EOR
Qualifications	Any mine-related engineering degree	Degree depends on review issue. Civil engineering likely to be required most.	Mine-related engineering degree preferably in civil engineering, especially for facilities with high risk. Technology degrees may also be suitable.	Civil engineering degree. Technology degree in civil engineering and earth science degrees may be suitable for lower risk facilities.
Experience	- 10 to 15 years CPD training - Pr Eng suitable but not required	- 15 to 20 years CPD training and ideally PG training - Pr Eng/Pr Tech Eng/Pr Sci Nat depending on the issue under review	- 5 to 10 years CPD training - Registered as a candidate engineer or technologist with a nominated mentor guiding them to registration.	- 15 to 20 years CPD training and ideally PG training - Pr Eng (Pr Tech Eng or Pr Sci Nat may be appropriate on consideration)
Competencies	- Know standards - Manage teams - Know risk management - Technical executive - Governance executive	- Know standards - Technical executive	- Know standards - Manage teams	- Know standards - Manage teams
Division	AE can have other responsibilities but may need to be dedicated depending on support and risk profile of facilities.		Ideally a dedicated role per mine. However, in cases, there will be scope for the RTFE to have other mine roles and/or be shared.	Between 3 and 10 appointments depending on consequence classification, capacity, and time to visit sites.
Flexibility	Most			Least

Defining optimal drill-hole spacing: A novel integrated analysis from exploration to ore control

by B.C. Afonseca[1] and V. Miguel-Silva[2]

Affiliation:
[1]AngloGold Ashanti – Sabará, Minas Gerais, Brazil.
[2]Vale – Nova Lima, Minas Gerais, Brazil.

Correspondence to:
B.C. Afonseca

Email:
brunocafonseca@yahoo.com.brr

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ORCID:
B.C. Afonseca
https://orcid.org/ 0000-0001-9567-4937
V. Miguel-Silva
https://orcid.org/ 0000-0001-7502-9543

Synopsis

Drill-hole spacing analysis (DHSA) and optimization are becoming commonplace for uncertainty assessment and management in the mining industry. However, there is no standardized DHSA workflow, and the outputs of certain methodologies are not interchangeable. We group available simulation-based DHSA methods according to their accounted uncertainty into (i) raw uncertainty, assessed by drawing realizations from synthetic data-sets with the drilling spacings to be tested; and (ii) model uncertainty, in which these synthetic data-sets are used to assess the variation between the estimated model and the (unknown) actual value. DHSA workflows available in the literature ignore the differences between both types of uncertainty. Commonly, the DHSA algorithm is chosen without a detailed analysis of its uncertainty output, which may lead to misleading results and suboptimal decisions. While available solutions are based only on assessing raw or model uncertainty, the proposed approach simultaneously analyses both and their relationship for models at different stages of the mine. The integrated analysis results deliver more information to support decision-making than available methods. Principles, practical considerations, and discussions of the advantages of the proposed integrated analysis are presented. The approach is applied to a real gold deposit to illustrate its use.

Keywords

drill-hole spacing analysis, conditional simulation, ordinary kriging, uniform conditioning, estimation error.

Introduction

Drill-hole spacing analysis (DHSA) is a set of geostatistical techniques applied to assess the associations among the uncertainty of the estimates, drilling spacing, and data availability. In this sense, the Joint Ore Reserves Committee (JORC, 2012) states that the reporting of Mineral Resources should be supported by significant geological information for all classifications of Inferred, Indicated, and Measured Mineral Resources. The reports must include evidence of the sampling methods and the appropriateness of data spacing to the mineral deposit's geological, physical, chemical, and mineralogical features. DHSA may provide important decision drivers from initial exploration to production models. Its outcomes may also be analysed from an optimization perspective, where we look for the optimal drill-hole spacing (the decision variable) to define an objective function to be optimized, such as a minimum misclassification, maximization of resource conversion, or the best balance between the sampling costs and operational losses caused by under-sampling (Li *et al*., 2004; Boucher, Dimitrakopoulos, and Vargas-Guzman, 2005; Koppe *et al*., 2011; Martínez-Vargas, 2017). DHSA tends to be understood as applicable exclusively for diamond or rotary drill-holes. However, these geostatistical techniques may be used to assess the spacing of any type of samples, such as production blast-holes or underground channel sampling. Hereafter, we use drilling and sampling spacing interchangeably to refer to the spacing of the type of data under analysis.

There is no standardized workflow for DHSA, but we may generalize the state-of-the-art and most widely used solutions into kriging- and simulation-based methods. Compared to kriging methods, the simulation-based algorithms demand considerably more computational and technical resources for running, processing, and checking all drawn realizations (Verly, Postolski, and Parker, 2014). DHSA, based on simulation algorithms, provides access to the probability distribution and properly considers the local variability, proportional, and support effects. We consider that the additional effort required by simulation algorithms is justified due to the risk of losses from suboptimal sampling strategies. Verly, Postolski, and Parker (2014) state that when the risk assessment requirements are not so complex or when the time to complete a simulation is lacking, DSHA involving kriging variance calculations can be useful.

We distinguish the simulated-based methods available in the literature into model uncertainty and raw uncertainty. This distinction is based on the workflow employed to measure the uncertainty in each case. In both algorithms, a set of synthetic data-sets corresponding to the drilling spacings to be tested is drawn by geostatistical simulation. However, on the model-uncertainty workflows (Figure 1a), these synthetic data-sets are input to a chosen kriging estimator. The local accuracy is assessed through the variation between the estimated model and the (unknown) actual value. In the second workflow (Figure 1b), named raw uncertainty, realizations are drawn from each synthetic data-set. The assessment of global accuracy of properties, such as tonnage *versus* grade relationship, is prioritized at the expense of local accuracy.

Both workflows presented in Figure 1 are widely discussed in the literature. However, the implications, distinctions, and relationship of their output uncertainty is an overlooked subject. The difference between the introduced raw and model uncertainties is directly connected to global and local accuracy concepts. The method in Figure 1a is affected by the fact that kriging methods, by definition, cannot be simultaneously conditionally unbiased and globally accurate. If a resource model accurately predicts the tonnages and grades available for selection at the time of mining, then the block grade estimates are conditionally biased. This is the kriging oxymoron discussed by Isaaks (2005). Based on this concept, DHSA should not be applied without considering the objective function to be optimized, the geostatistical methods, and an adequate definition of its parameters.

The novelty of the presented workflow lies in the fact that DHSA studies should always consider the interdependence between the function being minimized, the method employed for modelling the uncertainty, and the purpose of the models from which decisions are made, from the required accuracy of global grade-tonnage relationship at exploration stages to the local accuracy required to classify mineable blocks of production models. This is especially true when global and local accuracies are compared (Journel and Huijbregts, 1978; Isaaks, 2005). We propose a novel solution in which raw and model uncertainty support an integrated analysis where each type of uncertainty complements the other. Their relationship is fundamental for supporting decision-making. The available algorithms are adapted to generate comparable and interchangeable outputs (Figure 1).

We address this subject as follows. We first distinguish the objective functions for short- or long-term models and their purposes. We analyse the singularities of both reviewed groups of DHSA methods and the objective function optimization, and discuss specifics. Next, we establish a distinction between the raw and model uncertainties. The approach formulated herein is then outlined. We argue that their results are not equivalent, directly comparable, or conceptually similar in some instances. Subsequently, the proposed approach is tested for a real gold deposit, where the raw and model uncertainties are merged for a unique risk assessment. This is followed by a discussion and conclusions.

Literature review: Raw and model uncertainty approaches

Various authors have presented optimization methods for drilling spacing to reduce the uncertainty of the transfer functions of interest. Geostatistical simulation methods are increasingly applied for DHSA because these stochastic methods

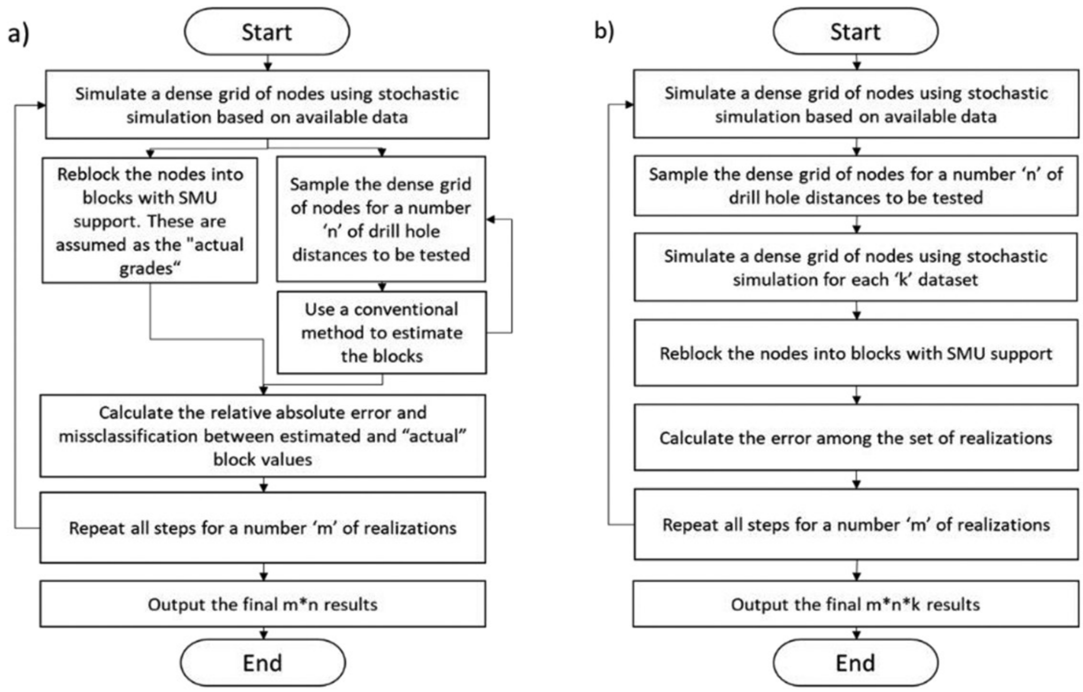

Figure 1—Flow charts for two DHSA workflows. In (a), the 'n' simulated synthetic data-sets are used to compare estimates obtained using these data-sets with the 'actual value' obtained by averaging the simulated nodes into block support. In (b), each synthetic data-set is used as input to the drawn realizations to compute the variability among realizations in each block

are recognized tools for quantifying the spatial distribution of uncertainty. The scope of this literature review is not to present details for geostatistical simulation (Deutsch and Journel, 1998; Goovaerts, 1997) but to discuss the differences between the most popular DHSA approaches based on simulation.

We may separate these methods into two groups based on their output uncertainties.

➤ The raw uncertainty approach (Figure 1b) accurately assesses the global risk attached to a random function (RF) spatial distribution. Synthetic data-sets representing the drilling spacings to be tested are simulated. Realizations are drawn from each data-set. The probability distribution of transfer functions, such as operational costs, net present value, or other economic and engineering parameters can, therefore, be calculated. It is generally assessed by Gaussian methods, maximum entropy methods that provide the most 'disorganized' spatial arrangement possible for a given RF. The reproduction of the RF parameters is prioritized at the expense of local accuracy (Goovaerts, 1997). Here, equiprobable realizations are simply a means to represent the uncertainty, and thus it is recommended to submit all realizations through the transfer function to achieve a full distribution of responses.

➤ The model uncertainty approach (Figure 1a) uses synthetic data-sets to assess the local accuracy. It better predicts the local uncertainty found in short-term and production models, such as the variation between the estimated model and the (unknown) actual value, or the expectation to classify a block as ore or waste correctly.

Kriging is a linear algorithm based on the minimization of the error variance to provide accurate local estimates (Matheron, 1963). Therefore, the actual deviation between model estimates and the true value is expected to be lower than the dispersion assessed by simulation algorithms, here classified as raw uncertainty. The model uncertainty also considers the unavoidable smoothing effect and its related conditional bias. The expected value of the true grade based on the estimates is not equal to the estimated value, and generally underestimates high values and overestimates low values (Journel and Huijbregts, 1978).

Table I summarizes references in the literature for the approaches defined herein.

One concern associated with both simulation-based groups is their excessive computational requirements. Some authors have suggested the use of scenario reduction, where the objective function would be analysed from a subset m' sampled from m based on similarity or dissimilarity conditions (Armstrong *et al.*, 2013; Okada *et al.*, 2019; Usero, Misk, and Saldanha, 2019). The use of scenario reduction, however, is a disputed subject. The problem to be optimized is key for correctly managing multiple realizations. In general, the full set of realizations should be used for objective functions, such as plan optimization, ultimate pit limits, net present value, or expected profit (Deutsch, 2017). There is no right or wrong realization, as it is impossible to state that one represents the reality better than the others. Incorrect or suboptimal decisions could be made if too few realizations are considered. However, optimization of the drilling spacing for linear objective functions, such as the average estimation error or misclassification rate, can be conducted with fewer realizations. The specific location of high or low variability areas within the simulated domain is not critical. The variability at specific locations averages out globally over multiple realizations, and any of these realizations reflect the overall variability required by DHSA studies.

Table I

Scheme of the available studies about drill-hole distancing optimization

Author	Optimized function	Uncertainty index[4]
Englund and Heravi, 1993[1]	Costs associated with misclassification	Misclassification rate
Li *et al.*, 2004[1]	Drilling patterns to match the desired risk level within a required confidence level	Relative absolute error between estimate and 'actual' grade
Boucher. Dimitrakopoulos, and Vargas-Guzman, 2005[1]	Drilling pattern that maximizes the gross profit	Profit per ton processed
Bertoli *et al.*, 2010[1]	Global ordinary kriging estimation variance	95% confidence interval *versus* a drilling spacing for the corresponding area
Koppe *et al.*, 2011[2]	Uncertainty related to the NPV	Std. dev. of the distribution from all simulated NPV scenarios
Koppe, Rubio, and Costa, 2017[2]	n.a.	$\frac{(Q95_{(i)} - Q5_{(i)})}{2E_{type(i)}}$
Martínez-Vargas, 2017[1]	Drill-hole spacing defined as that where cost equals the cost of misclassifying ore and waste in selection mining units (SMU)	Misclassification rate
Usero *et al.* 2019[3]	Dispersion of different simulated attributes within a confidence interval	$\frac{(Q95_{(i)} - Q5_{(i)})}{2E_{type(i)}}$
Drumond *et al.*, 2019[2]	n.a.	$\frac{(Q95_{(i)} - Q5_{(i)})}{2E_{type(i)}}$

[1] Model uncertainty methods.
[2] Raw uncertainty methods.
[3] Variation of the raw uncertainty methods. A subset n' represents the entire set of realizations n.
[4] Where: Q15; Q95; E-type are respectively the quantiles 5th, 95th, and the average of the set of realizations.

It is worth emphasizing that the methods discussed here are exclusive for grade uncertainty. No information involving the uncertainty of the geological boundaries of each geological domain is provided by the methods. However, adaptations can capture the joint uncertainty of grade and geological features.

Define the variables and outline the optimization problem

No sampling spacing is optimal by itself. When performing DHSA studies, the drilling spacing is tested against the variable to be optimized, such as the miscalculation rate, resource conversion, or expected profit. The best spacings differ for those different variables. Typical applications for DHSA are as follows.

- Mineral Resource: The DHSA is applied to find the most efficient spacing that supports the resource categories according to confidence levels of the estimates over a large production area. A very frequent practice in the mining industry states that the available information should be enough to support the grade and tonnage prediction within a ±15% accuracy at a 90% confidence interval over a quarterly or monthly production increment for a measured class. The annual production accuracy should be within ±15% at a 90% confidence interval for Indicated Resources. Thus, the DHSA quantifies the investment required for resource conversion or categorization.
- Grade control/production models: The main purpose of grade control models is to provide local precision for the selection of ore and waste. These models provide the last opportunity during mining operations to ensure that the material is correctly assigned to the stockpile or waste dump, which reduces the number of misclassified blocks. The DHSA for grade control is commonly used to evaluate whether a denser drill-hole campaign reduces the block misclassification, the cost of which is, on average, higher than the cost of acquiring new data.

Next, we discuss relevant elements to be considered when performing optimization studies.

The scale of the decisions to be made

Fitting the model scale to the function to be optimized is particularly relevant for DHSA studies. The 'scale of the decision' term addresses the appropriate volume or area relevant for a decision to be made. For instance, in the early project stages, the global grade-tonnage relationship may be much more valuable information for decision-making than the grade accuracy at the mining support. In contrast, assessing the local accuracy, such as the local uncertainty of each estimated block, becomes especially relevant for mining selectivity decisions.

From a geostatistical perspective, the estimation must consider the average distancing of the available data. A widely used rule of thumb states that the block size should vary between 1/4 and 1/2 of the data spacing. This proposition arises from the relationship between the block support, estimation error, and internal block variance. Considering a stationary domain G, the 'smoothing relation' (Equation [1]) explains how the average kriging variance (σ^2_{kv}) and dispersion of the estimated block (v) distribution (D^{2*}_k) are negatively related (Journel and Huijbregts 1978):

$$D^2(v/G) \cong D^{2^*}_k(v/G) + \overline{\sigma^2_{kv}} \qquad [1]$$

We observe that large blocks are likely to be close to the actual true grade, while very small blocks result in over-smoothed estimates due to the higher estimation variances. Figure 2 shows the influence of the block dimension on the maximum estimated error. Note that the 24 × 24 × 4 m block model using 12 × 12 × 1 m spaced drill-holes shows uncertainties similar to the 50 × 50 × 4 m block model using 24 × 24 × 1 m spaced data.

The geostatistical criterion for defining the block size to be used during DHSA leads to a problem in which the block size impacts the drill-hole spacing definition, and *vice-versa*. Therefore, this paper considers the smallest scale for a decision in mining. It is called a selective mining unit (SMU) size, and production volumes as constant parameters are defined by operational constraints and not as variables to be optimized. An SMU is defined as the minimum volume that allows ore-waste selectivity, which is a function of the mining method and technological conditions.

While local accuracy is commonly measured block by block, the global accuracy for resource classification is generally computed for a panel representing a given monthly, quarterly, or annual production increment (Figure 3a). An uncomplicated scheme is often used when a mining plan is not available. Grids commonly employed by commercial mining software packages are sorted out by their x, y, and z coordinates, and then their masses are summed until a desired production increment volume is reached (Figure 3b). Constraints may be applied to mimic realistic operational shapes.

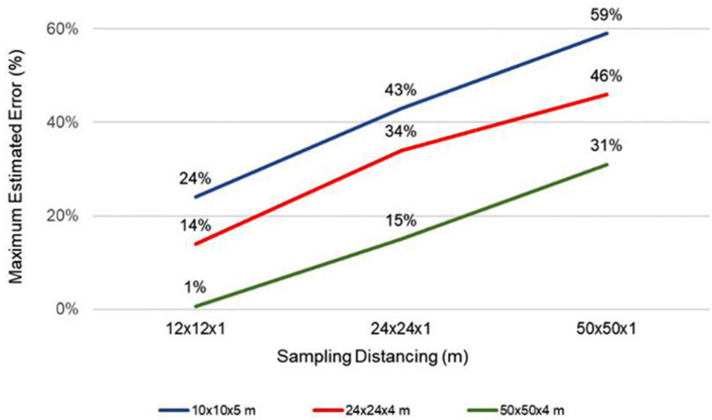

Figure 2—The relative maximum estimation error (MEE) as a function of the sampling grid for different block dimensions (modified from Koppe, Rubio, and Costa, 2017). Details of the error calculation are presented in Table I

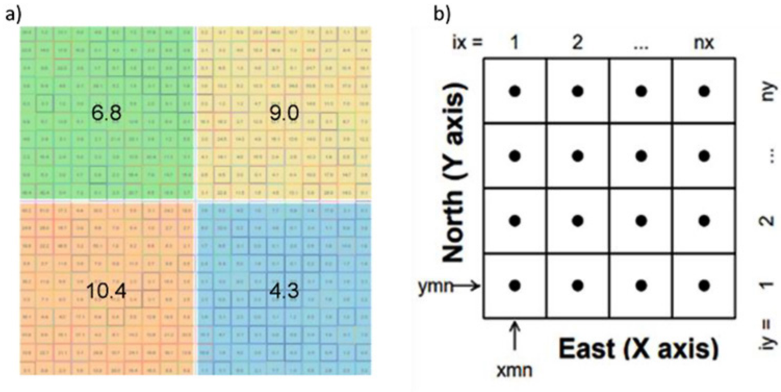

Figure 3—(a) 400 estimated blocks are combined into four volumes corresponding to a given production increment, and (b) plan cross-section view illustrating the grid definition used in GSLIB, DM Studio (adapted from Deutsch and Journel, 1998)

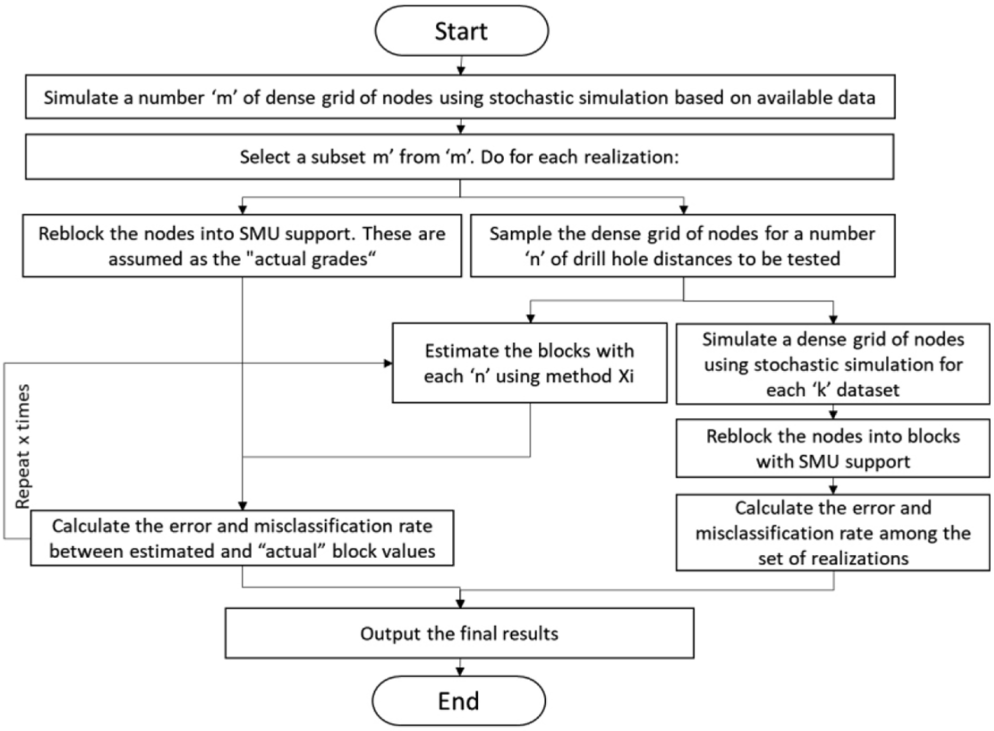

Figure 4—Proposed workflow for integrated DHSA. The same synthetic data-sets are input for drawing realizations and measuring the raw uncertainty and input for estimating blocks and measuring the model uncertainty

The following section discusses the applicability of raw and model uncertainties from the perspective of different uncertainty indicators, functions to be minimized, and methodologies available in the literature.

Proposed methodology

The reviewed DHSA methods focus on setting the relationship between the drill-hole spacing and a specific uncertainty index considering a single model purpose, such as the required local accuracy of production models, or the global accuracy for a resource model. Therefore, DHSA does not connect the optimal drill-hole spacing for an exploratory model with the infill campaign to be drilled in the future. This relationship is not fully captured by the methods available in the literature and no optimal decision can be made without considering an integrated DHSA. In consequence of this limitation, the proposed methodology defines an integrated analysis of raw and model uncertainty, which provides uncertainty information considering the different model purposes throughout the life of the mine.

The proposed methodology is an adaptation of the reviewed and widely used methods. Its novelty is the integrated DHSA to support a complete drilling plan from exploration to production models, their limits, and the best geostatistical method for each step. Available DHSA methods and concepts were kept, but algorithms were revised to reduce the computational effort required to run both simultaneously and assure interchangeable results. The integrated DHSA workflow (Figure 4) benefits from the best of both uncertainty workflows that account for local and global uncertainty. The gains arise from the complementarity between raw and model uncertainty, which leads to an increased information level of assessed uncertainties and fewer arbitrary decisions among different methods, scales of decisions, drill-hole spacings, and resource classes.

Computational performance and the results are directly associated with the use of one or all realizations in the DHSA workflow. A guideline is provided by Armstrong *et al.* (2013) and (Deustch, 2018):

- The optimal drill-hole spacing and its impact on local parameters, such as the block-by-block error or misclassification rate, may be assessed by a single set or subset of realizations because the variability at specific locations averages out over multiple realizations.
- In the case of nonlinear relationships or more complex functions, such as a profit expectation or definition of the pit limits, it is recommended to pass all realizations through the transfer function to assess the whole response distribution.

The ideal number of realizations should be defined for each study. Different mineral deposits may require a different number of realizations to model the uncertainty, depending on their grade variability and the scale under analysis. A widely used solution is to measure the convergence of statistics of interest, such as the mean and standard deviations, for increasing values of 'm' and 'n'. This and other approaches may be found in Rossi (1994) and Deutsch and Journel (1998).

Applications

Realizing how the practitioner's DHSA premises impact the whole perception of uncertainty is important. Even so, it is not unusual to see drill-hole spacing studies limited to standard strategies for modelling the uncertainty, which may not be suitable for the problems being solved. DHSA should not be exclusively sampling-dependent but should also integrate the geostatistical method used and model purpose into the uncertainty modelling. For example, projects at very early exploration stages support viability studies and technological decisions over the global predictions of grade and metal content. This means that the global grade-tonnage proportion is more relevant than the grade uncertainty and selectivity at a mining scale. However, prior exploration drilling may be combined with infill data for estimating production models. During the mining process, local accuracy is fundamental for the final selection. At this stage, minimizing the misclassification of ore and waste blocks is the primary concern. A real optimal sampling plan only may be assessed by an integrated DHSA. Operational conditions usually constrain the sampling programmes in real-world problems. The optimal spacing should consider technical limitations such as the mining scheduling, the grid of blast-hole drilling, or the separation between two consecutive stopes in underground mines. Next, we present some practical considerations on how to apply the proposed solution to fit a unique uncertainty assessment to different DHSA problems.

Example

In this hypothetical case, drill-hole spacing analysis is carried out to define (i) the broadest sample spacing that supports an acceptable misclassification error in production models, and (ii) the sample spacing suitable for classifying the model areas as Measured, Indicated, or Inferred. It is an example applicable to many mining operations, where an integrated study supports the correct geostatistical workflows and drill-hole spacing for each model, as well as defining if the exploration or production team is accountable for the drilling campaign. As discussed, the uncertainties to be modelled in each case come from different sources and it is advisable to treat them with an integrated approach.

Figure 5 shows a schematic plot for local and global uncertainties as a function of the drill-hole spacing. The plot is an example of how the results of the integrated DHSA should be analysed after following the workflow in Figure 4. The mod1, mod2, and mod3 may represent three different geostatistical methods, *e.g*., ordinary kriging (OK; Matheron, 1963), sequential Gaussian simulation (SGS; Isaaks, 1990; Deutsch and Journel, 1998), and LUC (Abzalov, 2006), or even a single method adjusted for three different parameters.

When considering a 20% misclassification rate as an acceptable tolerance in Figure 5, mod3 should be selected for grade control. In this case, we see that 25 × 25 m would be the wider grid that supports the accuracy required for short-term models. For resource categories, *i.e*., Measured/Indicated/Inferred, as a function of the expected profit uncertainty, the long-term models should be estimated with grids between 25 × 25 m and 150 × 150 m. In such cases, mod1 should be selected because it has lower values for the global uncertainty. Models using a grid beyond 150 × 150 m are of little use from a resource perspective because of their high uncertainty. From this conceptual case, it is quite clear that model uncertainty, if taken from a local or global perspective, changes depending on the evaluation strategy. The essence of the integrated approach is to capture these disparities.

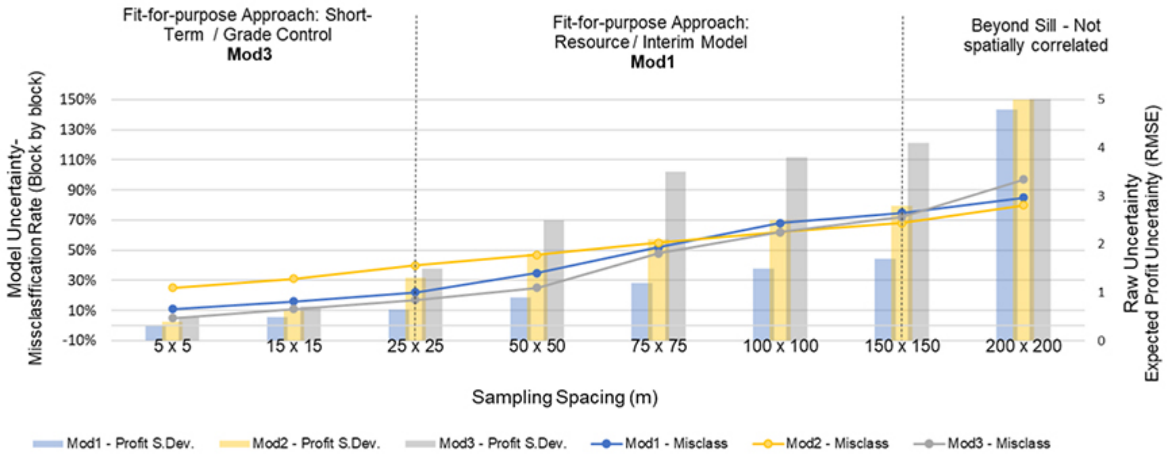

Figure 5—Schematic integrated DHSA. The mod1, mod2, and mod3 represent models of different estimation methods

Integrated DHSA applied to a real gold deposit

The studied orebody is part of a world-class gold deposit in the Rio das Velhas greenstone belt located on the north border of the Iron Quadrangle (QF) district, Minas Gerais, Brazil. Geologically, it is classified as a typical association of mafic volcanic rocks, banded iron formation (BIF), carbonaceous phyllite, and micaceous phyllite metamorphosed at greenschist facies conditions (Lobato, 1998). Considering the host rock and the mineral assemblage, Vieira (1987) recognized three main gold mineralization types in the Iron Quadrangle district: (i) rich-pyrrhotite hosted in BIF, (ii) related to pyrite and arsenopyrite replacing the iron layers of banded formations, and (iii) disseminated arsenopyrite in mafic schists.

The case study is developed in an underground mine currently in operation. Long-term models are gradually replaced by detailed grade-control ones as the production and drilling campaign progresses. Depending on how dynamic the operation is, additional interim models may be necessary to support strategic and operational decisions. As the estimates are designed to fit the model purpose, the uncertainty modelling and the DHSA to define the optimal drill-hole spacing are recommended to be likewise.

Simulating the reference scenarios

The original data-set came from a depleted area extensively sampled by diamond drill-holes (DDH) and face channels. Figure 6 shows the declustered distribution of the data-set, where the variogram models were fitted to original and normal-score units (Table II).

The original data was used as SGS input to produce 30 equiprobable realizations in the deposit discretized in a dense 1 × 1 × 1 m grid. The sectorized SGS search ellipse was adjusted to fit the ore anisotropy and variogram ranges. The simple kriging was conditioned to 12-64 original samples and up to 36 previously simulated nodes. The 30 resulting realizations satisfactorily reproduced the declustered average grade, distribution, variogram model, and directional anisotropy (Figure 7).

The simulated realizations at the 1 × 1 × 1 m grid were used to generate 30 new synthetic data-sets for seven drill-hole spacings to mimic exploration and infill drilling: 5 × 30 × 1 m (representing the actual grade control spacing), 10 × 15 × 1 m, 20 × 30 × 1 m, 30 × 45 × 1 m, 40 × 60 × 1, 60 × 90 × 1 m, and 80 × 120 × 1 m along the strike, plunge, and width, respectively (Figure 8). The listed sample spacings are possible considering the technical and operational conditions.

Accounting for the local and global uncertainties

To compute the uncertainty, the integrated workflow (Figure 4) was applied as follows.

- The 30 'true' realizations were sampled at seven drilling spacings, resulting in 210 synthetic data-sets (Figure 9a).
- Thirty realizations were drawn by the SGS method from the 210 data-sets. The raw uncertainty of each drill-hole spacing was measured as the difference among 1 × 1 × 1 m realizations averaged into 10 × 10 × 10 m blocks. The synthetic data from SGS was used for the normal score variogram of the original data. The search ellipse orientation and ranges considered the variogram parameters defined in Table II. A sectorized search was conditioned for 12-64 actual samples and up to 36 simulated nodes.
- Ordinary kriging was applied to the 10 × 10 × 10 m blocks (Figure 9b). The OK used the original units variogram

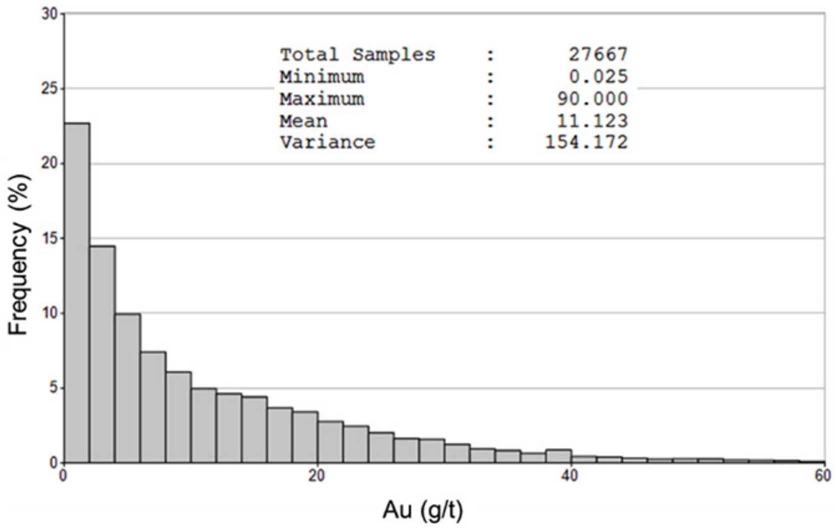

Figure 6—Original declustered distribution of data

Table II

Variogram model parameters for original and normal-scored data

Variable	co	Structure 1					Structure 2				
		Type	c1	North	East	Vert.	Type	c2	North	East	Vert.
Au	60	Sph	75	15	9	8	Sph	19	250	112	19
Au-Nscore	0.49	Sph	0.36	9	10	18	Sph	0.15	120	78	20

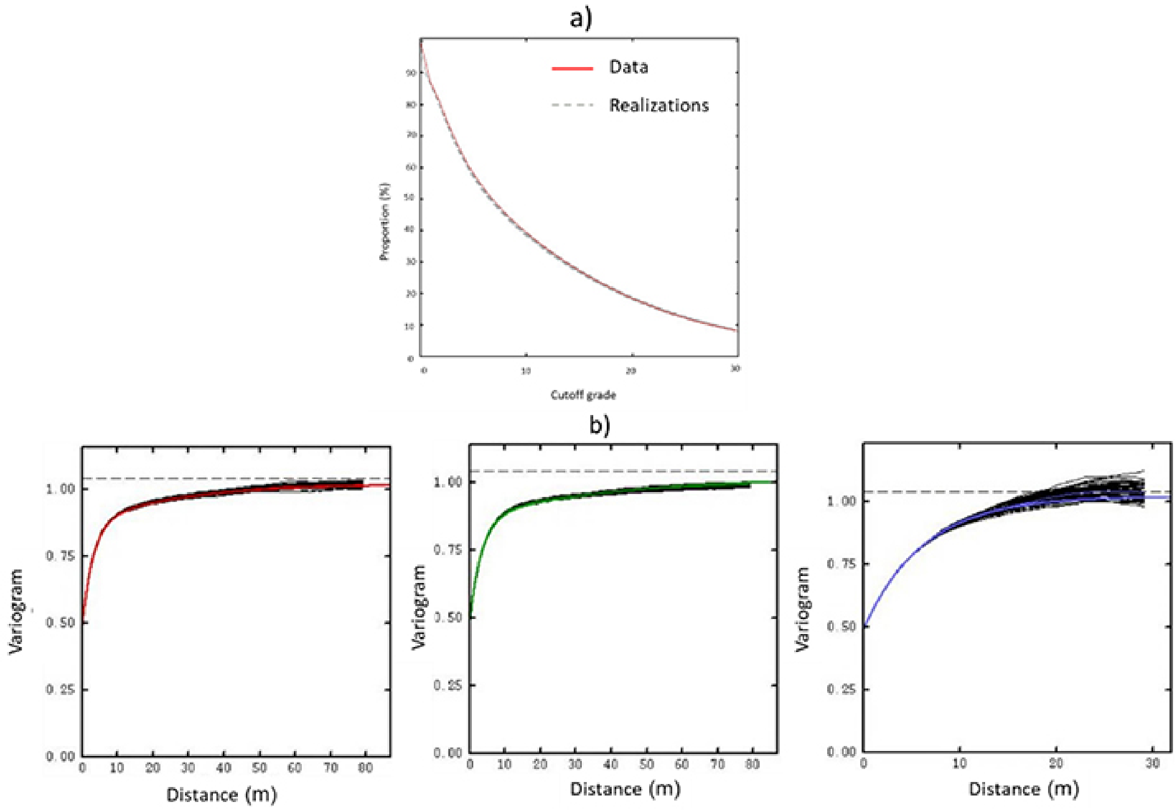

Figure 7—(a) Proportion *versus* grade of the original data (red) and SGS realizations (dashed grey). (b) Directional Gaussian variograms of SGS realizations (black) and data variograms for the east (left), north (centre), and vertical (right) directions

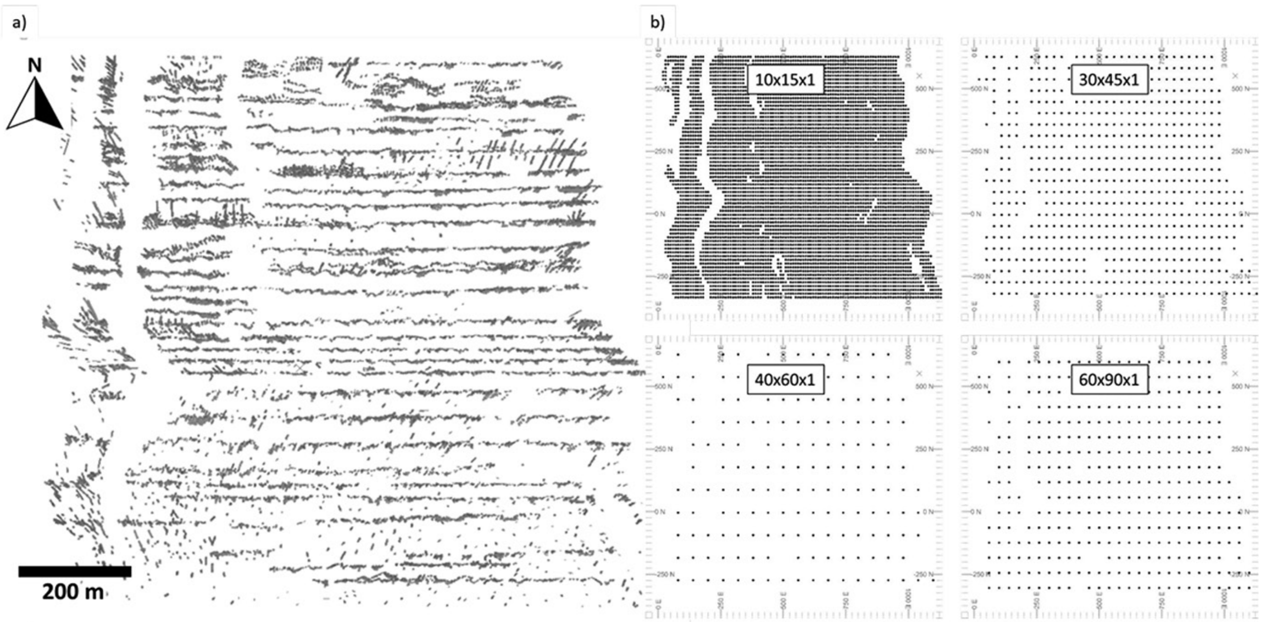

Figure 8—(a) Location map of the original samples of the deposit (database is composed of diamond drilling and channel samples). (b) Location map of four synthetic drilling grids established by sampling the SGS results. Each point contains 30 Au values sampled from the 1 × 1 × 1 m realizations

(Table II), a search ellipse range equal and parallel to this variogram. The sectorized ellipse was conditioned for 16-64 samples, and each block was discretized into 5 × 5 × 5 points.

➤ LUC was applied to the 40 × 40 × 40 m panels before 10 × 10 × 10 m localization (Figure 9b). The LUC used the original unit variograms (Table II) and search ellipse range equal and parallel to the modeled continuity. The sectorized ellipse was conditioned for 16-64 samples, and each block was discretized into 5 × 5 × 5 points.

Considering 5 g/t as a theoretical cut-off grade for the reference models, the local accuracy was measured by the misclassification rate of blocks and the average estimation error. The local errors, *i.e.*, the variations between the estimated and

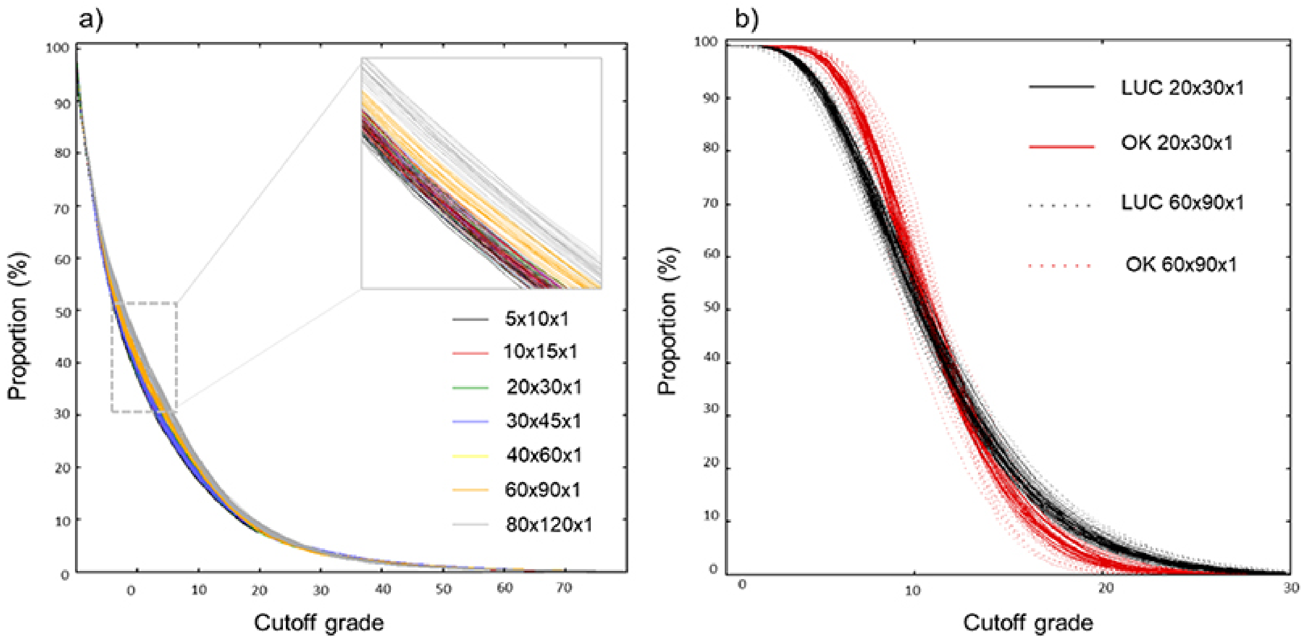

Figure 9—(a) Proportion of records above the cut-off for the seven drilling grids extracted from 30 realizations, and (b) proportion of 10 × 10 × 10 m blocks above the cut-off for the OK and LUC estimates (drilling spacing 20 × 30× 1 m and 60 × 90 × 1 m)

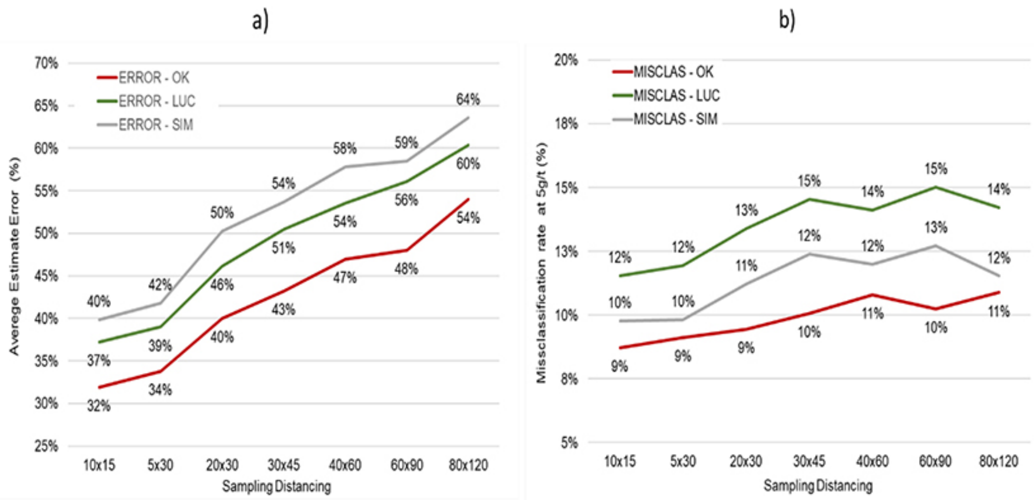

Figure 10—Average error (a) and misclassification rate (b) as a function of drilling spacing and estimation method

the 'actual' values, were quantified by the root mean square error (RMSE). The same was applied to account for global accuracy. We measured the uncertainty of the overall metal-grade relationship for different drill-hole spacings at a range of cut-offs.

Figure 10 presents the DHSA results for local accuracy. The drill-hole spacing (x-axis) was plotted *versus* the average estimation error and the block's misclassification rate (y-axis). The estimated block was compared to its 'actual' reference value resulting from averaging all simulated nodes inside each block in both cases.

From a global perspective, Figures 11a and 11b show the RMSE for the metal content at 5 and 15 g/t for different drill-hole spacings. Additionally, the overall performance may be tested by comparing the estimated grade-cut-off and grade-tonnage relationships to the 'true' reference model (Figure 11c-d)

This case study highlighted that the errors were not exclusively due to the sample spacing. In contrast, the total model uncertainty arose from different sources, such as the estimation method, parameters, time-frame analysed, support dimension, and data availability.

Discussion

The results presented in this case study are consistent with the reviewed literature. While OK provides local estimates with minimum error, the same is not valid from a global perspective. SGS and LUC proved to be better solutions for representing the actual grade-tonnage relationhip and total metal content (Figure 11c-d). LUC incorporates the volume-variance effect into the estimated model. It makes uniform conditioning very effective in reproducing the global grade-tonnage distribution as it reduces smoothing impacts. In this sense, to assess the risks in the metal prediction in cases of sparsely distributed data or over-smoothed kriging, DHSA performed on LUC estimates would provide better uncertainty models.

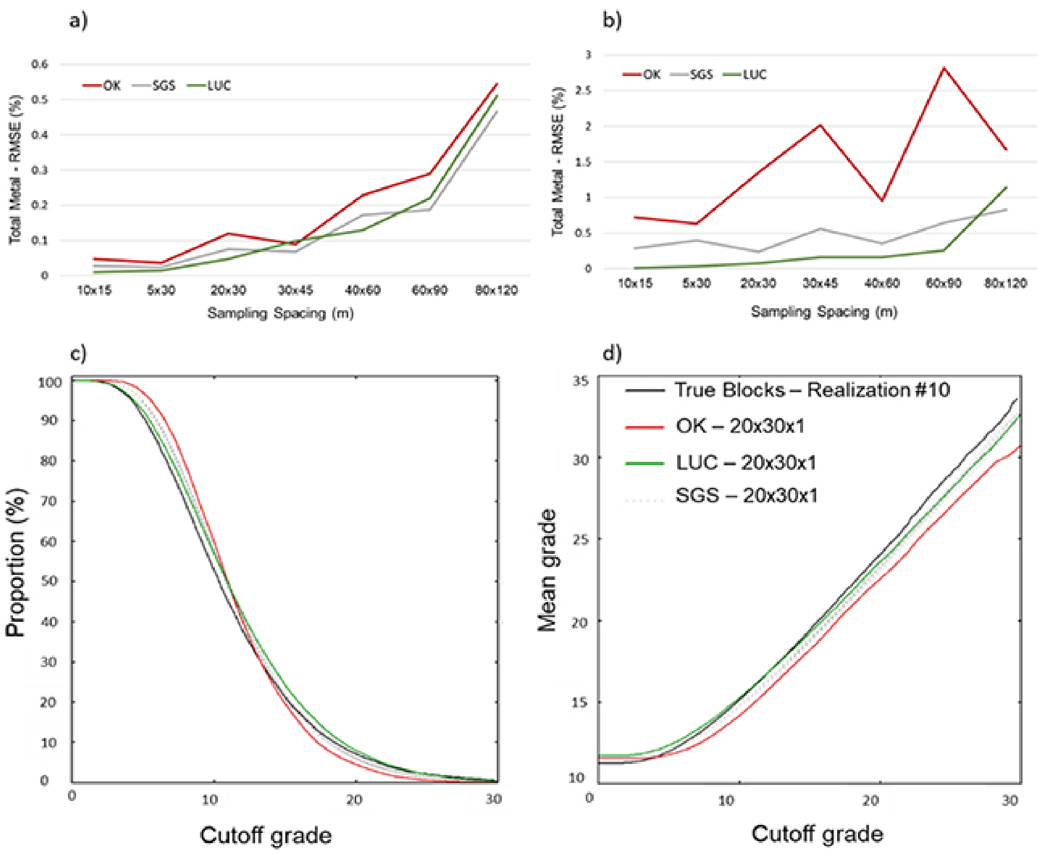

Figure 11—Global uncertainty analysis for the three evaluation methods. Metal content error at 5 g/t (a) and 15 g/t (b) cut-offs. (c) Overall grade × tonnage relation for the estimation method and 'true' reference distribution. (d) Average grade *versus* cut-off for the tested methods and 'true' reference distribution

The metal prediction errors (RSME) from the LUC and SGS methods were smaller than the error associated with the OK estimates (Figure 11a-b). Locally, OK estimates using a 20 × 30 m drilling grid equal the uncertainty for the SGS simulation with a 10 × 15 m grid (Figure 10). The metrics for quantifying the local uncertainty are constant, but varying the estimation method leads to different error values. The localization step of the LUC workflow provides SMU estimates from the panel histogram. However, this process may be highly inaccurate from a local perspective (Figure 10a-b). Thus, it is not advisable to perform DHSA studies for measuring the mining selectivity risk without considering the method´s characteristics.

The proposed DHSA approach may define limits among the different models and support the selection of geostatistical methods for each application. For grade control models, a higher block-by-block accuracy and lower misclassification rate is required for production and, thus, should be based on OK estimates that support a drilling spacing of 10 × 15 m or 5 × 30 m. Considering the maximum uncertainty over the mass analysed at different production scales, a resource model should be defined.

Moreover, one point arising in this study that may be revisited in future studies arises from Figure 10. This figure shows a reasonable linear relationship between the averaged error and the drill-hole spacing. This linearity seems to be a general feature observed in other studies (Koppe, 2017; Usero, Misk, and Saldanha, 2019; Li *et al*., 2004). If DHSA studies are conducted accordingly, the computational demand could be decreased without overall quality losses. However, that experimental observation must be checked for specific cases or mathematically proved in future studies.

Conclusion

The drilling programme, strategy, and their use for supporting grade and geological modelling are some of the most critical activities in any mine. The model uncertainty results from a complex combination of data availability, estimation method, geological features, and the objective function of interest. Therefore, in most cases, DSHA studies require an integrated analysis that considers the problem being addressed under the different applications of the drill-hole data. DHSA workflows available in the literature lead to different results that may not be interchangeable for many problems. Ignoring their differences and choosing any of them without a detailed analysis may result in misleading analysis or suboptimal decisions. We grouped simulation-based DHSA methods as a function of their resulting raw or model uncertainties.

- Raw uncertainty methods provide a means for objective functions, such as the expected profit of a given mine plan, operational dilution, and other engineering or economic parameters. In these global cases, it is recommended to consider the raw uncertainty, where the entire set of realizations is directly passed through the analysed transfer functions.
- Raw uncertainty, however, is not suitable for assessing the risks of estimating the block grade or its expected misclassification rate. Raw uncertainty workflows ignore method-related outcomes, such as minimum variance optimization, information effects, smoothing effects, and conditional biases. In those cases, the model uncertainty approach better predicts the local uncertainty found in short-term and production models.

The proposed integrated DHSA allows a complete understanding of how the drill-hole spacing responds to the geostatistical method and its limitations, the model purpose, and transfer functions. The proposed method is especially relevant if we consider that resource and grade-control models have different purposes. It offers a wider overview of the uncertainty throughout the life of mine by integrating the short- and long-term perspectives.

The last point to be discussed is the sensitivity of the results to the short-scale behaviour of the modelled variogram, in particular to the nugget effect. This parameter must be carefully defined as it plays a relevant role in DHSA. No optimization study will lead to accurate outputs if the nugget effect is poorly defined. The larger the nugget effect, the larger the point of diminishing returns where the model accuracy is no longer reduced by decreasing the sample spacing. Moreover, a second factor to be considered is the sampling protocol used, how it changes the nugget effect, and the optimal grid. Any optimal sampling strategy needs to consider an optimal and cost-effective ratio between drill-hole spacing and sampling protocol (Abzalov, 2014; Silva and Costa., 2016). Computationally, a higher nugget effect also increases the number of required realizations.

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The Southern African Institute of Mining and Metallurgy (SAIMM), in collaboration with the University of the Witwatersrand through the DSI/NRF SARChI chair in Hydrometallurgy and Sustainable Development, and Mintek, will be hosting a hybrid conference on mine-impacted water including acid mine drainage (AMD) in October 2022. With a theme of "impacting the circular economy, closing the water loop", the conference will run over a period of two days. This second SAIMM AMD themed conference will provide an excellent opportunity for industry, researchers and other global stakeholders to share their knowledge, new processes and technologies that can be used to advance the implementation of sustainable solutions to the challenges associated with mine-impacted water. The conference, with its extensive program, will also offer notable keynote speakers and, the popular student session, all with the purpose of giving a unique view into novel solutions and industry progression on the issue of mine-impacted water.

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- Case studies
- Mine closure practices
- Legislation and policy drivers for sustainability
- Novel and emerging strategies for sustainable management of mine-impacted water
- Circular economy concepts, closing the water loop

FOR FURTHER INFORMATION, CONTACT:

Camielah Jardine
Head of Conferencing
SAIMM

E-mail: camielah@saimm.co.za
Tel: +27 11 538-0238
Web: www.saimm.co.za

SAIMM THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

Investigation of the effects of SiC reinforcement ratio in iron-based composite materials on corrosion properties

by H. Karabulut[1], M.A. Erden[2], K. Karacif[3], and S. Gündüz[4]

Affiliation:
[1]Program of Metallurgy, TOBB Technical Sciences Vocational School, Karabuk University, Karabuk, Turkey.
[2]Department of Biomedical Engineering, Karabuk University, Karabuk, Turkey.
[3]Department of Metallurgical and Materials Engineering, Hitit University, Çorum, Turkey.
[4]Department of Manufacturing Engineering, Karabuk University, Karabuk, Turkey.

Correspondence to:
H. Karabulut

Email:
hasankarabulut@karabuk.edu.tr

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ORCID:
H. Karabulut
https://orcid.org/0000-0002-3370-9994
M.A. Erden
https://orcid.org/0000-0003-1081-4713
K. Karacif
https://orcid.org/0000-0001-7180-7897
S. Gündüz
https://orcid.org/0000-0003-4285-5114

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Synopsis

The corrosion properties of iron-based composite materials containing graphite and silicon carbide (SiC) reinforcement were investigated. The effects of silicon carbide reinforcement were investigated by adding 0.5% graphite and 1%, 2%, and 4% SiC. A powder metallurgy method was used to produce the composite samples. Iron, graphite, and silicon carbide powders were blended for one hour with a three-axis mixer and then unidirectionally pressed under a pressure of 750 MPa. After pressing, the composite materials were sintered at 1100°C for one hour. The corrosion properties and microstructure, density, and hardness properties of the composite materials that can affect the corrosion properties were also investigated. It was determined that the pore ratio and hardness of the composite material increased, and corrosion resistance decreased, with increasing silicon carbide content.

Keywords

iron, silicon carbide, SiC, composite, hardness, corrosion.

Introduction

Composite materials have been produced and used for many years due to their advantageous properties. Composite materials are defined as materials that are formed to combine the best properties of two or more similar or different groups of materials in a new material. These materials are composed of reinforcing elements and surrounding matrix material. The main function of the matrix is to transmit load to the reinforcing elements, and that of the reinforcing elements in the composite structure is to carry the load. (Hull and Clyne, 1996; Balasubramanian, 2013; Saxena *et al*., 2017).

Although iron metal has good ductility and toughness, its mechanical properties such as hardness, yield strength, tensile strength, abrasion resistance, and fatigue strength are quite poor. The low-strength properties of iron and low-carbon steels limit the use of these metals. By adding carbon and various alloying elements or hard ceramic particles to iron or cast iron, iron-based composite materials are obtained (Wu *et al*., 2019; Majumdar *et al*., 2008; Szklarz *et al*., 2018). Composite materials containing a matrix metal are called metal matrix composites (MMCs) (Smith, Hashemi, and Prakash, 2014; Kataria and Mangal, 2018). Metallic matrix materials are generally Fe, Al, Cu, Ti, or Co metals or alloys (Chang *et al*., 2018). While copper-based metal matrix composites constitute the majority of the market by mass, significant amounts of Fe and Ti composites are also produced (Malaya, Troy, and Sarat, 2019). Different ceramic reinforcements such as SiC, Cr_3C_2, TiC, Ti (C, N), WC, VC, CrB, and Cr_2O_3 are used in the production of high-strength iron-based composite materials (Wu *et al*., 2019; Majumdar *et al*., 2008; Thawari, Sundarararjan, and Joshi, 2003). One of the most powerful reinforcing elements in MMC production is SiC particles (Wu *et al*., 2019). In SiC-reinforced MMCs, very high hardness, yield strength, abrasion resistance, high-temperature oxidation resistance, and creep resistance are obtained (Wu *et al*., 2019; Majumdar *et al*., 2008; Szklarz *et al*., 2018; Thawari, Sundarararjan, and Joshi, 2003; Abenojar *et al*., 2002, 2003). In addition to these excellent physical properties, SiC reinforcing elements are also cost-effective (Chang *et al*., 2018).

As is known, the mechanical properties of the composites are improved by the presence of rigid reinforcing elements. Chang *et al*. (2018) reported that Ti- and Mo-coated SiC-reinforced iron-based composites had higher hardness and flexural strength than coated composites. There are few studies on the corrosion properties of SiC-reinforced iron-based composite materials. In some of these studies, SiC particles were added to the structure by a powder metallurgy method, while in others liquid production methods or SiC-containing composite surface coating methods were used (Wu *et al*., 2019; Majumdar *et al*., 2008; Szklarz *et al*., 2018; Thawari, Sundarararjan, and Joshi, 2003; Abenojar *et al*., 2002, 2003). In a study by Wu *et al*. (2019), phase transformations, microstructure, hardness, and corrosion behaviour of Si Creinforced 316 L stainless steel matrix composites were investigated. It was reported that the grain size of the solidification microstructure was reduced by the addition of SiC, and the hardness increased due to solid-solution and second-phase hardening. Solid-solution strengthening by C and Si originated from the decomposition of SiC. With the addition of SiC, α-(FeCrNi) phases were precipitated out of the γ-(FeCrNi) phases and the inherent characteristic of α-(FeCrNi) was hard. The corrosion resistance decreased with increasing SiC ratio.

Szklarz *et al*. (2018) added SiC particles to Fe Co Cr Mn Ni alloy powders by mechanical alloying to investigate the effects of SiC reinforcement on the electrochemical properties of the composites. It was reported that with the addition of SiC, the mechanical properties of the composite were improved and the corrosion properties deteriorated (Szklarz *et al*., 2018). Abenojar *et al*. (2002, 2003) investigated SiC reinforcement in iron-based 316L stainless steel composite and the effects of sintering media during production. They reported that with increasing SiC content the hardness and abrasion resistance of the composite increased and corrosion resistance decreased. Ramesh, Srinivas, and Channabasappa (2009) produced iron-based SiC-reinforced composites by laser sintering. They observed an increase in micro-hardness and a decrease in density with increasing SiC content. Volumetric wear rate decreased with increasing SiC content.

Fe-based composites are used for many applications. Some examples in the literature include composites for biodegradable implant applications (Malgorzata, 2018), AC magnetic properties (Kollár et. al., 2010), anti-friction composites (Babets, Vasil'ev, and Ismailov, 2012), composites with very good abrasion resistance (Hulin, Haiping, and Jianhong, 2019), intermetallic-ceramic composites combining the properties of ceramics and metals (Kopec, Jozẃiak, and Kowalewski, 2021), increasing the strength of metal materials (Zemtsova *et. al*., 2020), and use as anode in lithium-ion batteries (Uzunov *et. al*., 2007).

Most of the works on SiC-reinforced iron-based composites are related to the mechanical properties. There are few studies on the corrosion properties of these materials. Stainless steel matrix composites are generally used in a limited number of studies on corrosion of SiC-reinforced iron-based composite materials. In this study, we report on the hardness properties of iron-based composite materials with different amounts of SiC ceramic reinforcement that were produced by a powder metallurgy method.

Experimental studies

Materials and method

Iron-based composite materials containing 0.5% graphite and 1%, 2%, and 4% SiC were produced. The average grain size of the SiC powders used as reinforcing elements was 8 µm. The Graphite-UF4 powders had a particle size below 20 µm, and the average grain size of the iron powders used as a matrix material was 100 µm. Zn stearate was used as a lubricant in all mixtures. Table I shows the chemical composition of the iron-based composite materials used in the experimental studies.

Although SiC reinforcement powders improve the hardness and wear resistance of the composite material, the electrochemical behaviour of SiC differs from that of the iron matrix material. Therefore, a galvanic couple is formed between iron matrix and SiC reinforcement, and the corrosion behaviour of the composite material is greatly affected.

The powders were weighed to 0.0001 g with a RADWAG AS-60-220 C/2 precision scale in the ratios given in Table I. The weighed powders were mixed with a three-axis mixer without a ball for one hour. The homogeneously blended powders were compacted at a pressure of 750 MPa to form cylindrical specimens 32 mm in diameter and 10 mm thick. Sintering of the samples was carried out in a 90% nitrogen 10% hydrogen atmosphere at 1100°C for one hour. The density of the composites was determined using the Archimedes method and the hardness tests were carried out by applying a 1 kg load using a Shimadzu microhardness device. Hardness measurements were taken from five points for each sample and the average value accepted as the hardness result.

Corrosion tests were carried out using a potentiodynamic (electrochemical) method. A 3.5% NaCl solution was used as the corrosion medium. In the corrosion cell, SiC-reinforced iron-based composite samples were used as the working electrode (anode), platinum plate as the counter-electrode (cathode), and a saturated calomel electrode (SCE) as the reference electrode. The composite working electrodes were cold-moulded with resin on the surfaces so that a surface area of 1 cm^2 was exposed and in contact with the corrosion environment. Before each electrochemical measurement, the exposed surfaces of the samples were cleaned by sanding and all measurements were performed on the surfaces with the same properties. Electrochemical corrosion tests were carried out in two stages. In the first stage, polarization curves were obtained between –1.5 V and –0.2 V, *i.e*. from the cathodic region to the anodic region and back to the cathodic region at a scan rate of 0.1 V/s. The purpose was to examine the general corrosion behaviour of the composite material, the immunity, and passivation and corrosion zones. In the second stage, Tafel polarization curves were obtained through scanning potentials between –1.5 V and –0.4 V at 0.002 V/s scan rate. The corrosion potential (E_{corr}), corrosion current density (I_{corr}), and corrosion rates of composite samples were determined from these curves.

Table I

Chemical composition of composite samples (mass fraction)

	Graphite	SiC	Fe
Composite 1	0.5	1	Balance
Composite 2	0.5	2	Balance
Composite 3	0.5	4	Balance

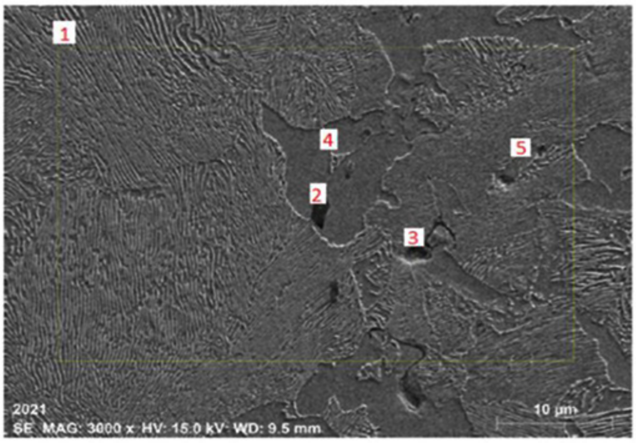
Results and discussion

The microstructure and analyses of the phases of the iron-based composite sample are shown in Figure 1. The structure consisted of ferrite and perlite phases and SiC particles. In the SEM micrograph, the lamellar grains are the perlite phase, the flat grains are the ferrite phase, and the dark particle is the SiC reinforcing element. The EDS results also confirm this view. In the micrograph spectrum 2 is a SiC reinforcement particle, and spectrum 3 is a pore. It is thought that the high iron content at point 2 is due to the contact of the spectrum with the interface.

Table II shows the density and hardness values of the samples after sintering. Theoretical densities of the mixed powders were calculated using the mixing rule. The density of each component making up the composite was calculated separately and summed. It is known that in powder metallurgy production, after sintering, as a result of the combination of powders by diffusion the density of the material increases. This increase depends on the original density, compaction pressure, and other factors. There can be a significant increase in density if there is significant amount of porosity prior to sintering. Although the densities of the samples after sintering were close to each other, it was observed that the density of the composite material decreased with an increase in SiC reinforcement content. The density of the iron-based composite material containing 1% SiC reinforcement was 7.3468 g/cm^3, decreasing to 7.1727 g/cm^3 with a SiC content of 4%. The relative density of the composite material decreased from 94.36% to 93.80% when the SiC reinforcement ratio was increased from 1% to 4%.As the SiC content increased, the pore ratio increased and accordingly the density of the composite material decreased slightly. It is believed that the increase in the pore ratio is a result of the increase in the hardness of the composite mixture powders with the increase in the ratio of hard and high-strength SiC reinforcing elements and consequently the weakening of the compressibility of the mixing powders during pressing.

With increasing SiC content, the hardness values of the composite materials also increased. The hardness of the iron-based composite material containing 1% SiC reinforcement was 110 HV. The hardness values increased to 235 HV and 281 HV when the SiC reinforcement content was increased to 2% and 4% respectively. SiC is a ceramic-based material with high hardness and wear resistance, which when added to the composite structure improves the hardness of the material . Various studies of different iron-based SiC-containing composite materials produced by different manufacturing methods have shown enhancement of the mechanical properties such as hardness and wear resistance (Wu *et al*., 2019; Szklarz *et al*., 2018; Abenojar *et al*., 2002, 2003; Ramesh, Srinivas, and Channabasappa, 2009; Pelleg, 1999).

Polarization curves and Tafel polarization curves of composite materials obtained in a 3.5% NaCl medium are shown in Figures 2 and 3. Corrosion data obtained from Tafel polarization curves is given in Table III, and surface SEM images of the samples after corrosion in Figure 4.



Mass percent (%)

Spectrum	C	Si	Fe
1	5.74	0.57	93.69
2	14.01	65.12	20.87
3	18.14	0.59	81.27
4	11.59	0.39	88.03
5	4.14	0.72	95.14
Mean value:	10.72	13.48	75.80
Sigma:	5.80	28.87	31.19
Sigma mean:	2.60	12.91	13.95

Figure 1—SEM image and EDS analysis of the SiC-reinforced iron-based composite material

Figure 2 shows the behaviour of the cathodic and anodic potentials in the polarization curves for the iron-based composite materials containing different ratios of SiC. There are three regions in the polarization curves. Low potential ranges are the immunity zone. There was no corrosion of the composite material in this region. With increasing potential the curve enters the passivation zone. Although the potential increased in this region, the current density did not change. Corrosion resistance is imparted by the oxide film formed on the surface of the material in this region. The passivation zone in iron-based SiC-reinforced composite samples covers a very narrow range. This is attributed to the deterioration of the integrity of the passive film by the SiC reinforcement. The third region starts with the potential increasing to higher values. This region is the corrosion region, where the current density suddenly increases. At a SiC reinforcement content as low as 1%, the increase in current density took more positive potentials, such as –0.750 V, whereas where SiC content was higher, at 2% and 4%, the increase in

Table II

Density and hardness values for SiC-reinforced iron-based composite materials

	SiC ratio (wt.%)	Experimental density (g/cm^3)	Theoretical density (g/cm^3)	Relative density (%)	Hardness value (HV1)
Composite 1	1	7.3468	7.7856	94.36	110
Composite 2	2	7.2909	7.7392	94.20	235
Composite 3	4	7.1727	7.6464	93.80	281

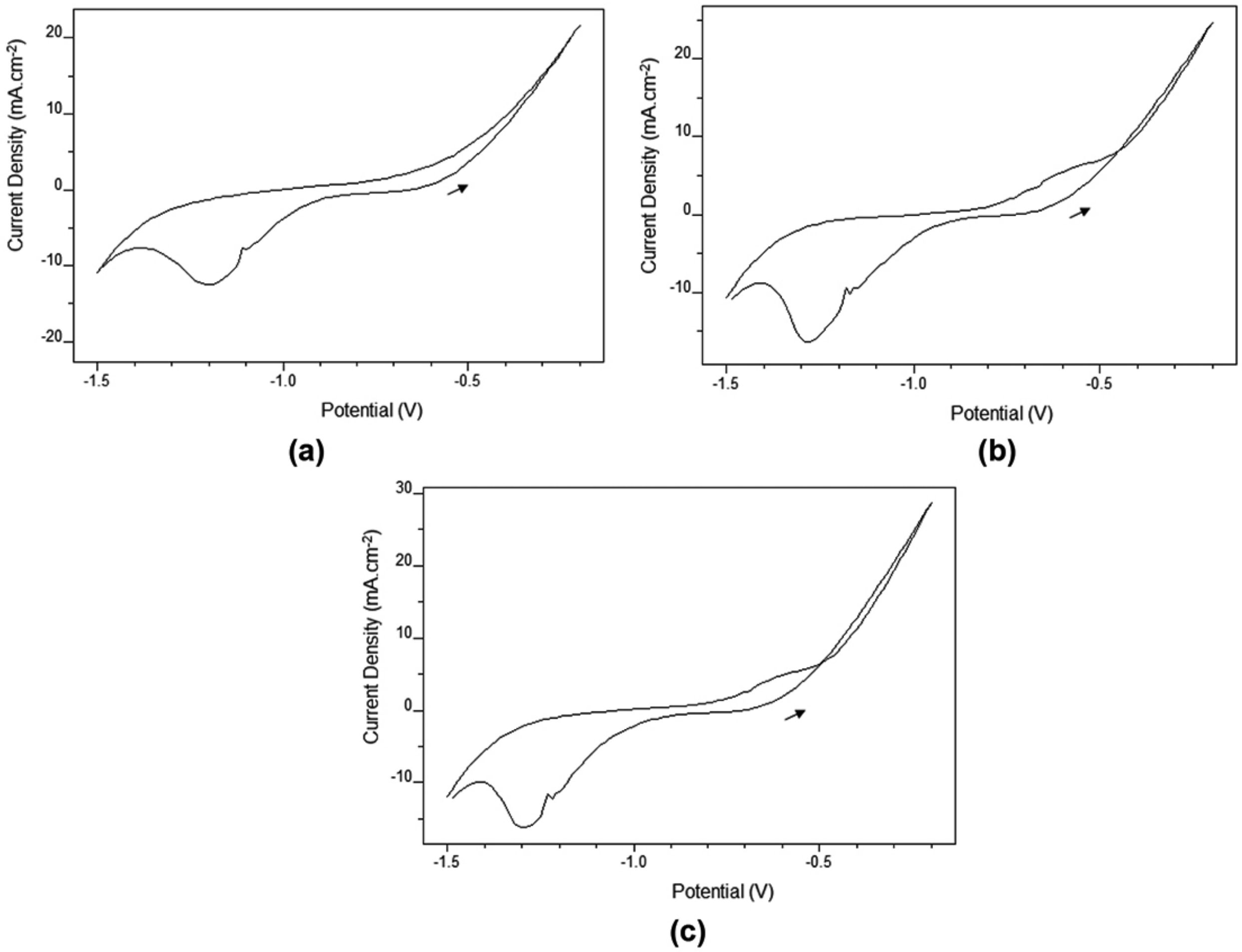


Figure 2—Polarization curves for (a) 1%, (b) 2%, and (c) 4% SiC-reinforced iron-based composite materials in a 3.5% NaCl medium

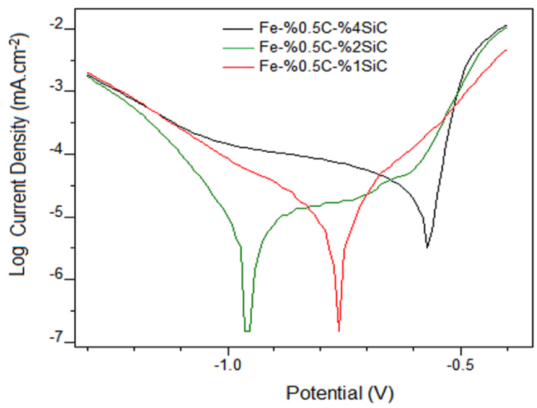


Figure 3—Tafel polarization curves for SiC-reinforced iron-based composite materials in a 3.5% NaCl medium

current density was in some negative values, around −0.850 V. The fact that the current density increased to more positive potentials, and that metal dissolution started at more positive potential values, is an indication of the material's resistance to corrosion. In addition, at the highest potential value in the anodic direction, −0.2 V, the current densities were approximately 20 $mA.cm^{-2}$ for the 1% SiC composite , 25 $mA.cm^{-2}$ for the 2% SiC composite, and 30 $mA.cm^{-2}$ for the 4% SiC composite. In other words, with increasing SiC content with the current density at the most anodic potential applied, metallic dissolution also increased.

According to the corrosion current density and corrosion rate values obtained from the Tafel polarization curves, corrosion current density and corrosion rate increased when the SiC content of the composite material increased. As seen in Table III, the corrosion rate was 0.0944 mm/a with 1% SiC reinforcement, 0.1125 mm/a with 2% SiC, and 0.4302 mm/a with 4% SiC reinforcement. When the SiC reinforcement content increased from 1% to 2%, the increase in corrosion rate was small, whereas when the reinforcement content increased to 4% a four-fold increase in corrosion rate was observed.

Since SiC ceramic particles in the structure have high hardness, high strength, and high abrasion resistance, they improve weak properties of the composite material. However, the SiC particles have different electrochemical properties from iron matrix and disrupt the electrochemical homogeneity of the structure. SiC particles form cathodic regions in the composite material, while the iron matrix forms anodic regions. As the SiC ratio increases, the cathodic regions and cathode-anode interfaces increase in the composite material structure, while anodic regions decrease. The decrease of anodic zones and increase of cathodic zones (small anode area, large cathode area) accelerates dissolution in the anodic zones. As a result of the decrease in the anodic area, the current density at the anode increases. The reinforcement-matrix interfaces, which are the cathode-anode interfaces, are sensitive areas in the corrosion of composite materials because these interfaces have a more irregular atomic structure and the atomic defect density is high in these regions. This situation can be attributed to the fact that the iron matrix-SiC ceramic interface provided sites for active dissolution, leading to local weakness of the passive films. Similar results were obtained in a study on SiC-reinforced stainless steel composite materials (Wu *et al*., 2019).

As a result of the increase in hardness with increasing SiC content, the compressibility of the composite powder mixture during pressing decreased. This led to an increase in the pore ratio and a decrease in the density of the material. Pore-type structural defects are main factor that reduces the corrosion resistance of the material. It is considered that the increase in hardness and pore ratio with increasing SiC content is another factor effective in decreasing corrosion resistance.

In the SEM images of the samples after corrosion in Figure 4, small pits, large pits, and fractures can be seen on the surfaces of the iron-based composite materials containing different ratios of SiC.

Another negative effect of the reinforcement in composite materials in terms of corrosion resistance is that it prevents the formation of a continuous passive film on the surface of the material (Wu *et al*., 2019). In metallic materials, thin, stable, and compact structures on the surface of the material and continuous oxide metal films form without leaving defects on the surface, and slow down the corrosion rate. While the formation of a passive film is more protective in pure metals, and some alloys such as stainless steel, passive films generally do not form in the alloys to slow surface corrosion. Likewise, a continuous passive film cannot

Table III

Corrosion data for SiC-reinforced iron-based composite samples

SiC content wt.%)	Corrosion potential (E_{corr}) (mV)	Corrosion current density (I_{corr}) (A.cm^{-2})	Corrosion rate (mm/a)
1	-761	$8.041.10^{-6}$	0.0944
2	-953	$9.576.10^{-6}$	0.1125
4	-587	$3.663.10^{-5}$	0.4302

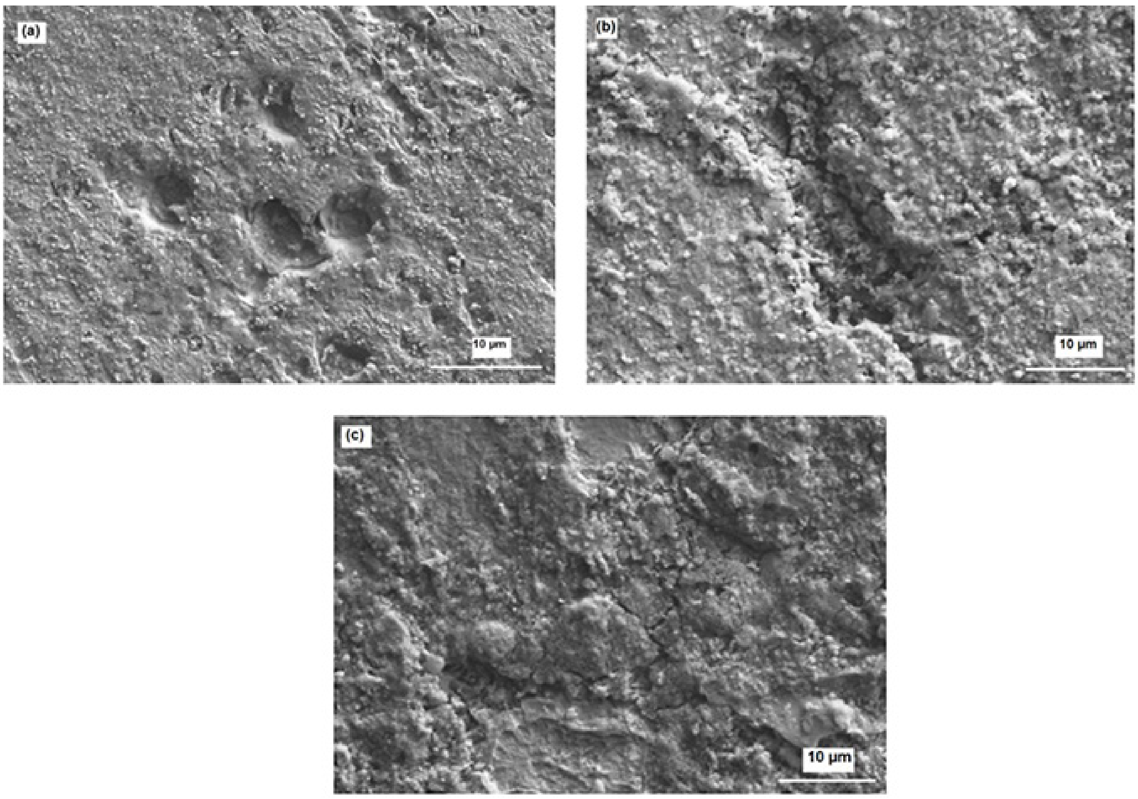


Figure 4—Surface SEM images of (a) 1%, (b) 2%, and (c) 4% SiC-reinforced iron-based composite materials after corrosion

be formed in composite materials with different reinforcements, since the passive film formed by the matrix material combining with oxygen is interrupted in the areas which are reinforced on the surface. In these regions, where a passive film cannot form, corrosion accelerates due to the interaction of the matrix material with the medium.

Conclusions

The effects of the addition of SiC in different ratios on the corrosion properties of iron-based composite materials were investigated. The main results can be summarized as follows

1. With increasing SiC reinforcement additions, the density of the composite material decreased and the pore ratio increased. The pore ratio increase was due to the increase in the reinforcement content and weakening of the compaction properties of the powder mixture during production.
2. With increasing SiC reinforcement, the hardness of the composite material increased linearly. The highest hardness was obtained in the 4% SiC-reinforced composite material. The increase in hardness is due to the superior mechanical properties of the SiC reinforcing material.
3. The addition of SiC up to 2% slightly increased the corrosion rate of the composite material, while the addition of 4% SiC caused a large increase in the corrosion rate. This is attributed to an increase of the cathodic regions and decrease of the anodic regions, an increase in the anode-cathode interfaces, increase in the porosity, and the discontinuity of the passive film with increasing reinforcement.

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2–3 August 2022 — Rocscience Africa Hybrid Conference 2022
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Website: https://www.rocscience.com/events/rocscience-africa-conference

21–23 August 2022 — International Mineral Processing Congress Asia-Pacific 2022 (IMPC)
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Website: https://impc2022.com/

21–25 August 2022 — XXXI International Mineral Processing Congress 2022
Melbourne, Australia + Online
Website: www.impc2022.com

24–25 August 2022 — Battery Materials Conference 2022
Misty Hills Conference Centre, Muldersdrift, Johannesburg, South Africa
Contact: Gugu Charlie
Tel: 011 538-0238
E-mail: gugu@saimm.co.za
Website: http://www.saimm.co.za

5–6 September 2022 — Implications of S-K1300 regulations and disclosures for dual-listed companies on the for dual listed companies on the JSE and NYSE Online Webinar
Contact: Camielah Jardine
Tel: 011 538-0238
E-mail: camielah@saimm.co.za
Website: http://www.saimm.co.za

12-14 September 2022 — 32ND Society of Mining Professors Annual Meeting and Conference 2022 (SOMP)
Windhoek Country Club & Resort, Windhoek, Namibia
Contact: Camielah Jardine
Tel: 011 538-0238
E-mail: camielah@saimm.co.za
Website: http://www.saimm.co.za

15–20 September 2022 — Sustainable Development in the Minerals Industry 2022 10TH Internationl Hybrid Conference (SDIMI) *´Making economies great through sustainable mineral development´*
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Contact: Gugu Charlie
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Contact: Camielah Jardine
Tel: 011 538-0238
E-mail: camielah@saimm.co.za
Website: http://www.saimm.co.za

27-28 September 2022 — Wits Mining Institute Seminar
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