Effect of clay minerals on deposition and safety of tailings storage facilities

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Clay minerals are present in ores as either a primary or secondary weathered product and their colloidal behaviour in slurries impacts on the full metallurgical process from comminution until deposition into the tailings storage facility (TSF). The colloidal properties of clay containing tailings bear a striking similarity to the behaviour of a class of problematic agricultural soils know as saline/sodic soils. Evidence of the effects of these properties on TSF safety is demonstrated by using high resolution optical satellite imagery to evaluate two kimberlite dump re-treatment projects. The thickening circuit performance, the behaviours of the slurries following deposition and temporal stability of the TSF are compared.

INTRODUCTION

The presence of clay minerals in ores affects the processing, disposal and geotechnical behaviour of the tailings from these ores. Clay minerals (phyllosilicates) can be present as primary or secondary weathered products of the host rock, liberated and concentrated into the tailings during the various stages of the applicable ore processing circuit. Clay minerals in kimberlite such as serpentine, smectite, talc and vermiculite are the weathered products of hydrothermal alteration by geo-reactive fluids, which also contribute to the *in-situ* cation exchanged state of these clays. During comminution and subsequent processing, the clays are re-hydrated with mine process water. The colloidal behaviour of the liberated clays is governed by the chemical quality of the new water source such that their cation exchanged state mimics the cation ratio within the contacting water. This seemingly minor change has significant impacts on mineral processing efficiency and tailings storage facility (TSF) integrity since it will determine the dewatering, rheological and geotechnical behaviour of the tailings.

A case study comparing the Jagersfontein TSF failure to a similar kimberlite TSF is presented as an argument in favour of this thesis. Temporal satellite imagery stacks indicate the potential of a change in depositional characteristics of the dewatered tailings. This includes a visible change in the depositional properties from a high-density to a low-density flow pattern and accelerated accumulation of pond water. This resulted in seepage of the external TSF walls and over-wetting of the foundation, culminating in failure.

BACKGROUND

Following several catastrophic failures, guidelines and regulations to address the monitoring of TSFs was introduced to support the codes on the construction of sites. This includes but is not limited to the International Commission on Large Dams; which has published a number of guidelines on the design, construction, and operation of TSFs, including Bulletin 190: Tailings Dams: Safety Guidelines. International Council on Mining and Metals (ICMM): ICMM has published the Global Industry Standard on Tailings Management, which includes a section on stability monitoring. International Organisation for Standardisation (ISO): ISO has published ISO 31000:2018 Risk Management, which provides a framework for managing risk in all aspects of an organisation's activities, including TSF stability monitoring. The Canadian Dam Association (CDA) has published the Health, Safety and Reclamation Code for Mines in British Columbia, which includes provisions on TSF stability monitoring. The United States Environmental Protection Agency has published the Tailings Dam Safety and Closure Guidance, which provides guidance on the stability monitoring of TSFs in the United States.

The following codes or guidelines regulate TSF stability monitoring in South Africa:

- SANS 10286: Code of Practice for Mine Residue Deposits. This code provides guidance on the design, construction, operation, monitoring, and closure of TSFs.
- Mining Residue Regulations: These regulations were established by the Department of Environmental Affairs in 2015 to control mine waste dumps, stockpiles, and tailings storage.
- The Reservoirs Act 1976: This act regulates the construction and operation of reservoirs, including TSFs that hold more than 25,000 m^3 of water above the natural level of the adjoining land.

The specific requirements for stability monitoring are set out in SANS 10286. These requirements include:

- Regular monitoring of the tailings facility's physical characteristics, such as the slope, pore water pressure, and piezometric head.
- Monitoring of the tailings facility's performance, such as the rate of settlement and the occurrence of seismic events.
- Interpreting the monitoring data to assess the stability of the tailings facility.

The frequency and extent of stability monitoring will vary depending on the size and complexity of the tailings facility.

Visual monitoring involves regularly inspecting the TSF for signs of instability, such as cracks, slumping, or seepage. Monitoring of the TSF stability is monitored using ground instrumentation to record the physical behaviour of the TSF and remote sensing to monitor the dimension and volume changes along with pond management for changes in slope, deformation, or other indicators of instability, as part of the risk assessment process.

CLAYS IN TAILINGS

Clay minerals are a common constituent of tailings, which are the waste materials liberated during the processing of ores to extract valuable metals. The types of clays present in tailings depends on the type of ore being mined and processed. Kimberlite ores tend to contain significant amounts of smectite clays, which are derived from hydrothermal alteration of the ore facies by meteoric waters during the emplacement process (Afanasyev *et al.*, 2014). The charged clay surfaces are capable of ion exchange and will tend to mimic the ionic profile of the contacting water source from highly sodium to highly calcium ion exchanged.

During mining and processing the dry ore is typically wetted at the milling or scrubbing unit process and the clays therein undergo re-hydration. Once hydrated, the clay surfaces may again undergo ion exchange to mimic the ionic profile of the new water source. Consequently, the chemical characteristics of the mine process water and the resulting ion exchanged nature of the clays will affect their colloidal properties within the tailing's slurry. These properties in turn have a profound effect on many metallurgical processes from sedimentation in the dewatering circuit through to the rheological and consolidation properties at the TSF.

In many respects, processed kimberlitic tailings bear a striking similarity to the characteristics of a class of agriculturally problematic soils known as saline/sodic soils. Normal agricultural soils contain low salt concentrations while saline/sodic soils contain both high total salt content (saline soils) and high sodium ion content (sodic soils). When saline soils are irrigated, the high salt content leaches into the water and is a major contributor to poor plant growth due to salt stress. The high salt content in these soils, however, tends to keep the clays in a so-called 'coagulated' or non-dispersive colloidal state and therefore the soil structure is maintained. On the other hand, when sodic soils are irrigated, the highly sodium ion exchanged clays within these soils become colloidally dispersive which destroys the soil structure and inhibits the natural percolation of water through the soil causing waterlogging problems (Rengasamy, 2018).
Saline/sodic soils are classified by obtaining a water extract from a saturated soil sample and measuring for:

1. Conductivity (in mS/cm) to provide a measure of the total water-soluble cations within the soil i.e., the salinity of the soil.

2. The ratio of monovalent sodium ions to divalent calcium and magnesium ions within the water which is expressed as the sodium adsorption ratio (SAR) in meq/l and provides a measure of the sodicity of the soil.

$$\text{SAR} = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

Agricultural practitioners have classified these soils according to certain criteria of conductivity and SAR value (Richards, 1969). Soils with conductivities greater than 2 mS/cm are classified as saline soils; soils with SAR values greater than 6 are classified as sodic soils and those with both high conductivity and high sodicity are classified at saline/sodic soils (Figure 1).

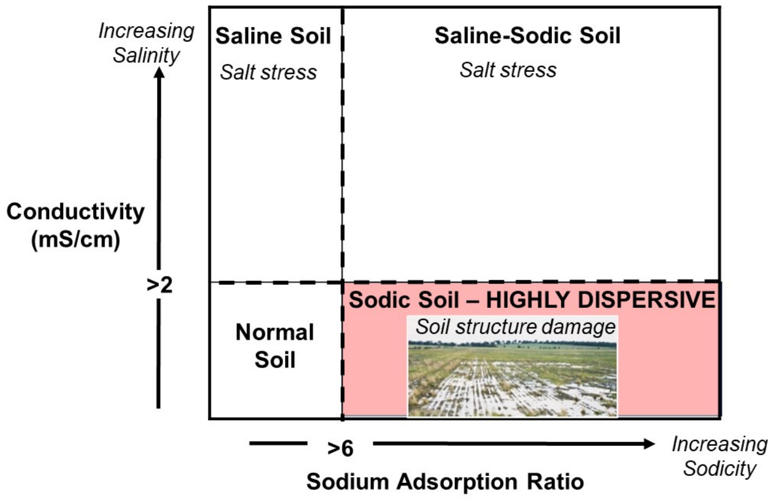

Figure 1. Classification of saline/sodic soils.

Mineral tailings can be regarded as very dilute soils. In this regard, their dispersive or coagulated states can be characterised using the same classification scheme as for saline/sodic soils. Within metallurgical circuits, the colloidal state of clays within these dilute slurries is nowhere more pronounced than at the dewatering unit processes such as the thickener. Thickener feed slurries, in which the clays are in a coagulated state, will be easily flocculated by polymer reagents and will settle to form a mud bed or 'vehicle' in which the silt and sand sized particles can be carried. In this condition, the thickener underflow being discharged to the TSF will have a high density (low water content); a measurable yield stress and importantly, will contain the original particle size distribution as the thickener feed.

By contrast, thickener feed slurries in which the clays are in a dispersive state will be poorly flocculated by polymer reagents such that no mud bed is formed to carry the larger particles. Instead, the clays will be suspended in the water fraction and a portion will be lost to the thickener overflow while the remainder will form part of the bulk fluid through which the larger particles settle to form a 'silt bed' in the base of the thickener. In this condition, the thickener underflow discharged to the TSF will consist of a coarse low density (high water content), Newtonian fluid which does not reflect the original feed slurry particle size distribution.

An understanding of the colloidal state of clays within mineral tailings can assist in predicting the performance of the dewatering unit process as well as the rheological and consolidation properties of these slurries at the TSF. An example comparing the Jagersfontein TSF failure to a similar kimberlite TSF as a case study is described in the following sections.

GEOTECHNICAL MONITORING

There are several geotechnical instruments that can be used to monitor TSF stability over time.

- Piezometers: These instruments measure pore water pressure in the tailings. Pore water pressure is an important factor in slope stability, as it can increase the shear stress on the slope and lead to failure.
- Inclinometers: These instruments measure the tilt of the tailings. Tilt can be an indicator of instability, as it can be caused by changes in pore water pressure, shear stress, or the weight of the tailings.
- Extensometers: These instruments measure the deformation of the tailings. Deformation can be an indicator of instability, as it can be caused by changes in pore water pressure, shear stress, or the weight of the tailings.
- Pressure cells: These instruments measure the pressure of the tailings. Pressure can be an indicator of instability, as it can increase the shear stress on the slope and lead to failure.
- Geo-resistivity monitors: These instruments measure the resistivity of the tailings. Resistivity can be an indicator of the presence of water, voids, or other anomalies in the tailings, which can all be factors in instability.

The specific instruments that are used to monitor a tailings storage facility will depend on the specific design of the facility and the risks that are identified. The data is then utilised in geotechnical modelling using computer models to simulate the behaviour of the tailings and predict the likelihood of instability.

Cone Penetration Testing

The most common method of monitoring the long-term stability of TSF sites is through the use of cone penetration tests (CPT). CPTs are in-situ soil testing that can be used to assess the geotechnical properties of tailings, including its strength, compressibility, and liquefaction potential.

The CPT measures the resistance of the tailings to penetration by a cone-shaped probe, and this resistance is used to calculate a number of soil properties, including the cone penetration resistance (qc), sleeve friction (fs), and pore pressure at the cone tip (u). These tailings properties can be used to assess the liquefaction potential of the tailings, which is a major concern for TSF stability. The main advantage of using in-site CPT test is that the tailings characteristics are done in-site in real time, whereas laboratory tests on undisturbed tailings samples can be difficult and time-consuming to obtain.

In addition to assessing liquefaction potential, the CPT can also be used to assess other aspects of TSF stability, such as the shear strength of the tailings and the potential for piping. Piping is a process by which water flows through a tailings dam, carrying with it fine particles. This can erode the dam and lead to its failure.

LABORATORY TESTS

Understanding the physical and chemical properties of the clays has an impact on the design criteria of the TSF and the environmental considerations. Identification of the bulk mineral composition and the clay mineral content is done through X-ray diffraction. The main physical and chemical characterisation (Grosso *et al*., 2021) considered entailed liquor, solid and slurry density, solid concentration, solid specific gravity and thorough analysis of yield stress, particle size distribution, elements and mineral phase detection.

REMOTE SENSING

Different remote sensing platforms can be utilised, including satellites, aerial platforms (such as aeroplanes or drones), and ground-based sensors. The choice of platform depends on factors like spatial resolution, temporal coverage, cost, and specific monitoring objectives.

Satellite-based observation

Only satellite-based observation is considered for the purposes of this paper. There are two main satellite-based observation methods which are utilised in the long-term temporal stability monitoring of TSF sites: optical and synthetic aperture radar (SAR). The types of data products will depend on the extent of the temporal imagery available to create interferometric data stacks. Single imagery obtained per over pass of the satellite may be used for change monitoring. Stereo images, i.e., two images captured at different angles can be used to create volume products or 3D representations. In the case of interferometric synthetic aperture radar (InSAR), a single ascending or descending image can be used to detect vertical movement, but a combination of an ascending and descending image pair, will allow both vertical and horizontal movement detection.

These sensors capture different aspects of the TSFs, such as surface topography, vegetation cover, temperature variations, and structural changes. Once the data is acquired, it undergoes processing and analysis to extract meaningful information. This involves techniques such as image classification, change detection, and feature extraction. For TSF monitoring, key parameters of interest may include changes in TSF size, shape, surface deformation, water levels, and vegetation health.

By comparing current measurements with historical data, trends and patterns can be identified, allowing for proactive management and mitigation of potential hazards. Risk assessment may involve evaluating factors such as stability, seepage, and the potential for catastrophic failure. Remote sensing data is often combined with other data sources, such as ground-based measurements, geological surveys, and hydrological data, to provide a comprehensive understanding of the TSFs.

Optical Satellite Imagery

The main application of optical satellite imagery is detecting changes in the TSF surface, by comparing images taken over time to look for changes in the shape, colour, or texture of the tailings surface. These changes can be indicative of a variety of problems, such as erosion, subsidence, or seepage. Monitoring the water levels in the tailings by identifying changes in the reflectivity of the water surface to determine the areal extent of the ponded water. Volume products allow the engineer to detect lower water levels which can be indicative of seepage, while high water levels can be a sign of potential overtopping if it exceeds the designed freeboard level.

Optical satellites can be used to track the growth of vegetation over time and the surrounding environment. Changes in the vegetation health is measured by the normalised difference vegetation index, land cover, or water bodies in the area around the TSF can be indicative of environmental impacts, such as the release of pollutants or the degradation of water quality through acid mine drainage as an example.

Synthetic Aperture Radar

InSAR works by comparing two or more radar images of the same area. The radar images are taken at different times, and the difference between the images can be used to measure the amount of surface deformation that has occurred in the intervening period.

InSAR can measure the amount of horizontal and vertical displacement that has occurred at a TSF over time. This data can be used to identify areas of potential instability, such as areas where the dam wall is bulging or where the tailings are subsiding. It is also able to measure the rate of displacement at a TSF. This data can be used to track changes in the stability of the dam over time and to identify areas where the risk of failure is increasing. The identification of deformation patterns at a TSF can provide indication about the underlying causes of instability, such as the presence of weak zones or the accumulation of water, resulting in over-wetting of the tailings. The data produced by InSAR can be used to create detailed TSF stability heat maps to identify areas of concern and to develop mitigation strategies to reduce the risk of failure.

BREACH FAILURE ANALYSES

In order to determine the extent of impact during a TSF failure, a breach analyses needs to be conducted as part of the emergency preparedness and response planning. The digital elevation model derived from the satellite imagery and surveys form the reference basis to predict the rate and extent of potential runout from hypothetical failures.

Adams *et al.*, (2022) suggested the breach assessment should consider the potential for a fluid flow release of ponded water along with eroded and liquefied tailings. Where a TSFs with no significant ponding, the breach assessment needs to consider flow slide or slump type failures due to liquefaction of the tailings. The input data would consider the results of index tests, rheological tests, and cone penetration test data to be combined to characterize the variability and expected behaviour of the tailings material.

CASE STUDY: JAGERSFONTEIN vs COMBINED TREATMENT PLANT

In order to demonstrate the significance of clay colloidal behaviour in tailings dam safety, two kimberlite dump re-mining projects operated within 200 km of one another in similar climatic and geographical environments are compared. Both metallurgical plants incorporated so-called high density or paste thickeners within their metallurgical circuits to discharge a low water content slurry to their respective TSFs.

The De Beers combined treatment plant (CTP) was commissioned in 2001 in Kimberley to treat both legacy tailing dumps and virgin underground ore (Johnson and Vietti 2003). The tailings dewatering circuit consisted of 5 x 16 m diameter deep cone paste thickeners which were designed to discharge a high density (1.6 kg/m^3) tailings over a 5 km distance to a central thickened discharge type TSF facility. The thickened tailings were discharged via a 'wagon wheel' distribution manifold within the centre of the facility.

The Jagersfontein ore body has been exploited since the 1870's and by 1971 De Beers terminated underground mining. In 2010, the resource was acquired by Jagersfontein Development to re-mine the legacy dumps and by 2011, a new plant had been commissioned which incorporated a single 25 m diameter high density/paste thickener to discharge a high density tailing into the newly designed ring dyke tailings facility which had been constructed over a historical TSF facility. Notably the southern wall of the new TSF overlapped the northern tip of the historical return water dam (Rivet 2023).

Thickened tailings were to be discharged directly into the TSF from the thickener through a single open ended discharge point located in the western wall of the facility. Jagersfontein Development later sold the operation to the Stargems Group in early 2022 (Wikipedia).

Table 1 below provides a comparison between the tailings slurry properties, the tailings thickeners and the TSF designs at the CTP and Jagersfontein operations respectively.

Table 1. Tailings properties and dewatering thickener type comparison (Jagersfontein and CTP)

Parameter	Unit	Jagersfontein	CTP
Tailings pH	-	8.7	8.3
Tailings Conductivity	mS/cm	1.1	4.3
Tailings SAR	-	25	15
Tailings Classification		Sodic	Saline/Sodic
Thickener Type	-	High Density/Paste 	Deep Cone Paste 
TSF Design	-	Ring Dyke 	Central Thickened Discharge 

From Table 1, it is evident that the CTP tailings can be classified as saline/sodic tailings having both high SAR values (15) and high conductivity (4.3 mS/cm) and consequently the smectite clays are likely to be in a coagulated and naturally settling state. By contrast, the Jagesrsfontein tailings can be classified as sodic tailings having high SAR (25) and low conductivity (1.1 mS/cm). In this condition, the smectite clays are likely to be dispersive and non-settling.

The CTP tailing facility has been operating successfully for over 20 years with only one wall lift needed. On 11 September 2022, the new Jagersfontein tailings dam which had been operating for only 12 years failed, releasing a 10 million cubic metre mudslide that travelled about 2 km, reaching the town of Jagersfontein, and swept away nine houses and damaged more than 20 others. Three people were killed in the collapse, and up to 40 people were injured. Four people remain missing. The cause of the collapse is still under investigation at the time of compiling this paper, but it is believed to have been caused by a combination of factors which may including poor maintenance. However, evidence suggests that the colloidal properties of the clays within the tailings may have had a greater contributing role than has been considered before.

A paper published by Torres-Cruz and O'Donovan (2023) considered the use of public domain and commercial optical satellite imagery to conduct a post-incident review of the failure. Their finding suggests a construction sequence that is inconsistent with sound tailings management practices, including asymmetric deposition, no remedial actions taken to address erosion gullies, the development of large ponds on top of the TSF and absence of beaches.

The high-resolution images in the paper along with a desktop review of imagery placed in the public domain by Google Earth, suggest that the density of the slurry being discharged from the thickener changed notably over time. The earlier imagery (July 2017) clearly shows the distinctive fan or lava-like flow pattern of a thickened tailings being discharged from the open-ended discharge into the TSF (Figure 2). During 2017 one of the authors (A. Vietti) visited the Jagersfontein site and noted that the mine was using an inorganic salt to increase the conductivity of the process water circuit to coagulate the dispersive clays. Consequently solid/liquid separation at the high-density thickener was achieved resulting in clear thickener overflow and a high-density thickened underflow which was being discharged to the TSF, which is consistent with the Google Earth imagery of the same time.

By February 2021, the imagery indicated that the properties of the tailings at the discharge point had changed dramatically. Instead of the lava flow pattern, a distinct delta has been generated, consistent with the deposition pattern of a low-density silty slurry. Water from the tailings containing colloidally dispersive clays had segregated and dramatically increased pool volume within the TSF. The imagery suggests that salt dosing had been abandoned at that time and that the clays within the tailings had reverted to their dispersive state as a result of the reduced slurry conductivity. Consequently, the performance of the thickener was compromised, and a low-density silty slurry was being discharged to the TSF. The accumulation of water within the TSF may have then resulted in increased seepage through the TSF walls and over-wetting of the southern wall foundations which corresponded to the northern tip of the legacy return water dam.

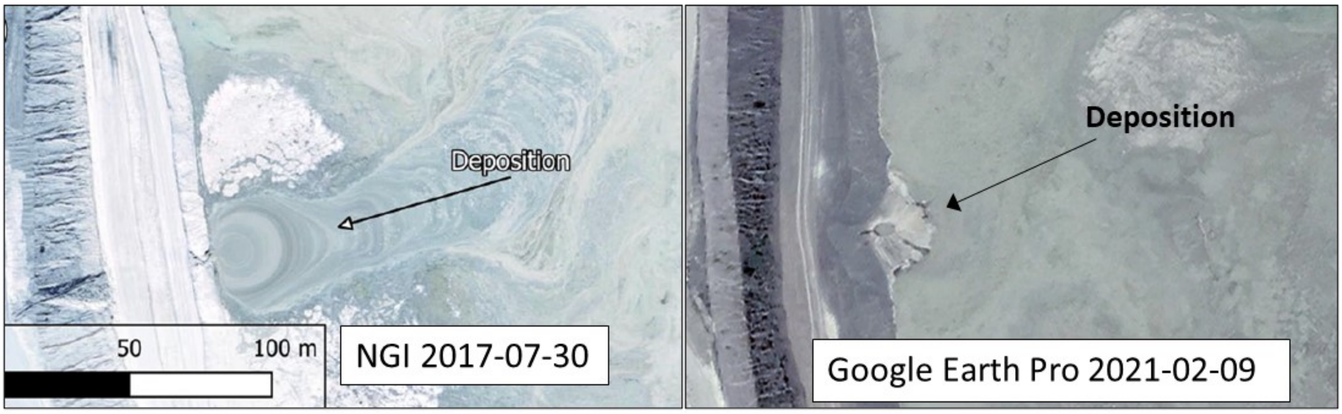

Figure 2. Thickener underflow discharge flow pattern between 2017 and 2021

CONCLUSION

An understanding of the colloidal state of clays within tailings is critical to ensure that the processing plant and the TSF operate according to the design criteria. Clay minerals are inherent in most ores, either as a primary or weathering component.

Geotechnical observations form the basis of stability monitoring of TSF sites, with visual inspections supported by the installation of instruments. The data can be ingested into a visual dashboard that overlays the ground data with remote sensing imagery to detect potential risks which may result in failure of the TSF and to prepare remedial measures.

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Andrew Vietti is a director of Vietti Slurrytec and has an MSc degree from the University of Natal in South Africa.

Andrew has over 30 years' experience in the solid/liquid separation field beginning at the De Beers Consolidated Mines research and development facility (Debtech) implementing Paste Thickening technology throughout the group. Thereafter Andrew co-founded a Vietti Slurrytec which is a specialist de-watering metallurgical test laboratory and consulting practice. The company provides test work data on which various solid/liquid separation circuits from Paste to filtered surface tailings disposal projects can be designed.

Vietti Slurrytec specializes in a fundamental understanding of how clay slurry colloidal behaviour influences the de-watering process. Our extensive data base encompasses most mineral types at both small and very large operational scale.

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Dr Nicolaas C Steenkamp is a Geoscience Professional, offering services to the geological, geotechnical and mining industry. He obtained a PhD in Geology from the University of Pretoria. He is a registered natural scientist with SACNASP and a fellow of the GSSA and member of various other professional and learned societies, including SAIMM. Nicolaas has spent several years in the exploration sector in South and East Africa. He also has a background in the mineral analytical sectors and remote sensing. The combination of these experiences equipped him with the background to assist in the evaluation artisanal mining activities, delivery of ores to purchasing centres and the keeping abreast of technological advances to ensure that ore supplied by these artisanal mining consortiums meet ethical sourcing standards and the supplied material is captured in an electronic platform which ensures the provenance of the material can be traced from source to final destination. He has also written several articles in mining industry magazines on the topic and delivered presentations and consultation on the topic to private and government entities.