The evolution of geotechnical testing in the tailings industry

T. Grobler
SRK Consulting, Johannesburg, South Africa

ABSTRACT: The tailings industry has transformed significantly with the Global Industry Standard on Tailings Management (GISTM), revolutionising Tailings Storage Facilities (TSFs) design and analysis. This paper examines the methodological evolution in TSF assessment, highlighting the shift from traditional limit equilibrium methods to advanced deformation analyses as required by GISTM. It explores the integration of Finite Element Modelling (FEM) techniques, which offer a nuanced understanding of interactions between soil, water, and tailings, enhancing stability predictions and optimising design for long-term safety. The transition towards sophisticated constitutive models, such as NorSand, HSS, PM4Sand, and SHANSEP, are outlined, providing a more accurate representation of material behaviour under various loading conditions. The implications of these models on assessing tailings and foundation materials are discussed. Additionally, advancements in laboratory testing are explored, detailing the necessity for precise calibration of constitutive models and the role of routine and advanced testing in determining critical material properties. Future trends in commercial testing methods are anticipated, suggesting the potential for incorporating SEM, EDS, XRD, and XRF analyses for deeper insights into material behaviour, with implications for risk management, environmental protection, and regulatory compliance in responsible mining.

1 INTRODUCTION

The tailings industry has undergone a transformation catalysed by the implementation of the GISTM. The GISTM has emerged as a cornerstone, underscoring the essential requirement for a comprehensive understanding of material parameters that dictate the structural integrity and safety of these facilities. This paper delves into the dynamic evolution of testing methodologies within the context of GISTM, elucidating the profound impact on both tailings and foundation materials. By exploring the nuanced intricacies of these testing protocols, a new era in geotechnical engineering that goes beyond conventional practices is unveiled.

In the tailings industry, it has become standard practice to establish tailings and natural material properties primarily through laboratory testing. In-situ testing, specifically Cone Penetration Testing (CPTu), serves as a screening tool for assessment. While laboratory testing takes precedence in determining soil properties, CPTu testing is employed to infer the state of the tailings, identify the phreatic surface, and understand the general behaviour and variability of the tailings in their in-situ condition. Laboratory results are also utilised to refine the screening-level CPTu correlations, elevating them to a more interpretive framework.

This paper outlines the change in approach commonly adopted for the construction of upstream tailings facilities in southern Africa.

2 METHODOLOGICAL EVOLUTION

2.1 *Historical*

Historically, the stability analyses of TSFs were undertaken using limit equilibrium methods. Mohr Coulomb and Vertical Stress Ratio (VSR) were typically used as material models. The parameters were determined by a limited number of shearbox and effective stress triaxial tests, with the primary focus on the tailings, with minimal information and consideration of the foundation materials. The sophistication of the analyses were limited with the mentioned material models neglecting the effects of strain and deformation.

2.2 *Need for deformation analysis*

Requirement 4.5 of the GISTM states that: “Apply design criteria, such as factors of safety for slope stability and seepage management, that consider estimated operational properties of materials and expected performance of design elements, and quality of the implementation of risk management systems. These issues should also be appropriately accounted for in designs based on deformation analyses." (Global Industry Standard on Tailings Management, 2020).

Thus, deformation analysis, using finite element methods is an absolute GISTM requirement.

2.3 Foundation material considerations

Requirement 5.4 of the GISTM states that: "Address all potential failure modes of the structure, its foundation, abutments, reservoir (tailings deposit and pond), reservoir rim and appurtenant structures to minimise risk to ALARP. Risk assessments must be used to inform the design."

This highlights the necessity for focused consideration on the strength and deformation characteristics of the foundation materials. It is important to note that numerous tailings storage facilities in southern Africa are underlain by residual and transported clay layers, often exhibiting low shear strength. Historically, the impact of the over consolidated state of these clay foundations was not considered

3 FINITE ELEMENT MODELLING

3.1 Overview

Finite element modelling (FEM) is integral to TSF design and analysis, enabling engineers to simulate interactions among soil, water, and tailings to assess stability, deformation, and seepage. This involves capturing geotechnical properties, incorporating boundaries, and simulating diverse loading scenarios for predicting challenges, optimising designs, and ensuring long-term stability. FEM contributes to understanding structural behaviour, offering insights for risk management.

The technique involves dividing the geometry into a mesh of finite elements, and the behaviour of each element is solved numerically. By using advanced constitutive soil and material models with nonlinear properties, the interactions between different materials can be captured. This enables complex analysis, providing detailed insights into stress distribution, deformation patterns, and localised failure mechanisms.

Within the tailings industry, it is a widely accepted practice to conduct the following analyses:

- The shear strength reduction (SSR) method is a numerical technique utilised to calculate safety factors under both drained and un-drained conditions of materials. This method is particularly useful when dealing with the variable undrained shear strengths of tailings, which are often subject to uncertainty. During SSR analysis, the strength parameters for all materials are systematically decreased until the system no longer converges. The SSR value at the point of non-convergence is taken as the Factor of Safety (FoS).
- Trigger analysis involves conducting numerical tests to assess the robustness of a geotechnical structure under specific loading scenarios. This type of analysis becomes particularly pertinent for materials that demonstrate strain-softening behaviour. Common triggers that are evaluated include:
- Distributed loads applied to different areas of the facility.
- The sudden liquefaction of a segment of the tailings.
- An increase in the phreatic surface within the facility.
- A loss of confinement at the facility's toe.

Although the loading conditions considered in trig-ger analyses may not always represent credible or realistic scenarios, they provide a valuable assessment of the facility's overall structural integrity and resilience.

3.2 Typical constitutive models used

The constitutive models employed in FEM are notably more sophisticated compared to those typically used in LE techniques. These advanced models typically include:

- NorSand: Soil and tailings exist over a spectrum of void ratios, and NorSand, falling within the framework of Critical State Soil Mechanics (CSSM), explains changes in soil behaviour caused by variations in void ratio. While Modified Cam Clay (Roscoe & Burland, 1968), the most widely taught CSSM model, it struggles to capture dilation in dense sands, fails to predict the behaviour of loose sands, and cannot handle liquefaction-related problems.
- HSS: The Hardening Soil model with small strain stiffness (Schanz & Vermeer 1999; Benz 2006) is an isotropic hardening model applicable to materials undergoing plastic compression and consolidation. It accurately reproduces the behaviour of various geo-materials experiencing monotonic stress paths, considering aspects like stiffness and shear strength dependency on confining pressure, small-strain elasticity, pre-failure hardening plasticity, hysteretic damping, and compression plasticity. While used for construction stages, static-liquefaction analyses, and dynamic analyses of non-tailings materials, HSS is calibrated for tailings and foundation materials, aligning with lab tests and in-situ results. For tailings material, the calibration addresses strain softening during undrained shearing, determining peak/residual shear strength ratios. However, the HSS model has limitations in capturing pore pressure generation during cyclic

shearing of contractive and saturated mate-rials, as observed in tailings.

- PM4Sand (Boulanger & Ziotopoulou 2015) is a bounding-surface plasticity model designed for sands, characterised by effective-stress, stress-ratio control, and compatibility with critical state principles. It incorporates fabric dilatancy and stress-reversal plastic deformation, enabling accurate simulation of pore pressure buildup during cyclic loading under undrained conditions. While proficient in simulating tailings material behaviour under dynamic loading conditions, the model has limitations in reproducing complex static stress paths, including primary compression. PM4Sand is regarded as a valuable tool in tailings engineering applications, offering insights into the dynamic response of sands subjected to varying loading conditions.
- SHANSEP: The SHANSEP model (Stress History and Normalised Soil Engineering Properties) is employed for modelling the undrained shear strength of specific clay soils, as outlined by Ladd and Foote (1974). This model, applicable in both limit equilibrium and finite element methods, is designed for undrained soil loading conditions. It is derived from the linear elastic perfectly plastic Mohr-Coulomb model but is modified to simulate potential changes in undrained shear strength (su) based on the effective stress state of the soil. SHANSEP incorporates the effects of stress history and stress path, enhancing its ability to characterise soil strength and predict soil behaviour.

(The list provided is not exhaustive but represents typical constitutive models commonly employed for deformation analyses in southern Africa).

4 LABORATORY TESTING

Calibrating the constitutive models required commercial laboratories to perform more sophisticated tests, traditionally conducted only by research laboratories, and demanded an enhancement in the precision of the reported data.

4.1 Sample selection and routine testing (tailing)

Samples are collected from various locations around a TSF, including positions on or near the crest and closer to the pool. Subsequently, routine laboratory testing is conducted on all pertinent samples. The typical suite of routine testing includes:

- Particle size determination (PSD) including hydrometer testing to 0.002 mm.
- Atterberg limit determination.
- Specific gravity determination.
- Modified Proctor testing to determine emin.
- Loose bulk density testing to determine emax.

Samples for advanced testing are chosen based on grading and emin values. Critical state lines determined for extreme tailings gradations have been shown to underestimate the range of critical state parameters in a tailings dam. Mixtures with intermediate fines content, in fact, exhibit the densest granular packing at critical state. The minimum void ratio emin proves to be a crucial index property, capturing the influence of particle shape and grain size distribution on granular packing. These underscores its importance as a valuable parameter for guiding sampling strategies in the assessment of spatial variability (Torres-Cruz & Santamarina 2019).

4.2 Sample selection and routine testing (foundation materials)

Samples are typically collected from test pits situated around a TSF. The assumption is based on the flat and horizontally stratified geological units beneath a TSF, suggesting uniformity in the foundation material below. Therefore, it is inferred that the material obtained from test pits along the perimeter is representative of the composition of the foundation material beneath a TSF.

- PSD including hydrometer testing to 0.002 mm.
- Atterberg limit determination.
- Specific gravity determination.

Samples for advanced testing are typically fine grained with a high plasticity index (PI).

4.3 Advanced testing

In the past, the conventional practice involved conducting three-specimen consolidated undrained triaxial tests to ascertain the drained friction angle of materials. However, in the current context, more sophisticated constitutive models necessitate a shift towards the following commonly undertaken tests for calibration:

- One-dimensional consolidation testing is undertaken to determine the one-dimensional stiffnesses and overconsolidation ratios of the materials. Testing is undertaken to determine the coefficient of consolidation, which is an input to determine whether there is a buildup of excess pore pressures in the clay below the TSFs
- Suites of consolidated undrained and -drained tests are conducted across various void ratios and confining pressures to establish the critical state line and other essential parameters needed for constitutive models. Precise void ratio determination is emphasised, with the post-test "freeze method" (Jefferies & Been 2016) and the "squeeze method" (Verdugo & Ishihara 1996) commonly employed to determine the post-test/shearing void ratio. The triaxial test results are not only used to determine the friction angle, but the consolidated undrained

tests are used to determine aspects like the undrained shear strength ratio and the dilatancy parameters.

- Triaxial testing of clays is conducted with confining pressures determined from one-dimensional stiffness tests. These tests are typically performed under conditions where the clay is normally consolidated and overconsolidated. The determination of the OCR is crucial, especially when employing the SHANSEP constitutive model, as it significantly influences the model's accuracy in predicting soil behaviour. Alterantively, the Finite Element Model (FEM) can be zoned to differentiate areas underlain by overconsolidated and normally consolidated foundation materials.
- Triaxial tests on foundation materials are also indicative of behaviour under larger strain levels. However, caution is advised during interpretation as the occurrence of shear banding may lead to inaccuracies in the mobilised shear strength values. Despite this limitation, triaxial testing remains one of the most reliable methods for approximating the true response of foundation materials under stress.
- Monotonic simple shear testing is a critical experimental technique that assesses the shear characteristics and undrained shear strength parameters of soil and tailings materials under specific confining pressures and void ratios. By providing detailed data on the peak and residual strengths of materials, these tests enable a more precise calibration of the models, ensuring that they accurately reflect the complex nonlinear behaviour.
- Cyclic simple shear tests provide dynamic shear property data for sands under cyclic loading, which is vital for calibrating the PM4Sand constitutive model. This calibration process involves executing tests at representative confining pressures, collecting data on pore pressure buildup and shear strain, and determining model parameters like the critical state line and reference shear modulus. The PM4Sand parameters are then iteratively adjusted to match test observations, ensuring the model accurately predicts sand behaviour under various cyclic loading conditions. Once validated, the calibrated model is used in FEM analyses to assess the seismic response of tailings facilities.
- The bender element test, a geophysical method for measuring shear wave velocity, is essential for determining the small strain shear modulus of soils and tailings. This test is integral to the calibration of various constitutive models, such as Linear Elastic Models, Hardening Soil Model (HSM) and its variant with Small Strain Stiffness (HSS). By accurately capturing the initial stiffness parameters.
- Ring shear testing has also been undertaken to determine the residual drained shear strength of materials, specifically for the foundation materials. It has however been concluded that it is unlikely that the high strain levels, obtained from ring shear testing will be mobilised in practice.

One of the aims of the testing is to undertake testing in triaxial compression and in horizontal simple shear, as illustrated in Figure. 1.

Typically, higher undrained shear strength ratios are determined when testing is taken in triaxial compression (Fig. 2).

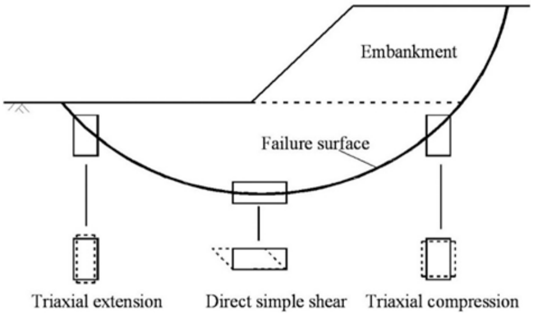

Figure 1. Subsoil failure mechanisms in different zones of potential failure surface under embankment (Zdravkovic, Potts & Hight 2002).

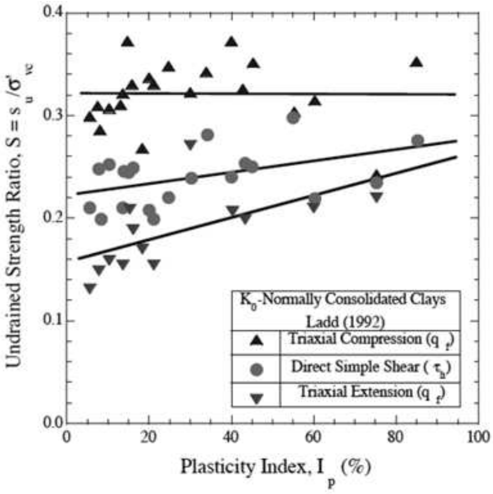

Figure 2. Strength ratio vs PI for clays tested in triaxial compression, simple shear, and extension modes.

Using the consolidated undrained triaxial results and monotonic simple shear results, it has become practice to derive site-specific relationships between the (peak and residual) undrained shear strength ratio and state parameter.

It is advisable to calibrate and model at least two constitutive models for each material type. While it may not always be practical, doing so would substantially enhance the understanding of the most suitable models for the given problems and material types.

4.4 Anticipated future commercial test methods in southern Africa

Anticipated trends suggest that Scanning Electron Microscopy (SEM) with Energy-Dispersive X-ray Spectroscopy (EDS), X-Ray Diffraction analysis

(XRD), and X-ray Fluorescence (XRF) will gain prominence as tests for determining particle shapes, mineralogical composition, and elemental composition. The impact of these analyses on material properties and behaviour necessitates further study and exploration. Although this may not influence the calibration of the constitutive models, it will give better insight into the behaviour of the materials such as cementation tendencies.

It is also anticipated that hollow cylinder and resonant column testing will become more prominent in the future.

5 SOUTH AFRICAN LABORATOR TESTING CAPACITY

South Africa has a rich history in in-situ geotechnical testing, although the specialist geotechnical laboratory testing sector remained relatively small. However, in response to the increased demand for testing, the South African laboratory industry has grown rapidly over the past decade. Figure 3 below summarises the specialist laboratory testing capabilities in South Africa.

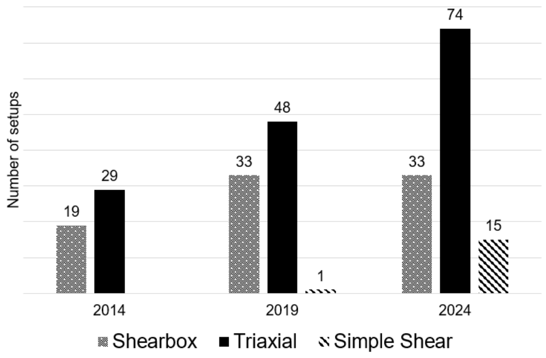

Figure 3. Number of test setups per test type available in South Africa (commercial laboratories only)

The demand for shearbox testing appears to have stabilised; however, the number of triaxial setups has nearly tripled over the last decade. The market has also responded to the increased demand for simple shear testing. Additionally, South African laboratories are now equipped to conduct other specialised tests, such as Bender Element and Rowe cell testing, which were previously limited to research facilities.

6 CONCLUSION

The paper presents a summary of the methodological advancements in geotechnical testing within the tailings industry, particularly following the implementation of the GISTM. The adoption of sophisticated constitutive models and FEM techniques marks a leap forward from traditional limit equilibrium methods, offering a more nuanced understanding of the complex interactions between soil, water, and tailings. This evolution in testing and analysis methodologies not only enhances the accuracy of stability predictions but also plays a pivotal role in optimising the design of TSFs for long-term safety.

The paper underscores the importance of considering the overconsolidated state of clay foundations, especially in southern Africa, and the role of advanced laboratory testing in calibrating constitutive models.

The South African laboratory sector has demonstrated significant growth and adaptability in response to rising demands for specialised geotechnical testing. This expansion not only enhances the country's testing capabilities but also positions South Africa as a competitive player in the global geotechnical testing arena.

These developments in laboratory testing, including the anticipation of future trends in commercial testing methods, are indicative of a broader commitment to risk management, environmental protection.,

REFERENCES

Benz, T. 2006. *Small-strain stiffness of soils and its numerical consequences*. Ph.D. Thesis. Stuttgart: Institut für Geotechnik, Universität Stuttgart.

Boulanger, R.W. & Ziotopoulou, K. 2015. *PM4Sand: A sand plasticity model for earthquake engineering applications*. Report No. UCD/CGM-15/01. Davis, CA: Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California.

ICMM. 2020. Global Industry Standard on Tailings Management, s.l.: GlobalTailingsReview.org.

Jefferies, M.G. & Been, K. 2016. *Soil Liquefaction – A critical state approach*. London: Taylor & Francis.

Ladd, C.C. 1992. Stability evaluation during staged construction. *J. Geotechnical Engineering* 117(4): 540-615.

Ladd, C.C. & Foot, R.A. 1974. New design procedure for stability on soft clays. *ASCE Journal of Geotechnical Eng.* 100(7): 763-786.

Roscoe, K.H. & Burland, J.B. 1968. *On the Generalized Stress-Strain Behaviour of Wet Clay*. In Engineering Plasticity, edited by J. Heyman and F. Leckie, pp. 535-609. Cambridge: Cambridge University Press.

Schanz, T., Vermeer, P.A. & Bonnier, P.G. 1999. The hardening soil model: formulation and verification. Beyond 2000. *Computational geotechnics*: 281-296.

Torres-Cruz, L.A. & Santamarina, J.C. 2019. The critical state line of non-plastic tailings. *Canadian Geotechnical Journal* 57(10): 1508-1517.

Verdugo, R. & Ishihara, J. 1996. The steady state of sandy soils. *Soils and Foundations* 36(2): 81-91.

Zdravkovic, L., Potts D.M. & Hight, D.M. The effect of strength anisotropy on the behaviour of embankments on ground. *Geotechnique* 52(6): 447-457.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 2nd Southern African Geotechnical Conference (SAGC2025) and was edited by SW Jacobsz. The conference was held from May 28th to May 30th 2025 in Durban, South Africa.