Advancements in geotechnical investigations for the characterisation of upstream tailings dams in SA

Since the introduction of the Global Industry Standard for Tailings Management, the South African geotechnical industry has had to recalibrate the planning of geotechnical investigations, laboratory testing, and stability modelling of tailings dams in South Africa and abroad to address the risks of tailings storage facilities to neighbouring communities, the environment, and their owners.

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Tailing storage facilities (TSFs) vary widely based on construction methodology (upstream, centreline, or downstream) and geometry (valley dam or impoundment). Each type requires a distinct approach to characterising in-situ conditions and tailings behaviour to ensure stability and safety.

South Africa is one of the few countries where detailed tailings characterisation is a standard requirement for most TSFs, as it forms part of the stability model due to the upstream construction method. Following the failure of the Brumadinho TSF in Brazil (an upstream dam), the industry has shifted significantly, with some regions banning upstream construction entirely and generally classifying it as very high risk.

Wates (2023) has outlined the key requirements for designing and assessing safe upstream TSFs. In addition to adhering to these standards, good teamwork is essential among:

- The mine's production managers, who oversee operations
- The TSF operator, responsible for ensuring tailings deposition follows agreed-upon criteria
- The Engineer of Record, who continuously forecasts TSF behaviour and identifies possible triggers and risks
- The Tailings Review Board, which serves as an independent advisory panel, typically comprising professionals with at least 20 years of local and international experience.

The characterisation of the in-situ ground conditions and tailings has increased over the past five years. This has led to extensive geotechnical investigations and laboratory campaigns to classify materials based on both drained and undrained behaviour, which can used to obtain a factor of safety in stability models.

EVOLUTION OF GEOTECHNICAL INVESTIGATIONS

Geotechnical investigations are often required for existing upstream TSFs to align their assessment with current standards and regulations. Many of these structures, built as far back as the 1970s and 1980s, were constructed with minimal geotechnical investigation or now have limited historical data due to changes in ownership or lost records.

For existing TSFs, a key challenge is understanding the in-situ ground conditions beneath the facility, often at depths of 30 m to 100 m below the current tailings level. Drilling with sampling is commonly used to recover tailings; however, obtaining undisturbed samples remains difficult, even with advanced techniques such as Dames and Moore or piston

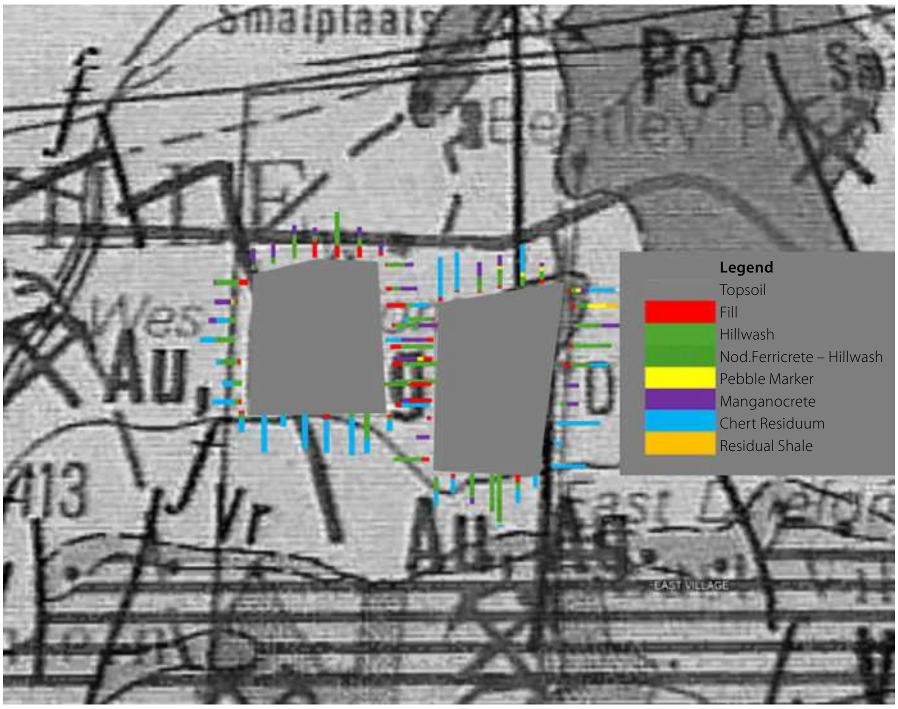

Figure 1 Test pitting profile

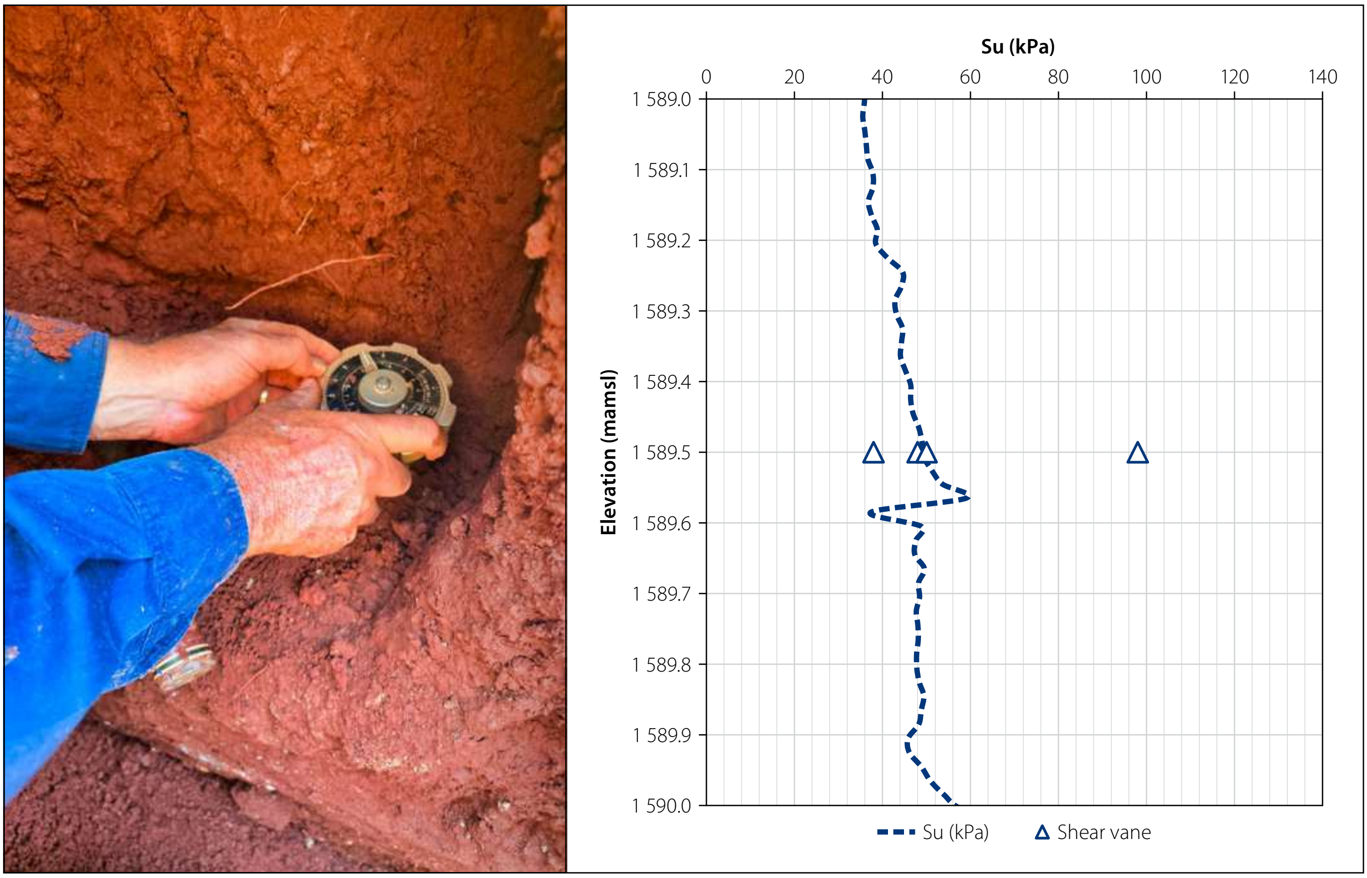

Figure 2 Undrained strength from hand shear vane and CPT

sampling – both preferred over a Shelby sampler due to the typically non-plastic nature of tailings, which makes recovery challenging. For foundation soils, a more cost-effective option is to dig test pits at the toe, with closer spacing, and collect block samples for undisturbed laboratory testing.

TEST PITTING

Test pitting generally provides a good indication of the in-situ conditions. A weak layer detected at a shallow depth within residual or transported material could be a potential trigger for block sliding failure.

Figure 1 illustrates a test pitting campaign designed to assess variations in ground conditions beneath two TSFs, where a high phreatic surface was known to exist in only one area. The presence of hillwash reduced permeability, limiting water infiltration, while in other areas, chert residuum transitioning to dolomite allowed for a higher infiltration rate. This level of detail would have been difficult to achieve through drilling, due to significantly higher costs, or geophysics, as the investigation focused on a relatively shallow depth.

A test pit can also be useful for conducting in-situ tests to validate laboratory results. In Figure 2, a series of hand shear vane tests were performed at the base of a retrieved block sample, providing data that could be compared to interpreted values from a piezocone or cone penetration test (CPT) campaign.

CONE PENETRATION TESTING (CPT)

When classifying tailings materials, particularly for an upstream TSF, it is crucial to highlight the outer shell, as defined by Wates (2023), which plays a key role in ensuring TSF stability. The most common in-situ test is the CPT with pore pressure measurements (CPT-u). This test not only provides data on the state of the soil and its strength, but also captures the pore pressure regime, which is essential for quantifying the extent of material saturation. Saturated zones may exhibit undrained shearing behaviour, either contractive or dilative, affecting overall stability.

The CPT can be coupled with a seismic module (measuring both compression and shear waves) and a resistivity module to better assess the saturation regime within a tailings dam, providing multiple interpretations of the pore pressure regime. Figure 3 illustrates an overlay of resistivity readings (orange line), compression wave

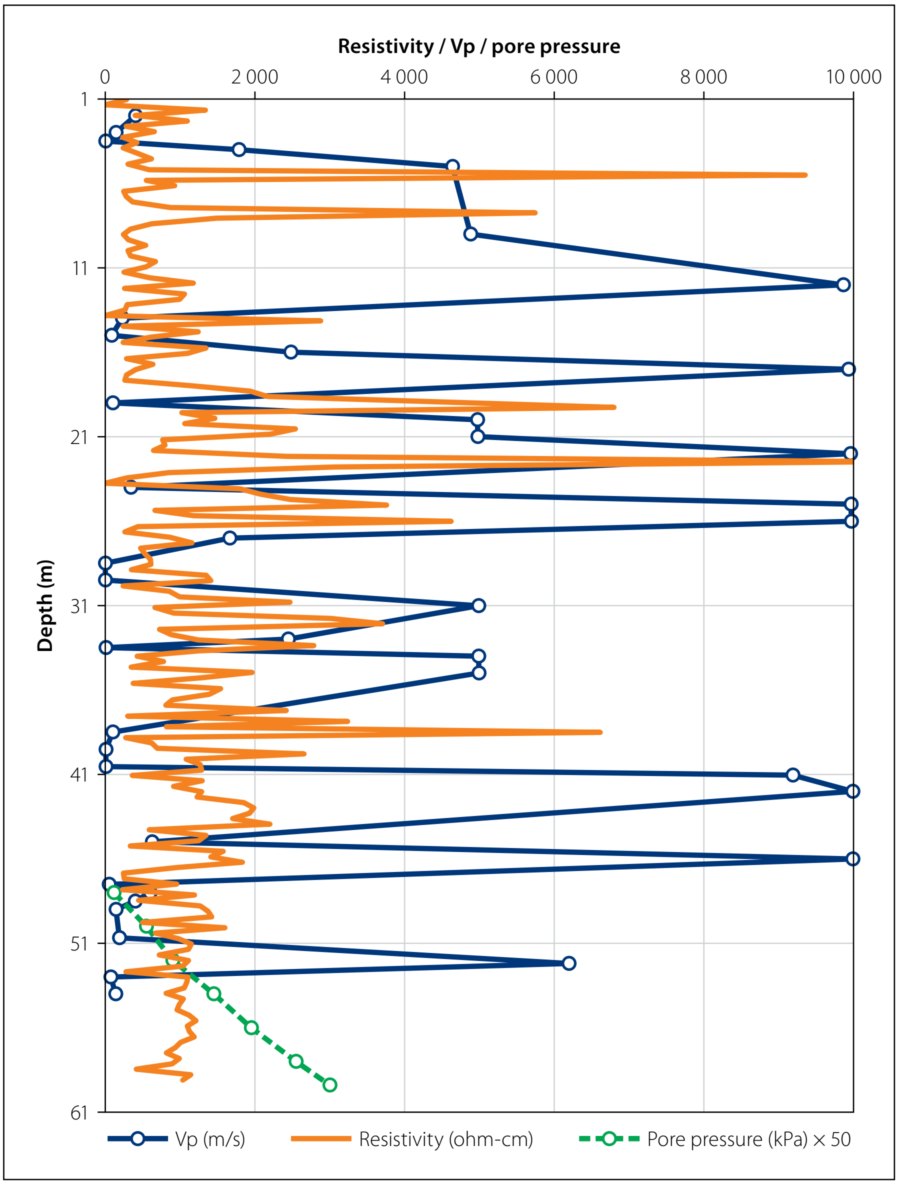

Figure 3 Resistivity and seismic interpretation of saturation compared to phreatic levels

(black line), and the interpreted phreatic surface from the CPT (green line). The resistivity and compression wave data identifies shallow saturated layers caused by cyclic deposition, as indicated by resistivity approaching zero and compression wave velocities exceeding 2 000 m/s to 2 500 m/s. Without the resistivity module, the perched water table could have been assumed to be continuous, changing the soil behaviour from unsaturated to saturated for the entire depth with significant repercussion on the stability.

Conducting field shear vane tests in conjunction with CPT allows for the calibration of undrained properties. The cone factor N_{kt} in tailings typically ranges between 10 and 20 (Mayne & Peuchen, 2018), so the shear vane test can serve to validate the dataset obtained from the CPT investigation. A key consideration with the shear vane test is ensuring that the rotation remains undrained; otherwise, the resulting strength will be overestimated, as drained strength values are higher. In Figure 4, shear vane results are plotted alongside several CPT interpretations and triaxial test results for comparison.

CPT INTERPRETATION

A CPT module records data every 2 cm, producing a considerable dataset over the entire depth of the probe. This can pose a challenge when it comes to interpreting the dataset.

First and foremost, layering is generated, identifying where natural ground transitions into tailings and the location of the different grades of tailings based on deposition methods and particle segregation.

Coarser particles tend to accumulate near the outer edges, while finer material settles further away from the walls, becoming ultrafine near the penstock. If the

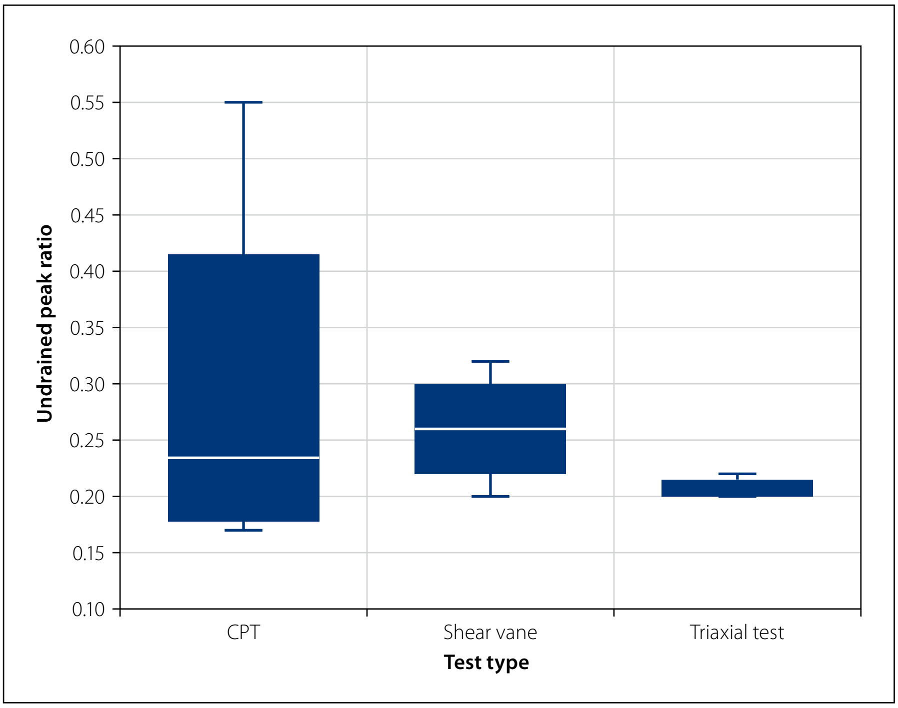

Figure 4 Shear vane results compared with CPT and triaxial testing

milling process has remained consistent, layering patterns typically remain uniform across sections. However, in cases where fine layers form due to deposition, low densities, or topographical variations, a section-by-section approach may be necessary.

Figure 5 presents a histogram of undrained strength properties for the tailings, along with various statistical ranges. When interpreting this data, it is essential to consider the failure mode:

- If stability is governed by a thin layer, a minimum or 20th percentile is typically used.
- If an entire slope is affected, the mean value can be used, as the overall stability is controlled by a larger volume and peaks will be counteracted by the lows.
- In cases where foundation layers are involved, failure may occur sequentially, with the weakest material failing first and triggering a chain reaction as the material transitions from peak to residual strength.

DILATOMETER MARCHETTI TEST (DMT)

The Dilatometer Marchetti Test (DMT) was recently added to the TSF investigation toolbox. While similar to the CPT in that similar parameters can be derived, using both tests together enhances data reliability. The DMT and CPT can be calibrated against each other, and the coefficient at rest (K_0) can be defined using correlations (ISSMGE, 2001).

Figure 6 represents the critical state line in deviatoric stress and mean effective stress, where the soil is stable under any configuration for which the point is below the critical state line. However, below the critical state, the instability line provides a further region called the "instability region", where the soil is in equilibrium but potentially unstable should any variation trigger a sudden failure leading to liquefaction. Those curves can be developed from triaxial compression test campaigns. However, the main question is how far the soil is from entering the instability region.

The ratio between normal and deviatoric stress at rest condition is defined by K_0, which can be interpreted from the DMT. A value of 1 means the soil is in isotropic conditions with no deviatoric stress. Once K_0 reduces due to construction/deposition layering, for instance, it means deviatoric stress is developed, and it reaches a new value. If a trigger occurs this will be the starting point. Therefore, the higher the K_0, the lower the risk of triggering a failure.

Understanding the K_0 value in a deformation model is important to recreate the stress history (staged construction). This can be used to test the dam's robustness against triggers and develop a credible failure mode analysis for which a trigger is shown not to be able to cause a dam failure.

CONCLUSIONS

Geotechnical investigations are becoming complex, especially when the TSFs pose an extreme risk to the neighbouring communities, environment, and owners – a failure can have local and national repercussions.

Simple tools such as test pitting and hand shear vane testing can be coupled with more complex in-situ investigations, such as the RSCPT-u, shear vane, and DMT, to correlate soil properties from more than one test or interpretation. This will give the engineer greater confidence

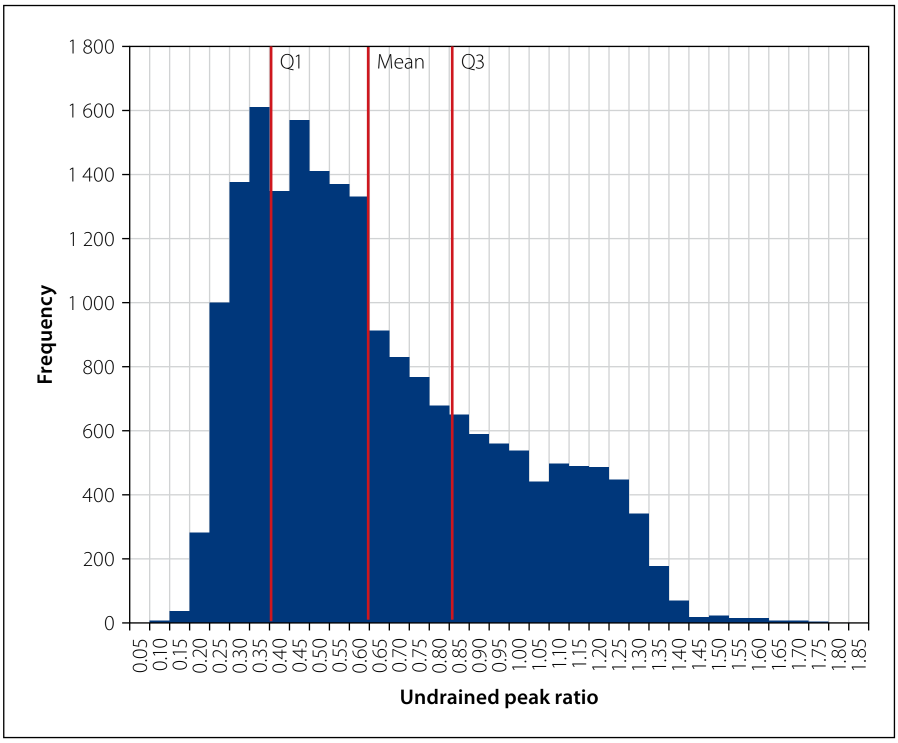

Figure 5 Histogram from CPT

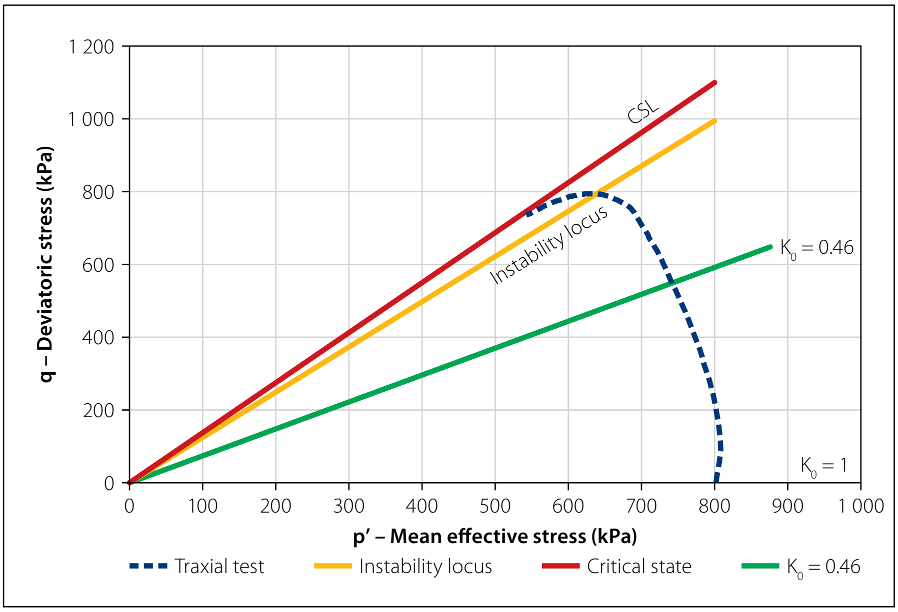

Figure 6 K_0 calculated from DMT testing plotted against CSL and instability locus for triaxial test

in the interpretation of the in-situ data, which can inform the laboratory testing campaign.

It is the engineer's responsibility to determine the appropriate values to use, considering both the robustness of the relationship between in-situ testing and geotechnical variables and the specific failure mode. For a global failure, an average value may be appropriate, whereas a localised foundation failure is better characterised using the minimum or 20th percentile.

Geotechnical investigations of this magnitude are also subject to change during the investigation. Until the first results are gathered there may be no baseline, and the geotechnical investigation needs to be adjusted to suit the conditions, such as hard layers where the CPT refuses, requiring pre-drilling. Without doing thorough geotechnical investigations, stability analyses may be conservative, with low factors of safety that lead to incorrect decision making with associated costs. □

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