Correlation of resistivity, pore pressure, and saturation for phreatic surface interpretation in gold tailings

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ABSTRACT: The geotechnical stability of tailings dams is critical for ensuring their longevity and safety. Traditional stability analyses often rely on principles derived from natural soils, such as sands and silts, which do not fully capture the unique behaviours of chemically processed tailings materials. This study investigates the relationship between in-situ measured resistivity, pore pressure dissipation trends, and degree of saturation within a gold tailings dam. Field investigations employed Resistivity Cone Penetration Testing (RCPTu) with pore pressure measurements, complemented by MOSTAP sampling to estimate the degree of saturation in laboratory conditions. Preliminary findings indicate a strong correlation between resistivity trends and the phreatic surface, with resistivity profiles effectively delineating this critical boundary. Results further confirm alignment with phreatic surface interpretations derived from pore pressure dissipation tests, suggesting that resistivity could serve as a reliable and field-integrated indicator of saturation levels in tailings storage facilities. These findings contribute to the development of an empirical framework for evaluating stability conditions in chemically processed tailings. By establishing a field-based approach to interpreting saturation boundaries using resistivity, this study provides a scientifically grounded tool for enhancing monitoring protocols and safety strategies in tailings dam management.

1 INTRODUCTION

The stability and integrity of tailings dams are critical for minimizing risks to human lives, the environment, and surrounding infrastructure. These engineered structures contain fine-grained mine tailings, which exhibit distinct geotechnical behaviour compared to natural soils due to their altered mineralogy and chemical composition. Unlike natural sands and silts, tailings are a byproduct of mining and mineral processing, often displaying unique physical and chemical characteristics. While TSFs can contain various types of tailings, this study focuses specifically on gold tailings, which may require specialized geotechnical assessment approaches. Traditional stability assessments, which primarily rely on geotechnical principles derived from sands and silts, may not fully capture the behaviour of chemically processed mine tailings (Mitchell 1993).

A growing body of research suggests that electrical resistivity measurements can be a valuable tool for geotechnical investigations, particularly for assessing saturation and moisture content in soils (Archie 1942, Santamarina et al. 2001). In natural soils, resistivity values typically decrease with increasing saturation; however, tailings materials may exhibit more complex electrical responses due to residual process chemicals and unique depositional properties (Jones et al. 2016).

One of the key challenges in tailings dam stability analysis is the accurate identification of the phreatic surface, as it directly influences pore pressure conditions and slope stability. Traditional methods rely on piezometer data and pore pressure dissipation tests; however, these provide only point-based measurements with limited spatial resolution.

This study investigates whether resistivity measurements, correlated with pore pressure dissipation trends and degree of saturation, can improve phreatic surface delineation in tailings storage facilities. By establishing empirical relationships between resistivity, pore pressure, and degree of saturation, this research aims to refine phreatic surface interpretations in gold tailings, enhancing geotechnical monitoring techniques.

Field investigations were conducted using Cone Penetration Testing with pore pressure measurements and a resistivity module (RCPTu configuration), complemented by MOSTAP sampling to determine the degree of saturation through laboratory analysis.

This research evaluates the effectiveness of the resistivity module in identifying saturation boundaries by comparing resistivity measurements with pore pressure dissipation trends, thereby complementing traditional CPTu and dissipation tests.

Ultimately, by comparing resistivity profiling with pore pressure dissipation trends, this study seeks to contribute toward the development of a tailings-specific empirical framework to support phreatic surface interpretation, stability assessments, and improved monitoring protocols.

2 METHODOLOGY

Field and laboratory investigations were conducted at two gold tailings dams to establish correlations between dynamic resistivity, pore pressure, and degree of saturation, which were then used to estimate the phreatic surface location. This section details the field-testing procedures, sampling methods, laboratory analyses, and data-processing techniques used in the study.

2.1 *Field Testing*

Resistivity Cone Penetration Testing with Pore Pressure Measurement (RCPTu) was employed using a Pagani CPT rig equipped with an AP van den Berg cone. The cone contained a conductivity sensor, which provided in-situ measurements of electrical conductivity (mS/m), later converted to resistivity (Ω·cm) using the standard equation:

$$Resistivity\ (\Omega cm) = \frac{1}{Conductivity\ (mS/m)^{-3}} x100 \qquad (1)$$

Testing was conducted at 36 locations across multiple benches on two tailings dams, with penetration depths extending to refusal, exceeding 50 m in some instances. To further analyse material properties, MOSTAP samples were obtained at selected RCPTu locations, reaching depths of up to 25 m (limited by rig capabilities).

All measurements followed international CPTu standards, with field data collected at consistent intervals to ensure accuracy and repeatability.

2.2 *Laboratory Analysis*

MOSTAP samples were analysed to determine the degree of saturation as follows:

$$S_r = \frac{wG_s}{e} \qquad (2)$$

where S_r is the degree of saturation, w is moisture content, G_s is specific gravity, and e is the void ratio.

Since MOSTAP samples are disturbed, the void ratio and bulk density may differ from in-situ conditions, which can introduce uncertainty in the calculated degree of saturation, particularly in partially saturated samples.

Moisture content was obtained using oven drying, and bulk densities were calculated through volumetric measurements and pycnometric methods to ensure consistency.

2.3 *Interpretation of the Phreatic Surface*

Phreatic surface interpretation was based on a combined analysis of RCPTu resistivity data, dynamic pore pressure measurements, and dissipation tests.

Trends in resistivity were compared with changes in pore pressure to assess how well resistivity delineates saturated and unsaturated zones.

All resistivity, moisture content, and pore pressure data were plotted and analysed to develop correlations for identifying saturation boundaries within the tailings dams.

3 RESULTS

The results of this study highlight clear correlations between resistivity, pore pressure dissipation, and degree of saturation, providing deeper insight into the behaviour of tailings above and below the phreatic surface.

3.1 *Resistivity and Pore Pressure Trends with Depth*

Figure 1 shows a combined plot of resistivity and pore pressure dissipation with depth. A notable transition is observed at the interpreted phreatic surface, with significant differences in data trends above and below this boundary.

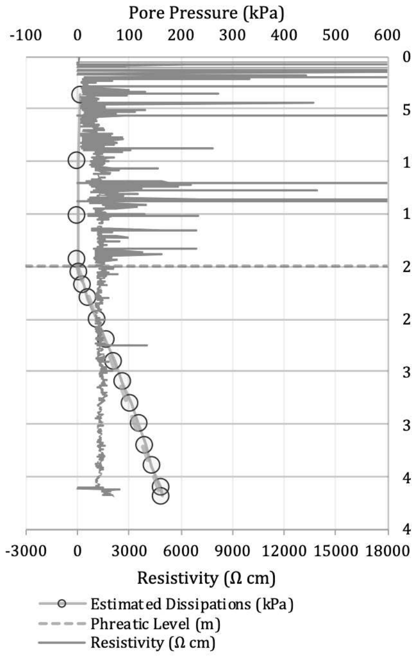

Figure 1. Resistivity and pore pressure dissipation trends.

Key Observations:

- Above the Phreatic Surface:
  - Resistivity values show high variability, with pronounced peaks corresponding to drier zones.
  - This is caused by lower water content and increased air-filled pore spaces, which lower electrical conductivity and increase resistivity.
- Below the Phreatic Surface:
  - Resistivity values are generally lower and more stable, reflecting higher moisture content and increased ionic conductivity.
  - Even in localized drier sections below the phreatic surface, resistivity values remain lower than similar saturation levels above the water table due to increased bulk density and fine-particle content.

To better visualise the pressure response, Figure 2 presents dynamic pore pressure alongside dissipation test results. These results reinforce the transition identified in Figure 1 and support phreatic surface interpretation using pore pressure behaviour.

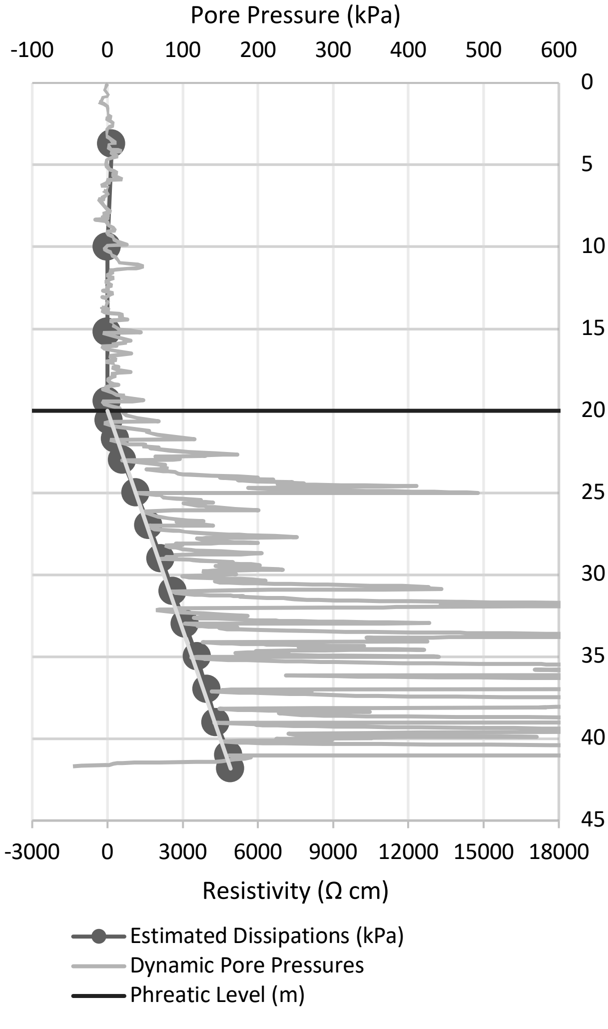

Figure 2. Dynamic pore pressure distributions supporting phreatic surface interpretation.

This further confirms that pore pressure data directly supports resistivity-based interpretations of the phreatic surface, enhancing confidence in resistivity as a complementary tool for defining saturation levels.

3.2 *Resistivity vs. Degree of Saturation*

To better understand the effect of degree of saturation on resistivity, the dataset was categorised into three groups:

- Group A – Data above the phreatic surface
- Group B – Data below the phreatic surface
- Group C – Combined dataset (above and below)

Figure 3a presents the data above the phreatic surface from Group A:

- A logarithmic decrease in resistivity is observed as saturation increases, consistent with trends observed in natural soils, where resistivity reduces rapidly at low saturation and begins to stabilise near full saturation (Santamarina et al., 2001)
- High variability is present at lower saturation levels, reflecting heterogeneous drying effects in tailings.

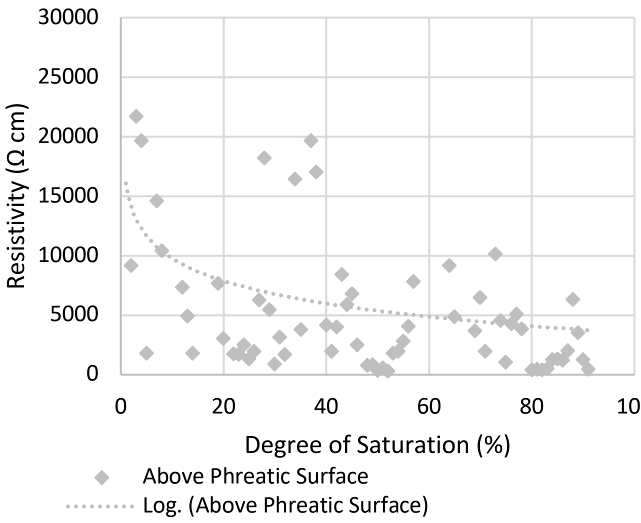

Figure 3a. Resistivity vs. Degree of Saturation (Above Phreatic Surface)

Figure 3b presents the data below the phreatic surface from Group B:

- Resistivity values are more stable across increasing saturation.
- The effect of pore fluid conductivity dominates, reducing resistivity variability.

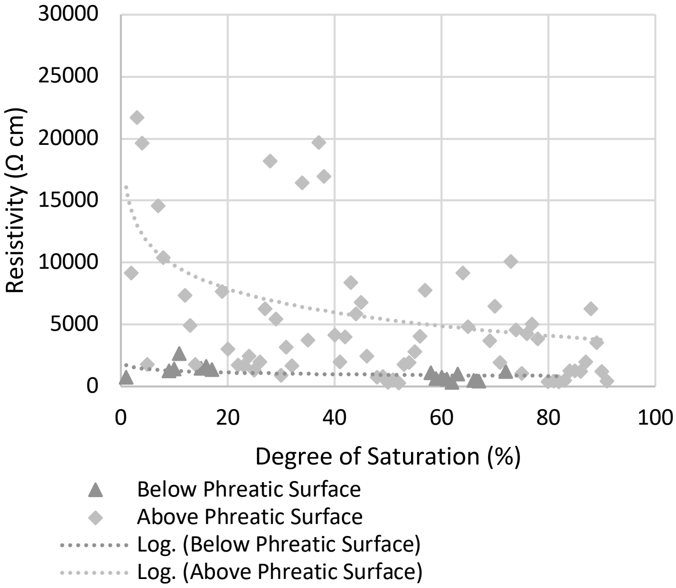

Figure 3b. Resistivity vs. Degree of Saturation (Below Phreatic Surface).

Figure 3c presents the combined data for above and below the phreatic surface from Group C:

- Scatter in resistivity values was observed both above and below the phreatic surface, likely influenced by instrument resolution as well as natural heterogeneity in tailings.

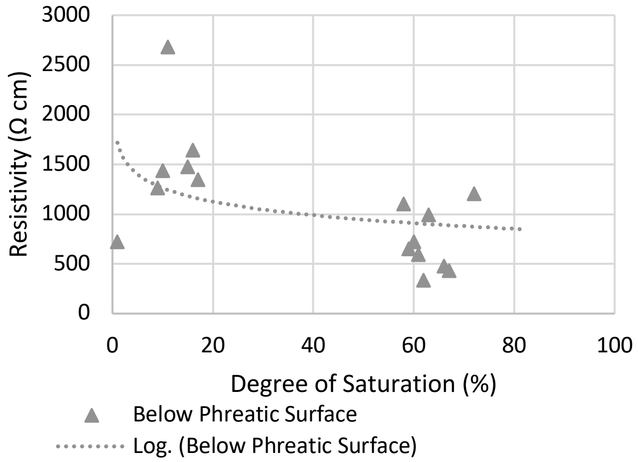

Figure 3c. Overall Resistivity vs. Degree of Saturation (Combined Analysis)

Additionally, MOSTAP samples, being disturbed samples, may not always reflect in-situ saturation conditions with high precision, introducing further variability.

While MOSTAP samples provide additional laboratory validation of degree of saturation, field pore pressure (PWP) measurements from CPTu alone may also be used as a direct indication of saturation boundaries.

For practical applications, using CPTu pore pressures alongside resistivity readings may reduce the need for additional sampling, though direct sampling remains valuable for calibration and validation.

3.3 *Correlation Between Resistivity and Phreatic Surface Location*

Resistivity transitions align closely with the dissipation trends, reinforcing the hypothesis that resistivity readings can serve as an auxiliary tool for defining saturation boundaries.

The observed transition at the phreatic surface is more distinct when resistivity and pore pressure data are considered together, reaffirming that isolated parameters do not provide as robust an interpretation as a multi-faceted approach.

These findings suggest that integrating resistivity into tailings stability assessments offers a reliable method for improving phreatic surface delineation, thereby enhancing geotechnical evaluation methods.

4 DISCUSSION

The results of this study confirm a strong correlation between resistivity profiles, pore pressure dissipation, and the phreatic surface, reinforcing the potential of resistivity as a field-integrated tool for geotechnical assessments of tailings dams. However, some variability in the dataset requires further analysis to fully understand the influencing factors.

4.1 *Factors Affecting Resistivity Trends*

While resistivity values above the phreatic surface exhibit expected variability due to moisture fluctuations, some unexpected trends were observed below the phreatic surface, where certain dry layers did not exhibit the anticipated high resistivity values. Possible explanations include:

- Density Effects in Saturated Layers
  - While direct density measurements were not collected in this study, the influence of density on resistivity values is well-documented in geotechnical literature.
  - Denser materials typically restrict air-filled voids, reducing resistivity variability even when partial saturation occurs. This may explain why certain dry layers below the phreatic surface did not exhibit expected high resistivity values.
- Depositional History of Tailings
  - Unlike naturally deposited soils, tailings undergo segregation, layering, and localized compaction, introducing inconsistencies in resistivity responses.
  - This suggests that some resistivity anomalies are linked to variability in tailings deposition rather than true saturation changes.

4.2 *Comparison of Resistivity and Pore Pressure Data*

The alignment between resistivity and pore pressure dissipation data supports the reliability of resistivity methods for detecting the phreatic surface. However, there are both advantages and limitations to consider when interpreting resistivity data in this context:

Advantages of Resistivity Data

- Provides a continuous profile of saturation variability rather than isolated point measurements.
- Offers a field-integrated alternative to traditional phreatic surface estimation methods.
- Captures the presence of localised wetting fronts and intermediate saturation zones — a valuable feature in stratified or layered tailings deposits.
- Enhances the interpretation of dry zones and transitions to saturation.

Limitations of Resistivity Data

- Cannot differentiate true saturation effects from density-driven conductivity changes in fine-grained materials.
- Variations in pore fluid conductivity may be influenced by residual process chemicals; however, this study did not directly measure ionic concentrations.
- While resistivity can indicate saturation boundaries, it does not provide information on pore pressure magnitude or dissipation behaviour, which would otherwise be captured through CPTu dissipation tests.

This study established a more reliable interpretation of phreatic surface location and saturation conditions by integrating both resistivity and pore pressure dissipation methods.

4.3 *Implications for Geotechnical Tailings Dam Assessment*

The key findings from this study support the use of resistivity profiling as a supplementary tool for tailings monitoring:

- Resistivity-based phreatic surface mapping could enhance safety monitoring protocols.
- Combining resistivity with traditional CPTu pore pressure data improves confidence in dam stability assessments.
- Future work should refine empirical resistivity models through laboratory calibration and field validation to improve prediction of saturation levels in chemically altered tailings.

While resistivity offers clear advantages for continuous saturation profiling, it does not provide information on pore pressure build-up or dissipation behaviour. Although RCPTu includes pore pressure sensors, the resistivity module on its own cannot determine pore pressure values. Therefore, if dissipation tests are omitted, critical information about the rate and magnitude of pore pressure response is lost. For comprehensive monitoring strategies, resistivity profiling should be used in conjunction with targeted dissipation testing, particularly during initial site investigations or model calibration phases.

5 CONCLUSION

This study examined the relationship between in-situ measured resistivity, pore pressure dissipation data, and degree of saturation in gold tailings, with the goal of enhancing phreatic surface interpretation.

Results indicate that resistivity correlates well with pore pressure dissipation trends, supporting its use as a complementary method for phreatic surface assessment.

Variability in resistivity readings highlights the influence of density, saturation conditions, and measurement limitations.

Further research should refine empirical resistivity models specific to tailings storage facilities and explore long-term resistivity monitoring for enhanced geotechnical safety assessments.

6 RECOMMENDATIONS

To strengthen the findings of this research and improve the practical use of resistivity-based geotechnical assessments in tailings storage facilities, the following recommendations are proposed:

- Conduct laboratory calibration testing
    - Assess how resistivity responds to varying tailings properties (e.g., density, particle size, saturation).
    - Include chemical analyses to evaluate the influence of pore fluid conductivity where applicable.
- Implement long-term resistivity monitoring
    - Use RCPTu or hybrid sensors to track phreatic surface movement and saturation changes over time.
    - Incorporate data into early warning or operational monitoring programs for tailings dams.
- Validate resistivity data using borehole instrumentation
    - Compare resistivity-based phreatic surface interpretations with direct measurements from piezometers or vibrating wire pressure cells.
    - Use discrepancies to refine interpretation methodologies and improve site-specific calibration.
- Account for uncertainty in measurement tools
    - Evaluate the accuracy and variability of resistivity modules and MOSTAP-derived saturation data.
    - Identify when CPTu pore pressure data alone may provide sufficient resolution, reducing the need for additional sampling.

- Apply methods to diverse tailings types
  - Test the presented approach on multiple mineral types (e.g., copper, nickel, PGM).
  - Validate whether the resistivity–saturation relationships established for gold tailings generalize to other TSFs.

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