# Assessing various *in situ* techniques to infer remoulded strength in coal tailings

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## ABSTRACT

With the increasing number of tragic failures of tailings storage facilities (TSFs), the reliable determination of remoulded strength for stability analyses has become essential. However, the determination of remoulded strength for contractive strain softening materials includes many uncertainties. Considering the difficulty of recovering undisturbed samples of contractive fine grained soils, and limitations associated with laboratory testing, different correlations have been developed for the determination of remoulded strengths. One widely used correlation for fine grained soils is between the sleeve friction from cone penetration tests and the remoulded strength of fine grained soils. In an attempt to re-evaluate that correlation, a wide range of *in situ* tests and sampling was carried out in a coal tailings deposit to enable comparisons of inferred remoulded strength from a variety of techniques. In particular, both conventional friction sleeves and an innovative new 3 MPa CPT were used to assess the performance of the new sleeve system in the context of remoulded strength estimation. Vane shear tests (VST) at a range of rotation rates were then used to compare to the friction sleeve measurements and critically assess their performance in the measurement of remoulded strength. Finally, as reliable VST measurements of remoulded strength require undrained conditions to be maintained, an assessment of the potential for drainage to have occurred in these tests is made and only remoulded values deemed to be undrained were used in comparisons to the sleeve measurements.

## INTRODUCTION

The proper estimation of the remoulded strength of tailings is a key challenge given the recent failures of TSFs resulting in devasting effects on human life, economic losses and irreversible damage to the downstream environment. Mount Polley's TSF failure in 2014 caused around 25 $Mm^3$ release of wastewater and tailings into the environment. Failure of the Feijão TSF in 2019 caused over 260 fatalities and a huge impact on the downstream environment (Fourie *et al*, 2022). With all the recent failures, the proper characterisation of contractive tailings and sensitivity behaviour is unarguably important.

Different laboratory tests and correlations are used to determine the remoulded strength. However, laboratory testing may fail to replicate the *in situ* liquefiable soil condition due to issues such as strain limitations of many experimental devices and sample disturbance/densification (Verdugo and Ishihara, 1996; Yamamuro and Covert, 2001). For the estimation of remoulded shear strength, *in situ* tests are arguably more commonly applied owing to the previously-noted difficulties regarding laboratory measurements. Many empirical approaches and relationships have been developed to calculate the residual shear strength based on the *in situ* results (Seed, 1987; Seed and Harder, 1990; Olson and Stark, 2002; Idriss and Boulanger, 2015; Kramer and Wang, 2015). Two approaches are common for case history-based residual strength estimation, the direct approach and the normalised strength approach (Kramer and Wang, 2015). The direct approach considers the residual strength as a direct function of penetration resistance. Similarly, in the normalised strength approach, the ratio of residual strength to initial vertical effective stress is considered to correlate better to the penetration resistance based on Castro (1987). Olson and Stark (2002) presented a relationship between the liquefied shear strength ratio (LSR) by normalising liquefied shear strength with pre-failure vertical strength from CPT and standard penetration test (SPT) from the back calculation of past failures. Similarly, Idriss and Boulanger (2015) recommended SPT and CPT based relationships between the residual shear strength ratio of liquefied non-plastic soils for significant void redistribution and without void redistribution.

Lunne, Robertson and Powell (1997) stated that the sleeve friction values are very small and similar to the remoulded undrained shear strength for sensitive soft clays. Based on the statement from Lunne, Robertson and Powell (1997) and the results of *in situ* VST, Robertson (2009) suggested that the remoulded shear strength could be measured from the sleeve friction for normally consolidated fine grained soils. Farrar (2010) compared the results of friction sleeves with field vane tests from the investigation at Scoggins Dam in Northwest Oregon and concluded that the CPT sleeve friction and the remoulded strengths of VST are similar. Alternatively, according to Lunne (2007), remoulded shear strength and sensitivity cannot be evaluated from sleeve friction and friction ratio as other factors can influence the value of sleeve friction, such as pore pressure effects, surface roughness of the sleeve, rate of penetration, instrumentation effects, and the amount of remoulding.

The major issue during the measurement of remoulded strength in VST is the drainage effect, which is a function of the rate of rotation of the vane and the soil permeability and coefficient of consolidation (Sharifounnasab and Ullrich, 1985). If partial drainage occurs during testing, the undrained shear strength measured is overestimated and the validity of the results becomes questionable (Fourie *et al*, 2022). The current engineering practice and standard is mostly focused on maintaining undrained conditions at peak strength but not considering the effect of drainage on measured remoulded strengths. Reid (2016) assessed the effects of drainage considering the time of failure using multiple rates for the estimation of undrained shear strengths. For silty tailings with high permeability, low plasticity and high brittleness index, it is particularly important to select the rotation rate to achieve an undrained condition, not only for the peak strength but for the remoulded strength at high rotations.

The purpose of this paper is to better understand the remoulded strength obtained with the vane shear testing under multiple rotation rates for the coal tailings. Friction sleeve measurements using an innovative special design 3 MPa cone and the conventional compression cone are compared with the remoulded strengths to review the correlation between the remoulded strength with sleeve friction. The effect of multiple rotation rate VSTs and consolidation parameters on the drainage condition were assessed considering the difficulty in achieving an undrained condition in the field.

# GEOTECHNICAL INVESTIGATION

## Site and material description

The *in situ* tests presented for this study are from the same location mentioned in McConnell and Wassenaar (2022), which is a coal tailings dam located in Australia. These tailings have low plasticity, with plasticity indices (PI) ranging around 6–9 per cent. The index properties obtained for this material are presented in Table 1.

**TABLE 1**

Index test characteristics of coal tailings.

| | |
|---|---|
| **Specific gravity** | 1.75 |
| **Plastic limit (%)** | 38 |
| **Liquid limit (%)** | 32 |
| **Plasticity index (%)** | 6–9 |
| **% <75 µm (wet sieve)** | 24% |

### *CPTu testing*

The CPTu results from a conventional 10 MPa capacity compression cone and an innovative special design cone with a 3 MPa capacity cone, designed by Insitu Geotech Services (IGS) and Geomil, was used in this study (McConnell and Wassenaar, 2022). The purpose of the special 3 MPa cone is to overcome the fundamental problem that normal industry-standard compression cones cannot properly detect and measure sleeve friction in extremely soft materials (Santos, Barwise and Alexander, 2014; Entezari *et al*, 2021). This new 3 MPa cone is a subtraction cone, with tip capacity of 3 MPa and sleeve capacity of 200 kPa. A special alloy base is used in the load cell for enhanced physical strain gauge response for higher sensitivity of the cone. Careful cone calibration was done before and after testing using dead weights for the application of load to the tip and sleeve.

*In situ* dissipation tests were part of the investigation to assess the phreatic level and coefficient of consolidation at regular depth intervals. This was carried out by measuring the time needed for the excess pore pressure to return to equilibrium pressure.

### *Vane shear test*

A field vane shear test is used extensively to measure peak and remoulded strengths. A series of VSTs were performed using an AP Van den Berg electronic down the hole vane with 75 mm diameter and 150 mm height at multiple rates of rotation for different depths to assess the impact of rotation rate on the drainage condition and remoulded strength. For the first approach, the vane was continuously rotated at the same initial rate of rotation to measure the remoulded strength. Continuous rotation was performed at two different rates (a slower rate of 60°/min and a faster rate of 360°/min). For the second approach, the vane was initially rotated at 60°/min to measure the peak strength, followed by a faster rate of 360°/min for five rotations to remould the soil and finally rotation at the initial rotation rate of 60°/min to measure the remoulded strength.

There are different approaches for the assessment of drainage in VSTs (Morris and Williams, 2000; Blight, 1968; Chandler, 1988). An approach based on Blight (1968) and Chandler (1988) was used to measure the dimensionless time factor, *T.* This approach assumes that the excess pore water pressure in the VST is generated during the vane rotation with subsequent reduction in undrained shear strength and directly links the degree of drainage to the time factor. This method suggests *T* should be smaller than 0.05 to ensure an undrained condition.

The dimensionless time factor, *T* to assess the drainage condition is calculated as:

$$T = c_v \, t_f / D^2 \tag{1}$$

where $c_v$ is the coefficient of consolidation, $t_f$ is the time to failure, and *D* is the vane diameter.

## RESULTS

### *In situ* phreatic conditions and rate of consolidation

The horizontal coefficient of consolidation ($c_h$) was determined using the equation proposed by Teh and Houlsby (1991) from the results of dissipation tests with time for 50 per cent of dissipation. The value of the coefficient of consolidation ($c_h$) ranged from 4 $m^2$/a to 16 $m^2$/a from the results of dissipation tests, as presented in Figure 1. The $c_h$ values of 5 $m^2$/a and 15 $m^2$/a were adopted, given it likely represents the most relevant value to ensure undrained conditions for the VST calculations. A plot of equilibrium pore pressure profile with depth from the dissipation test results is presented in Figure 2.

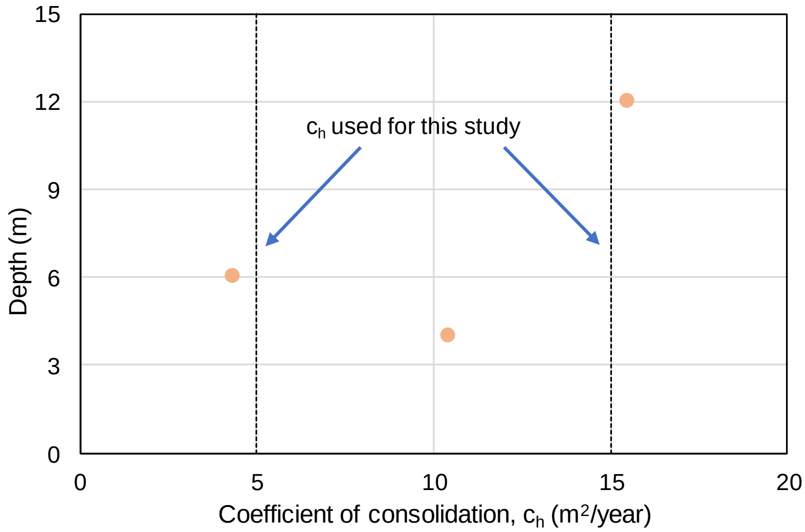


**FIG 1** – Summary of coefficient of consolidation.

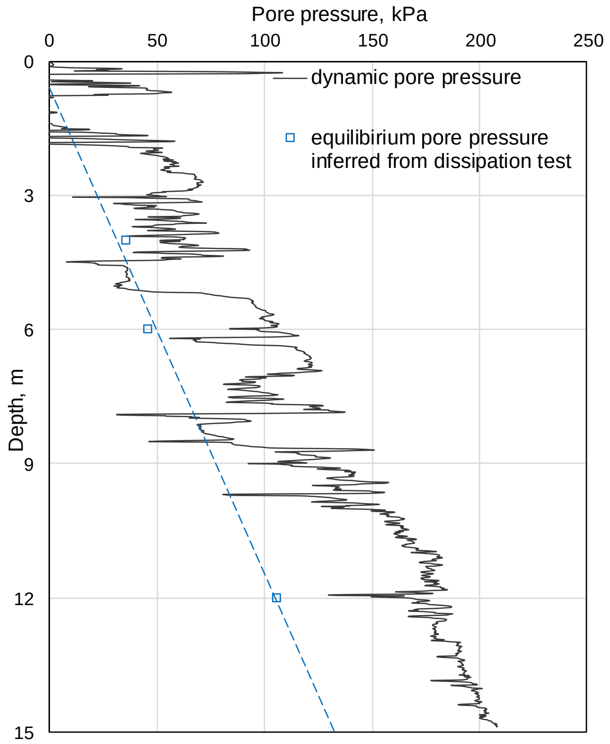


**FIG 2** – Pore water pressure with depth.

## Comparison of different sleeve friction measurements

The results of the CPT tests undertaken using two different cone types is presented in Figure 3. The result clearly shows variation of the friction sleeve measurements. The sleeve friction values measured by the special 3 MPa cone (which is specifically designed for accurate measurement of low sleeve frictions) are slightly higher in comparison to values measured by the conventional 10 MPa compression cone at most depths. The 3 MPa cone measuring higher sleeve friction values with the line of equivalence is clearer in Figure 4 for the comparison friction sleeve values measured by different types of cone.

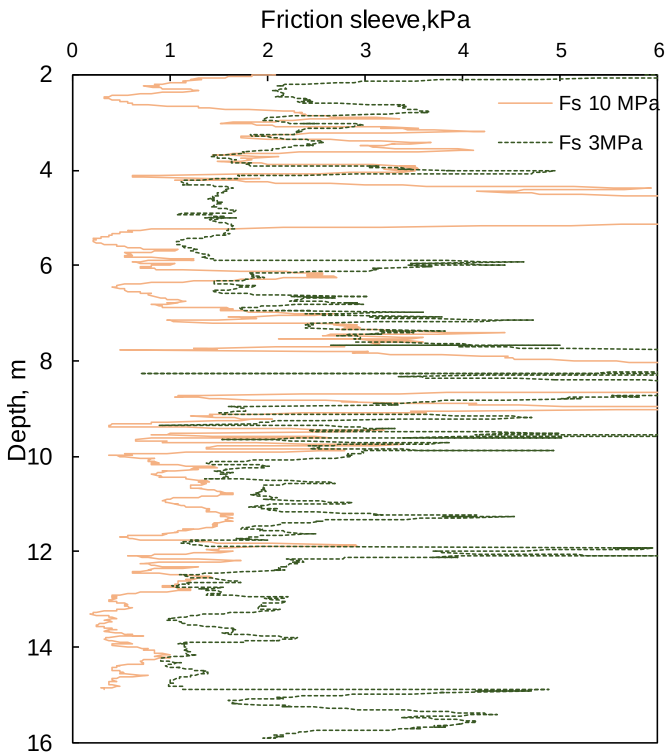


**FIG 3** – Depth versus friction sleeve measurements for 3 MPa and 10 MPa capacity cones.

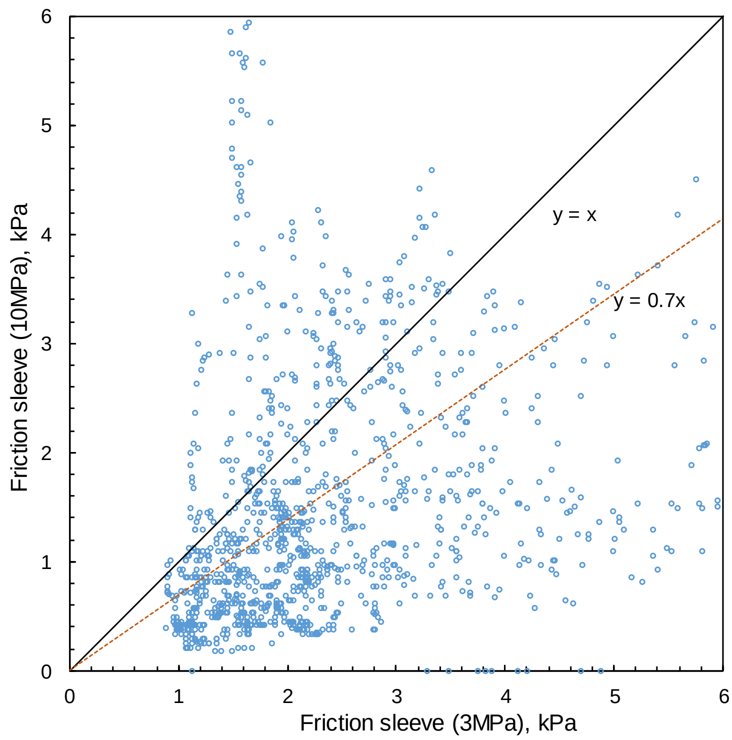


**FIG 4** – Comparison of friction sleeve using different cone capacities.

## Vane shear test interpretation

The summary of peak and remoulded shear strength of the VST, normalised by effective overburden stress at different depths for multiple rotation rates is shown in Table 2. Here, the remoulded strength refers to the lowest strength obtained during the vane rotation. The peak strengths at the faster rotation rate (360°/min) are higher than the peak obtained for the lower shear rate (60°/min) whereas the remoulded strengths are higher at lower rotation rates in most of the vane tests performed at the same depths. However, the discrepancy in the peak stress ratio is higher than that for the remoulded strength ratio while comparing the results from different rotation rates for the same depth value.

**TABLE 2**

Summary of vane shear test.

| Rate (°/min) | Depth (m) | Peak stress ratio | Remoulded stress ratio |
|---|---|---|---|
| 360 | 3.5 | 0.320 | 0.093 |
| 360 | 4.5 | 0.349 | 0.099 |
| 360 | 5.5 | 0.391 | 0.103 |
| 360 | 6.5 | 0.353 | 0.105 |
| 360 | 11.5 | 0.350 | 0.078 |
| 360 | 12.5 | 0.269 | 0.050 |
| 360 | 14.5 | 0.167 | 0.041 |
| 360 | 15.5 | 0.193 | 0.049 |
| 60/360/60 | 4.5 | 0.374 | 0.112 |
| 60/360/60 | 6.5 | 0.313 | 0.117 |
| 60/360/60 | 12.5 | 0.196 | 0.062 |
| 60/360/60 | 15.5 | 0.170 | 0.048 |
| 60 | 3.5 | 0.405 | 0.084 |
| 60 | 5.5 | 0.302 | 0.117 |
| 60 | 11.5 | 0.309 | 0.096 |
| 60 | 14.5 | 0.165 | 0.039 |

A typical illustration of the change in the dimensionless time factor with vane rotation rate in terms of the measured shear stress ratio and $c_h$ of 15 $m^2/a$ is presented in Figure 5, using the Blight/Chandler method. For the VST with continuous rotation at 360°/min, the strength is decreases continuously until the end of rotation, with a time factor for the minimum strength of around 0.03. When the vane is rotated at 60°/min, the time factor for the minimum strength is around 0.04–0.05, which is at around 540 to 750° of rotation with a constant strength for further rotation of vanes. Similarly, for rotation at multiple rates, the time factor initially reaches a value around 0.0037 within the first 40° peak. However, with the increase in rotation rate to 360°/min the time factor changes from $6.3\times10^{-5}$ to around 0.0025 at the end of five rotations and when the rotation rate is adjusted to the initial rate of 60°/min, the time factor becomes 0.18 as shown in Figure 5c.

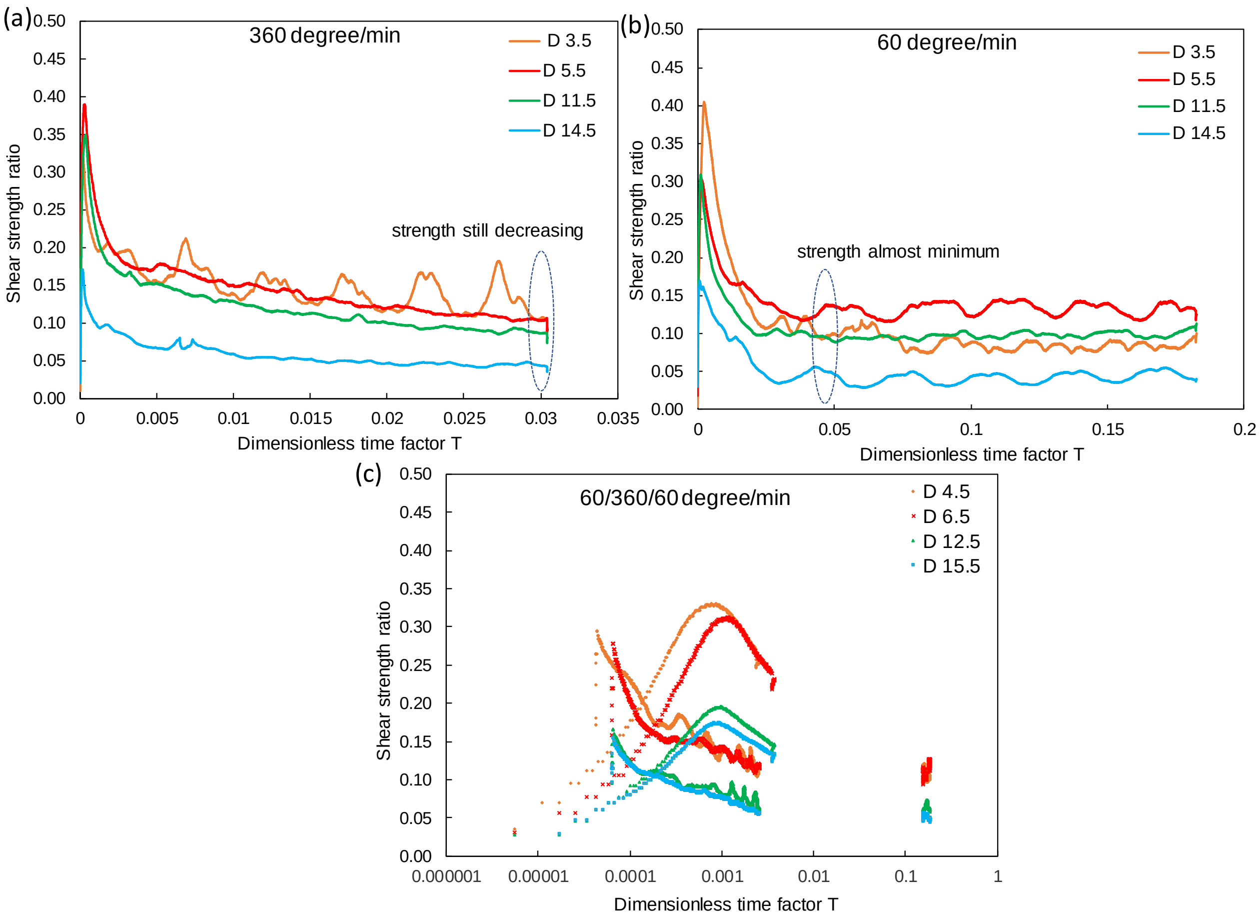


**FIG 5** – Typical illustration of variation of undrained strength ratio with time factor for different rates of rotation for $c_v$ of 15 $m^2$/a (based on Blight/Chandler): (a) 360°/min; (b) 60°/min; (c) multiple rates.

For a better understanding of the effect of the $c_v$ on the drainage condition for multiple rotation rates of VST, the dimensionless time factor based on Blight/Chandler was calculated adopting values of $c_v$ of 5 $m^2$/a and 15 $m^2$/a, respectively, as presented in Figure 6. In both conditions, the peak strength appears to be in undrained condition for all rotation rates. For a higher $c_v$ of 15 $m^2$/a, the possibility of partial drainage is amplified for the lower rate of rotation in VST in comparison to $c_v$ of 5 $m^2$/a. The remoulded strength determined from a partially drained condition may not represent the behaviour of tailings, particularly with regards to the influence on the brittleness and sensitivity behaviour. This highlights the importance of a better understanding of the consolidation parameters and rotation rate for obtaining fully undrained remoulded strengths.

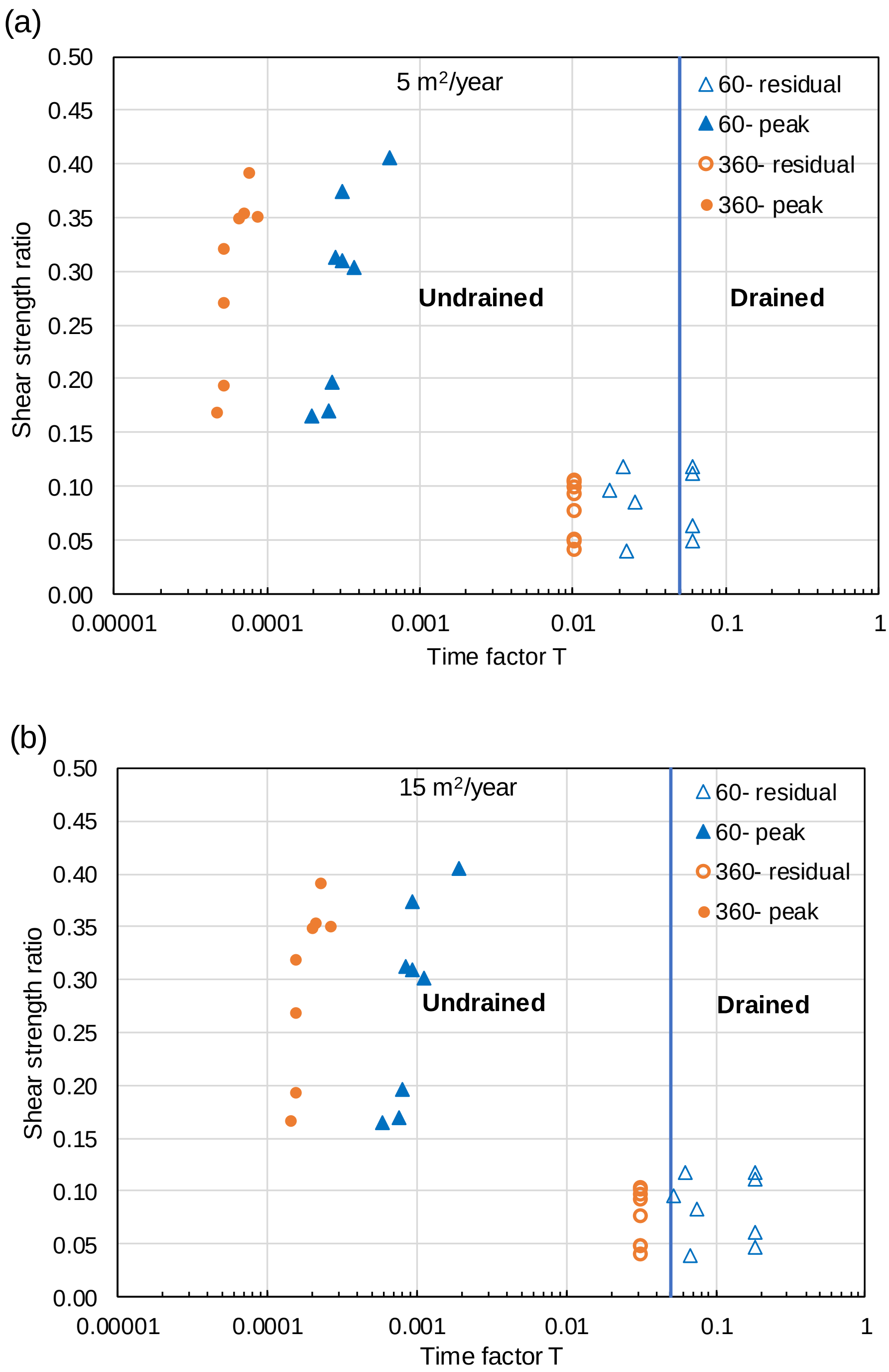


**FIG 6** – Change in time factor and drainage condition (based on Blight/Chandler): (a) $c_v$ of 5 $m^2/a$; (b) $c_v$ of 15 $m^2/a$ from vane results.

## Synthesis of *in situ* data

The results of the CPT undertaken using a conventional compression cone, a special 3 MPa cone and VST in the coal tailings are presented in Figure 7. The results indicate that the remoulded strength measured using the VST is slightly higher in comparison to the sleeve friction value measured by both types of cones. However, the remoulded strength values measured by the VST are closer to the sleeve friction measured by the special 3 MPa cone rather than the conventional 10 MPa cone.

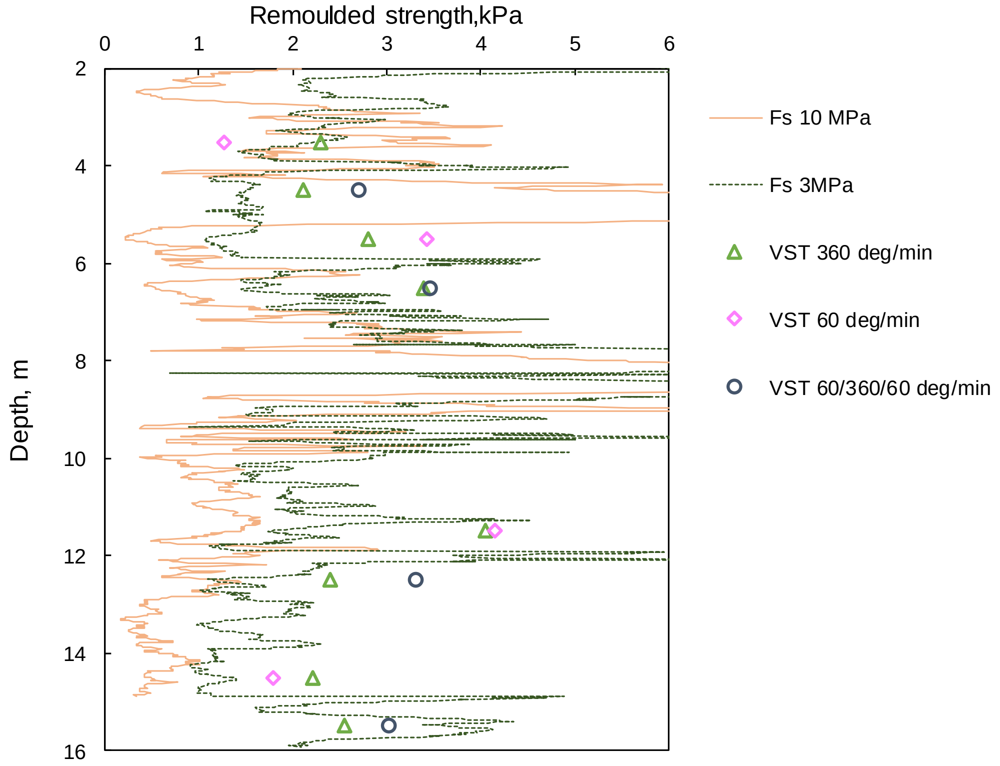


**FIG 7** – Summary of remoulded strength inferred from VSTs and friction sleeve.

A comparison between the remoulded strength from the VST with the friction sleeve from 3 MPa and 10 MPa cones is presented in Figure 8. The values obtained using the 3 MPa cone correlate better with the remoulded shear strength from the VST than with the results of the 10 MPa cone, as mentioned above.

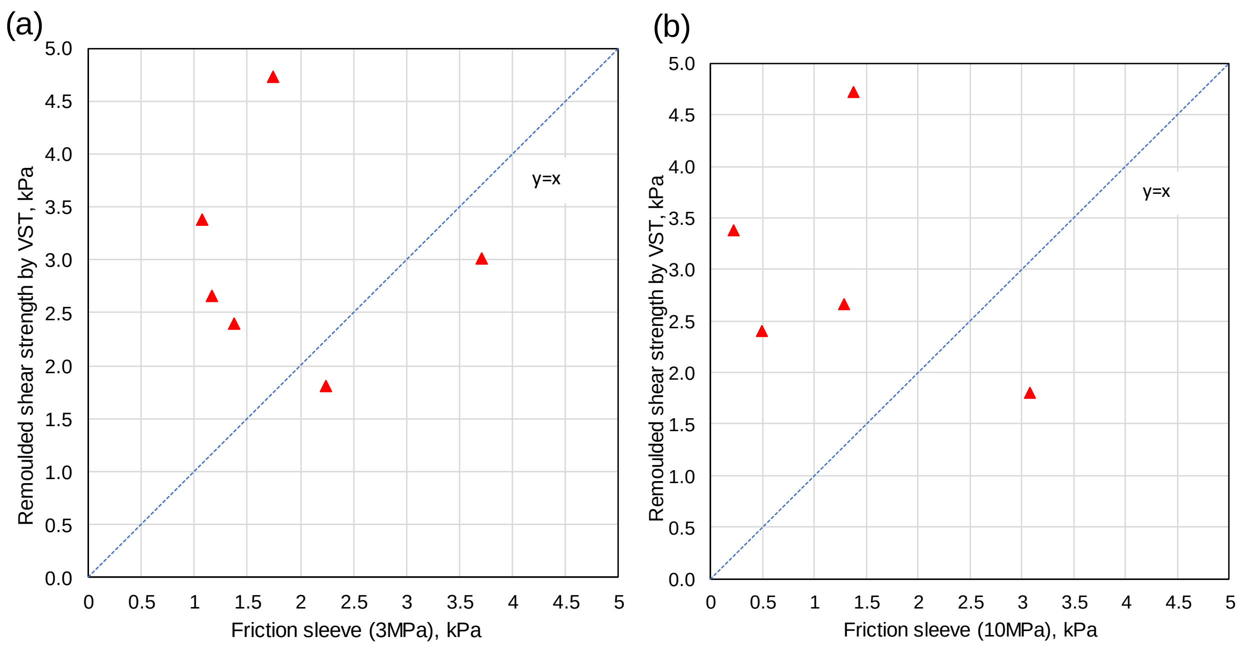


**FIG 8** – Comparison of remoulded strength from different *in situ* tests with: (a) 3 MPa cone friction sleeve; (b) 10 MPa cone.

Sleeve friction results from the CPT results can be influenced by various factors such as geometry, interface roughness of the cone, the extent of remoulding of soil, unequal end areas of the cone, or drainage conditions due to the rate of penetration and viscous effects (when a fully undrained condition is maintained) all of which may contribute to the measured friction sleeve, as explained by

Lunne (2007). Also, Frost and DeJong (2005) have verified that the interface roughness between the sleeve and the soil surface potentially influences the sleeve friction measured.

## CONCLUSIONS

*In situ* techniques including VST and CPTu were used to infer the remoulded strength in coal tailings. The correlation between the remoulded strength and friction sleeve was assessed by using two cones of different mechanical designs. The values of sleeve friction measured using a special 3 MPa cone were higher than the values obtained with a conventional 10 MPa compression cone and were found to have better agreement with the remoulded strength values from the VST. A discussion was presented for the propensity of a drained condition in the VST for a material with higher coefficient of consolidation and its impact on the remoulded shear strength, when lower rates of rotation are used in the VST.

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