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Cone resistance and soil state of tailing sand deposits using the Material Point Method

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ABSTRACT: Cone penetration tests (CPTs) can quantify the mechanical state of a sand. Typically, calibration chamber (CC) test data are the preferred method to correlate a soil's state with the CPT-acquired data. However, many (if not most) mine tailings are different from the soils historically used in CC studies, as these tests were mostly conducted at denser states than typically found in tailings storage facilities (TSFs) as well as primarily using clean sands.
Recently, the University of Western Australia developed a small-scale CC and performed many tests on a range of different tailings materials. This paper provides new evidence of the value added to this area by modern large-deformation modelling based on the material point method (MPM). This study relies on the predictive capabilities of the critical state NorSand model. Results of MPM-CPT simulations are compared against CC tests. MPM-CPT simulations of increasing quality will positively impact the state of the art of CPT interpretation procedures, which to date is still largely based on simplified cavity expansion theories, calibrated to different materials to those usually found in TSFs.

Keywords: CPT; Calibration chamber; MPM; NorSand; Tailings

1 INTRODUCTION

The cone penetration test (CPT) has rapidly become one of the more spread and trusted instruments to obtain an understanding of the tailing's storage facilities-state parameters (ψ) in depth. Considering that tailings can widely vary their mechanical properties between different mine sites, mineral processes, and deposition systems among others, obtaining a reliable site-specific CPT- ψ correlation is preferred to replying on literature-based correlations that may not apply to all sites assessed by practicing engineers.
Recently published laboratory-CPT data in contractive silty mine tailings, tested in a small calibration chamber (CC) (Ayala, 2022), is compared to a modern axisymmetric virtual CC based in the material point method (MPM), additionally, the industry standard-spherical cavity expansion method is used to simulate these CPT-ψ correlations, finding an improved agreement for the novel large-displacement method when compared to the laboratory acquired CPT data.

2 LABORATORY DATA

Two main sources of laboratory data were be used in this work, triaxial testing and CPT-CC data. The triaxial compression tests were a mix of drained and undrained, prepared at dense and loose densities depending on the test purpose, with dense samples mainly oriented to infer dilation parameters, while loose samples were primarily oriented to infer the critical state line (CSL) (Been et al., 1991), and stress-strain curves for additional parameters calibration of the NorSand constitutive model (Jefferies and Shuttle, 2005, Jefferies and Been, 2015). The CPT-CC tests were performed in a modified triaxial device (Ayala et al., 2020), in which larger samples to those the equipment was originally designed, were prepared using mainly the moist tamping technique , although one test was prepared as a slurry deposition . All the CPTs shown in this study were pushed slower (0.2 to 0.015 mm/s) than the standard penetration velocities (20 mm/s) with the intention of recording drained responses. The analysis of partially drained or undrained penetrations is out of the scope of this work, however, it is recommended to consider the dilative, steady, and contractive behaviour of soils when analysing non-drained penetrations, as these concepts tend to be misunderstood (Ayala et al., 2023).

2.1 *Triaxial testing and NorSand calibration*

Loose drained and undrained compression triaxial testing were perform for two silty tailing materials to infer the CSL, additionally, dense drained samples were tested to obtain the additional NorSand properties, as outlined by Ayala et al. (2022). These properties are summarised in Table 1 including both commonly used forms of the CSL, the Semi-Logarithmic (Γ_{1kPa} , λ_e) and Power-Law (A, B, C) as described by (Jefferies and Been, 2015).

Table 1. NorSand properties summary

Property	Gold	Platinum
Γ_{1kPa}	0.796	0.833
λ_e	0.038	0.037
A	0.774	0.822
B	0.15	0.151
C	0.229	0.246
M_{tc}	1.45	1.47
N	0.21	0.25
X_{tc}	5	2.7
$H_{\psi_i=0}$	60 (43*)	100 (61*)
∇H_{ψ_i}	420	1090
G_{ref} (MPa)	12	30
G_{exp}	1	0.7
ν	0.2	0.2

* Value used for MPM simulation as described by Martinelli (2019).

2.2 CPT-Calibration chamber testing

The Mini CC used on this study allows the preparation of samples with ~200 mm in diameter and ~300 mm in height. Two different cone diameters were used on these tests with 6.4 and 10 mm each. The smaller cone could only record tip resistance while the larger cone also included friction sleeve and pore water pressure in the shoulder position (u_2). Further details and photographs can be found on Ayala et al. (2020) and Ayala et al. (2021) where the normalised excess pore water pressure was also plotted showing drained conditions prevailed during testing.
A full list of the CC results can be found in Table 2, and the plots of selected normalised tip resistances with depth for both tailings can be seeing in Figure 1.

3 CPT NUMERICAL SIMULATIONS

Two different numerical methods are presented on this work, with the main one being the simulations of an axisymmetric (2D) model using the MPM. The second uses the spherical cavity expansion method to calculate the limiting pressure of radially chained elements (1D) when being deformed at constant strain (Shuttle and Jefferies, 1998, Ghafghazi and Shuttle, 2008, Shuttle and Jefferies, 2016). Both simulations use finite elements for the calculations with slightly different implementations of the NorSand constitutive model, further details can be found on Martinelli (2019) for the MPM models, and in Shuttle (2019) for the spherical cavity expansion models.

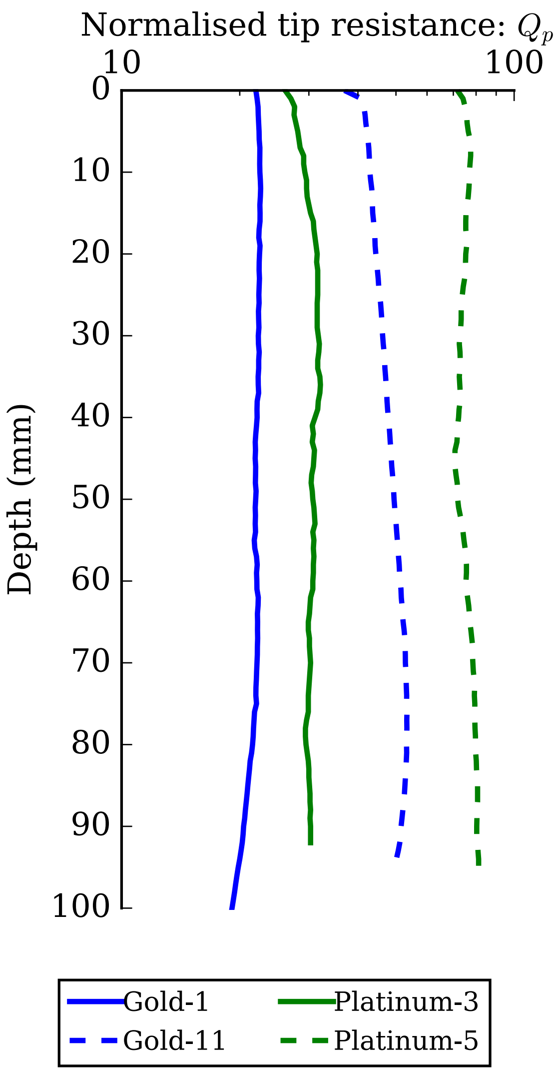

Figure 1 CPT data from the laboratory-CC tests in the Gold and Platinum tailings

3.1 Material Point Method simulations

The suitability of the MPM for the large-deformation analysis of CPT testing in soils has been shown by several recent studies (Ghasemi et al., 2018, Martinelli and Galavi, 2021, Martinelli and Galavi, 2022, Martinelli and Pisanò, 2022). In this paper, the MPM formulation of Martinelli and Galavi (2022) is adopted to simulate the cone penetration in two tailing materials. The features of the MPM numerical model are:

- dynamic MPM formulation, with the soil acceleration used as primary unknown variable (Jassim et al., 2013);
- explicit, conditionally stable time integration, with automatic CFL-based adaptation of the time step size;
- simulation of cone–soil detachment and sliding by means of the contact algorithm of Bardenhagen et al. (2000);
- background mesh formed by four-node quadrilateral elements;

- The 'moving mesh' concept is used to ensure fine discretisation around the soil-plate interface and accurate performance of the contact algorithm (Kafaji, 2013);

Additional computational aspects regarding mass scaling, numerical damping and mitigation of stress oscillations and volumetric locking are covered in the original paper of Martinelli and Galavi (2022).
The computational mesh and the distribution of the material points are shown in Figure 2. At all boundaries, the displacements are constrained in the perpendicular direction and free in the longitudinal one. The cone-soil contact friction angle is set to 18° constant throughout the simulations (1/2 of M_{tc}) as adopted in Martinelli and Pisanò (2022). A very soft layer (Young modulus set to 1 Pa) around the tailing soil body is used to maintain practically constant lateral confinement around the tailing soil mass during cone penetration. The Anura3D NorSand implementation (Martinelli, 2019) is used to simulations with the parameters listed in Table 1.

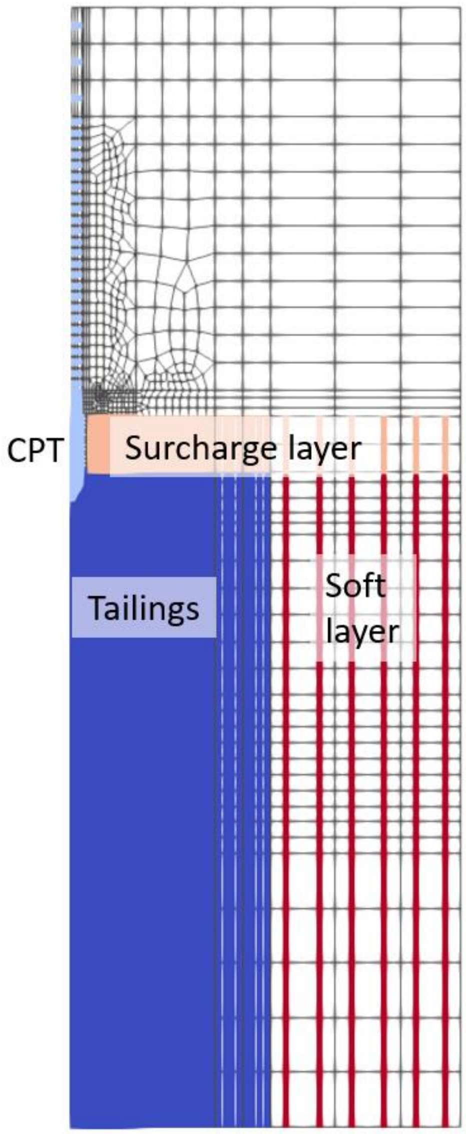

Figure 2 Geometry of the numerical model mesh

3.2 CPTwidget simulations

Additional CPT simulations using the CPTwidget v2.5 (Shuttle, 2019) were obtained from Ayala et al. (2022) to compare the results with the CC and MPM results. It is important to note that the current version of the CPTwidget scales the simulation results to a factor of C_q, this factor is calibrated to four sandy materials (Shuttle and Jefferies, 2016), unfortunately, those calibration tests were prepared at denser/dilative states than those tested for these silty tailings (Ayala et al., 2022). Since details of the CPTwidget are widely presented in the literature (Shuttle and Jefferies, 1998, Shuttle and Cunning, 2007, Ghafghazi and Shuttle, 2008, Shuttle and Jefferies, 2016, Shuttle et al., 2022), only the results of these simulations are presented in Table 2.

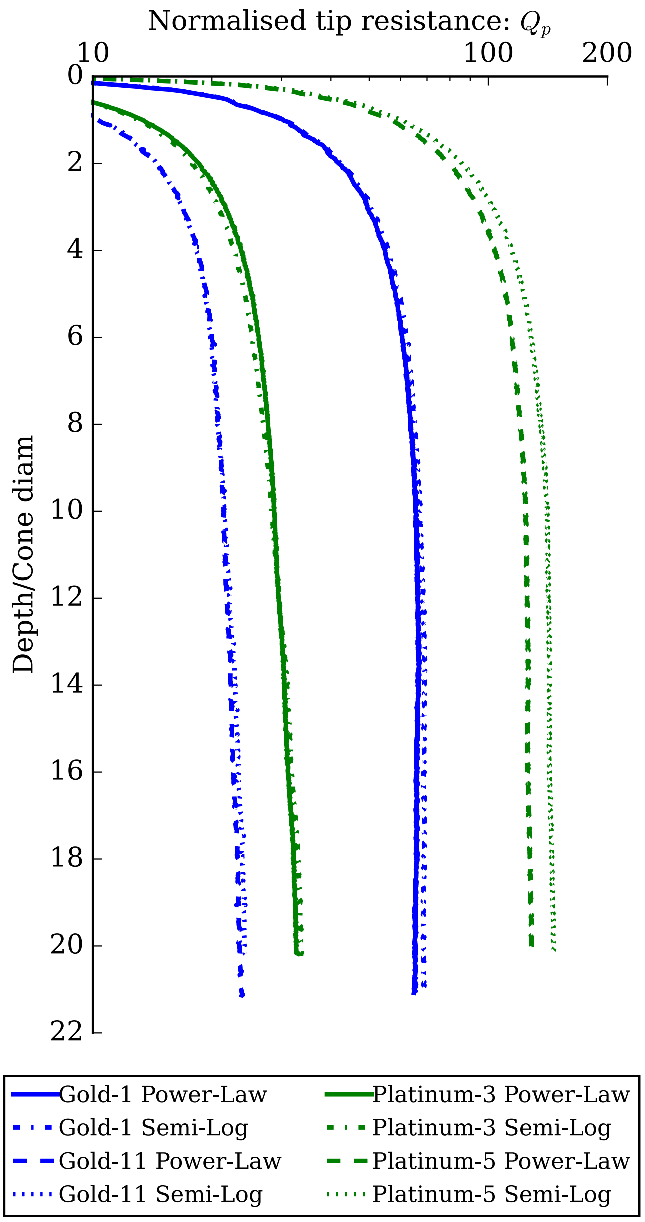

Figure 3 MPM simulation results for the Gold and Platinum tailings, for both CSL forms (Power-Law and Semi-Log)

4 COMPARISSON OF SIMULATIONS RESULTS TO LABORATORY DATA

A summary of the Q_p results of the i) laboratory CC data, ii) CPTwidget, and MPM simulations calculated with the iii) Semi-Logarithmic and iv) Power-Law forms of the CSLs, is presented in Table 2, and the Qp-ψ_0 plots and trendlines for all of these results is shown in Figure 4 for the Gold (a) and Platinum (b) tailings respectively.

As can be seeing in Figure 4, there is an improved match between the data acquired in the laboratory and the MPM simulations for both forms of the CSL (especially for the Power-Law), when compared to the spherical cavity expansion simulations usually used by practitioner engineers. This improved match is particularly clear for the contractive data, whereas the match is poorer for the dilative tests. Nonetheless, these simulations show a promising way of obtaining Qp-ψ_0 correlations from the NorSand constitutive model calibrated with triaxial testing in an MPM framework.

Table 2. CC test state parameters and normalised penetration resistances for the laboratory tested, and simulated Gold and Platinum tailings

Test Id	State Parameter	Qp CC	Qp CPTwidget	Qp MPM Semi-Log	Qp MPM Power-Law
Gold-1	-0.048	48.9	46.8	68.7	66
Gold-2	-0.034	56.9	41.5	61.5	59.5
Gold-3	0.02	37.4	25.9	40.6	39.8
Gold-4	0.031	42.4	23.4	37.4	35.7
Gold-5	0.04	24.8	21.5	34.5	33.8
Gold-6	0.063	26	17.2	28.4	28.7
Gold-7	0.071	24.2	15.9	27	26.9
Gold-8	0.065	27.1	16.9	28.3	28.1
Gold-9	0.068	23.5	16.4	27.9	27.3
Gold-10	0.078	22.7	14.8	25.6	25.7
Gold-11	0.094	22	12.7	23.1	22.5
Gold-12	0	36.4	30.1	47.4	46.2
Platinum-1	0.092	27.1	13.8	25.4	24.9
Platinum-2	0.111	27	11.7	22.6	22.1
Platinum-3	0.068	30.7	18.6	31.3	30.9
Platinum-4	0.087	29.2	14.6	26.6	25.9
Platinum-5	-0.115	87.4	99.1	143.2	126.3
Platinum-6	0.053	23.3	22.2	36.7	35.1

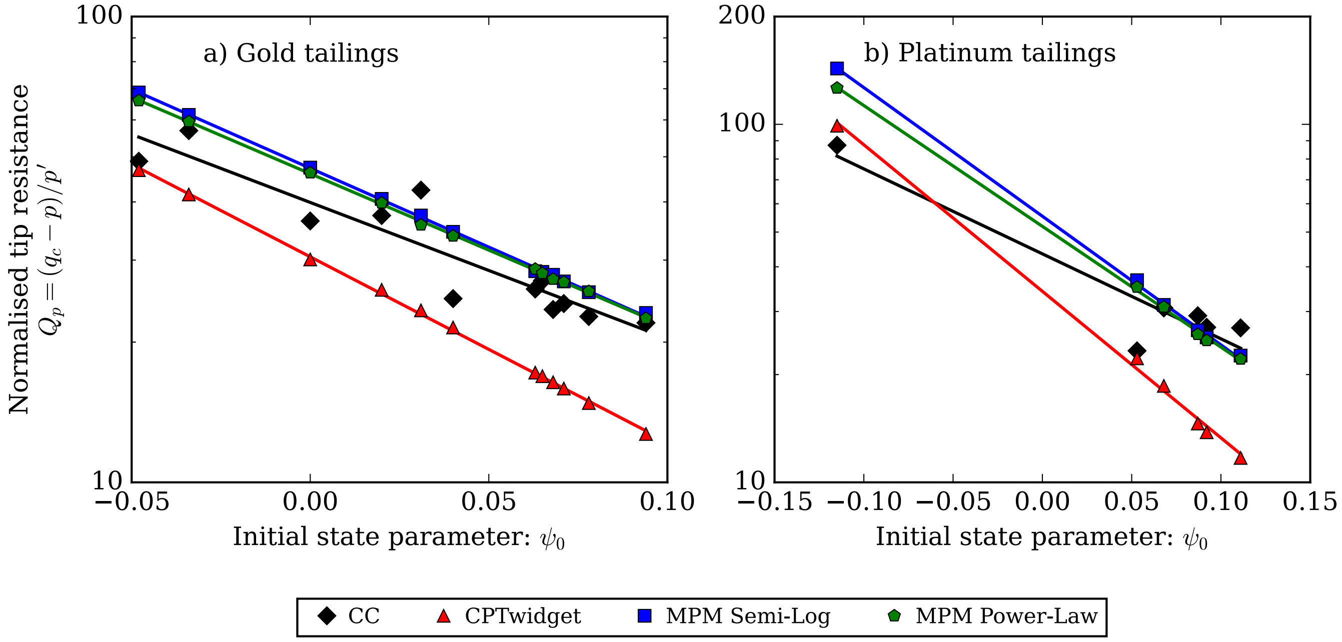

Figure 4 Laboratory and simulations results comparison for the Gold and Platinum tailings

5 CONCLUSIONS

From the comparison of the simulation results presented on this work to the laboratory data of CPT calibration chamber testing, the following conclusions can be made:

- For looser soils, the state parameters estimations with the MPM simulations generates improved estimations of the state parameter when compared to current widely used methods.
- The current version of the CPTwidget, that uses the spherical cavity expansion method with NorSand embedded in the code, after applying the scaling factor, outputs an under estimation of the normalised tip resistance when compared to the laboratory data, resulting in under estimations of the inferred in situ state parameter and over estimations of the void ratio-density of the prospected material.
- The MPM simulations present an improved match with the laboratory data, for both critical state lines forms used on this work, the Semi-Logarithmic and Power-Law equations.
- A slight overestimation can be observer with the MPM simulations, especially for the Semi-Logarithmic simulations on the dilative region, with smaller differences found in the contractive behaviour region. While this could be considered a difference that infers slightly loosest densities, it can be argued that is slightly more conservative when compared to current widely used CPTwidget.
- The main reason for these software's results difference, is that the MPM simulations don't need to scale the results to any calibrated factor, making the results a direct output of the underlying physics of NorSand and the material parameters/initial state.
- The mismatch between the contractive CC/MPM and the CPTwidget results, it is associated to the lack/shortage of contractive results in the mainly dilative database used to calibrate the scaling factor, hence, the mismatch is related to the extrapolation of the scaled relation to the contractive behaviour region.

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