

Parameter determination using static & dynamic methods on two sandy tailings

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ABSTRACT: On two TSFs, static (CPT) and dynamic probing (DCP & SPT) have been used to determine the state parameter and post liquefied shear strength ratios to assess if dynamic and static methods produce different results. A geostatistical assessment using Ordinary Kriging was carried out comparing the semivariograms of the dynamic probings with that of the CPTs, which allows the compilation of interpolation maps, allowing demarcation of liquefiable zones within a TSF. The state parameter was found to be dilative by the static and contractive by the dynamic methods, indicating that contractiveness/dilativeness is method dependent. The dynamic probings found the post liquefied shear strength ratios to be higher than the CPT. The geostatistical analyses found the CPT to be of higher semivariance and larger ranges. An optimum hole-hole distance was found to be about 150 m for both TSFs. The more numerous DCP probings result in lower variance which allow detailed interpolation maps to accurately demarcate liquefiable zones.

1 INTRODUCTION

The Cone Penetration Test (CPT) has traditionally been used to determine the state parameter (Been 1987) and the post liquefied s_u/σ'_{v0} ratio (Jefferies et al. 1990). However, the undrained, large strain shearing of sands cannot be directly assessed by the CPT (Robertson 2022), as CPT penetration is drained (Kim et al. 2010) and is also influenced by saturation as unsaturated material can have higher tip resistances due to suction (Yang & Russel 2016). The CPT cannot induce liquefaction (Schnaid et al. 2017) whilst the Standard Penetration Test (SPT) has been found to induce cyclic liquefaction on sands (Clayton & Dikran 1982) and its acceleration spectrum mimics that of an earthquake damping effects (Goble & Abou-matar 1994, Howie et al. 2003, Odebrecht et al. 2005).

The SPT based liquefaction database is extensive and dates back since the 1960s (Kishida 1966). This has made the SPT an ideal tool historically to assess liquefaction susceptibility. Due to the high inertia of the SPT, it is considered unsuitable for soft tailings hence the Dynamic Cone Penetrometer (DCP) offers an attractive alternative. The SPT has been correlated to the DCP (Livneh 1989) which allows easy comparison of the DCP to the vast SPT database. Due to the lower inertia, it does not suffer from the often-poor repeatability of the SPT.

On a normal TSF, the DCP also offers advantages over the CPT such as economics: up to 90 DCPs can be carried out for the cost of one CPT, therefore the high number of DCPs allow complex geostatistical analyses; the DCP's acceleration mimics that of an earthquake (Byun & Lee 2013, Kim et al. 2021, EN ISO 22476-2:2005); the existence of a second impact was recorded (Byun & Lee 2013), thus introducing a cyclicality; DCPs can be carried out on weak ground inaccessible for CPT rigs; the DCP records undrained conditions even for sands and can probe to large depths when applying an inertia correction.

The aims of this research are firstly to investigate how the results from the dynamic (SPT & DCP) and static testing (CPT) compare on two sandy tailings for the determination of the state parameter and the post liquefied s_u/σ'_{v0} ratio. Secondly, to undertake a geostatistical analysis of the state parameter using Ordinary Kriging (OK), to assess whether the demarcation of liquefiable zones via SPT & DCP is advantageous to the CPT.

2 PROJECT DESCRIPTION

Two Tailings Storage Facilities (TSFs) were investigated using CPT, DCP and SPT. One is the 129 ha Bibiani Gold Mine (BiGM) in Ghana and the other is the 75 ha Bulyanhulu Gold Mine (BuGM) in Tanzania, both are of a silty sand texture.

2.1 Bibiani, Ghana

At BiGM, CPTs were carried out at four locations and DCPs at 47 locations across the TSF as indicated in Figure 1.



Figure 1. Locations of DCP (diamond) and CPT (cross).

The CPT testing was carried out according to ISO 22476-1:2012 to 15 m and the DCP testing was carried out according to ASTM D 6951-03:2010 to depths of 7 m. It was interpreted using the inertia correction for depths greater than 2 m (Bergdahl 1989 and Butcher et al. 1996).

2.2 Bulyanhulu, Tanzania

At BuGM, along the TSF's daywall, SPT testing was carried out at 36 boreholes and CPT testing at 22 locations as indicated in Figure 2.

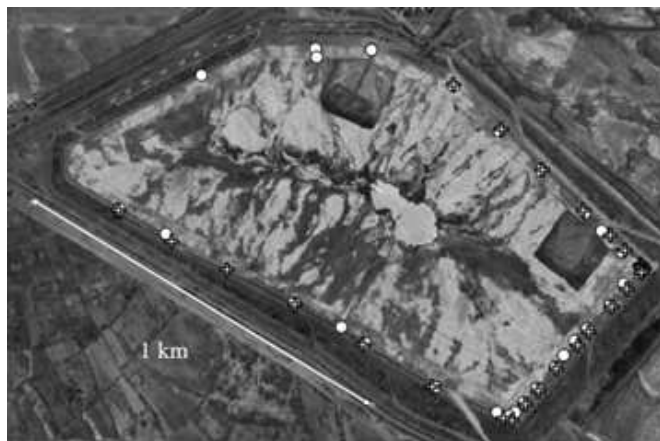


Figure 2. Locations of SPT (cross) and CPT (circle).

2.3 State parameter

At BiGM, the friction angle for the DCP was derived using the relation of Mohammadi et al. (2008) and consequently the state parameter was derived from the friction angle (Jefferies 2018). For comparison, the state parameter was also derived from the SPT N values using the correlation of Martin et al. (2002).

At BuGM, the state parameter has been determined from the CPT using the methods of Plewes

(1992) and Robertson (2010). For comparison, the state parameter was also derived from the SPT N values using the correlation of Martin et al. (2002).

Although the standard use of the characteristic value of the state parameter for liquefaction analyses lies between the 80th and 90th percentile (Jefferies and Been, 2016), the 50th (median) percentile was used for easy comparison between the various methods.

2.4 The post liquefied s_u/σ'_{v0} ratio

The post liquefied s_u/σ'_{v0} ratio was determined from the CPT, SPT and DCP using the relations of Olson & Stark (2002), Mesri (2007) and Sadrekarimi (2014).

2.5 Geostatistics

The geostatistical analyses were undertaken by using Ordinary Kriging via the SmartMap plugin (Pereira et al. 2022) which is a plugin in QGIS 3.38.

3 RESULTS

3.1 Pore pressure and classification

At BiGM, the 2011 CPT investigation recorded the piezometric surface from ambient pore pressure (u_0) measurements at 0.05 m and that of 2022 at about 5 m and dry in some locations. The t_{50} ranges from 9 to 24s indicating highly permeable sands. The SBTn and Modified Norm SBTn indicates “dilative sand” for the top 3 m and then “contractive sand or silt” at greater depths. The t_{50} and the SBT classifications generally do not agree at depths deeper than 3 m as the t_{50} values indicate well drained sand and the SBTn indicates silt and clay.

At BuGM, the SBTn classification is generally “clay to silty clay” and a water table deeper than 8m. The t_{50} values ranged from 20 to 40 s, indicating a free draining material, i.e. sand.

It is clear from both sites that the soils classification based on dissipation testing using t_{50} (Parez and Fauriel 1988), differs from the traditional classification based on tip resistance and sleeve friction.

3.2 Static and dynamically derived SPT-N

To allow a comparison between static and dynamically derived SPTN values, the SPTN values were derived from the CPT data (Phoon and Kulhway 1999). The SPT N value from the CPT, DCP and SPT testing are presented in Figure 3.

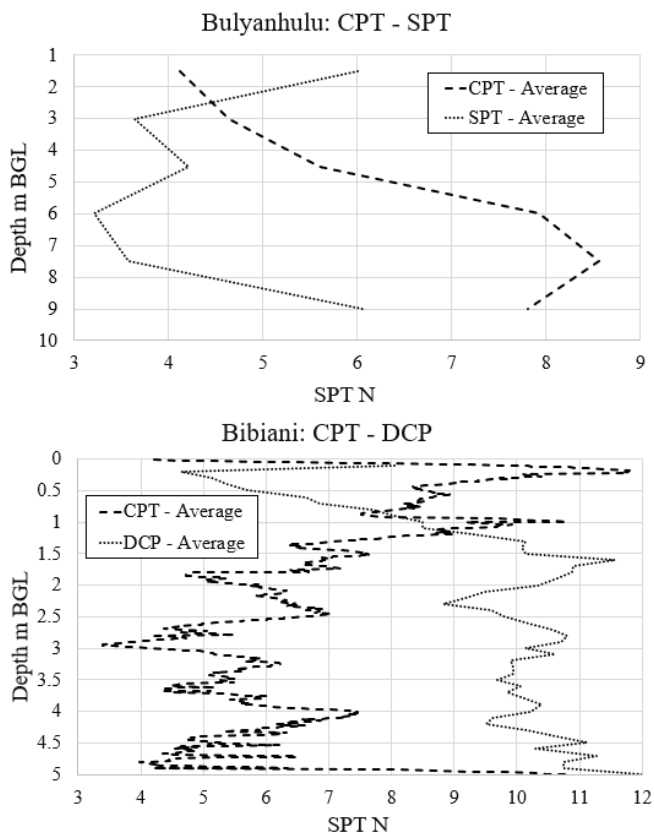


Figure 3. SPT values from static and dynamic techniques

It is indicated by Figure 3 that the recorded SPT values are different pending the static/dynamic technique. At BuGM, the static CPT recorded higher N values than the dynamic SPT whilst at BiGM, the dynamic DCP recorded higher N values than the static CPT. With depth, the static and dynamic techniques' values' trends both reverse between 1 and 2 m, indicating that the upper dessicated layer's values are opposite of that recorded at greater depths.

3.3 State parameter

The state parameter as derived from various techniques at BiGM is presented in Figure 4.

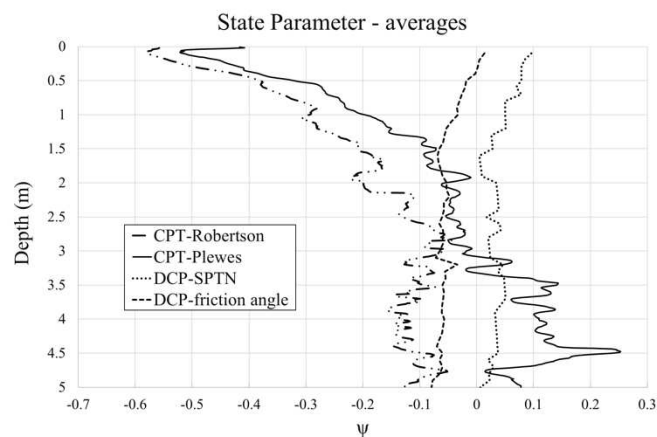


Figure 4. State parameter from CPT and DCP.

As indicated by Figure 4, the static CPT indicates the tailings to be dilative up to 3 m depth whilst the dynamic DCP indicates it to be contractive at all depths.

For BuGM the state parameter as derived from various methods is presented in Figure 5.

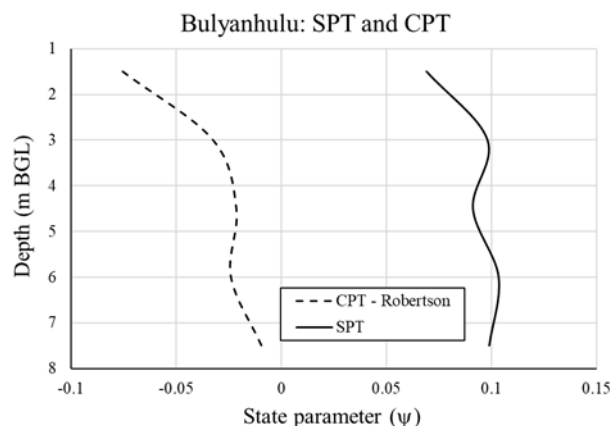


Figure 5. State parameter at BuGM from CPT and SPT.

Similar to Figure 4, it is indicated by Figure 5 that the dynamic indicates a contractive state parameter, the static indicates the tailings to be mostly dilative.

3.4 The post liquefied s_u/σ'_{v0} ratio

The recorded post liquefied s_u/σ'_{v0} ratio from static and dynamic techniques for BiGM is presented in Figure 6.

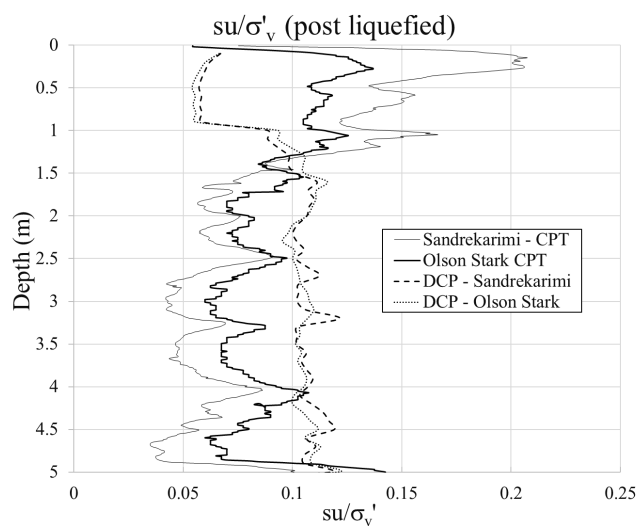


Figure 6. The post liquefied s_u/σ'_{v0} ratio at BiGM from CPT and DCP.

The trends indicated in Figure 6 are that the static and dynamic techniques behave opposite, not only within the upper dessicated layer but also at depth.

The post liquefied s_u/σ'_{v0} ratios from the static and dynamic methods for BuGM is presented in Figure 7.

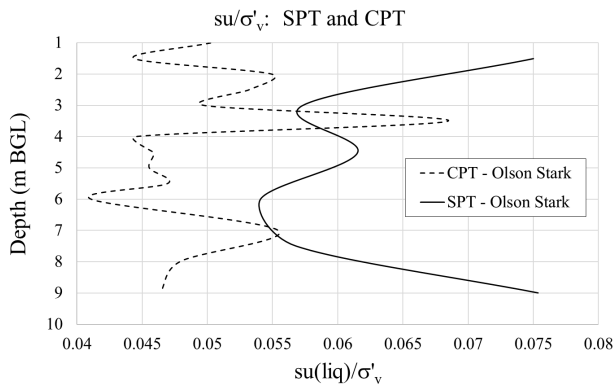


Figure 7. The post liquefied s_u/σ'_{v0} ratios at BuGM from CPT and SPT.

Both Figures 6 & 7 indicate that the static and dynamic methods differ in that the static method's results are lower.

3.5 Kriging

Geostatistical analyses and comparisons between the CPT and DCP derived state parameter were carried out using Ordinary Kriging (OK). Semivariograms for four different depths were constructed and the semivariogram for the DCP data at BiGM is presented in Figure 8.

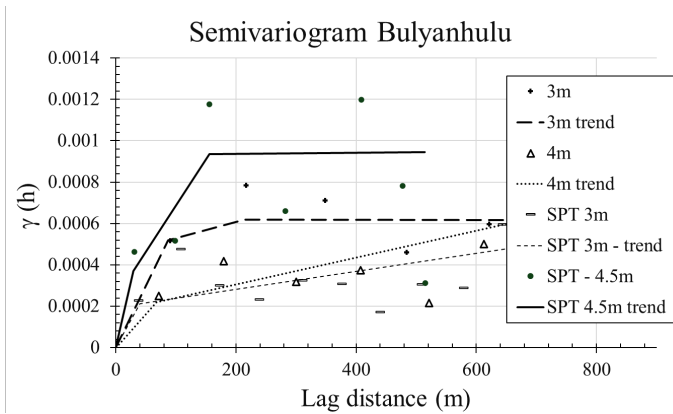


Figure 8. Semivariogram for BuGM

It is indicated by Figure 8 that the “sill” value (C) ranges from 0.0001 to 0.0003 and the “lag” distance from 80 m to 200 m. A comparison between the semivariograms for the DCP and CPT data for BiGM is presented in Table 1.

Table 1. Comparison of semivariogram data for DCP and CPT

Depth (m)	$\gamma(h)$		("sill", C)	
	CPT	DCP	CPT	DCP
1	0.0012	0.00030	679	153
2	0.028	0.00029	684	154
3	0.0024	0.00017	138	158
4	0.009	0.00011	138	158

It can be seen from Table 1 that the lag distance is fivefold lower for the DCP than for the CPT. The semivariance, $\gamma(h)$, for the DCP is nearly 50 times

lower. This is simply attributable to the higher number of DCP probings. A comparison between the semivariograms for the SPT and CPT data for BuGM is presented in Table 2.

Table 2. Comparison of semivariogram data for SPT and CPT

Depth (m)	$\gamma(h)$		("sill", C)	
	CPT	SPT	CPT	SPT
3	0.00038	0.00030	126	67
4	0.008	0.00075	126	62

Despite having similar hole to hole distances, the SPT has lower variance compared to the CPT, as shown by Table 2, indicating the effect of dynamic versus static penetration.

There is a good agreement between the variograms of BiGM's DCP that of BuGM's CPT, which suggests that 150 m between probings result in the same variance.

To illustrate the advantage of 47 datapoints of the DCP instead of four of the CPT at BiGM, the interpolation using OK to estimate the state parameter is presented in Figure 9.

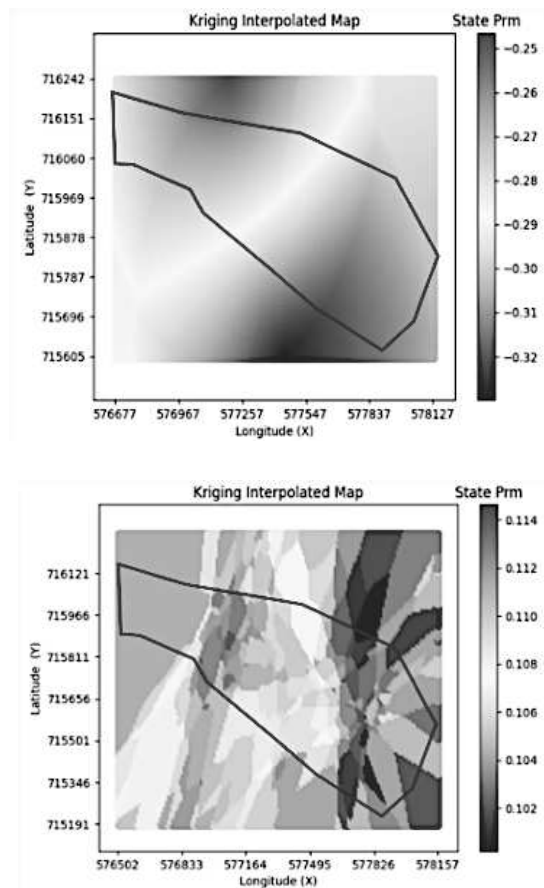


Figure 9. Interpolation for the CPT and the DCP

It is clear from Figure 9 that the more numerous DCP probings allows a more detailed demarcation between the state parameter's high and low areas. As with the geostatistical maps, heatmaps illustrate the advantage of having more numerous sampling positions, as indicated in Figure 10.

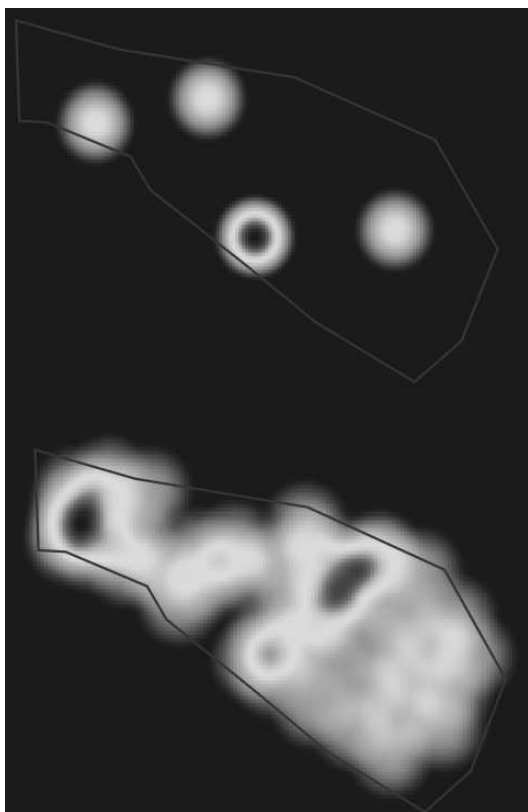


Figure 10. Heatmaps for the CPT (top) and DCP. Highest values in red.

4 DISCUSSION

The state parameter values for both tailings are slightly dilative according to the static CPT, whilst the dynamically derived state parameter values are significantly contractive i.e. opposite. This is a similar finding to that of Contreras & Grosser (2019), where varying the CPT's penetration rate produced different results on tailings.

A possible explanation is that the penetration of the dynamic techniques is essentially undrained and that the pore pressures are elevated, hence the dynamic nature of these techniques evaluates the undrained strength of the sandy tailings differently than the static CPT.

The dynamic techniques indicate the post liquefied s_u/σ'_{v0} ratios to be higher than indicated by the CPT. A possible reason could be that the DCP densifies the tailings. However, at BuGM, the observation is opposite in that the SPT has a much lower value than the CPT. A possible explanation can be that the higher inertia of the SPT increases the pore pressures.

5 CONCLUSION

The static (CPT) and the dynamic (DCP and SPT) methods were used to evaluate the state parameter and post liquefied s_u/σ'_{v0} ratios on two different

sandy tailings using various methods such as Olson Stark etc.

Within the techniques, the results of the various methods were in close agreement. However major disagreements were recorded between the static and dynamic techniques' results, with the static CPT indicating the tailings to be dilative whilst the dynamic techniques indicate the tailings to be contractive. The explanation could be that the dynamic techniques do not allow dissipation of pore pressures and measures the actual undrained shear of the sands.

Similar to the findings of the state parameter, the dynamic techniques yielded much different post liquefied s_u/σ'_{v0} ratios. This implies that when a dynamic technique is employed the answers are not comparable with those of static techniques such as the CPT and triaxial testing.

With the dynamic techniques being able to simulate seismic loading, the dynamic techniques may be more correct for seismic assessments.

As up to 90 DCPs can be employed for one CPT, allowing meaningful geostatistics to be employed—such as Ordinary Kriging. By employing the more numerous DCP, detailed demarcation of liquefiable zones within a TSF using heatmaps and Kriging interpolation maps can be achieved. The range (“lag” distance) were fivefold lower for the DCP than the CPT and the semivariance $\gamma(h)$ for the DCP is nearly 50 times lower.

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