

A geological principle for the density of thickened tailings

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Abstract

The strength of thickened tailings, under both static and earthquake loads, depends on its state parameter. The state parameter can be measured by cone penetration test (CPT) soundings within an existing impoundment, but that does not help when designing/planning a new storage facility. In particular, there are currently no known laboratory sample preparation methods that can reliably replicate the depositional environment of silt/sand tailings within a tailings area, including the resulting in situ state. These issues are of particular importance in the design of thickened tailings deposits, where often a steepened beach profile results in tailings storage above the crest of containment structures. For such a facility, reliable prediction of the range of states likely to develop is crucial in estimating the stability of the tailing stack. To provide reference and realistic bounds to the range of states observed in practice in thickened tailings deposits, CPT data from publicly available sources and Golder Associates' project files were collected and analysed to provide an indication of the effects of depositional environment and tailings type on resulting state. This extends previous work by the authors on this topic for conventional tailings.

Keywords: *state parameter, cone penetration test, liquefaction*

1 Introduction

1.1 General

Tailings strength, under both static and earthquake loads, depends on its state parameter. The state parameter can be measured by cone penetration test (CPT) soundings within an existing impoundment, but that does not help when designing/planning a new tailings storage facility (TSFs). The difficulty for design or planning is that, while standard laboratory tests provide properties that control how a tailings consolidates, there are no tests (or theory) that can predict/measure the initial tailings condition (particularly fabric) as it changes from a slurry to a soil – the 'starting point' for standard geotechnical calculations is unknown. There is a further consideration that laboratory-scale sedimentation tests are known to not replicate the depositional environment, with misleading results in at least the case of some silty sands and sandy silts. The difficulty in predicting state, and hence behaviour, in the design stage for thickened tailings has previously been discussed by Reid and Fourie (2014). This is a particular issue in thickened tailings design, as (i) most schemes are likely to result in 'unsupported' tailings above the elevation of the perimeter embankments, (ii) implementing thickened tailings requires significant capital investment, thus requiring an assessment of state prior to major deposition, and (iii) many thickened TSFs are likely to be large, thus indicating significant risk should they be susceptible to flow liquefaction.

It is obviously helpful for design/planning of any storage facility if existing experience for the in situ state of tailings could be synthesised in terms of the tailings type (gradation, mineralogy, specific gravity) and depositional environment (subaerial beach, sub-aqueous). This paper presents such a synthesis for thickened tailings, premised around a geological principle that the depositional environment has a strong effect of the achieved in situ state parameter (e.g. high-energy situations, such as wave action on a beach sand, produces a denser state than pluviation through a water column). It extends similar work by the authors for conventional and filtered TSFs (Reid & Jefferies 2017).

1.2 Framework

The paper is based on CPT data from a variety of sites, and includes both tailings and one natural soil.

CPT soundings will show increasing penetration resistance with depth, all else equal, because confined stress increases with depth. Understanding soil behaviour from CPT data requires removal of the confining stress effect – generally referred to as ‘normalisation’. This paper uses the standard normalised (dimensionless) groups derived from the measured data of Q , F_r , and B_q . Plotting CPT data as $Q(1-B_q)+1$ versus F_r provides a convenient way of summarising CPT data in what is referred to as a ‘soil behaviour type’ (SBT) plot, this name arising because different soil types plot in different zones.

A further utility of the SBT plot is that, by assuming typical properties for each soil type, it can be contoured by lines of equal ‘state parameter’. The state parameter Ψ is defined as the void ratio difference of a soil to its critical void ratio at the same stress (Been & Jefferies 1985), and is a controlling factor for much soil behaviour. The contours are developed using the equations given by Plewes et al. (1992). Further detailed numerical work by Shuttle and Cunniff (2008) provided more insight and defined a line, colloquially known as the ‘green line’, that distinguished between potential flowslides versus loss of stiffness on the SBT diagram.

Thus, simply presenting CPT data in an SBT diagram can reveal a lot about tailings. This form of presentation is a good way to summarise the various case histories considered – and is the approach followed here. A quick caveat is needed, however, as tailings tend to be more angular particles than natural sands and this can lead to tailings appearing to be denser than they are; an SBT is a starting point to appreciate trends, but further quantitative evaluation will be needed for stability assessments.

1.3 Data presentation

CPT data in tailings shows natural variability. The data shown in this paper is generally presented in one of two forms:

- An extent representing the range between the 20th and 80th percentile of the data in the x and y axis, when the quantity of data from a site was such that clarity of the figures would suffer if each data point was presented.
- Where digitisation of figures in publications was required, in some cases an extent of the data was presented based on the maximum and minimum values seen.

It is noted that the percentile range indicated has been selected only to enable presentation of the general trends observed at a site, and is not a suggestion as to the relevant ‘characteristic’ state for use in design. Detailed examinations of the effects of material variability suggest that the 80th percentile is a reasonable characteristic state (Jefferies & Been 2015), as applied in recently well-documented geotechnical practice (Morgenstern et al. 2016).

1.4 Site selection

Sites presented are either thickened tailings sites from Golder Associates’ project files, or relevant sites from the literature that assists in highlighting the themes of the discussion. These sites are compared to data, some from two filter stack TSFs, and data from two recent TSF failures.

2 Effects of deposition conditions on resulting state

One of the key challenges in the design stage is the assessment of the range of Ψ that will be achieved in situ. Arguably, undergraduate level geotechnical education has led to an under-appreciation of this issue, with much instruction based on the concept of a single normal consolidation line (NCL). Further, it is also common for such an NCL to be presented as parallel to and ‘above’ (i.e. on wet side) of the critical state line (CSL) – that is, when critical state soil mechanics forms a part of the curriculum. While this idealisation is potentially

useful in some limited educational settings, it ignores a number of important factors with respect to the deposition, fabric, and consolidation of tailings:

- Even for the same preparation method in the laboratory, pouring slurries of different (non-segregating) densities into consolidation test devices can also, in some cases, result in different non-converging NCLs. After a surprisingly long debate at various Paste and Thickened Tailings series seminars, this point was made clear by a literature review and further testing presented by Reid and Fourie (2015).
- Different depositional conditions often result in different fabrics which produce non-converging NCLs – at least across the range of stresses of relevance for most TSFs. Further, there is no assurance that quiescent pouring of a thickened slurry into a consolidation test device will produce the same fabric as deposition on a higher-energy tailings beach.

The effect of deposition conditions on in situ state is illustrated in Figure 1 for hydraulically placed Beaufort Sea sands and a medium-plasticity gold tailings. The hydraulically placed sand data is drawn from work assessing the in situ state of sands as part of the construction of artificial islands for oil exploration (Jefferies et al. 1988). As part of these works, essentially identical sands were deposited using both ‘bottom dumped’ methods direct from hopper dredges to the seafloor (to create berms), and from pipelines to fill the core of caisson structures. The gold tailings is deposited as a conventional slurry, in some areas subaerially and in others (near the decant pond) pluviating through water (Reid & Jefferies 2017). The two deposition conditions for each of the sites would have considerably different energy.

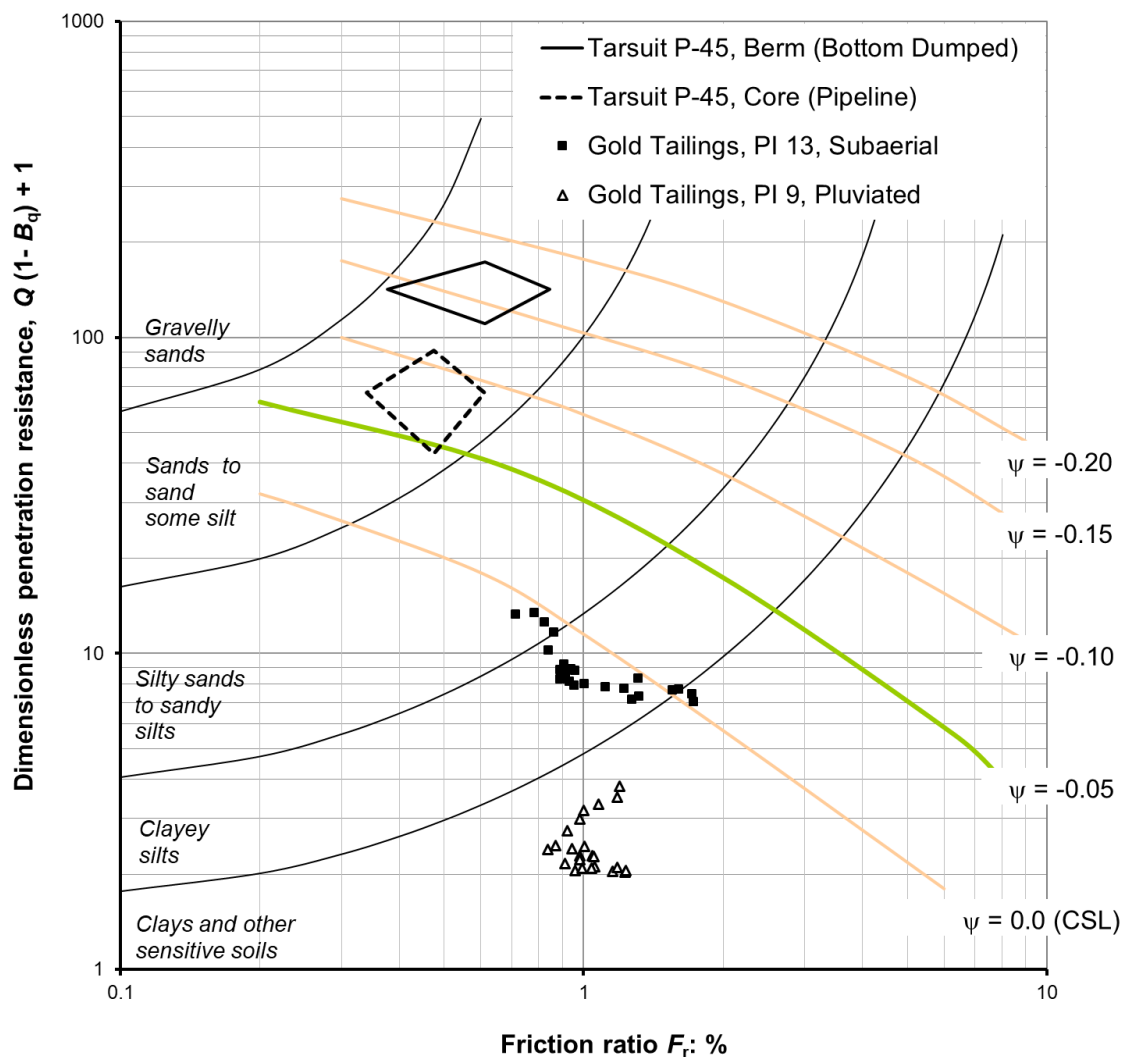


Figure 1 Beaufort Sea hydraulically placed sands and moderate plasticity gold tailings comparisons

Comparison of the data in Figure 1 indicates the distinct states resulting for both materials based on deposition conditions. This is despite the fact that the comparisons made for each example were of essentially identical material – as reflected by the similar Fr results for each. In both cases, higher energy deposition in the form of either bottom dumping or subaerial deposition on a beach result in denser states in situ. This highlights some of the difficulties in precisely predicting the likely in situ state that will occur from laboratory test data in isolation.

3 Thickened tailings data

3.1 Sites considered

The sites considered are outlined in Table 1, along with some limited index test data in the form of percent fines ($<75\mu\text{m}$) and plasticity index (PI). Site data available from publications is referred to, using the same site name and/or anonymous description as in the relevant publication. Site data from Golder Associates' job files is generally provided as a site number, to maintain project anonymity. Three of the sites listed have included specific testing to assess the CSL – Osborne on representative material as part of design studies, and Site 4 and Site 5 on material taken from targeted sample depths. Testing procedures to obtain the CSL are outside the scope of this paper – additional information for interested readers is provided by Jefferies and Been (2015).

Table 1 Thickened TSFs considered

Site name	Mineral type	% < 75 (μm)	Plasticity index (%)	Critical state properties (λ_e/Γ)	Reference/source
Osborne	Copper–gold	50–60	Non-plastic	0.054/0.909	McPhail et al. (2004)
Lead–zinc TSF	Lead–zinc	55–75	6–10	–	Dillon and Wardlaw (2010)
Musselwhite	Gold	60–85	0–5	–	Golder project files
Site 4	Unclassified	50–70	10–25	–	Golder project files
Site 5	Unclassified	80–100	0–5	–	Golder project files
Site 6	Unclassified	70–90	0–5	0.044/0.870	Golder project files
Site 7	Unclassified	40	10–18	0.107/1.423	Golder project files

The sites are presented the same $Q(1-Bq)+1$ versus Fr plot as previously in Figure 1. Consistent with the gradations and plasticity of the tailings, a wide range of densities and soil types are observed. For the four low-plasticity (i.e. $PI < 5$) thickened tailings considered, the results are generally quite close to the CSL. This is consistent with the hypothesis of Been and Li (2009) that thickened tailings would have a tendency to exhibit states quite close to the CSL on the basis of their deposition process. Of the low-plasticity sites, Osborne exhibits the densest state, potentially as a result of the significant drying that occurs at that site compared to the others.

For sites with higher plasticity (PI 6 to 25), looser states are evident. The inferred states of these materials in a normally consolidated condition may be approaching that of 'idealised' clay behaviour as briefly discussed earlier – that is, where the material when deposited is inherently likely to exhibit a looser state than critical, potentially with a parallel NCL and CSL. This observation is generally consistent with suggestions by Boulanger and Idriss (2007) that the separation between 'sand like' and 'clay like' soils is in the range of PI 5 to 7, given the different states seen in the lower and higher-plasticity sites presented.

Data from Site 7 on material deposited prior to commencement of thickened deposition is included for comparison in Figure 2. This historical material was deposited as a conventional slurry and pluviated through standing water during the deposition process. Consistent with previous discussions on the typical outcomes of subaerial deposition and pluviuation through water, the historical Site 7 material exhibits a looser state than the thickened tailings at that site.

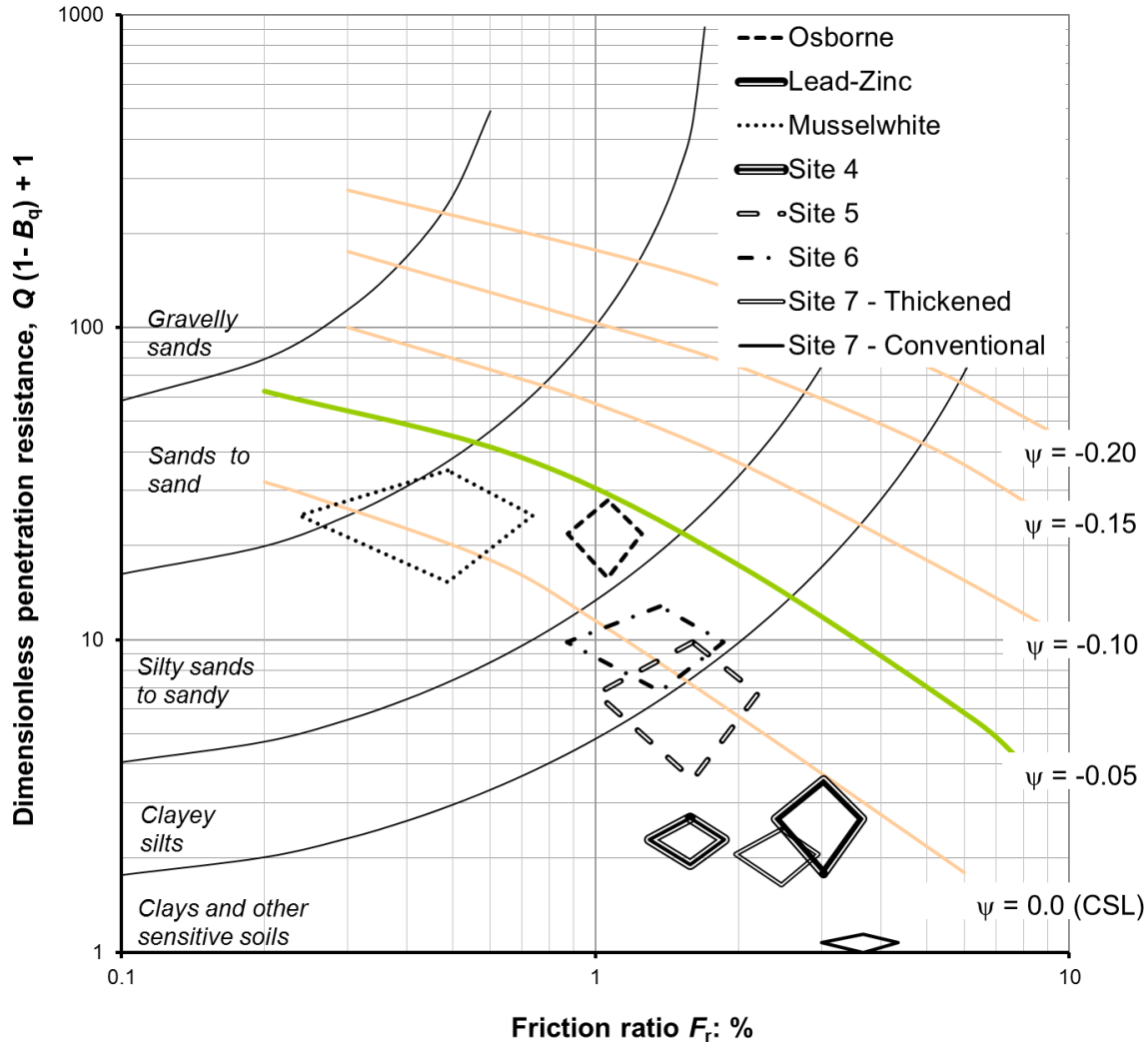


Figure 2 Thickened TSF data

Another point worth noting is that despite many of the tailings examined having similar gradations and plasticity indices, there is a wide range of F_r values. This is of importance as F_r is likely the best-available indicator of compressibility that can be used in CPT screening-level estimates of in situ state (Plewes et al. 1992; Reid 2015). The range of F_r seen here for similarly graded tailings is another illustration of the poor performance and inapplicability of methods based on ‘fines content corrections’ for use in assessing the state and engineering properties of tailings comprising predominately silt.

To illustrate the performance of the Plewes et al. (1992) method on predicting compressibility, the three sites presented in this paper that included CSL testing on samples relevant to the CPT data are presented in Figure 3. To include the variability of F_r data in the plot, the range shown for each site is from the 20th to 80th percentile, similar to previous data presentation in Figure 2. Each site plots on the Plewes et al. correlation of $\lambda_{10} = F_r/10$. This is a similar performance to that indicated by Reid (2015) when assessing the performance of this method by means of additional site data.

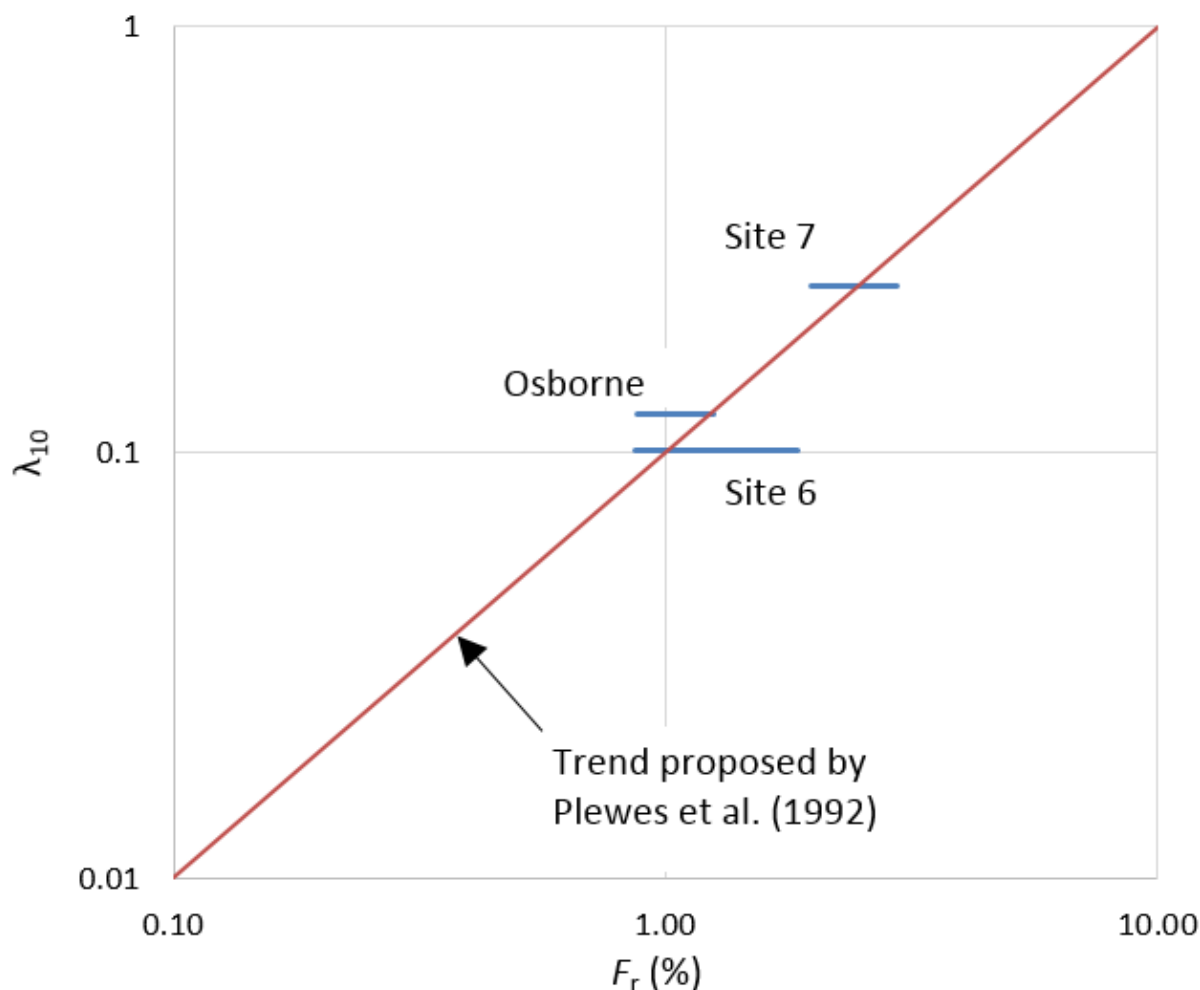


Figure 3 Comparison of results from this study to Plewes et al. (1992) correlation

3.2 Comparison to two filtered TSFs

The increasing popularity of filtering dewatering technology, and investigations of such deposits, means a number of examples of CPT probe data through filter stacks are now available. Two examples are presented to compare the in situ states of the filter stacks to the previous thickened tailings data. Both sites are noted to have undergone minimal compaction after placement of the material.

- Filtered A: An unsaturated stack comprising sandy silts and silty sands, as outlined by Robertson et al. (2017). The stack was of significant depth, with stresses of >1 MPa relevant to much of the available CPT data.
- Filtered B: A silty sand stack from our project files. Owing to some historic higher than desired moisture contents of the deposited material, a zone of approximately 6 to 20 m depth was in a saturated state. This zone was selected for analysis herein.

Examination of the state of filter stacks in an unsaturated condition requires caution, as suctions may affect both the CSL location (for materials with fines), and CPT tip resistance if suctions are sufficiently high (for example, Yang & Russell 2015). These issues as they apply to tailings with a fluctuating phreatic level are discussed by Russell and Reid (2016). For the purpose of this paper, the stack outlined by Robertson et al. (2017) appeared to be of sufficiently low suctions such that CPT results gave appropriate response (with respect to the saturated conditions of the material, were it to rewet), while for the stack from our project files we focused on the saturated region to avoid unsaturated effects.

The data from the two sites discussed are compared to the thickened tailings data in Figure 4. Interestingly, the two filtered states show generally denser states than the thickened tailings. This is curious, as placement of an unsaturated material with minimal compaction is probably the closest field analogue to moist tamping – the sample method that produces the loosest possible specimens in the laboratory. It is possible that the minimal compaction that occurs through bulldozer traffic is having a larger effect on initial deposition fabric and density in these materials than might be expected. Alternatively, drying of the layers after placement may also be having an effect on the subsequent material behaviour – an in situ process that would differ substantially from moist tamping in the laboratory. While the dilative condition of either material is surprising, the looser state of Filtered Stack A compared to B may be affected by the higher stresses relevant to that case history, combined with a potentially non-parallel CSL and NCL.

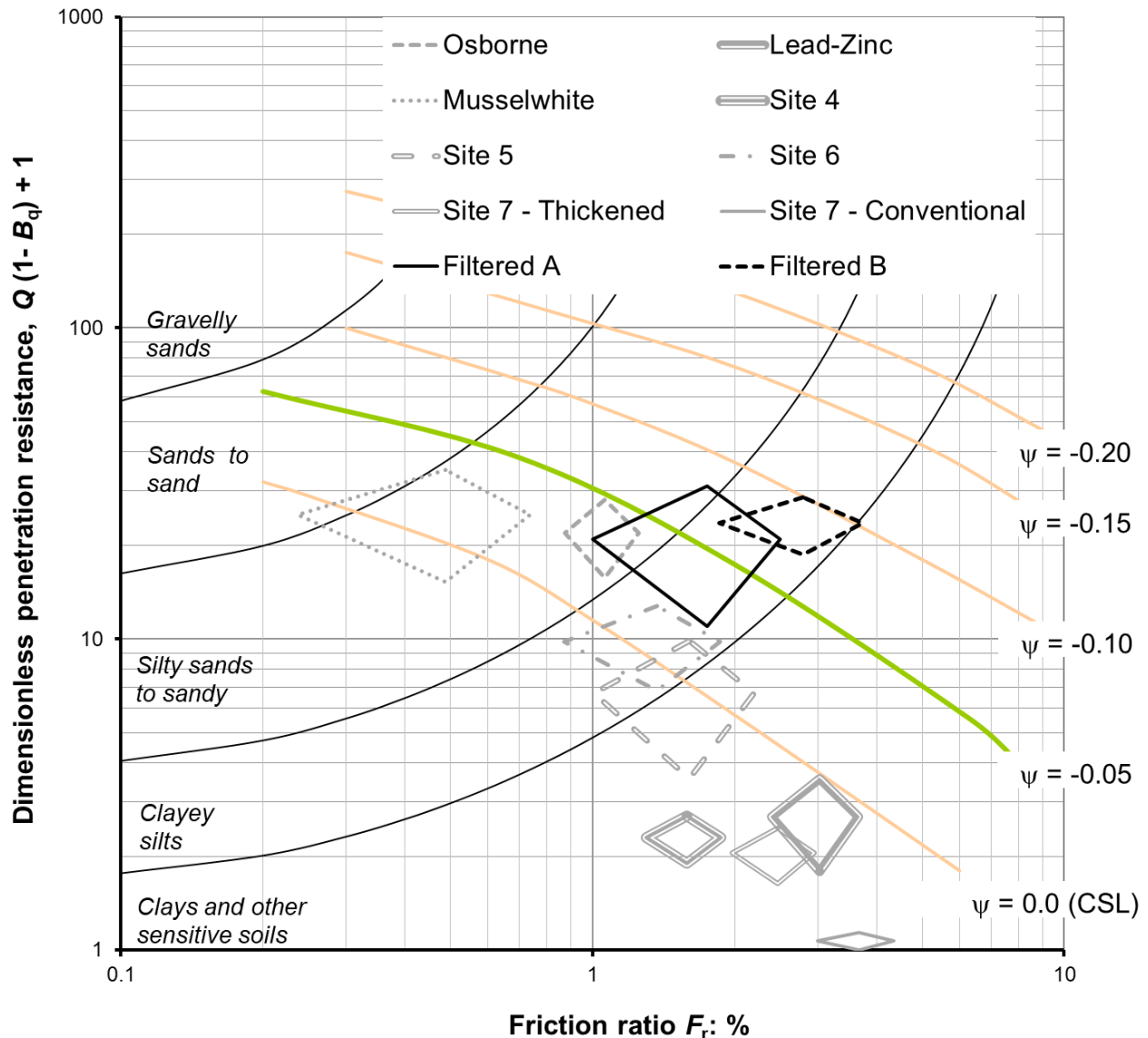


Figure 4 Select thickened TSF data compared to two filtered TSFs

3.3 Comparison to data from two recent TSF failures

Over the past ten years there has been a significant number of TSF failures, including some with robust post-failure investigations and CPT interpretation. CPT data from two of these sites was previously organised into the typical format used herein by Reid and Jefferies (2017) – that is, in $Q(1+B_q)-1$ versus F_r space, and presented as the 20th to 80th percentile range. These are presented for comparison to the thickened tailings data in Figure 5. The failed TSFs from which data was included for comparison are:

- Fundão TSF: CPT results from probes F01 and F02 through the sandy tailings upstream of the left abutment are presented (Morgenstern et al. 2016). Index testing of the sandy tailings indicated a range of fines contents ranging from 30 to 70%, with the blend used for CSL determination during the investigation having 40% fines. CPT data from elevations 860 to 880 m were selected.
- Tennessee Valley Authority (TVA) Kingston dredge cells: An ash storage facility that failed in 2008, with significant root cause analyses carried out. The cause of failure identified by AECOM was static liquefaction of contractive ash material, triggered by creep-based deformation and/or failure of underlying slimes. The ash material was generally silt size – typically 70 to 80% fines content. CPT data were available in disturbed, failed ash (Cell 2), and in nearby unfailed areas (Cell 1). Owing to the likely disturbance in failed areas, the data presented in Figure 4 are from CPT 303 in Cell 1, across depths 21 to 30 m.

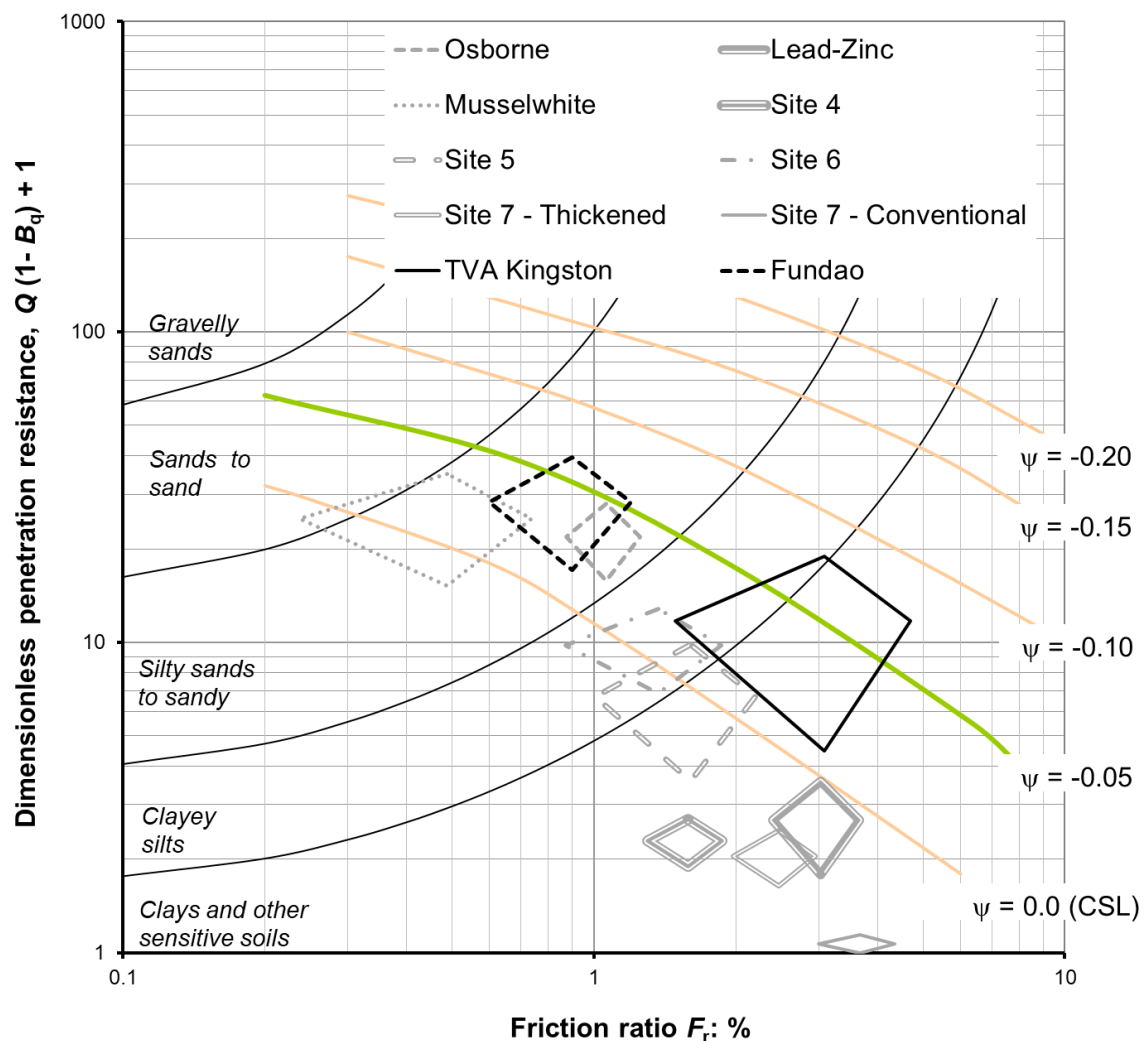


Figure 5 Select thickened TSF data compared to data from two recent conventional slurry TSF failures

Deposition processes on the beach at Fundão and TVA Kingston were generally subaerial deposition of a conventional slurry. Although the failed portion of the TVA Kingston facility included a zone where finer-grained slimes pluviated through water, such depositional conditions do not appear relevant to the CPT 303 location based on the AECOM (2009) review of historical aerial photographs.

The results of the conventionally deposited tailings from two failed TSFs indicates, perhaps surprisingly, a denser in situ state than most of the thickened tailings data presented herein. This observation is generally inconsistent with previous discussions on the potential for a thicker slurry to result in a denser in situ state. However, the state likely to be achieved in situ is also highly dependent on a given material and its deposition conditions, not simply whether it was conventionally deposited or thickened tailings. Clearly, comparison of the sites in this paper (thickened, filtered, and failed conventional TSFs) highlights the significant difficulty in predicting expected in situ state in the design stage.

It should be noted that the authors are not implying, by virtue of the previous comparison to data from failed TSFs, that any of the thickened tailings considered are at risk of a static failure. The significant difference of the thickened TSFs is their modest slopes – rarely have slopes greater than about 5% been achieved regularly. This, compared to the average slopes of the Fundão (Left Abutment) and TVA Kingston slopes which were approximately 20 to 25% grade, implies much higher static shear stresses in the tailings and zones of slime tailings or foundation materials than at any known thickened TSF.

4 Conclusion

CPT data from thickened TSFs with a range of different material properties were organised and compared to assess the range of in situ states achieved. Low-plasticity sites generally had states quite close to the CSL, with higher-plasticity sites exhibiting a looser state. Evaporation of the Osborne TSF may have resulted in it having the densest state of any of the thickened TSFs examined. A wide range of F_r was seen for the sites, despite in many cases quite similar gradations, confirming the inapplicability of ‘fines content corrections’ to silty tailings.

Comparison to two filtered TSFs indicated denser states than the thickened TSFs, a result that was unexpected given the loose unsaturated placement method of many filter stacks. Comparison of the thickened TSFs to the Fundão and TVA Kingston TSFs indicated that those failed TSFs actually had slightly denser in situ states than most of the thickened TSF data examined. However, the different range of in situ stresses of those failed TSFs and a typical steepened beach were emphasised. In general, the difficulty in reliably predicting in situ state was highlighted throughout the work.

References

- AECOM 2009, *Root Cause Analysis of the TVA Kingston Dredge Pond Failure on December 22, 2008*, Project Number 60095742, AECOM, Vernon Hills.
- Been, K & Jefferies, MG 1985, ‘A state parameter for sands’, *Géotechnique*, vol. 35, no. 2, pp. 99–112.
- Been, K & Li, A 2009, ‘Soil liquefaction and paste tailings’, in RJ Jewell, AB Fourie, S Barrera and J Wiertz (eds), *Proceedings of the Twelfth International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 281–290.
- Boulanger, R & Idriss, I 2007, ‘Evaluation of Cyclic Softening in Silts and Clays’, *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 6, pp. 641–652.
- Dillon, MJ & Wardlaw, HJ 2010 ‘Strength and liquefaction assessment of tailings’, in AB Fourie and RJ Jewell (eds), *Proceedings of the First International Seminar on the Reduction of Risk in the Management of Tailings and Mine Waste*, Australian Centre for Geomechanics, Perth, pp. 347–360.
- Jefferies, MG, Roberts, BT, Stewart, HR, Shinde, S, James, D & Williams-Fitzpatrick, S 1988, ‘Island Construction in the Canadian Beaufort Sea’, in DJA van Zyl and SG Vick (eds), *Proceedings of the ASCE Specialty Conference on Hydraulic Fill Structures*, American Society of Civil Engineers, Reston, pp. 816–883.
- Jefferies, MG & Been, K 2015, *Soil Liquefaction: A Critical State Approach*, CRC Press, Boca Raton.
- McPhail, GI, Noble, A, Papageorgiou, G & Wilkinson, D 2004, ‘Development and implementation of thickened tailings discharge at Osborne Mine, Queensland, Australia’, in RJ Jewell and AB Fourie (eds), *Proceedings of the 7th International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth.

- Morgenstern, NR, Vick, SG, Viotti, CB & Watts, BD 2016, *Fundão Tailings Dam Review Panel: Report in the immediate causes of the failure of the Fundão Dam*, viewed 25 January 2018, <http://fundaoinvestigation.com/wp-content/uploads/general/PR/en/FinalReport.pdf>
- Plewes, HD, Davies, MP & Jefferies, MG 1992, 'CPT based screening procedure for evaluation liquefaction susceptibility', *Proceedings of the 45th Canadian Geotechnical Conference*, Canadian Geotechnical Society, pp. 41–49.
- Reid, D 2015, 'Estimating slope of critical state line from cone penetration test — an update', *Canadian Geotechnical Journal*, vol. 52, no. 1, pp. 46–57.
- Reid, D & Fourie, AB 2014, 'Assessing the post-liquefaction shear strength of thickened tailings in the design stage - a review and update', in RJ Jewell, AB Fourie, PS Wells and DV Van Zyl (eds), *Proceedings of the 17th International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 429–444.
- Reid, D & Jefferies, MG 2017, 'State parameter as a geological principle in tailings', in GW Ward, DC Sego and NA Beier (eds), *Proceedings of Tailings and Mine Waste 2017*, University of Alberta, Edmonton.
- Reid, D & Fourie, AB 2015, 'The influence of slurry density on in situ density', in RJ Jewell and AB Fourie (eds), *Proceedings of the 18th International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, Australia, pp. 95–106.
- Robertson, P, da Fonseca, AV, Ulrich, B & Coffin, J 2017, 'Characterization of unsaturated mine waste: a case history', *Canadian Geotechnical Journal*, vol. 54, no. 12, pp. 1752–1761, <https://doi.org/10.1139/cgj-2017-0129>
- Russell, AR & Reid, D 2016, 'Effects of suction on CPT results and soil classification', in BM Lehane, HE Acosta-Martínez & R Kelly (eds), *Proceedings of the 5th International Conference on Geotechnical and Geophysical Characterisation*, Australian Geomechanics Society, Sydney, pp. 521–526.
- Shuttle, DA & Cunniff, J 2008, 'Reply to the discussion by Robertson on "Liquefaction potential of silts from CPTu"', *Canadian Geotechnical Journal*, vol. 45, no. 1, pp. 142–145.
- Yang, H & Russell, AR 2015, 'Cone penetration tests in unsaturated silty sands', *Canadian Geotechnical Journal*, vol. 53, no. 3, pp. 431–444.