Evaluation of Liquefied Strength of Uncompacted Tailings Sand Using Cone Penetration Test at an Oil Sands Tailings Facility

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Abstract

Tailings sand placed hydraulically and uncompacted in a beach above water (BAW) setting can be potentially liquefiable when the structure is raised at a high rate. Experience has shown that flow liquefaction often takes place with small trigger events and no warning and can have serious safety, environmental, and infrastructure consequences. Although dozer compaction is commonly used to construct a non-liquefiable shell, flow liquefaction of the uncompacted tailings sand upstream of the shell remains a key design element.

An upstream tailings sand structure (Sand Dump) at Suncor has been constructed with 5 m lifts at a rate between 10 m and 20 m per year since 2012. The final height of the sand structure is approximately 130 m and it is expected to be completed by 2024. The Cone Penetration Test (CPT) is commonly used as a field investigation tool to evaluate the potential of flow liquefaction and has been used extensively at the Sand Dump for this purpose for the compacted and uncompacted BAW zones.

This paper focuses on the liquefaction assessment for the uncompacted tailings sand. CPTs have been carried out across the project site at the same locations in successive years to evaluate the impact of subsequent sand loading on the liquefaction potential of the uncompacted tailings sand. This paper provides the estimated liquefied strength of the uncompacted tailings sand and its correlation with the distance from the discharge location. The findings are used to verify the initial design assumptions and could provide valuable information for the design of similar future structures.

Introduction

The Sand Dump is a tailings sand structure at Suncor's Millennium mine site, north of Fort McMurray, Alberta, Canada, as shown in Figure 1. An overview of the Sand Dump design was provided by Pollock et al. (2014). The sand structure has been constructed with 5 m lifts at a rate between 10 m and 20 m per year since 2012 and it is expected to reach its final height of approximately 130 m in 2024. Tailings sand placed hydraulically in a BAW setting can be potentially liquefiable when the structure is raised at a high rate. Continuous dozer compaction has been implemented during tailings placement to form a non-liquefiable shell as part of the upstream tailings dam. The assessment and management of the liquefaction potential of compacted tailings sand at the Sand Dump were discussed by Zhang et al. (2020).

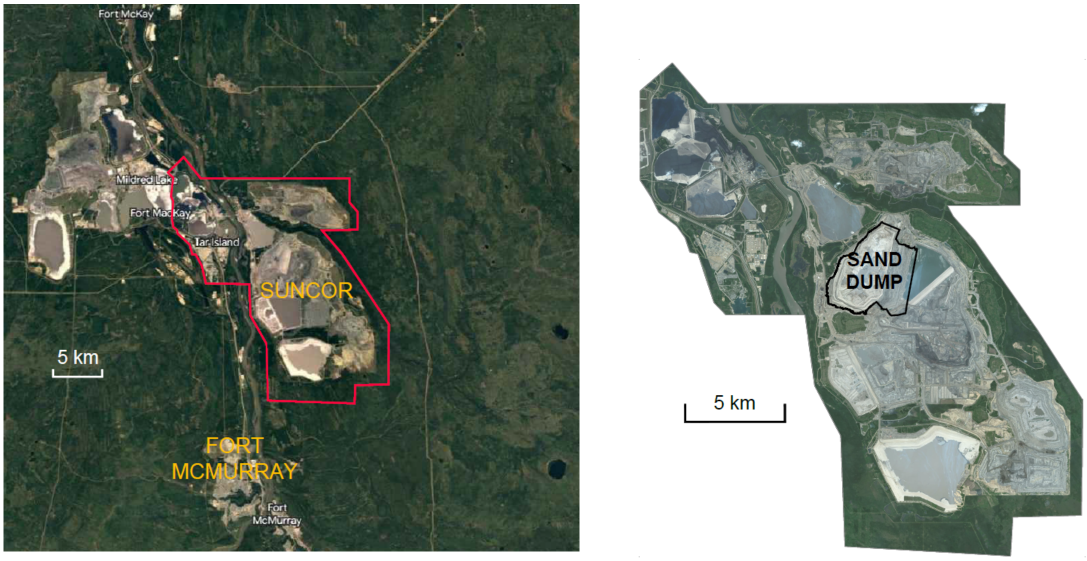


Figure 1: Location and plan view of the Sand Dump at Suncor

The tailings sand between the compacted shell and the supernatant tailings pond, as shown in Figure 2, is uncompacted and assumed potentially liquefiable in the design. The uncompacted tailings sand, if liquefied, forms a significant portion of the failure mass, as indicated in Figure 3, and therefore is an important design element of the structure. This paper focusses on the liquefaction assessment for the uncompacted BAW zone using CPT data. The impact of subsequent sand loading on the liquefaction potential of the uncompacted tailings sand is also discussed through evaluating CPT data from successive years at the same locations. An estimation of the post liquefied strength of the tailings sand based on published CPT correlations is discussed, as well as the correlation with the distance from the tailings discharge location.

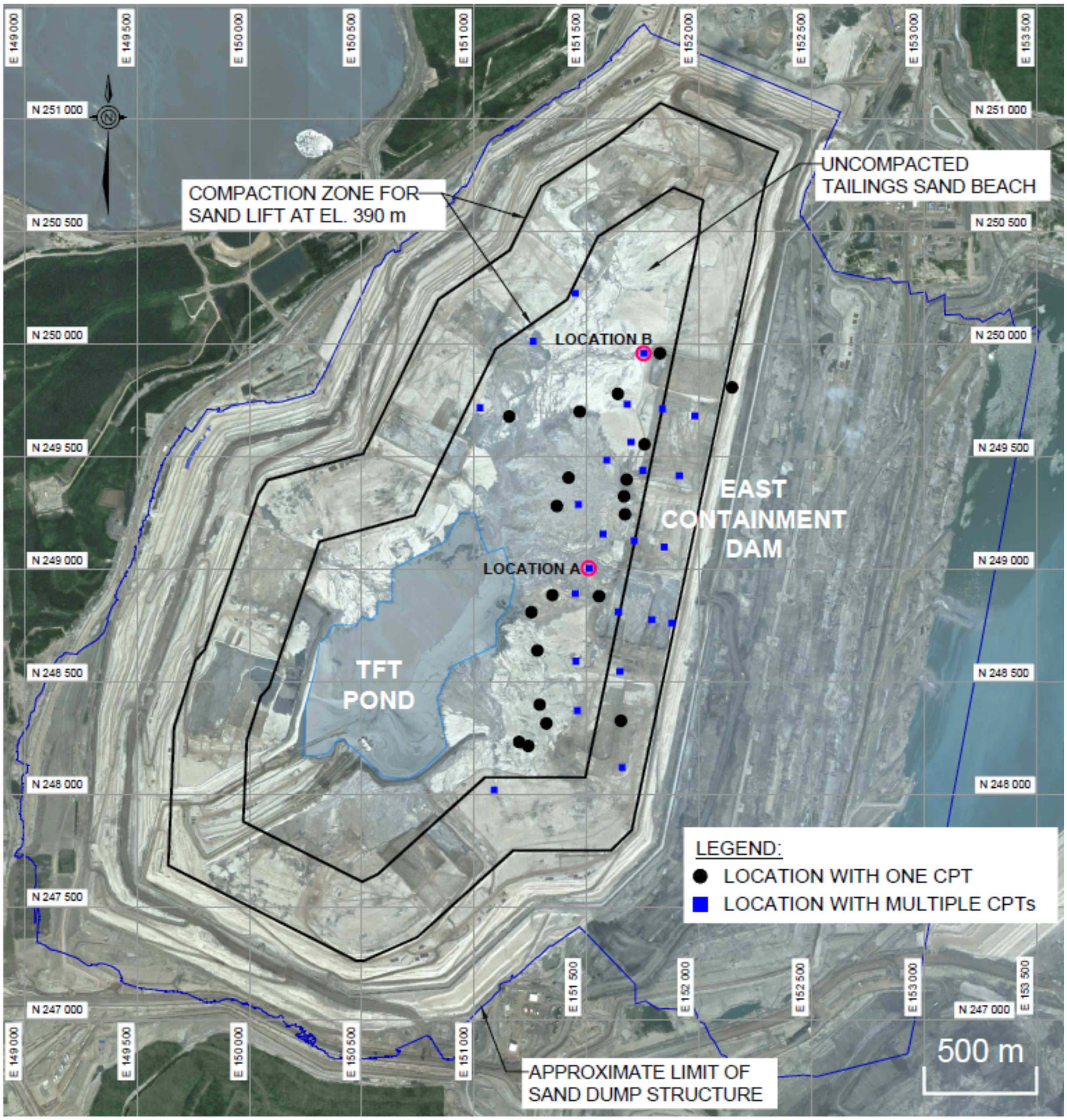


Figure 2: Satellite image of the Sand Dump in June 2023

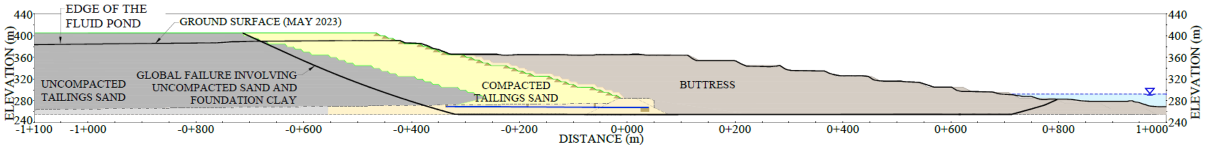


Figure 3: Typical profile of the east containment dam

Tailings placement and tailings sand properties

At Suncor, whole tailings are hydraulically transported from the extraction plants through pipelines to the perimeter of the Sand Dump. The compacted zone is constructed by spigotting tailings into a cell that is surrounded by several dry dykes, with one end of the cell open to facilitate flow towards the pond. Occasionally, due to operational constraints, the end of cell has a dry dyke with a spill pipe installed to facilitate drainage out of the cell. Upon deposition, the sand particles settle down near the discharge location to form the sand beach. Some fines are trapped in the beach while the rest flows to the fluid pond. There are also occasions of discharging tailings with high fines content directly into the uncompacted beach, which could create high fines layers within the tailings beach. Continuous dozer compaction has been implemented in the cells, and tailings outside the cells are left uncompacted. The fluid fine tailings and water in the fluid pond are pumped to another tailings facility to keep a minimal pond size at the Sand Dump.

Tailings sand at the Sand Dump is fine-grained sand with a trace (< 5%) of medium-grained sand and a trace of silt and clay. The fines content (particle size < 45 µm) is typically in the range of 3% to 5% in the compacted zone and 3% to 7% in the uncompacted sand zone (Abusaid et al, 2020).

Liquefaction susceptibility assessment method

Zhang et al. (2020) provided an overview of flow liquefaction susceptibility analysis methods, among which the $Q_{tn,cs}$ method by Robertson (2010) was used as the primary approach at the Sand Dump. The soil at a specific depth is considered to be susceptible to liquefaction if $Q_{tn,cs} \leq 70$. Robertson (2016) indicated that using $Q_{tn,cs} = 70$ is slightly conservative but it is considered as an appropriate screening tool for tailings structures with very high consequence. Robertson (2022) updated the fines content correction coefficient (K_c), mainly for clay-like soils. The Robertson (2022) update considers the soils as contractive when $Q_{tn,cs} \leq 70$, dilative when $Q_{tn,cs} \geq 80$, and partially contractive for soils with $Q_{tn,cs}$ between 70 and 80.

Although the Robertson method is considered to be the state of the art for interpreting CPT results with respect to liquefaction, one uncertainty in using $Q_{tn,cs}$ in this regard is that it is calculated using vertical stress even though lateral effective stress strongly influences the cone resistance (Houlsby and Hitchman, 1988, 1989). It is recognized that it is challenging to determine the in-situ lateral stress at each CPT location.

Liquefaction potential of uncompacted tailings sand at the sand dump

Thirteen CPT programs with about 230 CPTs at 120 locations in the uncompacted tailings sand at the Sand Dump were conducted between 2012 and 2022. The CPT data from the locations that might be influenced by dozer compaction were excluded from the database used in this analysis. Figure 2 shows 20 locations (black circle symbols) with only one CPT conducted at those locations and 25 locations (blue square symbols) with multiple CPTs conducted at those locations. The $Q_{tn,cs}$ method by Robertson (2010, 2022) was used to assess the liquefaction potential of the uncompacted tailings sand. Figure 4 shows the distribution of the $Q_{tn,cs}$ values from the CPT testing in the uncompacted tailings sand at the Sand Dump. About 45% of $Q_{tn,cs}$ values are lower than 70, indicating the sand is contractive and could experience significant strength loss at large strain. Approximately 40% of the $Q_{tn,cs}$ values are higher than 80, indicating the sand is dilative and not liquefiable. Slightly over 15% of the $Q_{tn,cs}$ values are between 70 and 80, indicating the sand is contractive but not expected to have significant strength loss during undrained shear.

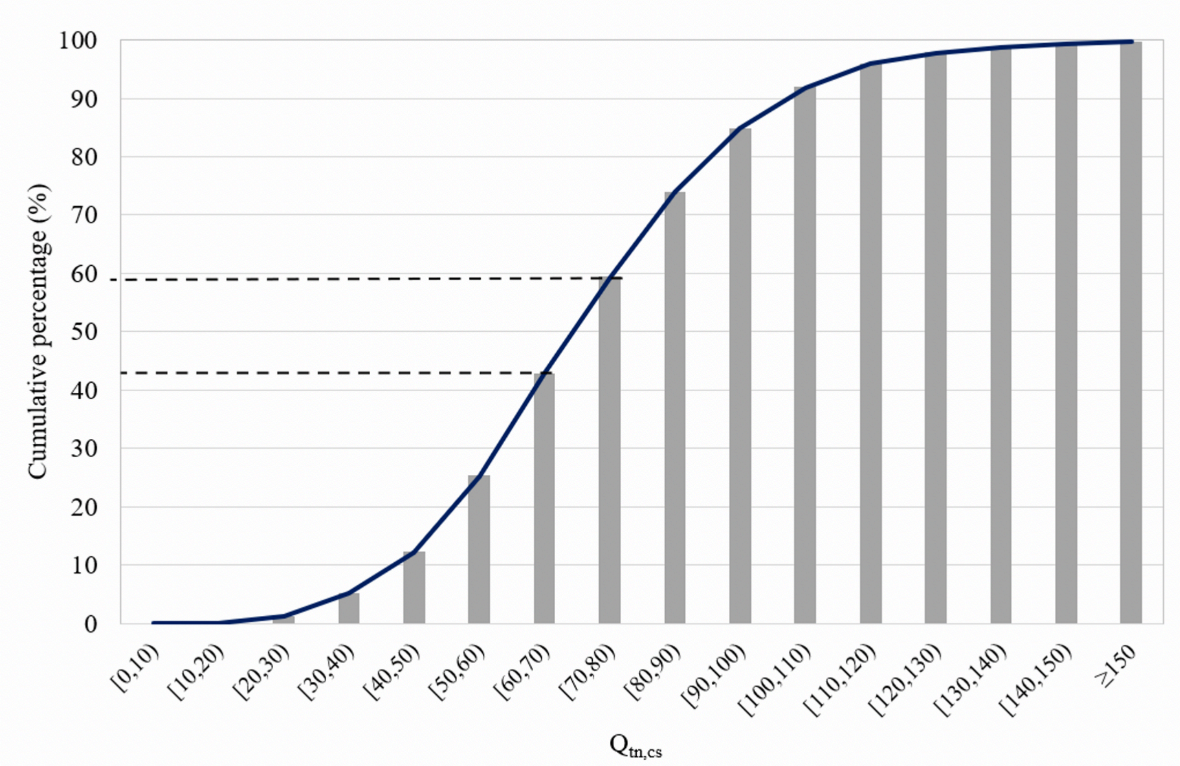


Figure 4: Distribution of $Q_{tn,cs}$ values from CPTs in the uncompacted tailings sand

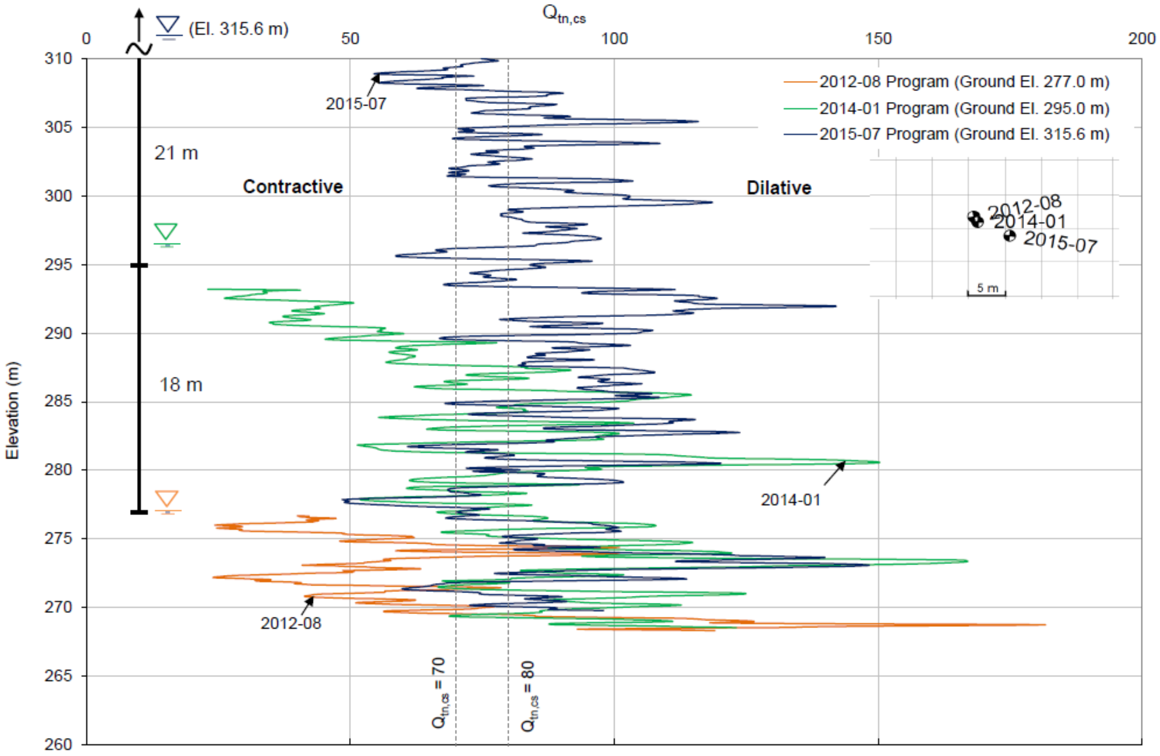
Impact of subsequent loading on the liquefaction potential

Hydraulically placed tailings sand is expected to consolidate and become denser upon the loading by subsequent sand placement especially for loose uncompacted sand. However, it is unclear if the increase in density can change the sand state from being contractive to dilative. A review of the $Q_{tn,cs}$ values from CPTs tested at the same locations in successive programs at the Sand Dump was carried out to examine the improvement in the sand state.

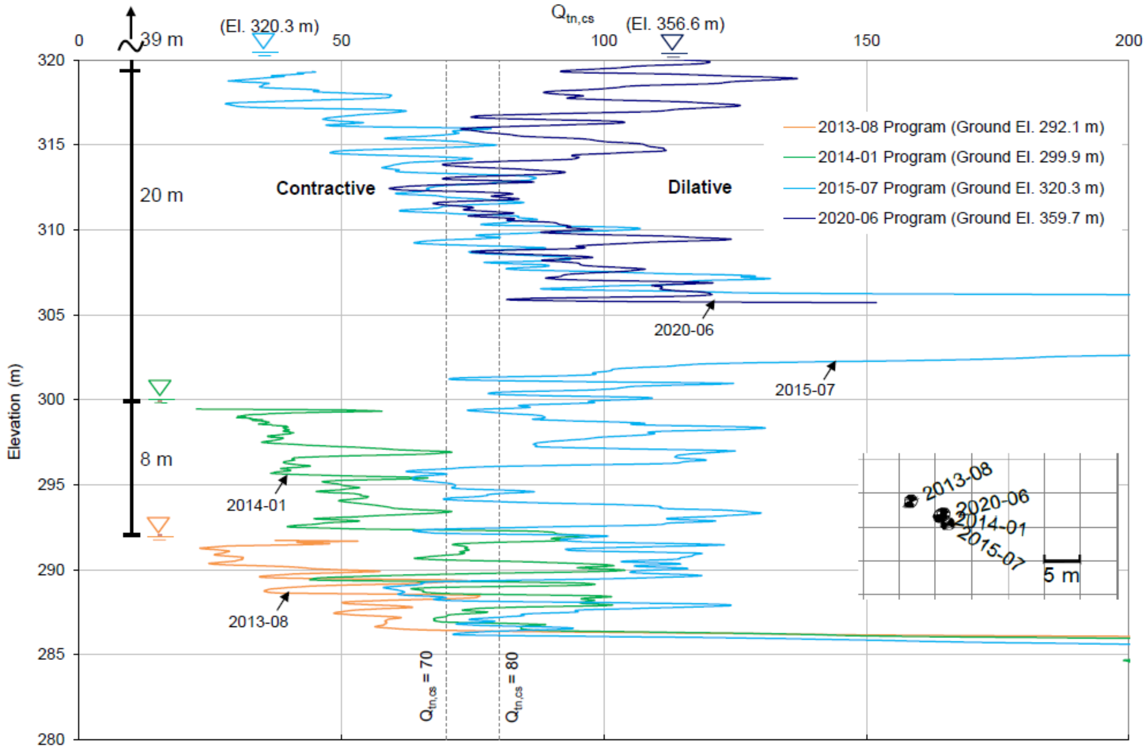
There are 20 locations along the east containment dam with CPTs from multiple programs, as shown in Figure 2. The thickness of the sand that was placed between two CPT tests at the same location ranged from 8 m to 40 m. Figure 5 presents examples of the $Q_{tn,cs}$ profiles from different programs at two CPT locations. The distance between the as-built locations of the CPTs from the different programs are less than 5 m. The thickness of the tailings sand placed between adjacent CPT programs (about 20 m for Location A) are labelled on the left side of Figure 5. The water tables at the time of CPT testing are also provided in the figure and are typically at or very close to the ground surface. A review of all the $Q_{tn,cs}$ comparison plots indicated that subsequent sand loading at the Sand Dump can improve the state of tailings sand when $Q_{tn,cs}$ is lower than 50. Subsequent loading can sometimes improve the state of tailings sand when $Q_{tn,cs}$ is up to 60, but there are cases with $Q_{tn,cs}$ between 50 and 60 and no improvement is observed. In general, subsequent sand loading is expected to increase the $Q_{tn,cs}$ for uncompacted tailings sand to at least 50 and sometimes up to 60, and occasionally to 70 and 80.

To further evaluate the state of the uncompacted tailings sand under loading, the $Q_{tn,cs}$ values from all 45 CPT locations in Figure 2 are plotted against the vertical effective stress at the time of the CPT testing in Figure 6. Since the water table was very close to the ground surface at the time of the CPT testing, the vertical effective stress corresponds to the depth below ground surface. For example, the vertical effective stress at a depth of 10 m is about 100 kPa. Along with the individual CPT data, the 10th, 20th, 30th percentile and the average $Q_{tn,cs}$ values are determined for an interval of 10 kPa when the vertical effective stress is less than 200 kPa and an interval of 50 kPa when vertical effective stress is higher than 200 kPa, as shown by the dashed lines. Solid lines are then used to represent the trends of the dash lines.

Figure 6 shows that $Q_{tn,cs}$ is low near the ground surface and increases significantly with vertical effective stress up to approximately 100 kPa after which there is little to no increase. Although the $Q_{tn,cs}$ values showed a general trend of increase with vertical effective stress (depth), the CPT database at the Sand Dump showed that $Q_{tn,cs}$ can be lower than 70 up to a vertical effective stress of 600 kPa (or a depth of 60 m) for the uncompacted tailings sand, which is consistent with the design assumption for the uncompacted tailings sand of this structure. The state of the uncompacted tailings sand is unclear at greater depth since CPT typically encounters refusal before reaching a depth of 60 m in the uncompacted zone at the Sand Dump.



a) CPT data from Aug 2012, Jan 2014, and Jul 2015 programs at Location A



b) CPT data from Aug 2013, Jan 2014, Jul 2015, and Jun 2020 programs at Location B

Figure 5: Impact of subsequent sand loading on the $Q_{tn,cs}$ values for uncompacted tailings sand

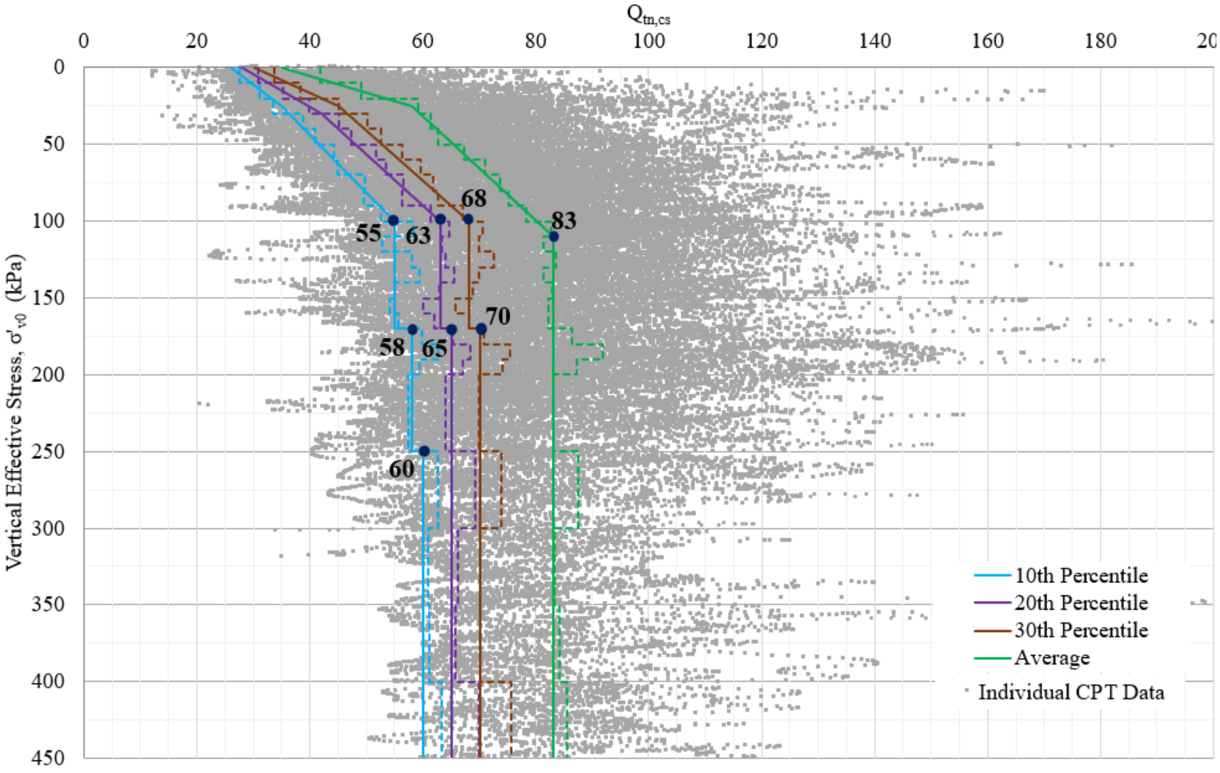


Figure 6: Correlations between the $Q_{tn,cs}$ values and the vertical effective stress

Impact of distance from the tailings discharge location

The impact of distance from the tailings discharge location on the state of the uncompacted sand was evaluated for the Sand Dump. Figure 7 shows the typical profile of the east containment dam with the CPT locations plotted in profile. The tailings discharge location was assumed to be the upstream edge of the compacted zone for this study; however the actual discharge location varies throughout the compacted zone for this particular structure. The data was also subdivided into zones above El. 320 m and below El. 320 m to take into account the impact of depth. Given the large amount of CPT data, the 10th, 20th, and average $Q_{tn,cs}$ values were determined for each 100 m distance zone for comparison with the representative $Q_{tn,cs}$ values from other zones.

Figure 8 shows some examples of the comparison of the 10th and 20th percentile $Q_{tn,cs}$ values below El. 320 m. A review of all the data comparison revealed a general trend of decrease in $Q_{tn,cs}$ values further away from the discharge location for both data sets, above El. 320 m and below El. 320 m, which could be attributed by the decreased deposition energy and change in tailings composition.

Liquefied shear strength ratio ($S_{u(liq)}/\sigma_{v0}'$)

Significant strength loss (strain softening) is expected when loose sand liquefies. Flow liquefaction often takes place with no warning and can result in significant loss of life, environment, and infrastructure. Therefore, the Sand Dump design assumed the uncompacted tailings sand is potentially liquefiable. Based on case histories, the designers' experience, and a field trial, a liquefied shear strength ratio ($S_{u(liq)}/\sigma_{v0}'$) of 0.05 was adopted in the design for the case with flow liquefaction. $S_{u(liq)}$ is the undrained shear strength at large strain which corresponds to the liquefied shear strength for loose sand. σ_{v0}' is the in-situ vertical effective stress prior to the liquefaction triggering event.

Researchers (Olson and Stark, 2003; Robertson, 2010; Jefferies and Been, 2016; and Robertson, 2022) have proposed various correlations to estimate the liquefied shear strength ratio using different corrected CPT tip resistances. The Robertson (2022) proposed $S_{u(liq)}/\sigma_{v0}'$ vs $Q_{tn,cs}$ relationship, as shown in Figure 9 and discussed below, was used in the current study:

- The proposed correlation covers sand-like soil ($I_c \leq 3$) and clay-like soil ($I_c > 3$) and it involves different equations to estimate the undrained shear strength of both types of soils. I_c is a soil behaviour type index used to categorize soils based on CPT data (Robertson and Cabal, 2022).
- The correlation is based on a database incorporating recent experience and case histories. The Class A and B case history data for both sand- and clay-like soils are used in establishing the correlation. The case histories only cover vertical effective stress less than 300 kPa, and most cases are less than 200 kPa. Robertson (2022) stated that the estimated undrained shear strength ratio could be conservatively low for soils under higher stresses and advanced laboratory testing is required to evaluate the curvature of the critical state line at those higher stresses so a higher undrained shear strength ratio can be used.
- The correlation uses the lower bound of the estimated undrained shear strength ratios for loose and very loose soils ($35 < Q_{tn,cs} < 60$) from the Class A and B case histories. The undrained shear strength ratios were estimated using the mean CPT values in the zones believed to be involved in the failure. For dense to very dense soils ($Q_{tn,cs} > 80$), the correlation uses the drained shear strength. For soils without case histories ($Q_{tn,cs}$ less than 35 or between 60 and 80), the correlation uses interpolation and extrapolation.

There are some sources of uncertainty in the back analysis of the case histories used in establishing the Robertson (2022) $S_{u(liq)}/\sigma_{v0}'$ vs $Q_{tn,cs}$ relationship. For example, Robertson (2010) notes that the back analyses may not represent the actual failure mechanism including retrogressive failure and inertia effects, and the CPT dataset used may not be entirely within the failure mass.

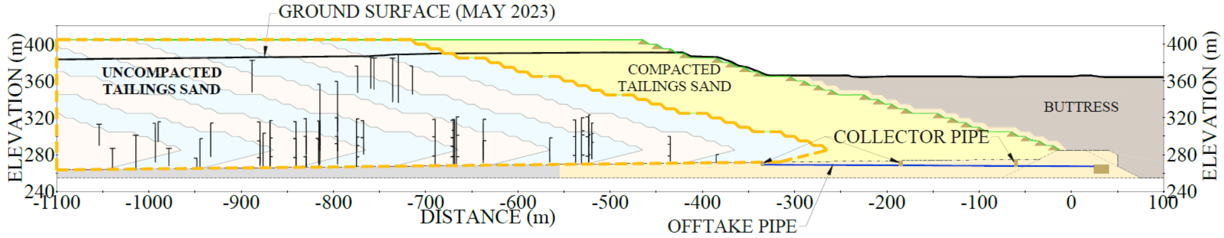
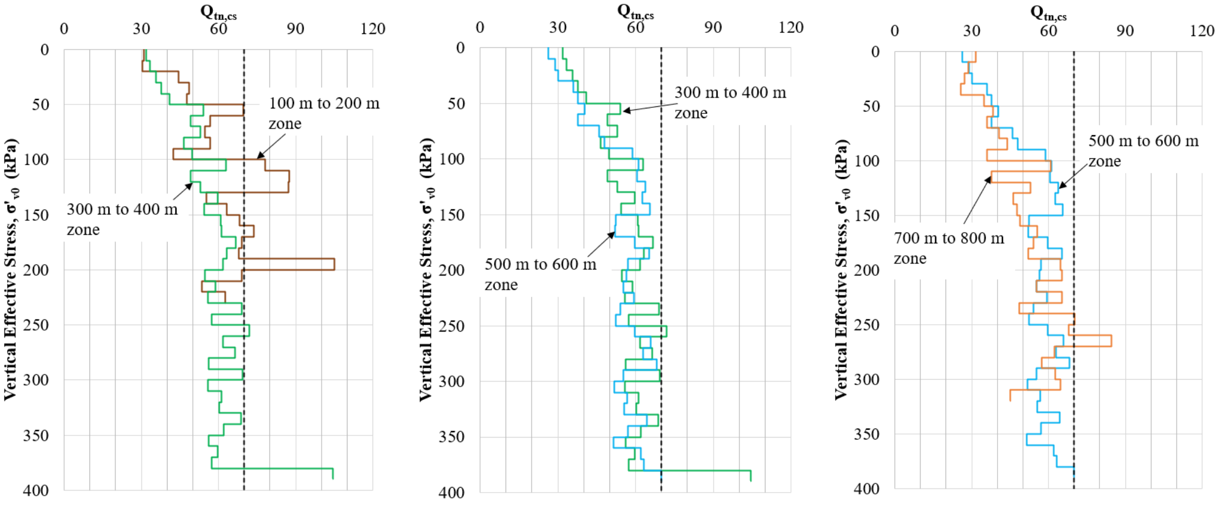
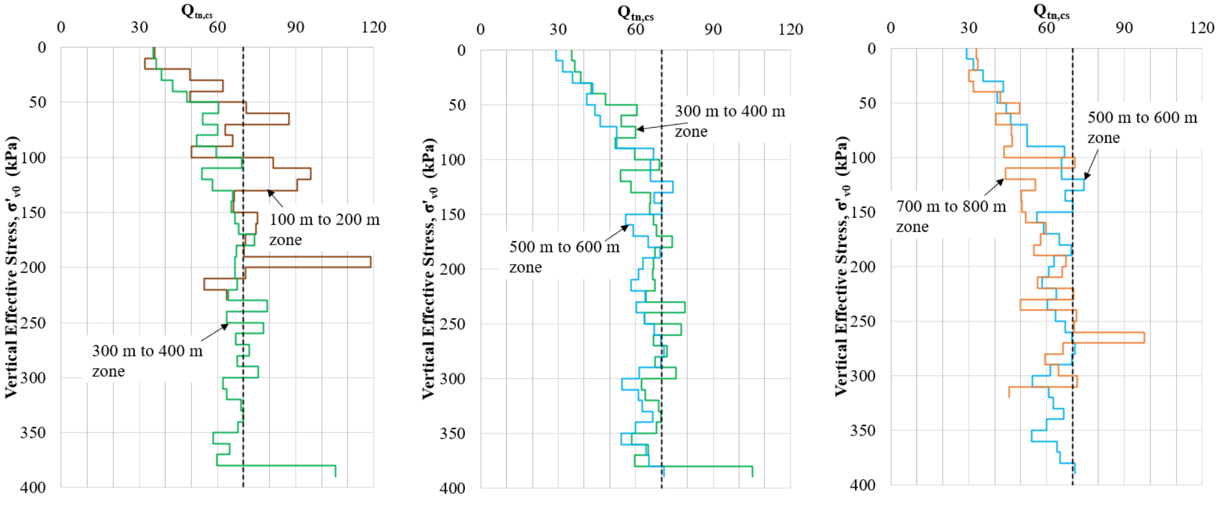


Figure 7: Distance categories for the east containment dam



a) 10th percentile $Q_{tn,cs}$ values



b) 20th percentile $Q_{tn,cs}$ values

Figure 8: Comparison of some representative $Q_{tn,cs}$ values for tailings sand with different distances to the discharge location

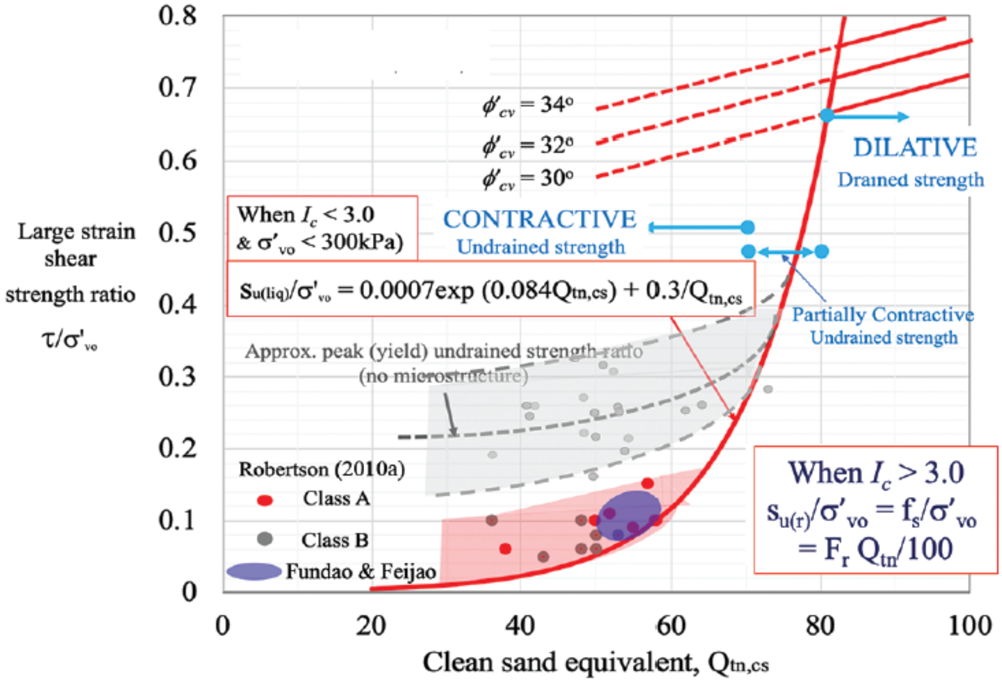


Figure 9: Proposed relationship between liquefied strength ratio and $Q_{tn,cs}$ (Robertson, 2022)

Figure 10 presents the estimated undrained shear strength ratio using the Robertson (2022) method for the $Q_{tn,cs}$ values for the uncompacted sand at the Sand Dump. Jefferies and Been (2016) suggested design values close to 10th percentile for cyclic loading cases and towards 20th percentile for static design problems, while recommending the design engineers to consider the influence of construction method and the scale of variation. Robertson (2022) indicated that 30th percentile (approximately mean minus one standard deviation) of the CPT values can be used to represent the weaker zones that control stability according to case histories. For the Sand Dump or similar structures, one undrained shear strength ratio could be selected for the weak plane (sliding along a potential loose layer) and a different one for the backscarp (to reflect cross bedding) of the failure surfaces.

Also, the liquefied shear strength ratio is expected to be higher near the discharge location and lower further away from the discharge location, based on the assessment of the impact of the distance from the discharge location. The undrained shear strength ratios estimated using all data from the uncompacted zone should be conservative since the critical slip surfaces are typically close, at least for the Sand Dump, to the compaction boundary for the liquefaction scenario. Therefore, the analysis of the data and the preceding commentary indicate that the design value of $S_{u(liq)}/\sigma_{v0}' = 0.05$ is conservative based on the Robertson (2022) relationship.

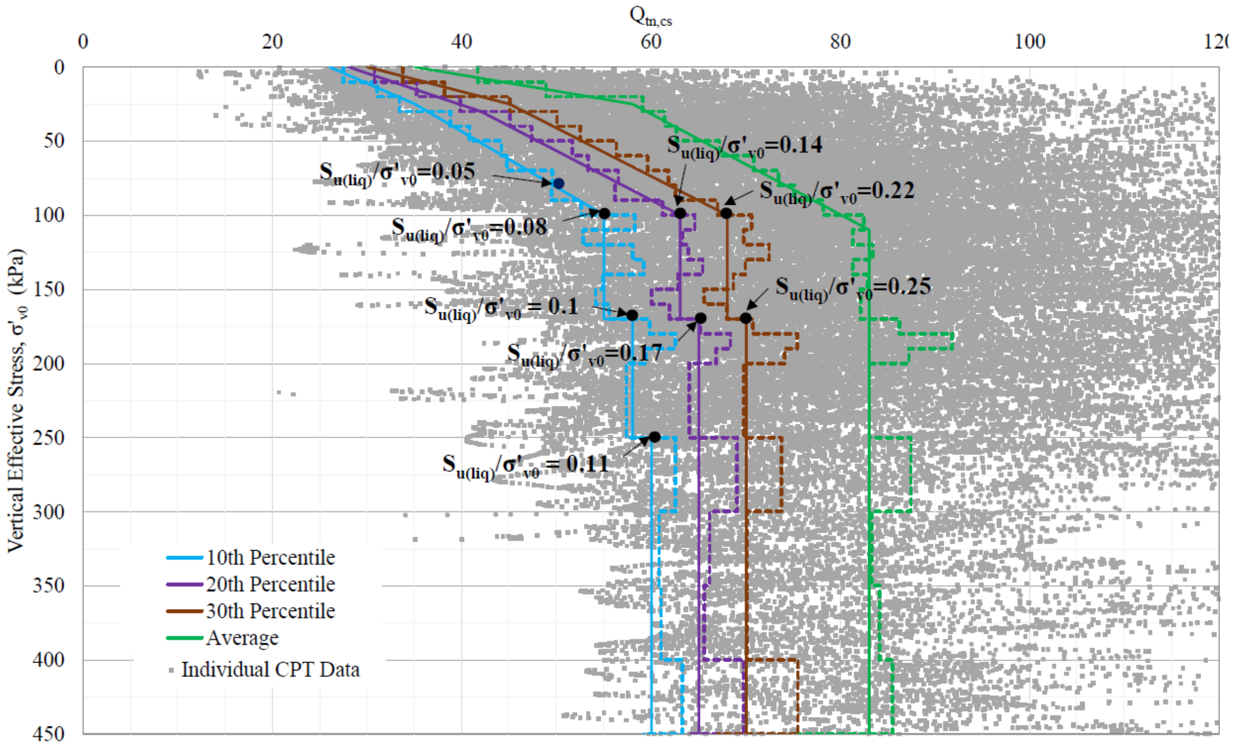


Figure 10: Estimated undrained shear strength ratio using Robertson (2022) method

Summary and conclusions

The uncompacted tailings sand beach at the Suncor Sand Dump was designed to be potentially liquefiable, and a post-liquefaction shear strength ratio of 0.05 was used in the design. The sand structure has been under construction since 2012 and reached a height of approximately 120 m as of June 2023. Multiple CPT programs were carried out over the course of the Sand Dump construction. Results of CPTs pushed in the uncompacted tailings sand were evaluated using the Robertson (2010, 2022) method and the following was concluded:

- A significant portion (~45%) of the uncompacted tailings sand is potentially liquefiable, confirming the original design assumption.
- The $Q_{tn,cs}$ values versus effective stress profile indicated that the uncompacted tailings sand is very loose near the ground surface, and the $Q_{tn,cs}$ increases significantly up to a stress level of 100 kPa, after which the increase in $Q_{tn,cs}$ becomes less prominent.
- Subsequent sand loading can improve the state of the uncompacted tailings sand when $Q_{tn,cs}$ is lower than 50. Subsequent loading can sometimes improve the state of tailings sand when $Q_{tn,cs}$ is up to 60. In general, subsequent sand loading is expected to increase $Q_{tn,cs}$ at uncompacted tailings sand to at least 50 and occasionally up to 60.

- The $Q_{tn,cs}$ values generally decrease further away from the tailings discharge location, and this is also expected to be true for the liquefied shear strength ratio.
- The liquefied shear strength ratio of the uncompacted tailings sand at the Sand Dump was estimated using the Robertson (2022) method. The majority of the estimated liquefied shear strength ratios are higher than the design value of 0.05, especially if a cross-bedding liquefied shear strength is used as part of the design. For other tailings sand structures, the liquefied shear strength ratio could be impacted by the tailings sand properties and the tailings placement methods and rate, which should be considered when selecting the design liquefied strength ratio.

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