MEASURING UNDRAINED SHEAR STRENGTH OF OIL SANDS TAILINGS DEPOSITS

Final Report
to

Canada's Oil Sands Innovation Alliance (COSIA)

Prepared by

COSIA Deposit Characterization Committee:

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Introduction

In 2009 the Alberta Energy Regulator (AER) implemented Directive 074 (D074). The main objective of the directive was to reduce the inventory of oil sands fluid fine tailings (FFT) across various leases of the mineable Athabasca oil sands. In response to the directive, operators have implemented a variety of site specific tailings measurement methods to monitor progress towards meeting the regulatory requirements.

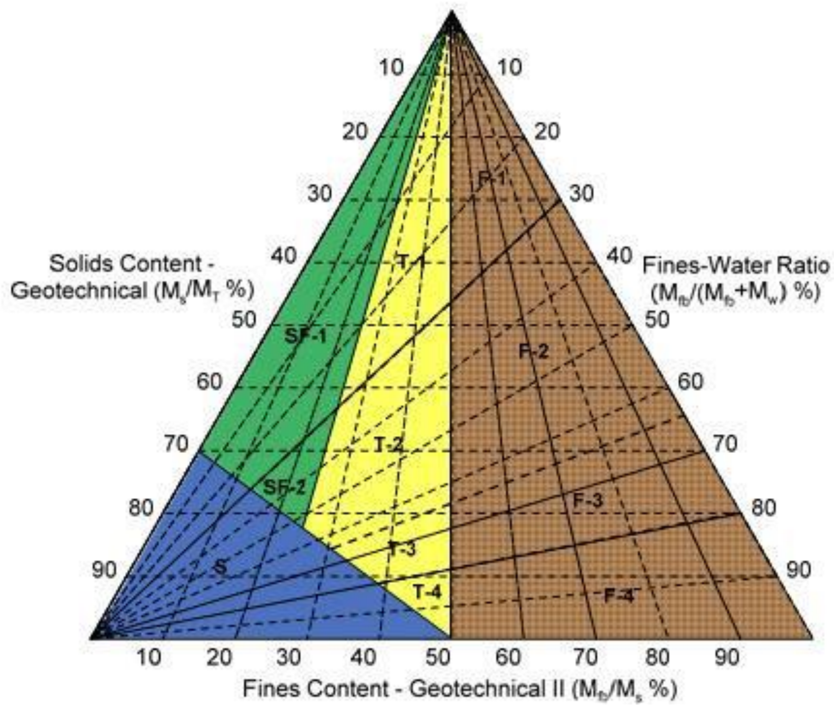
The industry realised that such a variety of measurement and reporting methods could create differing approaches in estimating fluid tailings volumes as well as tailings performance. To introduce consistency in reporting, the Canadian Oil Sands Innovation Alliance (COSIA) was asked to evaluate the technical merits of various measurement techniques and propose a set of industry recommended practices.

To meet this need, the COSIA Tailings Environmental Priority Area (EPA) tasked the Tailings Measurement Steering Committee (TMSC) to produce these recommended practices. The scope developed into four areas of focus, including; Fines Measurement, FFT Volume Determination, Deposit Characterization, Sampling and Geostatistics.

This report provides the results of the "*Deposit Characterization"* working group, which was tasked with identifying and recommending a standard method for measuring the *in situ* undrained shear strength (or appropriate equivalent measurement methods) for all tailings deposit types that are technically and statistically appropriate for AER reporting, and is provided as a final submission to the TMSC.

Background

In January 2013, a composition based oil sand tailings classification system utilizing the ternary diagram, as reproduced in Figure 1, was developed (COSIA 2013).



Primary Division		Secondary Division	Symbol	Name
Sand Void Ratio≤1.1		none	S	Sand
Fines Dominated Tailings Sand void ratio > 1.1	Sandy-Fine Tailings SFR ≥ 3 (fines content geotechnical II ≤ 25%)	FWR < static segregation boundary	SF-1	Sandy Fine Tailings - Zone 1
		Liquid limit > FWR ≥ static segregation boundary	SF-2	Sandy Fine Tailings - Zone 2
	Transition Tailings 3 > SFR > 1 (25% < fines content geotechnical II < 50%)	FWR < static segregation boundary	T-1	Transition Zone 1
		Liquid limit > FWR ≥ static segregation boundary	T-2	Transition Zone 2
		Plastic limit > FWR ≥ liquid limit	T-3	Transition Zone 3
		FWR ≥ plastic limit	T-4	Transition Zone 4
	Fine Tailings SFR ≤ 1 (fines content geotechnical II≥ 50%)	FWR < static segregation boundary	F-1	Fine Tailings Zone 1
		Liquid limit > FWR ≥ static segregation boundary	F-2	Fine Tailings Zone 2
		Plastic limit > FWR ≥ liquid limit	F-3	Fine Tailings Zone 3
		FWR ≥ plastic limit	F-4	Fine Tailings Zone 4

Figure 1: Unified Oil Sands Tailings Classification System (Adopted from COSIA, 2014)

The Unified Oil Sands Tailings Classification System (UOSTCS) identified four main groups of tailings deposits; Sand (S), Sandy Fines (SF), Transition (T), and Fines (F) to provide a standard method of naming and communicating oil sands tailings types, and to define areas of suitability for tailings deposit sampling and measurement methods.

During development of the UOSTCS it was considered that the measurement of the undrained shear strength may be an appropriate tool for monitoring regulatory compliance in fines-dominated deposits, and that current measurement methods used for *in situ* strength testing in SF deposits might not be meaningful. It was also recommended that further work be undertaken to assess the suitability of undrained shear strength measurement in T deposits.

In 2014, COSIA developed guidelines (COSIA, 2014) for creating a FFT management plan consistent with AER D074 that would facilitate closure of oil sand mines by accelerating the conversion of FFT into a trafficable reclaimable landscape. The document provides guidance on performance measures for six different dedicated disposal area (DDA) deposit types that are consistent with the accelerated closure objectives and regulatory reporting structure. Owners and practitioners should consider the use and applicability of strength, as a performance measure in a given FFT deposit, within the context of these guidelines.

Definitions and Application

Shear Strength

Shear strength is defined as the maximum or ultimate shear stress that a soil can sustain without undergoing large deformations. When a soil is subjected to shear there is typically an increase in the pore water pressure (or excess pore pressure) generated within the soil that given enough time will dissipate (through drainage) with a corresponding volume change of the soil matrix. Under various loading conditions, it is possible to have drained, undrained and partially drained responses during shear.

Drained Shear Strength

When the shear stress is applied at a sufficiently slow rate and the drainage boundary conditions are such that excess pore pressure is zero when the failure occurs, then it is said that failure has taken place under drained conditions, or the drained shear strength of the soil has been mobilized. High permeability granular materials generally mobilize the drained strength when shear stresses are applied relatively slowly.

Undrained Shear Strength

When shear stress is applied relatively quickly or the drainage boundary conditions are such that the shear-induced excess pore pressure does not dissipate as the material is strained, then it is said that failure has taken place under undrained conditions, or that the undrained shear strength has been mobilized. There are small volume changes during an undrained failure.

Equivalence to Directive 074 Undrained Shear Strength Requirement in Drained Deposits

It was considered that the development of undrained shear strength was not possible in all deposit types. Options that would provide undrained shear strength equivalency were explored in S, SF, and T deposits (SFR>1) where the material may exhibit drained behaviour under shear.

In these soil types, three proposals for equivalency to 5 kPa undrained strength were considered for drained or partially drained deposits:

- Detecting liquefaction potential,
- Detecting solid/fluid boundary using Cone Penetrometer Test (CPT)[1] tip resistance, or
- Developing a standard CPT tip resistance based on 5 kPa undrained shear strength.

Use of Liquefaction Potential

Soil liquefaction describes a phenomenon whereby a loose, saturated or partially saturated soil loses strength (with associated volume change) in response to an applied static or dynamic stress. The committee reviewed the applicability of this approach and concluded that where such a parameter may be suitable for assessment of long term stability of the deposits, it was likely not an appropriate method for standardized reporting of year over year changes within the tailings deposits. Similarly, it was recognized that assessment of the liquefaction potential of a deposit is site specific and is considered as part by the containment design. It was concluded that a regulatory criterion based on liquefaction or liquefaction potential was not appropriate for relatively short-term compliance monitoring.

Detecting Solid/Fluid boundary

The liquid limit of fine-grained deposits defines the boundary between its fluid and solid states. Also, fine grained soils that are at, or slightly below, its liquid limit will have an undrained shear strength of about 2 kPa (Terzaghi and Peck, 1997). It was on this basis, during the development of D074, that fine-grained deposits having an undrained shear strength exceeding 5 kPa could be classified as solid deposits (i.e. they are soils, not fluids).

It was considered that since the CPT tip resistance can be used to determine undrained shear strength in fine-grained soils and drained/partially drained soil strength in coarser grained soils;

[1] CPT is used generically throughout this document and encompasses a variety of equipment tips: cones, balls, and tips with piezometers to measure pore pressures. CPT_u specifies that the equipment must be equipped with a piezometer to measure pore pressure.

that it might also be possible to use the tip resistance to identify the solid/fluid boundary across all of the oil sands tailings types. The committee analyzed 108 CPT logs, from three (3) oil sands operators, paired with laboratory solids and fines content data. The data was analyzed to determine if there was a particular CPT tip resistance value (i.e. a tip resistance "Index") which would differentiate between fluids and solids across the various deposit types. It was concluded that the solids content data from available sonic sampling were not of sufficient quality to define tip resistance values consistent with the solid/liquid boundary. However, it was also observed that the proposed approach had a strong technical basis and practical merit such that it might be possible to refine further through additional studies and/or research to evaluate and develop correlations between solids/fines contents and the solid/liquid boundary for various tailings types. One suggestion is to use CPT_u tip resistance and pore pressure measured with a piezo-cone to calculate the undrained shear strength and use this value as an index of the deposit strength, regardless of the actual drainage state of the deposit. It was generally agreed that this has strong technical merit as an index but it was not determined to be an equivalent to D074. It was also suggested that COSIA consider looking into other solid content measurement methods (e.g. geophysical methods of measuring volumetric water content) to assess the practicality of this approach.

Standard Tip Resistance Profile

As noted in the previous section, by virtue of its tip resistance value, the CPT could be used to characterize tailings deposits across all of the UOSTCS deposit types. It was suggested that a relatively simple regulatory compliance tool could be constructed by comparing standard tip resistance profiles for theoretical deposits with 5 kPa undrained shear strength with a measured CPT tip resistance profile from a particular deposit. The basis for this approach and the method of development of the proposed standard profile, including an assumption that the deposits will have a minimum undrained strength to overburden stress ratio of 0.2 (which produces a change in slope in the lines at a certain depth) is described in Appendix D.

Data from the available 108 CPT profiles were compared to the proposed standard profiles with limited success. While this approach could simplify regulatory compliance monitoring, the committee was not convinced that the approach provided equivalent performance measures for undrained shear strength within drained or partially drained deposits (i.e. S, SF, and T deposits with SFR>1) which would encompass deposits such as composite tailings (CT) and non-segregating tailings (NST).

Application

The Tailings Measurement Protocol concluded that deposits with an SFR<1.5 (i.e. F and some of T) typically exhibit undrained behaviour under most loading conditions.

DeJong et al. (2013) suggested that materials in which a CPT_u dissipation test gives the time to 50% pore pressure dissipation, t_{50}, greater than 100 seconds will behave in an undrained fashion for a 10 cm^2 penetrometer tip at the standard penetration rate of 2 cm/s. Similarly, the committee considered that for a 15 cm^2 cone, the threshold dissipation time should be 150 seconds (standard penetration rate of 2 cm/s). CPT_u profiles can be used to accurately measure pore pressures in deposits, however, it was considered that they do not present an efficient methodology for year-over-year compliance monitoring.

Directive 074 is not specific whether peak or residual strength is required for compliance. For regulatory compliance the subcommittee understands the 5 kPa requirement to be the peak shear strength of the deposit under undrained conditions.

Measurement Methodology

Two methods of measuring undrained shear strength were considered to be the most appropriate for measuring strength for regulatory compliance: the CPT; and the Field Vane Shear Test (FVST).

Field Vane Shear Test

The FVST is performed by inserting a four-bladed vane into intact soil at discrete depths and rotating the vane at a constant rate by applying a measured torque to create a cylindrical failure surface in the material. Both peak and remolded undrained shear strength can be obtained without further strength corrections. FVST measures undrained shear strength (S_u) directly, but is less efficient than CPT and is limited to fines-dominated soils with undrained shear strength, S_u < 200 kPa.

To achieve good FVST results it is important to ensure that the material being tested is undrained. It is considered that cone penetration and pore pressure dissipation testing be carried out in accordance with ASTM D 5778-12, prior to FVST to define stratigraphy and determine zones of fine-grained tailings in which FVST may be appropriate.

High-quality FVST should be used to calibrate the bearing factors (N_{kt}) for CPT and to determine shear strength of tailings. The FVST should be of sufficient quality to determine shear strengths accurately between 0.5 and 10 kPa with calibration error less than 0.05 kPa and, if done properly, should be more accurate than the production CPT and similarly reliable and repeatable. FVST results can be operator dependent when measuring undrained shear strength.

In such soils, the FVST should be carried out in accordance with the ASTM D 2573-08 to provide a measurement of undrained shear strength. In order to achieve a suitable precision compliant with D074 (± 0.5 kPa), the torque load cell must be calibrated to account for all factors affecting the measured torque. The recommended minimum thickness of the deposit to be tested should be 6H, where H is the height of the vane.

It was considered that the COSIA Tailings EPA could write an addendum to the existing ASTM standard D 2573-08, for FVST, outlining requirements specific to the very low shear strengths of the oil sand tailings. It is, therefore, recommended that for oil sands tailings the test be conducted using ASTM D 2573-08 along with the addendum provided in Appendix E.

Error! Reference source not found. shows the regions of suitability for FVST for various oil sands tailings deposits (adopted from COSIA 2014).

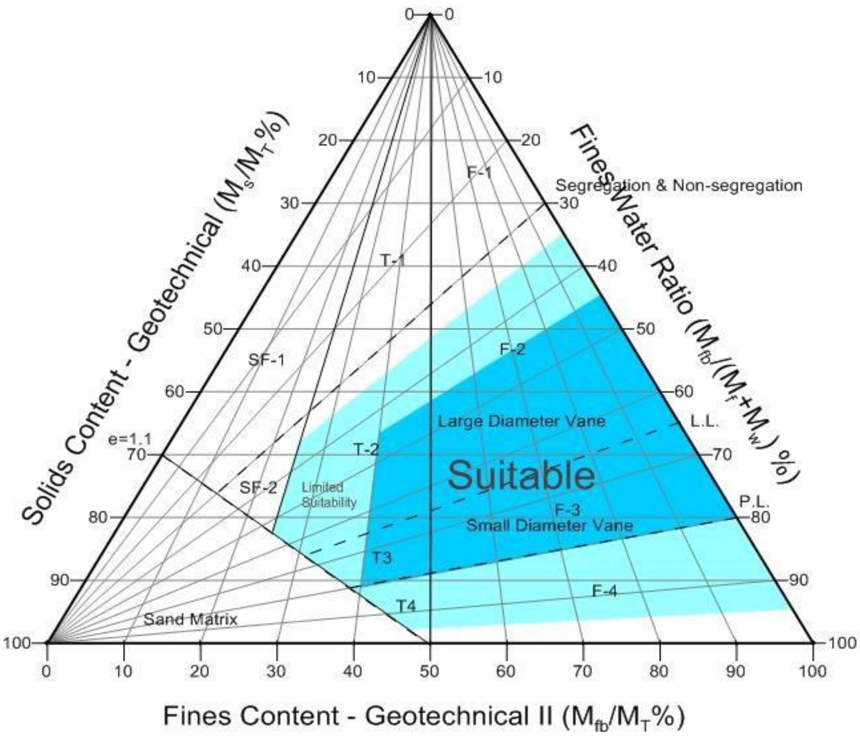


Figure 2: Suitability Chart for Field Vane Shear Test (Adopted from COSIA 2014)

Cone Penetration Test

A cone penetration test consists of inserting a penetrometer with a conical or ball point and friction sleeve into the soil at a constant penetration rate while electronically measuring cone resistance, sleeve resistance, and pore water pressure to produce a continuous data profile with depth. The tip resistance can be corrected for necessary design data (undrained shear strength, friction angle, state parameters, etc.) through the use of well-established correlations after a determination of the appropriate site specific correction factors. For example, the S_u of a fines dominated deposit (SFR<1) can be interpreted from cone tip resistance by a relationship with the site specific N_{kt}.

Based on field work performed by oil sands operators, undrained shear strength derived from CPT tip resistance in fines dominated deposits correlates well with those from FVST. **Error! Reference source not found.** adopted from Oil Sands Measurement Protocol shows regions of suitability of CPT for various oil sands tailings deposits. The test procedures should follow ASTM D 5778-12. For Ball Penetration Test, modification suggested by DeJong (2010) should be followed along with ASTM D 5778-12 (i.e. locating the pore pressure measurement at the equator of the ball, penetration rate of 0.2-0.3 diameters/second, appropriate calibration and recording measurements on both extraction and penetration of the ball).

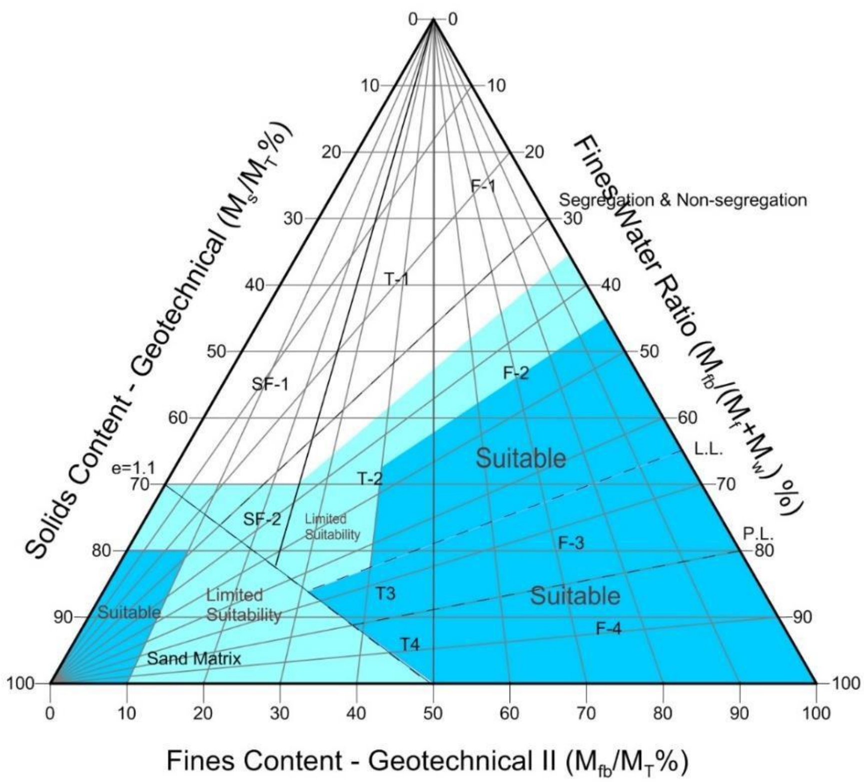


Figure 3: Suitability Chart for CPT (adopted from COSIA 2014)

The CPT is an indirect measurement technique which requires empirically and theoretically derived relationships to convert the cone tip resistance to various soil parameters. The conventional limit of accuracy for cone tip resistance is 25 kPa and 10 kPa for ball, for typical oil sand this would mean an accuracy of ~1.5 kPa for the cone and ~1 kPa for the ball (see Appendix D).

Care should be taken to ensure the cone capacity and tip size is in the appropriate range to provide the desired accuracy. In addition, extra attention must be paid to the load cell calibration to ensure repeatability. Most cones have an accuracy/repeatability of about 0.2% of full-scale output (FSO), although it is possible to be better than 0.1% under ideal conditions. If a cone has a measurement accuracy/repeatability of 0.2% of FSO, the FSO for the tip resistance (q_c) should not exceed about 5 MPa for accuracy of 10 kPa and 15 MPa for an accuracy of 30 kPa.

The CPT measurement is influenced by the material properties - not only the soil layer the cone is in, but by the soil layers ahead of and behind the penetrating cone. The transition from one soil layer to another will not necessarily be registered as a sharp change in tip resistance at the interlayer boundary. In soft material, the cone it is typically reading information 5 cone diameters ahead of the tip, while in harder materials it is influenced by material 20-25 cone diameters ahead of the tip (Ahmadi and Robertson, 2005). Most tailings deposits are relatively soft and the zone of influence ahead of the cone tip is relatively short, typically within about 20 cm of the CPT tip. Exceptions are when a hard layer overlies a softer layer (e.g. when going from a stiff cap to softer deposits underneath). This effect must be well understood when analyzing CPT data. It is for this reason that proper care and caution be employed when analyzing CPT profiles in deposits less than 1 m thick. It is also recommended that CPT traces be interpreted by properly trained professionals equipped with appropriate supporting information from above and below the deposit of interest. It was suggested that low capacity small diameter cones maybe suitable in deposits or layers thinner than 1 m as the smaller tip diameter means a smaller sphere of influence ahead of the cone. Smaller tips may, however, lead to a reduced sensitivity which may be inappropriate in very soft deposits.

Conclusions

Based on the committee deliberations, expert reviews, workshops, and inputs from technical experts the following main conclusions were developed:

- Undrained shear strength as specified in D074 can only be measured in undrained deposits. Undrained deposits are defined as having an SFR $\leq$ 1.5 or t_{50} greater than 100 seconds as measured by a standard 10 cm^2 cone at 2 cm/s advance rate with pore pressure measurement at the cone shoulder (u_2 position ; ASTM D 5778-12), or a t_{50} greater than 150 seconds as measured by a 15 cm^2 cone at a 2 cm/s advance rate.
- It was concluded that FVST is a direct measure of undrained strength and an appropriate technique for calibration of CPT when performed to ASTM standards with sufficient accuracy and repeatability.
- CPT is an indirect measure of undrained shear strength with appropriate reliability, repeatability and productivity to be the preferred method for determining the undrained

shear strength of fines dominated deposits. The correlation between tip resistance and undrained shear strength is site specific, depending on the unit weight and the N_{kt} factor of the tailings.

- Hand-held vane shear testing is recognized as a less reliable version of FVST or CPT but the test is acceptable for testing deposits where FVST or CPT is impractical or uneconomical. CPT should be calibrated/verified with FVST at a limited number of locations for oil sands tailings testing purposes. Other tests which can demonstrate a correlation to FVST are also considered acceptable by the committee.
- CPT is appropriate to “characterize” all deposits types and could be used to provide the stratigraphy of deep or mixed deposits. It may be technically feasible to use the calculation of undrained shear strength as an index of strength in drained deposits.
- A CPT done in accordance with ASTM D 5778-12, and calibrated to FVST measured in accordance with ASTM D 2573 and the proposed addendum (Appendix E), is the recommended method for measuring undrained shear strength in fines-dominated deposits.
- The threshold of $S_u = 5$ kPa is at the very low end of the shear strengths typically measured in land-based geotechnical characterization.
- The committee found no “equivalence to D074” in drained or partially drained deposits (SFR > 1.5, with $t_{50} < 100$ s). These encompass S, SF, & T deposits where SFR > 1 (e.g. deposits such as CT and NST).

List of Appendixes

Acronyms and Definitions

AER	Alberta Energy Regulator
AESRD	Alberta Environment and Sustainable Resource Development
Bitumen Content	Mass of bitumen divided by (mass of solids + water) X100%
Composite Tailings/Consolidated Tailings (CT)	Combined mixture of fluid fine tailings or mature fine tailings, sand and coagulant (e.g.; gypsum)
Cone Penetration Testing (CPT & CPT_u)	CPT is used generically throughout this document and encompasses a variety of equipment tips: cones, balls, and tips with piezometers to measure pore pressures. CPT_u specifies that the equipment must be equipped with a piezometer to measure pore pressure
Consolidation	Compression or densification of a soil deposit through a change in the effective stresses, reduction in void space, and expulsion of pore fluids
COSIA	Canada's Oil Sands Innovation Alliance
Dedicated Disposal Area (DDA)	Defined in D074 as "an area dedicated to the deposition of captured fines using a technology or suite of technologies"
Drained Shear Strength	Measured shear strength when shear stress is applied at a sufficiently slow rate and the drainage boundary conditions are such that excess pore pressure is zero when the failure occurs
FVST	Field Vane Shear Test
Fines Content (FC) or percent fines	Mass of fines divided by mass of mineral solids
Fines, Fine Solids	Mineral solids with particle sizes equal to or less than 44 µm
Fines/(fines + water) ratio (FOFW)	Mass of fines divided by (mass of fines + water) X 100%

Fluid Fine Tailings (FFT)	A liquid suspension of fine tailings or fines-dominated tailings in water, with a solids content greater than 2% but less than the solids content corresponding to the liquid limit. In the context of this report the term “Fluid Tailings” is used synonymously with “Fluid Fine Tailings”.
FSO	Full Scale Output
Geotechnical fines content	Mass of fines divided by mass of solids X 100%
Geotechnical Water Content	Mass of water divided by mass of solids X 100%
Liquid Limit	The geotechnical water content defining the boundary between a liquid and solid in soil mechanics. This state is defined by a standard laboratory test (ASTM D 4318-10; modified for use in oil sands tailings containing bitumen). It can also be described in terms of an equivalent FOFW or solids content. This test results in equivalent remoulded shear strength of 1 to 2 kPa.
L	Litre
m	Metre
µm	Micron or micrometres ($1x10^{-6}$ metres)
mm	Millimetres
Mature Fine Tails (MFT)	A subset of FFT with SFR less than 1 and solids content greater than 30%, nominal
Mineral Solids	Fines and sand
Non-segregating Tailings (NST)	Tailings that form a homogeneous mass upon deposition (i.e. tailings that do not have coarser particles that separate from the finer particles, which are then carried away in runoff water or are re-deposited in discrete layers or zones with particle size distributions dissimilar to that of the original tailings materials)

Pa or kPa	Pascals or kilopascals
Plastic Limit	The geotechnical water content defining the boundary between a plastic (i.e. remouldable) solid and brittle solid in soil mechanics. This state is defined by a standard laboratory test (ASTM D 4318-10; modified for use in oil sands tailings containing bitumen). It can also be described in terms of an equivalent FOFW or solids content. This test results in equivalent remoulded shear strength of about 100 kPa.
Sand	Mineral solids with particle size greater than 44 µm and less than 2 mm (does not include bitumen)
Sand to Fines Ratio (SFR)	The mass ratio of sand to fines; the mass of mineral solids with a particle size greater than 44 µm divided by the mass of mineral solids less than 44 µm
Shear Strength	Shear strength is defined as the maximum or ultimate shear stress that a soil can sustain without undergoing large deformations
Shrinkage Limit	The geotechnical water content defining the point at which a soil, on loss of moisture, will experience no further volume reduction. This state is defined by a standard laboratory test (ASTM D 4318-10; modified for use in oil sands tailings containing bitumen).
Solids	Sand, clay and other solid mineral particles contained in oil sands tailings (does not included bitumen)
Solids Content (SC) or percent solids	Mass of mineral solids divided by total mass (mineral solids + bitumen + water)
Sedimentation	Downward movement of solid particles through a fluid to form a sediment or soil layer at the base of the fluid volume
Settlement	Resulting downward movement of a soil deposit through consolidation or compression within the deposit (often measured on the surface of the deposit)
t_{50}	Time to 50% pore pressure dissipation in a CPT_u pore pressure

	dissipation test
Tailings	A by-product of the bitumen extraction process composed of water, sand, fines, and residual hydrocarbons
Thin Fine Tailings (TFT)	A subset of FFT with SFR less than 1 and solids content less than 30%, nominal
Thickened Tailings (TT)	Tailings treated through thickeners and in-line flocculation
Undrained Shear Strength	Measured shear strength when the drainage boundary conditions are such that the shear-induced excess pore pressure does not dissipate as the material is strained
UOSTCS	Unified Oil Sands Tailings Classification System
Void Ratio (e)	Volume of voids divided by volume of solids
Water Content (w)	Mass of water divided by mass of (solids + bitumen + water)
Whole Tailings (WT)	Tailings produced directly from the primary and secondary separation vessels in the extraction plant, containing sand, fines and water from the oil sands ore plus recycle water

Non-segregating Tailings (NST)	Tailings that form a homogeneous mass upon deposition (i.e.; tailings that do not have coarser particles that separate from the finer particles, which are then carried away in runoff water or are re-deposited in discrete layers or zones with particle size distributions dissimilar to that of the original tailings materials)
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