ON THE FLOW AND BEACHING BEHAVIOUR OF SUB-AERIALLY DEPOSITED, POLYMER-FLOCCULATED OIL SANDS TAILINGS: A CONCEPTUAL AND ENERGY-BASED MODEL

by

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Abstract

This thesis presents the background, observations, and analyses performed during an investigation of the flocculated mature fine tailings (MFT) technology at the Suncor Energy Oil Sands Tailings Reduction Operation (TRO) in Fort McMurray, Alberta, Canada.

The sub-aerial flow and deposition of flocculated MFT on a sloping beach can be described in the context of a rheology-energy conceptual model. The conceptual model, or flow map, can provide deposition cell designers and operators with a useful framework for managing beach development in a sub-aerial deposition cell. Observations during field work resulted in the development of the flow map and the establishment of numerical boundaries for the transitions between flow types. Practical applications for this new conceptual model are provided.

The database of fully-developed beach surveys presented in this thesis demonstrates the trend of strongly concave profiles. This concavity has significant repercussions for tailings management and cell design, and cannot be ignored when calculating storage volumes. Furthermore, it is shown that the McPhail (1995) stream power model provides a robust tool for estimating ultimate beach profiles developed from the sub-aerial discharge of polymer-flocculated MFT. The model has been validated against field-scale measurements and is consistent with the rheology-energy conceptual model developed to describe the flocculated MFT flow behaviour.
Preface

The work documented in this thesis results from the author’s employment with Robertson GeoConsultants Inc. (Vancouver, British Columbia) under contract with Suncor Energy Inc. (Calgary, Alberta). The Suncor Energy sponsor for this work, and main contact during field activities, was Ana Sanchez of Suncor’s Tailings Reduction Operations (Fort McMurray, Alberta).

The preparation of this thesis was completed under the supervision of Professor Dirk van Zyl, PhD., of the University of British Columbia (Vancouver campus).

Rheological data in Chapter 3 was reproduced in this thesis with the permission of Dr. Adrian Revington (Suncor Energy Inc.).

In Chapter 7, beach profiles S4A, S4B, S4C, S5A, and S5B were extracted from LIDAR survey data obtained and post-processed by SNC-Lavalin Inc. (formerly MDH Engineered Solutions Ltd. of Saskatoon, Saskatchewan) under contract with Suncor Energy Inc. Dr. Gordon McPhail of Metago Environmental Engineers Ltd. (Perth, Australia) kindly provided his spreadsheet model for beach modelling in Chapter 7.

The field work and analyses presented in Chapters 4, 5, 6, 7, and 8 were completed by the author, with the exception of laboratory analyses presented in Tables 5-3 and 5-4 which were conducted by SGS Laboratories (Fort McMurray, Alberta) under contract with Suncor Energy Inc.
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\( g \) acceleration due to gravity \([L/T^2]\)
\( p \) fluid pressure \([F/L^2]\)
\( \Delta n \) fluid element depth \([L]\)
\( \Delta s \) fluid element length \([L]\)
\( W \) fluid weight \([F]\)
\( \Theta, i, \alpha \) inclination of the element relative to the horizontal plane \([^\circ]\)
\( \gamma \) fluid unit weight \([F/L^3]\)
\( t \) time \([T]\)
\( v_x, V_x \) fluid velocity in the \( x \) direction \([L/T]\)
\( E_k \) unit volume kinetic energy (dynamic pressure) \([ML^2/T^2]\)
\( \rho \) fluid mass density \([M/L^3]\)
\( Re \) Reynolds number [-]
\( \mu \) dynamic viscosity \([FT/L^3]\); see also \( \mu \) shape parameter (McPhail, 1995)
\( L \) characteristic linear dimension for an open channel (hydraulic radius) \([L]\)
\( R_h \) hydraulic radius \([L]\)
\( A \) cross-sectional flow area (perpendicular to flow direction) \([L^2]\)
\( P \) wetted perimeter \([L]\)
\( r \) channel half-width \([L]\)
\( Fr \) Froude number [-]
\( y \) mean flow depth \([L]\)
\( \tau \) shear stress \([F/L^2]\)
\( \tau_{0}, \tau_c \) yield stress, critical shear stress \([F/L^2]\)
\( \gamma \) shear rate \([T^{-1}]\)
\( K, n \) Herschel-Bulkley fluid model parameters [-]
\( R_{HB} \) Reynolds number for a Herschel-Bulkley fluid [-]
\( h \) fluid height perpendicular to the inclined plane \([L]\)
\( h_c \) critical fluid height \([L]\)
\( d \) flow thickness \([L]\)
\( w \) levee width \([L]\)
\( \Theta \) solids volume fraction [-]
$z, z_0$ elevation of the beach, elevation at the beach head [L]

$x$ distance along the beach [L]

$n$ Melent’ev (1973) profile shape parameter [-]

$S, S_0$ Melent’ev (1973) slope of beach surface, slope at beach head [-]

$A, \omega$ Williams and Morris (1989) beach slope parameters [-]

$Q$ flow rate [L$^3$/T]

$c_v$ slurry solids concentration by volume [-]

$d_{50}$ median particle diameter [L]

$d_{90}$ 90$^{th}$ percentile particle diameter [L]

$v_c$ minimum transport velocity [L/T]

$f$ Fanning friction factor [-]

$S_0$ Fitton (2007) equilibrium slope [-]

$y/V$ normalized vertical beach coordinate [-]

$x/H$ normalized horizontal beach coordinate [-]

$c$ normalized beach profile shape factor [-]

$H$ head difference between point of discharge and end of beach slope [L]

$P_x$ stream power at distance $x$ from the downstream lip of the plunge pool [ML$^2$/T$^3$]

$\mu$ McPhail (1995) shape factor for stream power decay curve (not equivalent to dynamic viscosity) [-]

MFT Mature Fine Tailings

tMFT (polymer) treated Mature Fine Tailings

dMFT tMFT deposited on a beach

TRO Tailings Reduction Operations (Suncor)

DDA Dedicated Drying Area (Suncor)
Acknowledgements

Many people and organizations have contributed to this project – many more than I can name here.

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Finally, thank you to Elizabeth for her patience, brilliance, and baking.
In memory of my grandmother, Marion
Chapter 1: Introduction

1.1 Overview

This thesis describes the background, observations, and analyses performed during an investigation of flocculated mature fine tailings technology at the Suncor Oil Sands Tailings Reduction Operation (TRO) in Fort McMurray, Alberta, Canada.

The Suncor TRO technology comprises the flocculation of suspended fine particles from impounded tailings to create a soil that can be dewatered and made trafficable. The strategy succeeds the Consolidated Tailings (CT) technology employed at the Oil Sands site. Suncor has led the industry in developing the TRO technology and has made great strides in reducing the operational and environmental risk associated with existing fluid tailings ponds.

This thesis focuses on the overland flow and beaching behaviour of the TRO flocculated tailings. A thorough understanding of the depositional tendencies and ultimate beach profiles is necessary for operational and reclamation planning purposes. The underlying context of this work is a need for field data for the validation of beach profile models, energy-based or otherwise.

1.2 Hypothesis and Objectives

This thesis tests the hypothesis that (i) the sub-aerial flow of flocculated oil sands tailings can be succinctly described within the context of rheology and energy principles using field measurements, and that (ii) the ultimate two-dimensional deposition profile can be predicted with an energy-based analytical model.

The objectives of this study are fourfold, namely to:

i. Identify and describe the key rheological, hydraulic, and geomorphological flow behaviours of the polymer-flocculated oil sands tailings at Suncor Energy’s Tailings Reduction Operation;

ii. Develop a conceptual framework that describes the range of flow conditions observed;

iii. Identify candidate models for the observed flow and depositional behaviours; and to

iv. Validate the most appropriate beach profile model with field data.
The product of this study is a more thorough understanding of the depositional behaviour of flocculated oil sands tailings and a field-validated model for forecasting beach profiles. This knowledge can be used to improve management of this material during the deposition process.

1.3 Research Needs

1.3.1 Integrated Models
There remains a need for user-friendly, integrated beach development models (combining beaching mechanics and elementary hydraulics, energy conservation principles, and the acknowledgement of non-linear beach profiles) that can be used at an operational level for planning and management purposes. An integrated model will also reflect the impacts of material variability as process and operational conditions change. Ideally, the integrated model should be based on readily obtainable field measurements and operational parameters like flow density, static yield stress, and discharge rate.

1.3.2 Field Validation
Field validation for current flow and deposition models is somewhat limited, owing perhaps to the relative youth of these models, and potentially due to a lack of adoption by industry. The latter point may be due to the inherent complexity and empirical data requirements of some models, combined with the need for a priori assumptions.

Much of the existing literature is based on laboratory flume studies (Fitton, 2007; Küpper, 1991; Simms and Henriquez, 2009) which are somewhat restrictive in that they (i) restrict flow to channels, (ii) impose flow on a monotonic (uniformly sloping) surface, and (iii) may not achieve flow rates and hydraulic conditions commensurate with field-scale deposition.

Fourie (2010) indicates that the application of flume-derived results is limited without appropriate scaling corrections, and that the variation in yield stress of the tailings, both as a result of process output and due to breakdown during deposition, may well be the most important factor determining beach slopes.

1.3.3 Role of this Work
This work aims to characterize the flow and deposition of flocculated oil sands tailings in the context of rheology and energy using readily obtained field measurements. It is the intent that this work will serve as the basis for further research into integrated models for beaching behaviour and deposit formation.
1.4 Thesis Structure

This thesis is organized into eight chapters by topic area, namely:

**Chapter 1: Introduction**

This chapter provides an overview of the objectives and hypotheses of this thesis.

**Chapter 2: Management of Flocculated Mature Fine Tailings**

This chapter provides an overview of flocculated mature fine tailings management at Suncor Energy’s Oil Sands and the problem setting.

**Chapter 3: Previous Work and Theory**

This chapter summarizes the previous work and theory developed to describe the flow and deposition of tailings and other analogous materials. Existing beaching models are reviewed.

**Chapter 4: Field Setting and Methods**

This chapter describes the field setting for this work and the methods used for data acquisition and interpretation.

**Chapter 5: Field Observations of Flow and Deposition of Flocculated Mature Fine Tailings**

This chapter collates and interprets the field observations of flocculated MFT flow and deposition.

**Chapter 6: The Flow Map – A Rheology-Energy Conceptual Model**

This chapter presents the conceptual model for flocculated tailings flow, supported by quantitative field measurements.

**Chapter 7: Beach Profile Modeling**

This chapter describes the modeling undertaken to validate the McPhail model for predicting the beach profile of sub-aerially deposited, polymer-flocculated MFT.

**Chapter 8: Application and Discussion of the Results**

This chapter provides an overview of practical applications for the results of this work and discusses implications for the management of flocculated mature fine tailings.

**Chapter 9: Conclusions and Recommendations**

This chapter summarizes the key conclusion of this thesis including the outcomes of the hypothesis and recommendations for future research.
Chapter 2 : Management of Flocculated Mature Fine Tailings

2.1 Flocculation of Mature Fine Tailings – The TRO Process

A thorough description of the flocculation process is beyond the scope of this thesis; however, the following section briefly summarizes the process as outlined in the process patent documentation (Suncor Energy Inc., 2011).

Oil sands tailings comprising sand and fines fractions which meet the criteria for mature fine tailings (MFT) are treated with a high molecular weight polymer to achieve flocculation and to promote dewatering. The Tailings Reduction Operations (TRO) process at Suncor’s Oil Sands can be simplified into the following main steps:

- Selective dredging of MFT from active or inactive tailings ponds
- Dispersion of polymer solution into feed MFT stream
- In-line mixing and conditioning of MFT and polymer solution during transport to the deposition cell
- Discharge from spigots to dewatering/drying cell with sloping beds
- In-situ dewatering and drying under climatic conditions

Additionally, under certain circumstances the following activities may be undertaken to enhance dewatering and to create new deposition area:

- In-situ mechanical working of flocculated MFT
- Mechanical excavation and relocation of dewatered MFT to stockpiles

The details of this process depend heavily on the characteristics of the feed material and are applied on a source-by-source (pond-by-pond) basis.

2.2 Characteristics of Flocculated Mature Fine Tailings

2.2.1 Dewatering Behaviour

The amount and extent of dewatering is dependent on the flocculation efficacy and the shear conditioning of the material as it exits the discharge pipe and flows across the deposition cell.

Dewatering performance is assessed using the net water release value, compared to the expected water release for a known material under laboratory conditions. During the flocculation process, polymer is...
introduced as a solution, thereby adding water to the stream. Therefore, the performance evaluation must take into account both the MFT pore water released as well as the amount of polymer solution water recovered. The calculation is performed on the basis of the initial, non-flocculated MFT moisture content (Equation 2-1):

\[
Net \ Water \ Release \ (NWR) = \frac{Volume \ Water \ Recovered - Volume \ Polymer \ Water \ Added}{Volume \ Initial \ MFT \ Water}
\]

Equation 2-1: Equation for calculation of net water release (NWR)

If the net water release is positive and high, then the material is relatively well flocculated and should experience significant dewatering upon deposition. The converse is true for materials showing negative NWR values.

Another metric for material performance is based on the measured yield stress. The various reaction stages are delineated by yield stress limits assigned according to the measured water release after designated mixing (conditioning) times (Figure 2-1).

![MFT Flocculent Reaction Stages](image.png)

Figure 2-1: Reaction stages for flocculated MFT (Suncor Energy Inc., 2011)
Note that the optimal water release stage does not coincide with the peak yield stress, rather it falls behind the peak; this phenomenon may be attributed to the breakage of flocculated masses ("flocs") during subsequent mixing.

2.2.2 Variability
Flocculated MFT is capable of exhibiting a variety of behaviours depending on several factors, namely the:

- MFT source characteristics,
- Efficacy of the flocculation (dispersion/mixing) process, and
- Conditioning of the flocculated material in-pipe before deposition.

Each of these factors contributes to the characteristics of materials deposited into dewatering cells. An investigation of these contributing factors is beyond the scope of this work; however, it is recognized that the process conditions are intimately linked to flow behaviour and beaching tendencies in the deposition cells.

2.3 Sub-aerial Deposition of Flocculated Mature Fine Tailings

2.3.1 Discharge and Containment
Flocculated MFT is discharged through linear spigot arrangements into cells which may or may not have physical separation berms between adjacent cells. The cells are generally rectangular, with the primary (long) axis aligned across the bed gradient and parallel to the direction of discharge. Each cell is typically fed by four to six spigots. The approximate footprint of the cells varies from 100 m by 50 m (0.5 Ha) to 280 m by 80 m (2.2 Ha).

The base of the cell is generally constructed with local materials, namely tailings sand or local clays. The cells are graded to promote drainage and to facilitate the collection of runoff. The grade varies from site to site, and generally reflects local topography with slopes of <1% to 5%.

Perimeter berms enclose the cells on all sides, except in the case of cells located on the perimeter of water ponds, where the water line represents the downstream limit of the cell (although materials may flow beyond this point into the water body). Header berms are raised in the upstream or centreline manner, depending on the availability of land adjacent to the cell and the ultimate height of the berm.
Flocculated MFT will fill the cells in different manners and with different efficiencies, depending on the relationship between the fluidity of the material, the energy of the flow, and the geometry of the cell. Fluidity is defined at this point as the inverse of apparent viscosity. Highly fluid materials with low viscosity will tend to fill the furthest reaches of the cell first (achieving the lowest potential energy at the lowest elevation), and then gradually increase the deposit thickness so that the surface approaches horizontal. This filling process is limited by the downstream berm height. High viscosity materials will tend to remain near the point of discharge and build upwards (aggrade) at a geometry related to the yield strength and discharge rate (McPhail, 1995) among other factors. This process is limited by the upstream berm height and elevation of the discharge spigots. A combination of both these accumulation processes will be most effective at filling the cell and maximizing footprint utilization on a tonnes-per-area basis.

2.3.2 Mechanical Disturbance

After having been discharged into the containment cell, flocculated MFT may be mechanically disturbed under the following circumstances:

- Under threat of overtopping the upstream containment berm or covering the discharge spigots due to stacking of material at the point of discharge, earthmoving equipment may have to reshape the beach
- Under inhibited drying conditions where the material needs to be over-turned to promote drying of the entire deposit profile (typically as the result of surface crusting that effectively shuts down evaporation)

Both of these conditions may arise due to the behaviour of high viscosity tailings, which are observed to form thick deposits near the point of discharge.

2.3.3 Reclamation

If the flocculated MFT deposit is to remain in place, it can be anticipated that the ultimate deposit surface will require some degree of reclamation. It is thus important to establish the range of ultimate beach profiles expected for accurate estimates of reclaimable surface area and for design of surface water run-off and erosion control measures.
2.4 The Role of Rheology in Tailings Management

Rheology in the broadest sense is the study of the flow of matter. The study of flow is an important concept with broad applicability to tailings management, and more generally to design challenges for extractive industries (Nyugen & Boger, 1998; Boger, 2009). More technically, rheology is the quantification of a material’s shear stress response to applied shear rate, or vice versa. Appendix A provides a review of basic rheological principles.

The two primary rheological quantities for tailings engineers both for pipeline design and deposition management are the yield stress and viscosity of the material. These two quantities can be related by fitting a mathematical model to empirical data, typically derived in the laboratory. Recently, however, practitioners have developed and refined field methods for quantifying tailings rheology (Pashias & Boger, 1996; Fisher et al., 2007; Boger, 2009). These field methods offer fast and reliable procedures for obtaining rheological data in the field. The significance of this development is that observations of field-scale flow and deposition behaviour can be readily supported by sound rheological measurements. The control of rheological behaviour is of particular significance for surface disposal of tailings (Boger, 2009).
Chapter 3: Previous Work and Theory

3.1 Open Channel Flow Regimes

3.1.1 Description of Open Channel Flow

This thesis is not restricted to the study of flocculated MFT flowing in open channels; however, several important concepts for the description of flow can be illustrated by application of the theory. Thus, it is useful here to review several key hydraulic principles.

Figure 3-1 illustrates the free body diagram for a fluid element flowing under gravitational influence where $p$ is the fluid pressure on the upstream face, $\Delta n$ is the depth of the fluid element, $\Delta s$ is the length of the fluid element, $W$ the weight, and $\theta$ the inclination of the element relative to a horizontal plane (datum).

![Free body diagram for a fluid in motion](image)

Figure 3-1: Free body diagram for a fluid in motion (from Chaudhry, 2008)

It can be shown that for an inviscous fluid, the motion of a fluid element is described by the Euler equation of motion (Equation 3-1):

$$
\rho \left( \frac{\partial V_s}{\partial t} + V_s \frac{\partial V_s}{\partial s} \right) + \frac{\partial}{\partial s} \left( p + \gamma_f z \right) = 0
$$

Equation 3-1: Euler equation for motion

where $\rho$ is the fluid mass density, $V_s$ is the velocity in the $s$ direction, $t$ is time, and $\gamma_f$ is the unit weight of the fluid.
For the special case of steady flow, the change in velocity over time is zero and Equation 3-1 reduces to the Bernoulli equation for flow (Equation 3-2):

$$\frac{1}{2} \rho V_s^2 + p + \gamma_f z = \text{Constant}$$

Equation 3-2: Bernoulli equation for flow

The three left-hand terms represent the velocity head, pressure head, and elevation head, respectively. The velocity dependent term is also referred to as the \textit{dynamic pressure}. In reality, this is not a pressure in the physical sense, rather the term results from a unit analysis that shows equivalence to the Pascal unit. In this thesis, the terms dynamic pressure and unit volume kinetic energy are synonymous and are defined as:

$$E_k = \frac{\rho v^2}{2}$$

Equation 3-3: Definition of unit volume kinetic energy

As a basis for comparing flocculated MFT flows with varying densities and velocities, the unit volume kinetic energy (Equation 3-3) was determined to be a valuable descriptor.

Furthermore, Albertson et al. (1963) elucidate the four essential elements required to describe the state of a fluid in motion. The classification scheme includes information on the temporal and spatial characteristics of the flow, as well as indices concerning the competition between viscous and inertial forces.

The eight end-member descriptors of the four elements are provided thus:

1. Uniform or nonuniform
2. Steady or unsteady
3. Laminar or turbulent
4. Tranquil or rapid

These descriptors are further examined in the following subsections as they provide a theoretical framework for documenting flow observations (Albertson et al., 1963).
3.1.1.1 Uniformity
Uniformity refers to the spatial consistency of flow geometry so that the depth, slope, and cross section of flow are identical along the entire length of the streamline. These conditions imply that the flow velocity does not change along the flow path, otherwise the flow is said to be nonuniform. A truly uniform flow is rarely observed in nature.

3.1.1.2 Steadiness
A steady flow is one which does not change over time; specifically, the velocity at a fixed point of observation does not change over time. Examples of unsteady flows are surges caused by rapid upstream increases or decreases in flow rate.

3.1.1.3 Turbulence
Classically, flows are described as laminar, turbulent, or transitional. In laminar flows, internal viscous forces dominate inertial forces such that the flow lines remain parallel along the length and depth of flow. Mixing in a laminar flow regime is relatively small as a result of molecular-level activity only.

Turbulent flows are characterized by a predominance of inertial forces over viscous forces, which results in instability, the random generation of eddy currents within the flow, and considerable mixing due to macroscopic particle motions.

The transition from laminar to turbulent flow is often defined by a characteristic Reynolds number \( Re \), Equation 3.4 as in pipe hydraulics, where:

\[
Re = \frac{\rho v L}{\mu}
\]

Equation 3.4: Reynolds number calculation

In Equation 3.4, \( \rho \) is the fluid mass density, \( v \) is the fluid velocity, \( \mu \) is the dynamic viscosity and \( L \), the characteristics linear dimension for an open channel, is given by Equation 3.5:

\[
L = \text{Hydraulic Radius}, R_h = \frac{A}{P}
\]

Equation 3.5: Hydraulic radius formula

where \( A \) is the cross sectional area of flow and \( P \) the wetted perimeter. For a circular cross-sectional area, this reduces to \( r/2 \) where \( r \) is half the width of the channel.
The value of $Re$ at the point of transition is widely debated (ranging from 150 for open channel flow to 4000 for pipe flow), thus no numerical value is suggested here; rather, it is noted that empirical evidence must support the delineation of a transitional boundary or range for any given fluid.

### 3.1.1.4 Critical Flow

Critical flow is a metric similar to the Reynolds number in that it provides a measure of flow stability and is used to distinguish between tranquil and rapid flows; however, its formulation is different and applies only to flows with a free surface (i.e. open channels). A flow is assessed to be sub-critical, critical, or super-critical based on the Froude number, $Fr$ (Equation 3-6):

$$Fr = \frac{v}{\sqrt{gy}}$$

**Equation 3-6: Calculation of the Froude number**

where $g$ and $y$ represent acceleration due to gravity and flow depth, respectively.

In essence, the Froude number describes the potential of downstream disturbances (waves) to migrate upstream, and hence illustrates the flow stability.

Generally, for $Fr < 1$ the flow is considered tranquil or sub-critical. At $Fr$ equal to 1, the flow is critical and beyond this threshold the flow is considered as rapid or super-critical. Very rapid flows may manifest as surges in otherwise uniform flow regimes (Albertson et al., 1963).

For the purposes of this thesis, and to avoid the ambiguity of the Reynolds number transitional range, the Froude number is the preferred metric of flow stability.

### 3.1.2 Open Channel Flow of Non-Newtonian Fluids

Non-Newtonian fluids exhibit a viscosity that is dependent on the rate of applied shear. A Herschel-Bulkley model can be applied to laboratory-derived rheological data to describe this relationship. The Herschel-Bulkley model relates shear strain to shear stress by Equation 3-7:

$$\tau = \tau_0 + Ky^n$$

**Equation 3-7: Herschel-Bulkley rheological model**
where the parameters $K$ and $n$ are empirically determined by curve fitting and $\tau_0$ is the static yield stress.

The form of this mathematical relationship and the coefficients adopted will dictate the predicted flow behaviour of a non-Newtonian fluid under different hydraulic conditions. Haldenwang (2003), Küpper (1991), and Haldenwang and Slatter (2006) provide methodologies for determining transitional boundaries for laminar and turbulent flow for a wide variety of control fluids including clay suspensions; however, this work is restricted to flume studies (typically 75 to 300 mm in width). The work provides a substantive database of flow observations; however, the data is not validated by field observations.

Haldenwang et al. (2002) define a Reynolds number for non-Newtonian fluids based on flume testing conducted with an array of flume geometries (including semi-circular) and present the new Reynolds number, $R_{HB}$, in the form of Equation 3-8.

$$R_{HB} = \frac{\theta \rho v^2}{\tau_y + k(\frac{2\rho v}{R_H})^a}$$

Equation 3-8: Equation for non-Newtonian Reynolds number (Haldenwang et al., 2002)

Burger et al. (2010) present results that show the onset of turbulent flow for various non-Newtonian fluids occurs at values of $R_{HB}$ greater than 1000 and Straub et al. (1958) show the onset of transition between a Reynolds number of 2000 and 3000. Again, the wide range of reported values for these open channel flows precludes the use of the Reynolds number in this thesis.

To the author’s best knowledge, the open channel flow of non-Newtonian fluids in a field environment, such as a mine tailings beach, has been described to a very limited degree and merits more attention.

### 3.2 Tailings Beaching Observations

#### 3.2.1 Beaching of Tailings

The beaching of tailings is defined in this thesis simply as the deposition of solid particles so that they come to rest at the base of the flow. This requires that the solid particle be removed from suspension in the fluid mass, or conversely, that the volume of matrix fluid be reduced to a point where the solid structure can come to static equilibrium. In a sub-aerial channel flowing with tailings slurry, beaching may be conceivably accomplished by several means, namely:
i. Settlement of particles through the fluid column due to a loss of buoyancy (decrease in density contrast between the solids and the carrier fluid) (Coussot, 1997); that is, the fluid carrier decreases in density due to addition of water or due to flocculation of fine matrix particulate;

ii. Relaxation of the suspension structure, allowing a previously supported particle to fall through the fluid column, or such that the tailings mass can reach static equilibrium (i.e. spreading or expansion of the fluid into a vessel or channel of different geometry) (Coussot, 1997);

iii. Decrease in carrier fluid velocity, resulting in the downward component of the gravitational force to dominate the system;

iv. Increase in the apparent size and mass of suspended particles due to flocculation, which also results in effects due to (i) and (ii); or by the

v. Loss of the carrier fluid through seepage to the bed, evaporation, or “run-away”.

The term run-away is used in this thesis to describe water that is expelled from the tailings slurry and neither seeps through the bed, nor is evaporated at surface. This water is expelled to the surface of the flow and has the ability to run down slope at a rate greater than the tailings mass due to its relatively low viscosity. This results in an apparent increase in the slurry solids content and yield stress, and will eventually cause the mass to stop flowing. At this point, the tailings may also be considered beached.

The following sub-sections outline the general mechanisms associated with the formation of mine tailings beaches.

### 3.2.1.1 Sedimentation and Segregation

Sedimentation of particles occurs when the kinetic energy (velocity) of the flow decreases to a point where the gravitational force dominates the system and the particles fall through the fluid column to settle on the channel bed or along the channel wall (Coussot, 1997). The change in velocity may be the result of changes in the discharge rate or by the natural loss of energy of the stream over distance (McPhail, 1995). Sedimentation requires that the free falling particles occupy a carrier fluid at a density that permits sufficient downward migration of particles over a reasonable time and distance relative to the length of the flow path (Coussot, 1997).

Sedimentation is naturally accompanied by segregation, whereby low density and relatively small particles are carried further downstream than more dense, larger particles. The combination of these
phenomena (sedimentation and segregation) is often cited as the dominant mechanism in beach formation for many situations (Melent’ev et al., 1973; Blight & Bentel, 1983; McPhail, 1995).

3.2.1.2 Yield Stress Fluid Stoppage

Flow of a yield stress fluid (that is, a fluid which requires some minimum stress be applied before it will move) occurs above its characteristic static yield stress. Below that point, the fluid may exhibit some elastic behaviour, but will not yield and flow (Coussot, 1997).

Hence, as a flow moves down gradient, it experiences internal and external energy losses until such point where the shear rate decreases and its stress state falls below the critical static yield stress (Coussot, 1997). Below the critical static yield stress, the fluid will no longer flow along the present gradient.

In the case of fluid stoppage applied to flocculated MFT, one must also conceptualize the flowing mass as a fluidized soil structure which loses moisture to the environment (through bed seepage and surface run-away) and not just as soil particles suspended in a carrier fluid.

The nature of this deposition mechanism is strongly dependant on the material rheology. It can be shown that a uniform steady flow will develop if the gravitational driving force on an element of fluid exceeds the viscous force (Coussot, 1997). For this circumstance to arise, some critical depth (and hence mass) of fluid must exist to exceed the resistive shear stress along the base of the fluid element (Figure 3-2).

![Figure 3-2: Free body diagram of a fluid element on an inclined plane (steady, uniform flow)](image-url)
The depth of fluid required to sustain flow is referred to as the critical height \( h_c \):

\[
h_c = \frac{\tau_c}{\rho g \sin i}
\]

**Equation 3-9: Calculation of the critical height**

where \( \tau_c \) is the yield stress of the fluid, \( \rho \) is the fluid density, and \( i \) is the inclination of the plane with which the fluid is in contact.

An illustration of the critical height as a function of inclination and yield stress is presented in Figure 3-3.

![Figure 3-3: Relationship between critical height, inclination, and yield stress.](image)

Equation 3-9 is very similar to the method of flow depth estimate provided by Hulme (1974) for viscous lava flows; however, the \( \sin(i) \) term is replaced by \( \tan(i) \), which under relatively shallow slopes yields nearly indistinguishable results.

It should be noted that for truly uniform flow to be realized, the critical height must be observed over the entire flow length. Assuming the fluid density does not vary significantly across the length of the
flow, then the beach inclination supporting the flow must be held constant over the flow distance (i.e. the previous underlying beach slope is monotonic). It will be shown in Chapter 6 that this is not the case for beaches formed of flocculated MFT.

3.2.2 Natural Analogues
Natural analogues are provided here as they illustrate the vast base of research regarding the overland flow of yield stress fluids and the deposition of solids from aqueous systems.

3.2.2.1 Lava Flows
Due to the risk associated with lava flows, their dynamics have been studied and modeled extensively (Park & Iverson, 1984). The primary areas of research include the prediction of flow velocities and the change in flow viscosity with time (Griffiths, 2000).

The Jeffreys Equation (Jeffreys, 1925) is employed extensively in lava flow modeling and permits estimation of the velocity (v) of a free-flowing lava mass based on the lava viscosity and the slope of the base on which it moves (Nichols, 1939; Griffiths, 2000). The equation (in centimetre-gram-second units) is given as:

$$v = \frac{\rho gt^2}{3\mu \sin (\alpha)}$$

Equation 3-10: Equation for calculation of flow velocity of lava (Jeffreys Equation)

where \( t \) is the average flow thickness, \( \mu \) is the dynamic viscosity of the lava, and \( \alpha \) is the inclination of the slope supporting the flow.

Equation 3-10 can be re-arranged to solve for the viscosity when a flow velocity is measured along with the flow thickness (Equation 3-11).

$$\mu = \frac{\rho gt^2}{3v \sin (i)}$$

Equation 3-11: Equation for calculation of dynamic viscosity of flowing lava

These relationships show the relative sensitivity of flow velocity to rheology and physical constraints such as the bed slope.
Lava flows are typically modeled as Bingham fluids (Shaw 1969; Hulme 1974; Mc Birney and Murase, 1984); however, application of a Herschel-Bulkley model has also been successful (Griffiths, 2000). In reality, the Bingham model is only a special case of the generalized Herschel-Bulkley formulation.

The main controls on lava viscosity, and hence on lava flow patterns and deposit formation, are mineralogical composition, crystallization, temperature, and the presence of gas bubbles (Griffiths, 2000). The viscosity is thus strongly time-dependant as a result of cooling and vesiculation.

Hulme (1974) shows that a flow at equilibrium on a steep slope will be thinner than a flow on a shallow slope (rheology being equal). The relationship between flow thickness (depth), bed slope, and yield stress is illustrated by Equation 3-12:

\[ d = \frac{\tau_y}{\rho g \tan(i)} \]

Equation 3-12: Calculation of lava flow thickness

Lava flows are described as ranging from rapid flowing channels flanked by solidifying levees, to slow, creeping flows (Griffiths, 2000). The geometry (width, \( w \)) of the levees has been empirically correlated to the yield strength of the lava by Equation 3-13:

\[ w = \frac{\tau_y}{2\rho g \tan(i)^2} \]

Equation 3-13: Calculation of levee width of a lava flow

Although yield strength, viscosity, and slope will affect the run-out distance of a lava flow, Walker (1973) concludes that eruption rate was the factor most strongly correlated with run-out.

### 3.2.2.2 Mudflows

The flow of concentrated suspensions of granular materials has been extensively studied. Coussot (1997) provides an exhaustive treatment on mudflow rheology and dynamics, relating the suspension behaviour to rheology, and ultimately to macroscopic flow behaviour. Coussot (1997) asserts that the viscosity of a concentrated suspension tends to infinity at some critical solids volume fraction, expressed as the volume of solids in a sample divided by the total volume of the sample (Equation 3-14).
At this critical value, the suspension attains the geometric packing limit. The use of the solid volume fraction for characterizing concentrated suspensions is motivated by the observation that fluid behaviour is not heavily dependent on density (and hence mass relationships) but is strongly related to the relative fractions of solid and fluid phases (Coussot, 1997).

Mudflows can be more generally classified as hyperconcentrated sediment flows, which, depending on the solids concentration may be considered either as mudfloods, mudflows, or debris flows (Julien & Leon, 2000). Most mudflow modeling efforts have focused on run-out prediction and resultant forces on stationary objects (Julien & Leon, 2000) and have not been used to predict deposit profiles explicitly although some 2D and 3D codes integrated with Geographical Information Systems are capable of producing mudflow cross sections over true topography (D’Ambrosio et al., 2003; Laigle & Coussot, 1997; Malet et al., 2004).

Coussot (1997) provides a conceptual model for momentum transfer effects in suspensions which describes the transitional boundaries between systems controlled by colloidal, Brownian, hydrodynamic, and inertial interactions.
Figure 3-4 suggests that the flow behaviour of a concentrated suspension will be a function of both the physical fluid characteristics and of the applied or embodied energy of the system.

Huang and Garcia (1998) show that the rheology of mudflows may be best modeled using a Hershel-Bulkley model and the run-out distance is significantly affected by shear-thinning effects but that the behaviour is highly sensitive to the concentration of solids in suspension.

### 3.2.2.3 Alluvial/Submarine Fans

Fans of sediment typically form sub-aqueously as rivers discharge to lakes or ocean environments. In these cases, the stream velocity is rapidly reduced and the energy required to maintain sediment particles in suspension is dissipated. The morphology of some fans mimics quite closely the geometry of hydraulically placed fills and mine tailings (Melent’ev et al., 1973).
3.3 Rheological Considerations for Flocculated MFT

3.3.1 General Considerations
Coussot (2005) provides a thorough description of rheological considerations for the testing of concentrated suspensions such as mineral suspensions and industrial fluids. Based on those principles, the rheometry (the measurement of rheological parameters) of flocculated MFT should take into account several key considerations. Specifically, a rheological measurement used to make field-scale extrapolations should be made:

- At a scale appropriate to the parameter of interest, giving consideration to the micro- and macro-scale structures observed in flocculated MFT;
- Over a range of applied shear rates so that the energy imparted to the material most closely reflects actual field conditions;
- While taking into consideration the evolution of a dewatering material; that is, the measurement must allow for loss of moisture through drainage and to a lesser extent, by evaporation. Furthermore, moisture may be reincorporated if too much energy is applied over a given time period; and
- With knowledge of the previous stress state(s) of the material.

More generally, the rheological measurement should account for the potential for thixotropy (or rheopexy), shear thinning (or thickening), and the effects of soft-jamming particles, boundary effects, shear heterogeneity, and particle settling (Coussot, 2005). These behaviours are described further in following sections.

3.3.1.1 Scale Effects
A flow of flocculated MFT may be observed at several useful scales (Figure 3-5). First, the complete flow pattern may be observed, where the entire flow interacts both with itself (internal viscous forces) and with the surrounding environment (external friction forces and momentum loss). In this thesis, this is referred to this as the flow scale. Secondly, the flow may be observed at the scale of visually discernible interactions between flocculated MFT particles (flocs) and colloidal structures (floc aggregates). This macroscopic scale of observation focuses on internal viscous forces and particle-particle interactions that determine the rate of energy loss within the system. Finally, there are the mesoscopic and microscopic scales of observation which focus on clay-clay and clay-polymer interactions (or more generally, particle-particle, and particle-polymer) interactions.
Scale-dependant measurements may be obtained under circumstances where the scale of the instrumentation is relatively close to or below the scale of the main structural-rheological components of the system. A scale-independent measurement of the rheological behaviour of flocculated MFT is desired so that upscaling is possible, thus the rheological measurement must be carried out at or above some critical scale. Theoretically, measurements made below this critical scale will show much variability and will not sufficiently describe the entire system.

The critical scale will depend on numerous factors (Coussot, 2005), but most significantly on the:

- Solids volume fraction, $\theta$ ($V_{\text{solids}}/V_{\text{total}}$);
- Efficacy and completeness of flocculation;
- Spatial distribution of solids, moisture, polymer, and voids; and the
- Presence or absence of micro- and macrostructures (flocs and aggregates).
The scale of observation for this study covers the range of macroscopic behaviour to flow scale behaviour. The critical scale for rheology of flocculated MFT exists somewhere between the macroscopic and flow-scale domains depending on the heterogeneity of the deposition.

3.3.1.2 Instrument Geometry
Rheological instruments vary widely in appearance and operation. The following list provides the tool configurations most commonly used in a rheological study (Coussot, 2005):

- Capillary tube (viscometer): for relatively low viscosity fluids with little to no macrostructure
- Parallel plate: for fluids with low yield stress and little to no macrostructure
- Cup-and-bob: (Couette or Searle type) for fluids with low to high viscosity and varying degrees of macrostructure

A cup-and-bob geometry is preferred for the characterization of soil-water mixtures and granular suspensions (Coussot, 1997). For tailings rheometry of tailings slurries, the standard spherical or conical bob is replaced by a rectangular 4-blade vane with an approximate 2:1 height to diameter ratio. The vane is better suited to granular suspensions as it maximizes particle-instrument contact and reduces the risk of slippage and shear inhomogeneity (Coussot, 1997; Nyugen & Boger, 1998; Boger, 2009).

3.3.1.3 Rate of Applied Shear
The rate of applied shear should reflect the rate of shear experienced at the field flow scale. The rate of shear in the field will be directly related to the velocity and geometry of a flowing stream of material. For flow in an open channel (circular cross-section), the bulk shear rate can be estimated using Equation 3-15 (Chaudhry, 2008; McPhail, 1995):

\[ \gamma = \frac{2v}{R_H} \]

Equation 3-15: Equation for calculating bulk shear rate in an open channel

where \( v \) is the bulk flow velocity (in m/s) and \( R_H \) is the hydraulic radius (the ratio of the cross-sectional flow area divided by the wetted perimeter). For non-circular cross sections, the calculation of the hydraulic radius parameter will vary depending on the channel geometry (Chaudhry, 2008).
3.3.1.4 Dewatering
Dewatering of a flowing stream effectively increases the solids volume fraction of the flocculated tailings and will increase its viscosity as particle-particle interactions and hydrodynamic forces predominate; however, dewatering may also result in migration of water from the internal structure of the material towards the boundaries of flow, hence lubricating the flow. This phenomenon is commonly observed in the field where free water and residual bitumen from the flocculated MFT migrate to the flow boundaries and reduce the friction against the channel wall. Therefore, the net effect of dewatering may not significantly impact the behaviour of a flowing material, so long as the rate of dewatering is less than the rate of flow.

3.3.1.5 Stress History
Conditioning of flocculated MFT occurs in the delivery pipe, from the point of polymer injection all the way to the point of discharge into the cell. A flocculated MFT stream may exit the discharge spigot in various states depending on the amount of shear experienced in the pipe. This conditioning could influence beaching behaviour and may influence the longer-term strength gain as a result of hysteresis effects.

3.3.1.6 Thixotropic and Rheopectic Behaviour
Thixotropy describes the decrease in viscosity as a result of shearing at a constant rate over time. A rheopectic behaviour is one where the viscosity increases as a result of a constant shear rate over time (Coussot, 1997).

Depending on the state of the flocculated material, both thixotropic and rheopectic behaviour are conceivable.

3.3.1.7 Shear Thinning and Thickening
Coussot (1997) illustrates how flocculated or colloidal structures in concentrated suspensions may be broken down at higher shear rates, while less break down is observed at low shear rates. Shear-thinning of flocculated MFT conceivably occurs when the flocculated structure is degraded as the rate of shear is increased. In the field, this may be realized as the flow rate increases past a point where the flocculated MFT is effectively over-sheared and the viscosity decreases rapidly.
3.3.1.8 Soft-Jamming Particles
Flocculated MFT tends to form agglomerated structures referred to as floc aggregates. Based on the author’s experience, these floc aggregate masses may range in size from several millimetres to half a decimetre. Floc aggregates can be easily identified visually, and physically separated from the flowing mass. Upon inspection of a floc aggregate, it is apparent that the structure exhibits some elasticity and is easily compressed.

In the study of mudflows and debris flows, this type of structure is more generally referred to as a soft-jamming particle (Coussot, 1997). Two or more of these particles interacting will result in energy losses attributable to the compression of particles and the transfer of momentum between elastic media.

3.3.1.9 Boundary Effects
During rheological measurements, boundary effects may influence equipment performance and the validity of measurement if certain precautions are not observed. Most critically, the gap size (the distance between the shearing and static surfaces) must be sufficient to avoid wall friction effects. Furthermore, the gap size must be sufficiently small so that the shear zone created in the apparatus is homogenous (i.e. there is a uniform distribution of stress across the shear zone) for the analytical interpretation to be valid (Coussot, 2005).

3.3.1.10 Particle Settling
Particle settling is a troublesome phenomenon observed during the rheometry of concentrated suspensions. Particle settling usually manifests during the initial stages of developing a flow-curve (shear rate versus shear stress plot), when the rate of shear is sufficiently low to allow sedimentation of once-suspended particles through the fluid column. Particle settling will typically result in a low-bias measurement of shear stress as the effective solid volume fraction of the sheared fluid is reduced along the vertical shear surface, in the case of a vane rheometer. If the shear zone is located at the lowest part of the instrument (e.g. in a parallel plate rheometer), the shear stress measurement may be biased high as the effective particle concentration increases in the shear zone.

If shear rates are maintained sufficiently high, particle settling may be avoided. The rate of settling will also be governed by the particle shape, specific gravity, and ratio of the solid volume to the total suspension volume (Coussot, 1997).

3.2.2 Previous Laboratory Rheological Observations
Suncor Energy has undertaken extensive laboratory rheological testing of flocculated MFT over various ranges of MFT clay content, solids fraction, and degrees of flocculation.
In reality, the quality of flocculation and mixing conditions will dictate the form of the flow curve. Assuming that the polymer was introduced to the MFT stream appropriately, the MFT should flocculate to an optimal water release structure after conditioning; however, changes in flow rate or MFT feed quality may cause changes in in-pipe conditioning requirements and the optimal flocculation structure may not be achieved. In these cases, an optimally dosed MFT may be sub-optimally mixed. Figure 3-6 presents the fitted Herschel-Bulkley flow curves for flocculated MFT after varying degrees of mixing.

![Figure 3-6: Fitted Herschel-Bulkley flow curves for flocculated MFT after 80, 110, and 140 seconds of mixing (Data courtesy of A. Revington, Suncor)](image)

The empirically derived Herschel-Bulkley parameters for flocculated MFT in various states are provided in Table 3-1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Herschel-Bulkley Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$T_0$ (Pa)</td>
</tr>
<tr>
<td>80 s mixing</td>
<td>25.6</td>
</tr>
<tr>
<td>110 s mixing</td>
<td>23.3</td>
</tr>
<tr>
<td>140 s mixing</td>
<td>25.4</td>
</tr>
</tbody>
</table>

Due to the thixotropic nature of flocculated MFT, the viscosity will decrease with time under shear. This phenomenon occurs only when the fluid is in motion.
Once the fluid has stopped flowing, it will continue to undergo dewatering by drainage and by evaporation. Both actions will act to decrease the overall moisture content, increase the solids volume fraction, and increase the yield stress. The increase in solids content (shown as mass fraction) and increase in static yield stress (presented as peak yield strength) are illustrated in Figure 3-7 and Figure 3-8.

![Graph](image)

**Figure 3-7:** Change in rheology as measured by static yield strength and percent solids by weight. (Data courtesy A. Revington, Suncor)

![Graph](image)

**Figure 3-8:** Rheology as a function of solids fraction (by weight) as measured in the field and laboratory (Data courtesy A. Revington, Suncor)
The relationship between yield stress and solids fraction is described by an exponential or power function with considerable scatter. The scatter is attributable to the MFT composition which can demonstrate significant variation in clay content.

### 3.4 Tailings Beach Profile Models

#### 3.4.1 General

Over the past 40 years, many researchers have approached the problem of tailings beach profile modeling, with a multitude of motivations and to varying degrees of success. Approaches are both theoretical (Fitton, 2007; McPhail, 1995; Morris, 2004; Simms & Henriquez, 2009) and semi-empirical, (Melent’ev et al. 1973; Fitton, 2007). These models are described and compared in the following sections.

#### 3.4.2 Melent’ev et al. (1973)

The Melent’ev et al. (1973)\(^1\) model has been successfully applied to profile prediction of both hydraulic fills and mine tailings. The empirical model is based on curve fitting to the cross sectional profiles of hydraulic fill beaches. The empirical relationship is provided in Equation 3-16:

\[
    z = z_0 \left(1 - \frac{x}{L}\right)^n
\]

Equation 3-16: Empirical equation for the Melent’ev (1973) profile

where \(z\) is the elevation along the beach, \(z_0\) is the elevation at the beach head, \(x\) is the distance along the beach measured from the point of discharge to the end of the beach at a distance \(L\).

The parameter \(n\) is dependent on the fill characteristics, namely particle size distribution and specific gravity.

The profile equation is easily differentiated to illustrate the change in slope (\(S\)) over the beach length:

\[
    S = S_0 \left(1 - \frac{x}{L}\right)^{n-1}
\]

Equation 3-17: Slope as a function of beach position (Melent’ev et al., 1973)

---

\(^1\) Original work in Russian, English translation sponsored by SRK Consulting and coordinated by D. van Zyl with University of Witwatersrand personnel (1979)
The work of Melent’ev et al. (1973) on hydraulic fill beaches has been subsequently validated on both sub-aerial and sub-aqueous tailings beaches (Blight et al., 1985; Blight & Bentel, 1983; McPhail, 1995; McPhail and Blight, 1998).

### 3.4.3 Williams and Morris (1989)

Morris and Williams (1998) identify that the empirical equation originally introduced by Williams and Morris in 1989 (reproduced here as Equation 3-18) provides a reasonable fit to measured beach profiles of coal and metalliferous tailings.

\[
\frac{Z}{Z_0} = Ae^{(-wL)^e^{-\omega}}
\]

*Equation 3-18: Empirical fit equation from Williams and Morris (1989)*

where:

\[
A = \frac{1}{1 - e^{-\omega}}
\]

*Equation 3-19: Equation for the A parameter in Williams and Morris (1989)*

and \(\omega\) is an empirically determined parameter.

Morris and Williams (1998) offer a statistical treatise on beach profile fitting and demonstrate that an exponential function provides a superior fit to the majority of profiles in a database of 46 surveys from coal mines and metal mines. Furthermore, the researchers discourage the use of a power-law for profile fitting as it has no theoretical basis and overlooks basic hydraulic principles.

### 3.4.4 Fitton (2007)

An equilibrium slope is a slope at which material is neither added nor removed from the channel bed (de Groot et al., 1988; Fitton, 2007) and is identified as a general predictor of deposit slope. Fitton (2007) proposes that the slope of a tailings deposit can be equated to the equilibrium slope achieved by channels that run across the beach and provides three models for calculating this unique slope. The simplified and semi-empirical models will not be discussed here; however, the *a priori* model is discussed as it is based on widely accepted hydraulic principles and is most easily generalized to describe a variety of tailings.
The \textit{a priori} model requires the following inputs:

- $Q$, the flow rate (m$^3$/s)
- $C_v$, the concentration of the tailings slurry in terms of volume (fraction)
- $d_{50}$, the median particle diameter of the tailings slurry (m)
- $d_{90}$, the 90th percentile particle diameter of the tailings slurry (m)
- $\rho_w$, the density of the carrier fluid of the tailings slurry (kg/m$^3$)
- $\rho_s$, the density of the solid particles in the tailings slurry (kg/m$^3$)
- $\tau_y$, $K$, and $n$ (rheological parameters for a Herschel-Bulkley slurry model)

Fitton (2007) introduces a straight-forward spreadsheet algorithm to calculate the equilibrium slope as:

1. Guess an initial value of the flow depth
2. Calculate the cross sectional area of flow, $A$, and the wetted perimeter, $P$, as a function of the geometry of the channel cross-section
3. Calculate $R_H$ (the ratio of $A/P$)
4. Calculate $V$, the mean velocity in the channel (equal to $Q/A$)
5. Calculate $V_C$, the minimum transport velocity
6. Repeat steps 1 to 5, adjusting the depth value (in step 1) until $V$ and $V_C$ in steps 4 and 5 equate
7. Calculate $Re_H$ using a modified Reynolds number equation
8. Calculate a friction factor ($f$) for the channel based on Step 7
9. Calculate $S_0$ (the equilibrium slope) using the Darcy-Weisbach equation:

$$S_0 = \frac{f V^2}{8R_H g}$$

\textit{Equation 3-20: Darcy-Weisbach equation}

The equilibrium model presented suffers from several key shortcomings, namely:

- The analysis is restricted to a fixed channel geometry both spatially and temporally
- The analysis is data intensive, requiring delineation of the $d_{50}$ and $d_{90}$ particle sizes
- Strict definition of the laminar-turbulent transition is required
- The model outcome is a monotonic slope value
The final point addressed in this list is without question the most detrimental for this model; that is, the non-monotonic beach profile cannot be described with a monotonic model.

### 3.4.5 Simms & Henriquez (2009)

Lubrication theory in the context of tailings engineering is explored by Simms and Henriquez (2009). The theory is limited in that, by principle, it is only applicable to the deposition of tailings by uniform sheet flow. The theory also requires the following conditions be met:

- The ratio between the thickness of the flow and the horizontal extent of the flow is small
- The flow velocity is low and the flow state is laminar

Although the uniform sheet flow condition is rarely met by flocculated MFT, this thesis will present the theory as it offers some theoretical background for the flow and stoppage of a yield stress fluid on an inclined plane.

First, the shear stress profile through a slow flowing, laminar flow can be written as:

$$\tau(z) = (h - z)[\rho g \cos \theta \left( \tan \theta \frac{\partial h}{\partial x} \right)]$$

where $h$ is the flow depth, $z$ is the vertical distance measured upward from the channel bed, $\theta$ the bed inclination measured from the horizontal, and $x$ is the displacement along the inclined plane.

At the base of a channel, the shear stress can be replaced by the yield stress (thus requiring that the flow is at equilibrium and has stopped flowing) and the expression can be written to express the tailings profile explicitly (Equation 3-21):

$$h^2 - h_0^2 = \frac{2\tau_y}{\rho g} (x - x_0)$$

**Equation 3-21: Fluid profile determined from lubrication theory**

where $\tau_y$ is the yield stress of the fluid.

Simms and Henriquez (2009) show examples of laboratory and field scale measurements which are fitted to theoretical profiles successfully.
3.4.6 McPhail (1995)

McPhail (1995) and McPhail and Blight (1998) suggest the introduction of a power law or exponential function to empirically capture the profile of beaches forming under natural conditions of energy loss. Where the system is constrained (i.e. the beach length is defined), the beach profile may be best described by a function similar in construction to the Melent’ev et al. (1973) equation; however, where the profile is dictated by the loss of energy down the beach, an exponential function (in the form of Equation 3-22) best fits measured beach profiles.

\[
\frac{y}{V} = 1 - e^{-c\frac{x}{H}}
\]

*Equation 3-22: The normalized profile equation*

where the concavity parameter, \( c \), is a function of the material properties and discharge conditions. The terms \( y/V \) and \( x/H \) are the normalized vertical and horizontal coordinates which together describe the profile in two dimensions. The term \( x/H \) increases from 0 to 1 from the point of discharge to the end of the deposit and the term \( y/V \) decreases from 1 to 0 from the point of discharge to the lowest elevation of the deposit.

The development of tailings beaches is a chaotic, random, natural process; therefore the exact profile of a tailings beach at equilibrium cannot be wholly satisfied by deterministic models. The stream power approach (McPhail, 1995; McPhail & Blight, 1998) applies the basic principles of open channel hydraulics and entropy theory to estimate the distribution of stream power along the tailings flow path. The stream power is calculated on the basis of a uniform flow rate, density, and driving gravitational (elevation) head. As the stream (channel) meanders down the length of the deposition cell it experiences frictional energy losses; hence, the velocity approaches zero and the flow eventually stops. The rate of the dissipation of energy can be calculated with known rheological behaviour and flow geometry. The dissipated energy as a function of distance down the beach can be seen as a naturally occurring process and can be probabilistically modelled using Shannon entropy theory (Shannon, 1948).

Several important model assumptions are necessary (McPhail, 1995):

1. Deposition along and within the flow channel is gradual and slow compared to the flow rate so that for all practical purposes the flow rate can be kept constant down the beach.
2. Built into this first assumption is the assumption that the slurry properties remain essentially constant down the beach (i.e. particle size distribution, percent solids, and rheology do not change significantly).
3. The reduction in stream power down the beach is a result of frictional loss and is represented by a change in flow velocity.
4. The flow channel is circular.
5. The Bernoulli equation applies to the circular flow channel without modification.

Stream power, $P$, is calculated as follows:

$$P = \rho g Q H$$

Equation 3-23: Stream power formula

where $Q$ is the volumetric flow rate and $H$ is the total head difference between the point of discharge and the end of the beach.

After the flocculated tailings are discharged from the pipe, they fall with some horizontal momentum supplied by the pressure difference between the pipe and the discharge environment. The stream will fall with some vertical momentum as a result of gravity and thus strike the beach at some nominal distance from the end of the pipe. For flocculated tailings, this distance is typically small for discharge rates up to 450 m$^3$ per hour – in the order of 0.2 to 0.5 metres (as observed by the author) – and henceforth will be considered negligible when compared to the total flow distance (in the order of 100 to 300 metres). At this discharge rate, the flocculated MFT will scour the bed material of the cell to create a depression. This depression is referred to as the plunge pool (McPhail, 1995) (Figure 3-9), and may vary in size from approximately 10 to 50 centimetres in depth and 20 to 50 centimetres in diameter (elongated in the direction of flow). The exact dimensions will vary as a function of the bed material and the energy of the flowing tailings stream. The role of the plunge pool is essentially that of an energy dissipater – reducing the velocity of the tailings as it contacts the beach head.
At the downstream lip of the plunge pool, the stream power for a flow of volumetric rate $Q$ is given the notation $P_0$ and the head term (H) is the elevation difference between the discharge and the toe of the cell, or the outfall to the pond. This signifies that the stream power will be a function of the overall gravitational potential of the flow, or put another way, the average bed inclination of the disposal cell. McPhail (1995) shows that the expression for stream power is subject to loose boundary conditions in a naturally formed channel under gravity flow from the plunge pool, such that the stream power at any distance $x$ from the downstream lip of the plunge pool will be a function of the velocity head at distance $x$ (Equation 3-24):

$$P_x = \rho Q \left(\frac{v^2}{2}\right)$$

Equation 3-24: Stream power as a function of velocity head

The initial stream power, $P_0$, is thus taken to be a function of the average velocity at the lip of the plunge pool, and not that of the initial discharge from the pipe.

The change in stream power along the beach is derived from Shannon entropy theory (Shannon, 1948) for a discrete random variable ($P$ in this case) at a distance, $x$, from the source. Simplified, the Shannon
entropy model asserts that at the system’s lowest energy state, the degree of disorder, or entropy, will be maximized. McPhail (1995) defines the most probable distribution of energy losses down the beach, from an initial stream power of $P_0$ to a final power equal to zero (where the stream stops flowing). The entropy-maximized stream power expression is given as:

$$P(x) = -\frac{1}{\mu} \ln \left( \left( 1 - \exp^{\mu P_0} \right) \frac{x}{L} + \exp^{\mu P_0} \right)$$

Equation 3-25: Entropy-maximized stream power as a function of distance from the plunge pool

The parameter $\mu$ is the shape factor for the stream power decay curve and is related to the stream’s rheology (but is not equivalent to dynamic viscosity). All other inputs are determined by the physical layout of the disposal cell ($L$, the effective length of the cell) and the initial discharge conditions (flow rate, density, and plunge pool characteristics).

Holistically, this model represents the rate of energy losses in the flowing stream as an exponential decay with shape parameters that can be defined based on a rheological model.

The profile of stream power can be differentiated to find the slope of the stream power profile at any distance along the beach and the slope of the stream power profile will parallel the slope profile of the final beach surface (McPhail, 1995). The beach profile is offset vertically by the upstream restriction (e.g. the header berm height, or elevation of the discharge pipe relative to the cell base). The slope of the stream power profile at distance $x$ from the discharge ($S_B(x)$), and hence of the final beach is then calculated as follows:

$$S_B(x) = \frac{1 - \exp^{\mu P_0}}{L \mu \exp^{\mu P(x)}}$$

Equation 3-26: Slope of the stream power profile

The complete beach profile can thus be constructed with any number of discrete slope calculations along the beach length. This model can be easily coded into a spreadsheet program and the $\mu$ term solved by iteration.
A procedure is included in the algorithm to verify that the calculated shear stress of the fluid (as a function of the computed flow velocity and channel geometry) is consistent with the sustainable shear stress\(^2\) which is determined from the Herschel-Bulkley model for the tailings.

\(^2\) The sustainable shear stress is the shear stress that would be measured for the given fluid at a given shear rate (McPhail, 1995) as illustrated in a rheogram or flow curve of shear stress versus shear rate.
Chapter 4: Field Setting and Methods

4.1 General

Field monitoring of flow conditions occurred over a period of two deposition seasons (approximately April through October of 2010 and 2011) at several locations at Suncor Energy’s Oil Sands mine near Fort McMurray, Alberta. Quantitative flow monitoring and sampling was restricted to the second field season, when access to deposition cells was made possible by the installation of scaffolding structures. Beach profiles were also obtained at a number of full-scale deposition cells.

An overview of the general method employed for the qualitative and quantitative assessment of flow and deposition at the various study cells is outlined in (Figure 4-1).

The following sub-sections describe the field setting and methods employed in this study to achieve the thesis objectives.
4.2 Deposition Cells

Flocculated tailings are deposited on sloping beds near, or on, existing tailings impoundments; in this thesis, these areas are referred to as deposition cells. The cells, taken in aggregate, form what is referred to as a Dedicated Drying Area (DDA), or System. The cells, generally rectangular in plan, range in length from 150 to 300 metres and in width from 50 to 80 metres, approximately. The initial bed slope depends on the underlying topography, but generally ranges from 1% to 5%, sloping away from the point of tailings discharge to facilitate tailings distribution and dewatering. In many cases, these cells are not truly isolated on all sides, but the arrangement of spigots at the header berm implies lateral boundaries. Typically, a linear arrangement of four spigots designates the extent of one cell. A number of cells are constructed in series to allow efficient distribution of the tailings to those cells (Figure 4-2). The downstream boundary of the cell may be supplied by a standing pool of water (either the supernatant pool of the impoundment, or stored water at the toe of the cell resulting from dewatering and run-off collection), or by a soil berm constructed to retain the tailings (Figure 4-3).

Figure 4-2: Schematic plan of typical deposition cell arrangement showing approximate boundaries of Cell D1 (5-ft interval LIDAR survey contours of fresh deposit overlaid)
Qualitative observations of flow behaviour and beaching tendencies were undertaken at numerous locations; however, quantitative observations and sampling was focused in three primary deposition cells. Table 4-1 describes the key locations for data collection during this study. The location names in the second column refer to Suncor nomenclature for the deposition areas, and are provided only for completeness. Figure 4-4 provides schematics for these deposition cells.
Table 4-1: Description of key deposition cells used in this study

<table>
<thead>
<tr>
<th>Cell Name (Thesis)</th>
<th>Location (DDA/System)</th>
<th>Approximate Length x Width (m)</th>
<th>Approximate Bed Slope</th>
<th>Purpose / Key Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell 1N</td>
<td>South Tailings Pond (System 3)</td>
<td>250 x 50</td>
<td>3.5%</td>
<td>Flow Monitoring / Sampling</td>
</tr>
<tr>
<td>Cell D1</td>
<td>System 5</td>
<td>270 x 70</td>
<td>0.8 to 1.0%</td>
<td>Profile Surveys / Flow Observation</td>
</tr>
<tr>
<td>Cell 6S</td>
<td>Pond 8A (System 1)</td>
<td>150 x 50 (max, triangular)</td>
<td>1.0% to 3% (variable)</td>
<td>Profile Survey</td>
</tr>
<tr>
<td>Various Cells</td>
<td>Systems 4 &amp; 5</td>
<td>250 x 50</td>
<td>0.8 to 1.0%</td>
<td>Profile Surveys</td>
</tr>
</tbody>
</table>

The study cells demonstrate the range of physical constraints on deposition, covering a bed slope range of approximately 1 to 3.5% and a range in cell length from 150 to 270 metres.

**SCHEMATICS OF KEY STUDY CELLS**

(a) Cell 1N

(b) Cell D1

(c) Cell 6S

*Deposition bed assumed to be slightly concave

Figure 4-4: Schematics of key study cells: (a) Cell 1N, (b) Cell D1, and (c) Cell 6S illustrating the relative bed slopes and cell lengths
The geographic location of the cell is significant in that it determines the specific tailings stream that it receives. For instance, at the time of this study, Cell 1N, D1, and 6S received tailings feeds from different MFT sources (tailings impoundments). The effect of these differences is beyond the scope of this thesis; however, it should be noted that the compositional differences in MFT between sources can influence the flocculated MFT characteristics.

The majority of the flow behaviour monitoring was conducted at Cell 1N (System 3), while beach profile data was readily obtained from Cell D1 (System 5), Cell 6S (System 1), and various other cells within the System 4 and System 5 locations.

4.3 Deposition Conditions
Deposition conditions were not controlled by the author during this investigation; that is, all monitoring occurred during regular operation of the commercial scale production of flocculated MFT. The reasons for this were three-fold, namely to:

- Permit observation of the true operational range of discharge conditions;
- Allow flexibility in terms of monitoring location and duration; and to
- Facilitate completion of this work within the constraints of the operating season.

The result of this methodology is observations and measurements that span a range of true, commercial scale operating conditions at the time of the study.

4.4 Monitoring Methods

4.4.1 Overview
A combination of qualitative and quantitative observations and measurements were undertaken to meet the objectives outlined in Section 1. Flow monitoring was aided by the installation of a scaffolding structure ("catwalks") which permitted safe access to the interior of deposition cells during operation. Figure 4-5 and Figure 4-6 depict the field setting at Cell 1N for reference.

Field methods for sampling and monitoring were adopted from accepted field practices to ensure accuracy and validity of results. These methods are discussed in the following sections.
Figure 4-5: Monitoring set-up at Cell 1N including 60 metre catwalk

Figure 4-6: Sampling of flow from catwalk at Cell 1N
4.4.1 Qualitative Monitoring
Time-lapse photography, video, and digital photography were undertaken to document flows of flocculated MFT over periods as long as 24 hours. Still images from these sources are used throughout this thesis to illustrate key observations where appropriate. Video was used in some instances to verify measured flow velocities. An example of the use of time lapse at Cell 1N is provided in Figure 4-7.

Figure 4-7: Illustration of time lapse photography used to monitor flow behaviour
4.4.2 Flow Classification & Quantitative Monitoring

During field monitoring, all observed flows were visually classified into one of four main flow regimes:

- Stacking flows
- Sheet flows
- Laminar channel flows
- Turbulent channel flows

Stacking flows and sheet flows are easily distinguished from channelized flow in the field; however, the distinction between laminar and turbulent channel flows requires a more strict qualitative definition. For the purposes of first identifying the channel flow regimes, and to later compare the qualitative and quantitative observations, the following guidelines were used to distinguish laminar and turbulent regimes.

Laminar flows were generally characterized by:

- Relatively slow-moving, stable channels;
- Higher degrees of sinuosity on shallow slopes;
- Easily distinguished parallel flowlines at surface (delineated by the residual bitumen expelled to the surface of the flow); and
- Little evidence of channel erosion

Turbulent flows were generally characterized by:

- Fast-moving, unstable flows;
- Generally straight, down-gradient channels on all slopes (low degree of sinuosity);
- No distinguishable flowlines at surface due to macroscopic mixing; and
- Evidence of channel erosion and sediment transport down-slope.

An effort was made to sample and monitor all four flow types as outlined above; however, the relative frequency of the flow regimes and practical considerations lends to some bias towards laminar channel flows being well represented in the dataset and lesser common sheet flows being under-represented. A total of 13 flows were monitored in detail and sampled for the purposes of this thesis.
4.4.2.1 *Flow Velocity*

In the field, flow velocity is most readily quantified by the surface velocity of the flowing stream (or the displacement of the mass with time for stacking or sheet flow). While velocity is assumed to vary with depth through a flow profile according to classical hydraulic theory, the use of surface velocity measurement provides an easily obtained, practical metric for flow velocity. The use of an acoustic profiler or other instrument was beyond the scope of this study. Surface velocity was measured using a physical floating tracer (50 mm diameter low-density polyethylene disk) placed in the flow centreline (Figure 4-8). A chronometer was used to measure the time required for the tracer to pass between measuring staffs placed along the flow path at measured intervals.

![Floating tracer placed in flow centreline for velocity measurement of a laminar channel. Flow is towards the camera.](image)

4.4.2.2 *Sampling*

Sampling along the flow path was accomplished by inserting a four-litre sampling vessel into the flow as the physical tracer passed established benchmarks (typically surveyed wooden stakes) within the deposition cell (Figure 4-9). The four-litre sample was sufficient to complete the density and slump testing along with retention of approximately 500 mL of sample for laboratory analysis. This method assumes that the tailings mass flows essentially as a plug of material. While for a slow flowing laminar regime this assumption is reasonable, some uncertainty is introduced for turbulent flows.
4.4.2.3 Rheology & Density Measurement

In the field, static yield stress is most readily estimated using a simple slump test. The test procedure and apparatus is modified from the traditional concrete slump test as outlined in ASTM C143/C143M – 10a (ASTM, 2010). Clayton et al. (2003), Pashias and Boger (1996), and Boger (2009) confirm that a modified slump test (Figure 4-10) is reliable for determination of the static yield stress of slurries. Figure 4-10 provides an illustration of the slump test and the yield stress distribution associated with this method.

![Figure 4-9: Sampling equipment including floating tracer](image)

![Figure 4-10: Schematic of modified cone slump test (reproduced from Clayton et al., 2003)](image)
A standardized four inch inside diameter, smooth-walled, open-ended cylinder with height-to-diameter aspect ratio of 1:1 was used for all testing. Flocculated tailings were sampled from the flowing stream using a long-reach sampling pole, and carefully poured to completely fill the cylinder. The slump cylinder rested on a portable Mettler-Toledo bench scale so that the sample mass could be measured for density calculation (Figure 4-11).

![Image](image_url)

**Figure 4-11: Field set-up for slump and density measurement**

The cylinder was lifted vertically to allow the material to slump and the change in height of the specimen was recorded (S). From this, a percentage slump value was calculated (Equation 4-1).

$$S = \frac{|H_0 - S|}{H_0} \times 100\%$$

**Equation 4-1: Calculation of percentage slump**

The slump values were correlated to static yield stress measurements using a manual shear vane (Geonor H-60) rotated through the tailings in a smooth-walled sample pail (Figure 4-12). Boger (2009)
and Fisher et al. (2007) assert that the vane geometry is best suited for determining the yield stress of mine tailings. Samples were sub-divided for slump testing and vane testing.

The use of a so-called bucket rheometer set-up is advocated in Fisher et al. (2007) and was used for vane testing. The nominal pail diameter was 265 mm with a depth of 385 mm and the vane diameter was 150 mm with a height-to-diameter ratio of 2:1. The total volume of sample tested during each measurement was approximately 20 litres. Attention was paid to insert the vane to a position no less than 50 mm from the bottom of the pail to avoid boundary effects. Fisher et al. (2007) recommend a gap spacing of more than 10 times the largest particle size in the system to preclude the influence of particle-wall effects on the rheological measurement. The gap spacing for the sidewall and bottom surface was a minimum of 50 mm in both instances. The vane was rotated at according to the manufacturer’s recommendation, and the instrument reading was converted to yield stress using the manufacturer’s correlation factor. The resulting yield stress measurement was recorded and correlated to the parallel slump test results (Figure 4-13).
Figure 4-13: Field correlation established for determination of static yield stress using a modified slump test.

4.4.3 Field Beach Profiles
Profiles of flocculated MFT deposits were obtained from a variety of TRO deposition areas by optical and laser measurement techniques over the course of two deposition seasons (summer 2010 and summer 2011). Surveying was carried out by the author with the aid of colleagues at Robertson GeoConsultants Inc., and MDH Engineered Solutions Incorporated (now SNC-Lavalin). A discussion of the observed and measured profiles is provided in Section 7.2.1.
Chapter 5: Field Observations of Flow and Deposition of Flocculated Mature Fine Tailings

5.1 Flow Regimes

5.1.1 General

The spectrum of flow regimes observed over two years of commercial scale production is broad, reflecting the variability of the process inputs and outputs. The flow categories range from high yield stress sheet flow behaviour to low viscosity turbulent channel flow. The shear stress incurred by the flocculated tailings varies according to the flow velocity, flow geometry, flow stability, and rheological properties. Hence, an understanding of the range and frequency of these flow regimes over any period of deposition is crucial in interpreting the deposit formation processes and performance.

Table 5-1 provides a concise reference for the classification of flow regimes and the observed relative frequency of occurrence.

<table>
<thead>
<tr>
<th>Regime</th>
<th>Condition / State</th>
<th>Relative Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uniformity</td>
<td>steadiness</td>
</tr>
<tr>
<td>Primary</td>
<td>Secondary</td>
<td>A_x = A_{x+1}...</td>
</tr>
<tr>
<td>Stacking</td>
<td>Non-uniform</td>
<td>Steady to non-steady</td>
</tr>
<tr>
<td>Sheet</td>
<td>Uniform</td>
<td>Steady</td>
</tr>
<tr>
<td>Channel</td>
<td>Laminar</td>
<td>Uniform</td>
</tr>
<tr>
<td>Turbulent</td>
<td>Non-uniform</td>
<td>Non-steady</td>
</tr>
</tbody>
</table>

The following subsections detail the generalized flow regimes observed.

5.1.2 Stacking Flow

Stacking flows (Figure 5-1) are rarely observed in the field but merit some description. They are characterized by a rising stack or cone of material that accumulates after contacting the beach, and then slowly progresses away from the point of discharge. The movement of material is generally upwards with outward migration as a result of increased vertical stress on the lower stack layers and failure radially outwards (analogous to a failing cone from a concrete slump test). The discharge is generally characterized by a low velocity, high density stream of material exiting the pipe with very little horizontal momentum.
Stacking flows are generally indicative of a high yield stress material discharged at low velocity. Although rarely observed in the field, stacking flows could negatively impact operations by jeopardizing the freeboard on the discharge berm and by blocking and possibly burying the discharge spigot. The TRO process is managed in such a way to preclude the formation of stacking flows.

While stacking flows will generally maintain a conical geometry, the direction of horizontal displacement is aligned with the beach gradient and hence the stack will tend to elongate along this axis.

Stacking flows have been observed on bed slopes varying from 0% to 4% and can form deposit stacks with slopes as high as 14%.

5.1.3 Laminar Channel Flow

Many examples of laminar channel flow have been documented across all deposition areas. Laminar channels develop during periods of relatively low velocity and stable discharge with well flocculated MFT. However, under certain conditions (low velocity), laminar channel flow is observed with relatively poorly flocculated material as well.

Laminar channel flows tend to follow the underlying beach gradient and maintain a sinuosity index (length of actual channel divided by down-gradient travel distance, Figure 5-2) approximately equal to 1.
but ranging to 2.5. A measure of sinuosity is important for correcting the flow path length for average flow velocity calculations.

\[
\text{Sinuosity Index (SI)} = \frac{\text{Length of Actual Channel Streamline}}{\text{Downgradient (Shortest) Length}}
\]

Figure 5-2: Examples of channel sinuous laminar channel flow

Laminar flows typically vary in width from 0.2 to 0.5 metres in width and 10 to 30 centimetres in depth with an approximately semi-circular cross-section. Several representative channel cross-sections as measured in the field are presented in Figure 5-3. These measurements were taken in dried channels where tailings were known to have flowed. An image of a flowing laminar channel is shown in Figure 5-3.
Laminar channel flows tend to develop on slopes less than 3\% and consistently on slopes between 1 and 2\%.

### 5.1.4 Turbulent Channel Flow

Turbulent channels develop when frictional forces within the fluid are overwhelmed by inertial forces that de-stabilize the flow. Such flows are typically observed when discharge rates are high and when low density material is produced.

Turbulent channels (Figure 5-4) are easily identified in the field by the presence of standing waves, hydraulic jumps, as well as pools and riffles along the flow path.
Figure 5-4: Examples of turbulent channel flows

Turbulent channels tend to assume a geometry so that the sinuosity index (SI) is much greater than 1 (SI in the order of SI = 2 to 4). Turbulent flow channels will form on practically any bed slope given the right conditions. Turbulent flows are dominant on bed slopes greater than 3.5%.

Both laminar and turbulent channel flows are responsible for distributing material down and across the beach; however, the different depositional mechanics at play are discussed in Section 6.3.

5.1.5 Uniform Sheets and Coating Flows

Uniform sheet flows demonstrate similar thickness across the majority of the sheet so that the material uniformly blankets or coats the surface onto which it is deposited. When observed in the field, the deposited flow mass continuously fails at a rate that maintains a constant thickness across the sheet (Figure 5-5).
While practically difficult to achieve in the field, this flow behaviour would be most desired as little excess shearing is imparted to the material and a deposit of uniform thickness is created that will experience spatially uniform dewatering, drying, and self-weight consolidation.

The most striking example of this flow was documented on a near-monotonic 2% bed slope with well flocculated MFT. The flow was also documented during the initial filling stages of a test cell measuring 80 m by 300 m with a monotonic 0.8% bed slope.

When confined by higher-strength material, the uniform sheet may approximate the behaviour of a laminar channel; however, the apparent cross section will be different with a depth much less than the radius (Figure 5-6).
5.2 Rheological Observations

5.2.1 Relationship between Flow Velocity and Yield Stress
The series of flow observations conducted at Cell 1N are summarized in Table 5-2. Where channel flow is indicated with no laminar or turbulent qualifier, the flow was not easily distinguished as having characteristics of either (as established in Section 4.4).

Figure 5-6: Example of confined sheet flow, bounded laterally by previously deposited material
Table 5-2: Summary of flow monitoring from Cell 1N

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Yield Stress from Slump Test (Pa)</th>
<th>Measured Density (kg/m³)</th>
<th>Visual Assessment of Flow</th>
<th>Measured Surface Velocity, v (m/s)</th>
<th>Dynamic Pressure, ρv²/2 (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.0</td>
<td>1100</td>
<td>channel</td>
<td>1</td>
<td>550.0</td>
</tr>
<tr>
<td>2</td>
<td>40.0</td>
<td>1100</td>
<td>channel</td>
<td>2.5</td>
<td>3437.5</td>
</tr>
<tr>
<td>3</td>
<td>120.0</td>
<td>1300</td>
<td>stack</td>
<td>0.4</td>
<td>104.0</td>
</tr>
<tr>
<td>4</td>
<td>100.0</td>
<td>1250</td>
<td>sheet</td>
<td>0.4</td>
<td>100.0</td>
</tr>
<tr>
<td>5</td>
<td>60.8</td>
<td>1268</td>
<td>channel (laminar)</td>
<td>0.66</td>
<td>276.2</td>
</tr>
<tr>
<td>6</td>
<td>17.7</td>
<td>1195</td>
<td>channel (turbulent)</td>
<td>1.5</td>
<td>1344.4</td>
</tr>
<tr>
<td>7</td>
<td>17.7</td>
<td>1195</td>
<td>channel (laminar)</td>
<td>1</td>
<td>597.5</td>
</tr>
<tr>
<td>8</td>
<td>22.8</td>
<td>1210</td>
<td>channel (turbulent)</td>
<td>2.22</td>
<td>2981.7</td>
</tr>
<tr>
<td>9</td>
<td>102.6</td>
<td>1299</td>
<td>channel (laminar)</td>
<td>1.08</td>
<td>757.6</td>
</tr>
<tr>
<td>10</td>
<td>1.6</td>
<td>1054</td>
<td>channel (turbulent)</td>
<td>2.15</td>
<td>2436.1</td>
</tr>
<tr>
<td>11</td>
<td>7.9</td>
<td>1147</td>
<td>channel (laminar)</td>
<td>1.06</td>
<td>644.4</td>
</tr>
<tr>
<td>12</td>
<td>255.6</td>
<td>1353</td>
<td>stack-sheet</td>
<td>0.61</td>
<td>251.7</td>
</tr>
<tr>
<td>13</td>
<td>36.6</td>
<td>1238</td>
<td>channel (laminar)</td>
<td>0.85</td>
<td>447.2</td>
</tr>
</tbody>
</table>

Measurements obtained at Cell 1N suggest a relationship between the flow velocity and yield stress (Figure 5-7) which is consistent with qualitative observations. Generally, high yield stress materials will flow slowly down the beach, if at all, while low yield stress tailings will flow relatively quickly.

![Figure 5-7: Relationship between flow velocity and static yield stress](image-url)

\[ y = 33.238x^{1.411} \]

\[ R^2 = 0.4123 \]
5.2.2 Change in Yield Stress with Flow Distance

Select flows were also monitored along the length of their flow path as a basis for determining the effects of flow on the tailings behaviour and rheological properties. As the flocculated MFT flows down the beach at a pseudo-constant rate, the static yield stress of the material will tend to decrease in most cases. In essence, the flocculated structure is subjected to energy inputs over time and the structure is degraded. Figure 5-8 illustrates this phenomenon based on field monitoring of flocculated MFT flows.

![Graph showing change in yield stress and percentage slump with distance travelled.](image)

Field monitoring of static yield stress in samples extracted from active flows suggest that most flows undergo structural degradation over the beach; however, there was one example (A2 Trial) where the static yield stress was shown to increase marginally (thus demonstrating a rheopectic behaviour,
possibly a result of ongoing polymer mixing and strength gain). In this isolated case, the measured yield stress increased from 76 Pa to 81 Pa over a distance of 34 metres.

For all other monitored flows in Table 5-2, the degree of degradation was variable and shown to be related to the flow velocity. Figure 5-8 illustrates the degree of degradation of the material as a function of the velocity (or kinetic energy) of the flow.

![Figure 5-8: Degradation of yield strength as a function of the kinetic energy of the flowing stream.](image)

The vertical axis of Figure 5-9 plots the fraction of the initial static yield stress lost over time in which the material flowed down the beach. Generally, the degree of strength loss over time was relatively small with a maximum degradation rate of 1.4% of the initial static yield stress per second of flow. Furthermore, the decrease in static yield stress was more apparent at higher flow velocities, suggesting enhanced degradation of the flocculated MFT over time.

### 5.3 Variability

Due to the variability of process inputs and the sensitivity of the flocculation technology, it is typical to observe several, if not all, of the aforementioned flow regimes during a deposition period (typically four to sixteen hours in duration).
Well-flocculated material that is deposited by means of a stacking or quiescent channel flow can easily be eroded and carried downstream by a subsequent high energy stream. In contrast, a relict channel may be in-filled by subsequent stacking or low energy channel deposits.

The variability in flow regime allows for the movement of materials away from the point of discharge and leads to a highly heterogeneous distribution of materials across the final deposit.

5.4 Process Controls on Flow

The kinetic energy of the discharge stream is dictated by the flow rate and density of the stream. The velocity and density of the stream are dependent on the feed MFT characteristics and the capacity for the pumping system to deliver the treated material to the cell. Oscillations in the system were not uncommon at the time of preparation of this thesis, as automated flocculation systems can at times struggle to keep pace with a highly variable source stream.

The initial kinetic energy is a key component of the system as, in essence, it represents the potential for generation of free flowing channels, sheet, or stacking flows and the maximum amount of energy imparted to those various systems. Along the course of flowing downstream, the system is continuously losing energy to internal and external frictional forces as well as losing potential energy as the flow loses elevation head (potential energy).

5.5 Flow Specific Deposition Mechanisms for Flocculated Mature Fine Tailings

5.5.1 Sedimentation & Segregation
Field sampling and monitoring suggest that particle settling is not a predominant mechanism of deposition for at least the first 45 metres of beach where bulk shear rates are sufficiently high to retain solids in suspension. Samples were taken from the same section of flow as it progressed down the beach (an assumption of plug-flow is required). Laboratory analyses were performed by SGS Laboratories (Fort McMurray, Canada). The results of the field sampling and laboratory analyses are presented in Table 5-3 and Figure 5-10. The Location column refers to the distance along the flow path, relative to the discharge spigot. Each Trial (e.g. A, B, C...) refers to a single flow channel that was monitored.
Table 5-3: Summary of laboratory results from initial round of flow monitoring at Cell 1N

Note here that the physical composition of the flowing mass does not change significantly over the intervals sampled. While there are variations in the reported parameters over the flow length, those differences may be attributable to measurement error. By weight, the percent mineral solids does not change considerably in any flow observation (different flows are denoted by the Trial identifier). This indicates that the moisture content of the flow is not changing considerably over these intervals. The relative percent of fines (<44µm) and clay content (calculated from the Methylene Blue Index test) do not show increase as one might expect if the coarser fractions were settling out.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Sample</th>
<th>Location (m)</th>
<th>%Bitumen</th>
<th>%Mineral</th>
<th>%Water</th>
<th>Total</th>
<th>% Fines (&lt;44 µm), as Percentage of Total Solids</th>
<th>MB Slurry method</th>
<th>% Clay</th>
<th>CWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 1</td>
<td>2</td>
<td>2</td>
<td>2.38</td>
<td>25.59</td>
<td>71.42</td>
<td>99.38</td>
<td>79.91</td>
<td>1500</td>
<td>64.58</td>
<td>0.231</td>
</tr>
<tr>
<td>A 2</td>
<td>26</td>
<td>2.96</td>
<td>24.96</td>
<td>72.04</td>
<td>99.96</td>
<td>78.64</td>
<td>1367</td>
<td>1479</td>
<td>58.88</td>
<td>0.204</td>
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<tr>
<td>A 3</td>
<td>44</td>
<td>2.49</td>
<td>25.35</td>
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<td>1137</td>
<td>63.68</td>
<td>0.225</td>
</tr>
<tr>
<td>B 1</td>
<td>2</td>
<td>2.89</td>
<td>26.35</td>
<td>70.26</td>
<td>99.50</td>
<td>79.33</td>
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<td>1414</td>
<td>55.00</td>
<td>0.206</td>
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<tr>
<td>B 2</td>
<td>26</td>
<td>2.93</td>
<td>25.40</td>
<td>71.05</td>
<td>99.38</td>
<td>82.92</td>
<td>1367</td>
<td>1137</td>
<td>49.02</td>
<td>0.175</td>
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<td>B 3</td>
<td>44</td>
<td>2.94</td>
<td>26.17</td>
<td>70.25</td>
<td>99.36</td>
<td>83.22</td>
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<td>1414</td>
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<td>0.227</td>
</tr>
<tr>
<td>C 1</td>
<td>2</td>
<td>2.09</td>
<td>26.37</td>
<td>71.04</td>
<td>99.49</td>
<td>80.15</td>
<td>1055</td>
<td>1112</td>
<td>47.93</td>
<td>0.169</td>
</tr>
<tr>
<td>C 2</td>
<td>26</td>
<td>2.16</td>
<td>24.42</td>
<td>74.23</td>
<td>100.80</td>
<td>81.45</td>
<td>1055</td>
<td>1112</td>
<td>45.50</td>
<td>0.169</td>
</tr>
<tr>
<td>C 3</td>
<td>44</td>
<td>2.31</td>
<td>24.51</td>
<td>73.10</td>
<td>99.93</td>
<td>80.81</td>
<td>1558</td>
<td>1558</td>
<td>67.05</td>
<td>0.225</td>
</tr>
<tr>
<td>D 1</td>
<td>2</td>
<td>2.70</td>
<td>25.60</td>
<td>71.62</td>
<td>99.92</td>
<td>79.86</td>
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<td>1236</td>
<td>53.26</td>
<td>0.190</td>
</tr>
<tr>
<td>D 2</td>
<td>26</td>
<td>3.09</td>
<td>24.92</td>
<td>72.09</td>
<td>100.11</td>
<td>84.35</td>
<td>799</td>
<td>799</td>
<td>34.54</td>
<td>0.119</td>
</tr>
<tr>
<td>D 3</td>
<td>34</td>
<td>3.12</td>
<td>24.33</td>
<td>71.98</td>
<td>99.42</td>
<td>78.15</td>
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<td>800</td>
<td>34.59</td>
<td>0.117</td>
</tr>
<tr>
<td>E 1</td>
<td>2</td>
<td>2.12</td>
<td>24.83</td>
<td>72.31</td>
<td>99.27</td>
<td>88.02</td>
<td>1012</td>
<td>1012</td>
<td>44.02</td>
<td>0.151</td>
</tr>
<tr>
<td>E 2</td>
<td>26</td>
<td>1.68</td>
<td>24.63</td>
<td>72.94</td>
<td>99.25</td>
<td>88.79</td>
<td>950</td>
<td>950</td>
<td>41.01</td>
<td>0.138</td>
</tr>
<tr>
<td>E 3</td>
<td>34</td>
<td>1.42</td>
<td>23.88</td>
<td>74.93</td>
<td>100.24</td>
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<td>1271</td>
<td>1271</td>
<td>54.78</td>
<td>0.175</td>
</tr>
<tr>
<td>AVERAGE</td>
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<td>2.49</td>
<td>25.15</td>
<td>72.06</td>
<td>99.70</td>
<td>82.57</td>
<td>1198.49</td>
<td>1198.49</td>
<td>51.65</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Figure 5-10: Percent solids, fines, and clay content with distance travelled across the beach
A second round of monitoring and sampling was conducted under similar flow conditions to verify the results of the initial observations. The laboratory results are summarized in Table 5-4 and Figure 5-11.

Table 5-4: Summary of laboratory results for second round of flow monitoring at Cell 1N

<table>
<thead>
<tr>
<th>Trial</th>
<th>Sample</th>
<th>Location (m)</th>
<th>BMW by closure</th>
<th>% Fines (&lt;44 um), as Percentage of Total Solids</th>
<th>MB Slurry method</th>
<th>% Clay</th>
<th>CWR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>% Bitumen</td>
<td>% Mineral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>4</td>
<td>1.48</td>
<td>26.35</td>
<td>71.18</td>
<td>99.01</td>
<td>85.82</td>
</tr>
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<td>2</td>
<td>30</td>
<td>2.12</td>
<td>27.90</td>
<td>69.22</td>
<td>99.23</td>
<td>89.04</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>40</td>
<td>2.45</td>
<td>32.11</td>
<td>64.55</td>
<td>99.12</td>
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</tr>
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</tr>
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<td>67.76</td>
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<td>77.35</td>
</tr>
<tr>
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<td>2</td>
<td>30</td>
<td>1.89</td>
<td>25.91</td>
<td>71.27</td>
<td>99.07</td>
<td>81.48</td>
</tr>
<tr>
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<td></td>
<td>1.83</td>
<td>28.07</td>
<td>69.49</td>
<td>99.39</td>
<td>85.51</td>
</tr>
</tbody>
</table>

The second set of results confirms that there is no apparent sedimentation over the first 30 metres of beach within the flowing channels; however, sedimentation is likely to have occurred beyond at lower reaches of the cell as the flow velocity decreases. One notable exception is Trial A (Table 5-4), where there is an apparent 6% increase in solids content. This flow does represent the lowest recorded velocity on this monitoring occasion, with a measured surface velocity of 0.67 m/s. It is conceivable that this represents the critical velocity for the onset of sedimentation (Luppnow et al., 2009); however, more data would be required for confirmation and this lies beyond the scope of this thesis. For all other flows, it is plausible that the flows maintained an average velocity greater than the critical velocity, and hence maintain all particles in motion.

Figure 5-12 is a cross section showing the vertical aggradation of the beach between the initial flow monitoring event and the subsequent flow monitoring event (approximately 30 days apart). This cross sections indicates that despite there being no indication of particle sedimentation within the channels, some other mechanism must be responsible for causing material to deposit over these upper reaches of the cell. The locations of cross-cutting, meandering channels is evident from this cross section.
Figure 5-11: Percent solids, fines, and clay content with distance travelled across the beach (second round of monitoring)
Figure 5-12: Cross section of beach development showing vertical aggradation and cross-cutting channels. Section is oriented along the slope of the underlying bed (i.e. from discharge spigot towards the toe of the deposit).

5.5.2 Yield Stress Fluid Stoppage

While the flow and stoppage of flocculated tailings was not rigorously documented as part of this thesis, several observations were made during the course of field activities, namely:

- At some point along the beach length, and preferentially where the slope of the bed flattens and approaches zero, flocculated tailings will slow down, spread out laterally, and come to rest;
- The distance at which this occurs, relative to the discharge point, appears to be a function of the flow rate within the channel, and inversely related to the relative yield strength of flocculated MFTs;
- For observations of sheet flow, the run-out distance appears to be limited and related to the internal strength of the material; that is, sheet flows were observed to continue expanding across the deposition cell until a channel broke through and spread material further downslope.

5.5.3 Overbanking & Lateral Aggradation

Overbanking is a term borrowed from geomorphology which describes a process of sediment deposition on the floodplains of river systems (Bedient et al., 2007; Rameshwaran & Shiono, 2011). This occurs in unsteady, non-uniform flows when the volume of water and sediments passing through the river channel increases such that the flow depth exceeds the channel depth, and hence water and sediments are carried over the banks and deposit on adjacent floodplains as flows recede.

Figure 5-13 presents schematic cross sections of a flowing channel as it experiences overbanking.
The phenomenon of overbanking is the predominant deposition mechanism observed in flocculated MFT channel flows experiencing highly variable discharge rate and density on sloped beaches. The flooding of the channel promotes lateral and vertical growth of the deposit while still allowing for down-gradient movement away from the point of discharge.

Griffiths (2000) offers an equation to calculate the yield stress of a flow based on the measured geometry of the levees that border an open channel. The expression shows that for flows of high yield stress materials, the width of those levees will be much larger than for flows of a lower yield stress material. This interpretation provides support for observation of flocculated MFT to build expansive levees near the head of the deposit when high yield stress material is discharged.

Overbanking as a depositional mechanism is not discussed in tailings literature; however, it is concluded in this thesis that after substantial field observation that this process, along with chaotic scrolling of the channels across the deposition area, constitutes a primary depositional mechanism for this material.
Figure 5-12 provides evidence that vertical aggradation of the beach occurs despite the flow velocity being too high to allow sedimentation.
Chapter 6: The Flow Map – A Rheology-Energy Conceptual Model

6.1 Conceptualization of the Flow Map

As a primary objective of this thesis, a conceptual model was developed to describe the relationship between rheology and energy in the context of the overland flow of flocculated tailings.

Traditionally, flow maps are applied by fluid dynamicists to the description of multiphase liquid-gas flows restricted to pipes or channels; however, in this thesis, the concept of a flow map is applied to a yield stress fluid (flocculated MFT). The flow map relates the characteristic static yield stress of the tailings to the energy associated with the flowing mass and is generalized to include all observed flow regimes (Figure 6-1).

![Flow Map Diagram](image)

*Figure 6-1: Flow map (conceptual model) for flocculated MFT deposited on a sub-aerial beach*

The flow map may be interpreted by considering system energy as a combination of potential and kinetic energy embodied in the flow. If the flows are observed at a constant elevation along the flow path (that is, a set of observations of different flow regimes are made from the same place along the
stream), then the flow systems can be compared on the basis of kinetic energy alone. The effects of gravitational head are thus ignored and velocity head defines the system.

In this conceptual model, as system energy increases for lower yield stress materials, the dominant flow regime is observed to be laminar channel (comprising particles undergoing Brownian motion and experiencing hydrodynamic effects), while at higher energy levels the flow changes to a more turbulent regime dominated by inertia. This model agrees well with the Coussot (1997) model for mudflows. At the highest yield stresses, flocculated MFT forms stacks or lobes. In flocculated MFT, this can be interpreted as the result of a higher solids volume fraction generated through flocculation of once dispersed particles. However, as the system’s energy level is increased (e.g. the rate of discharge is increased), the stacking regime transitions to sheet flow and eventually to channelling flow, moving once again into an inertia-dominated system.

Figure 6-1 was conceived after field observations of numerous hours of active discharge to containment cells; however, it was acknowledged that quantification of the major boundaries could provide operators numerical guidance for managing the overland flow of tailings in their facilities.

### 6.2 Development of Numerical Boundaries

For quantification of system energy in Figure 6-1, the unit volume kinetic energy was used (as presented in Section 5.2).

The initial observations and measurements are summarized in Section 5.2 (Table 5-2). Where the visual flow assessment states only ‘channel’, the flow was not easily defined as either turbulent or laminar. For these observations, the measured flow velocity and dynamic pressure were later used to assign the specific flow regime on the basis of trends from the other data.

Figure 6-2 plots the field observations and measurements with the conceptual boundaries superimposed. For consistency, all of the data plotted here represent measurements taken at the initiation of flow, that is, within approximately two metres of the discharge spigot. This distance allows for the stabilization of the flow after leaving the plunge pool which is inherently turbulent. For this reason, these data can be taken to represent the initial rheological-energetic state of the material and the point at which the maximum unit volume kinetic energy (dynamic pressure) is achieved in the flow. Field data suggests that the conceptual model depicted in the flow map satisfies the range of observed field conditions.
The boundary separating laminar and turbulent channel regimes is situated at 1050 J/m$^3$ to separate the data; however, the data collected did not provide a sufficiently dense distribution of data points to allow the exact determination of this transition.

Given a typical measured density of 1100 kg/m$^3$, the flow velocity at this transition will be approximately 0.95 m/s. Furthermore, by assuming a typical channel flow depth of 10 centimetres, a Froude number of 0.96 is computed. This calculation suggests that the sub-critical to critical transitional boundary should be positioned closer to 1.0 m/s or 1100 J/m$^3$, thereby expanding the laminar channel domain slightly. The Froude criterion introduced in Section 3.4.5 appears to be a good indicator of the observed transitional flow region.
6.3 An Integrated Conceptual Model

Based on the nature of flocculated MFT, an integrated conceptual model for the deposition of solids was developed by the author. In some instances, fluid stoppage is predominant and may disperse solids over a large areal extent of the beach, yet in other instances a variable flow rate will cause channel overbanking and confine deposition to relatively narrow corridors down the beach.

The depositional process to dominate a flow will be based on the plotting position of the flocculated MFT in the rheology-energy space (see flow map conceptual model in Section 5.3). To develop a predictive model for this behaviour is beyond the scope of this work; however, a hybridized conceptual model is provided in Figure 6-3 as a starting point.

At high yield stresses, the material will tend to demonstrate a sheet flow or stacking behaviour; in this case, the primary depositional mechanism will be yield stress fluid stoppage. As is shown in Section 3.2.1.2, this fluid stoppage will occur at the point where the flow depth decreases and the gravitational driving force is insufficient to overcome the shear stress along the bed.

Figure 6-3: An integrated conceptual model for deposition and erosion of flocculated MFT on a sloped beach
For relatively low yield stress materials at low flow velocities, sedimentation within the channel is anticipated to be the main deposition mechanism. As the flow velocity increases to some critical value, sedimentation will be inhibited, the flow will become turbulent, and erosion may be observed along the channel walls.

For flows of moderately high yield stress material, at moderately high flow rates (particularly fluctuating flow rates), deposition is observed to occur by overbanking process described in Section 5.3.3. A moderate yield stress is required so that the overbanked material remains close to the channel, and does not flow down slope. Where fluctuations in flow rate are not the direct result of discharge conditions, it is conceivable that the channel may be flooded and overbanked as a result of downstream impedances to flow (e.g. a collapsed channel or downstream plug).

Note the appearance of an erosion space in the high energy, low yield stress region. While erosion of underlying materials is conceivable across almost all regions of the flow map, deep channels are primarily observed to form in the turbulent regime.
Chapter 7: Beach Profile Modeling

7.1 Background

Beaches created by natural processes have long been known to form non-monotonic, concave-up surfaces (Blight & Bentel, 1983). The beach profiles of hydraulically placed sediments in marine environments have also been analysed and reflect the same geometry (Melent’ev et al., 1973).

More recently, the surfaces created by the sub-aqueous and sub-aerial deposition of mine tailings have also been studied (Blight et al., 1985; McPhail, 1995) and have been shown to demonstrate the same characteristics as naturally formed beaches and hydraulically-placed sediments.

7.2 Observations

7.2.1 Profiles

All fully developed deposits (i.e. filled to capacity) were characterized by concave-up geometry; however, due to the variable beach length and thickness of deposit, direct comparison is difficult.

Figure 7-1 shows a representative set of normalized profiles, converted from raw field measurements. The horizontal axis represents the relative horizontal distance from the point of discharge to the end of the deposit (either the end of the flow or a body of water) while the vertical axis plots the vertical relief of the deposit surface relative to the total elevation difference between the point of discharge and the end of the deposit. The survey stations measured along the profiles are plotted without interpolation for later comparison to theoretical profiles (solid lines). A perfectly planar slope is provided for reference (dashed grey). Henceforth, the area of the deposit proximal to the point of discharge will be referred to as the head and the most distal point as the toe.
The selected profiles plotted in Figure 7-1 represent a range of deposits with total lengths from 118 to 275 metres, maximum thicknesses (as measured at the head) from approximately 1.0 to 3.5 metres, and bed inclinations ranging from 0.8% to 3.5%. For reference, Profile S5A is taken from Cell D1 and profile S1C6 is taken from Cell 6S. Furthermore, the profiles reflect various MFT source ponds and variable discharge conditioning. The range of expected deposit profiles of flocculated MFT is demonstrated by Figure 7-1.

Note that all profiles clearly demonstrate a non-planar, concave-up surface. The clustering of data points suggests the following form for description of the normalized profile according to Equation 3-22 presented in Section 3.4.6. The best-fit value of the concavity index, $c$, varies but clusters around a nominal value of 2.0. Note that the divergence of the measured values beyond 70% of the beach length ($x/H = 0.7$) is due to the inherent difficulty in defining the end of the deposit and the influence of the
variable extent of the water pool that accumulates at the downstream berm. Furthermore, the largest divergence from the master profiles is observed in deposits that were surveyed remotely while the deposit was actively dewatering and subsiding, while profiles that adhere more stringently to the empirical curves were more completely dewatered and trafficable by foot. This introduces the observation of time-dependency of the profiles.

A power law function would be better suited to match the observed profiles of S4A/B and S5A/B for example; however, as a logarithmic function has no theoretical basis, the exponential curve is preferred (as discussed in Section 3.4.3).

7.3 Energy-Based Profile Modelling

7.3.1 Modeling Objective
The objective of this modeling exercise is to assess the validity of the McPhail (1995) stream power approach as a predictive tool for estimating the two-dimensional beach profile of a flocculated MFT deposit.

7.3.2 Model Selection
The McPhail (1995) model was selected as it requires only the input of deposition cell geometry, operational discharge parameters (flow rate, density) and an estimate of the rheological properties which can be obtained through laboratory and field measurements. The hydraulic theory applied in the McPhail (1995) model is valid for steady, uniform, laminar flow. While these conditions do not always apply in the field given variations in feed quality and flocculation efficacy, these conditions are met more frequently than unsteady, surging flows when the system is operated diligently.

7.3.3 Conceptual Model
The conceptual model for flow and deposition is best illustrated by Figure 6-1 (Chapter 6) which presents the predominant flow regimes for flocculated MFT. The McPhail (1995) model is applicable, in theory, only to the laminar channel regime. In this regime, the loss of kinetic energy from a slowing stream must be counterbalanced by a potential energy increase which indicates that the channel base, and hence the beach surface, aggrades with time.

7.3.4 Data Review
During the course of field investigations, beach profiles from both fresh and dewatered deposits were obtained through level profiling and remote sensing with Light Detection and Ranging (LiDAR)
techniques. LIDAR surveys were conducted by MDH Engineered Solutions (Saskatoon, Canada) along with post-processing. Generally, level profiling was used for short beaches (less than 200 metres) while longer beaches, up to 300 metres, were surveyed using stationary, land-based LIDAR equipment.

Baseline rheological data was provided by Dr. Adrian Revington (Suncor) with permission for use in this modeling effort. The baseline data provides a range of plausible rheological parameters that are not easily obtained in the field (namely, dynamic viscosity and coefficients for the Herschel-Bulkley model). This baseline data was fitted with Herschel-Bulkley parameters for use in the McPhail (1995) model.

### 7.3.5 Application of the McPhail (1995) Profile Model

#### 7.3.5.1 Rationale

Given the inherent variability in process and discharge conditions, the most robust beach profile prediction model is preferred. The McPhail (1995) stream power-entropy approach allows for profile predictions based on assumed average or back-analyzed rheological parameters. In reality, the beach will be formed by a variety of materials with varying rheological behaviours; however, the majority of the beach profile will reflect the average rheological behaviour which may be difficult to determine experimentally.

In this case, the energy-rheology flow map (Chapter 6, Figure 6-1) was used to determine the appropriate rheological parameters to apply. Upon examination, it is apparent (based on the distribution of field observations) that an average flow condition may be best described by a laminar channel regime. Stacking flows are limited in influence to several tens of metres from the point of discharge (assuming a header height of 1 to 4 metres). Sheet flows are rarely observed and will thus not be considered. Turbulent flows, while prevalent under high discharge conditions, will tend to flow all the way to the toe of the cell and have little positive contributions to the beach building process.

Conveniently, a laminar channel regime will be accurately reflected in the hydraulic theory employed in the McPhail (1995) model.

#### 7.3.5.2 General Assumptions for Model Runs

Beyond the hydraulic and rheological assumptions required for the McPhail (1995) model (Section 3.4.6), several assumptions regarding operational parameters were required. These assumptions were supported by observations, field measurements, and laboratory analysis wherever possible.
For all model runs, unless otherwise noted, a discharge rate of 450 m$^3$/hr (divided between 4 spigots) was used. During field observations, this was the operational flow rate target. There is uncertainty associated with this parameter; hence its effect was evaluated in further sensitivity analysis (Section 7.3.7).

A bulk density of 1150 kg/m$^3$ was used for all model runs, unless otherwise noted. This density represents the average measured field density at the point of discharge at Cell 1N and corresponds to a mineral concentration of approximately 21% (assuming a specific gravity of solids of 2.65 which is reasonable based on field measurements of density and moisture content). This value is somewhat lower than the lab measured values during this investigation in the range of 23% to 26% solids. Furthermore, this range is lower than operational targets, but represents the reality of a variable discharge. The low solids content and density represent a conservative parameter which results in the development of long, flat beaches. For modeling purposes, the field measurements of density are considered to be more reliable. Within the range of observed field values, the beach profile is relatively insensitive to the density.

The Herschel-Bulkley rheological parameters were assumed from the Suncor laboratory results presented in Section 3.2.2 as an initial best-guess. The values of the coefficients were adjusted within a reasonable range during the calibration process to achieve the best fit for the measured beach profiles. For consistency, the same calibrated Herschel-Bulkley model parameters were assumed for all modeled profiles to demonstrate the predictive capability of the model. The effect of varying the yield stress is examined in Section 7.3.7.

### 7.3.5.3 Calibration and Application to Fresh Deposits

Although numerous beach profiles were measured during field investigations, few exhibit ideal boundary conditions for back-analysis and calibration. While the effects of boundary conditions are beyond the scope of this thesis, it should be regarded as a potential source of uncertainty.

Due to the deposition history and boundary conditions at Cell D1 (rectangular geometry, near-uniform 1% bed slope, and a fully developed profile), calibration was first carried out on this surface.

During calibration, average rheological parameters (Herschel-Bulkley model) from Suncor laboratory testing were used as initial best-guess values. From there, the average empirical rheological values were determined by fitting the stream-entropy profile to the measured profile elevations. Equation 7-1 and
Figure 7-2 present the Herschel-Bulkley model resulting from calibration of the McPhail profile to the measured beach profile.

\[ \tau = 18 + 3y^{0.67} \]

Equation 7-1: Herschel-Bulkley model assumed for McPhail beach profile modeling

The fitted beach profile is provided in Figure 7-3 and shows good agreement between the surveyed profile (red squares) and the simulated profile (blue crosses). Note that there is an apparent discrepancy between the measured and simulated beach run-out distance. The model fits a beach with a total length of approximately 190 metres, while the apparent measured beach is 250 metres in length. At these distances from discharge, defining the extent of the deposit becomes difficult. Errant product (poorly flocculated or over-sheared MFT) tends to run to the toe of the cell, filling the lower reaches with a shallowly-sloping, near horizontal deposit that is often water-covered. Extrapolation of the bed shows that the measured deposit thickness beyond 190 metres is no more than 0.2 m (or less than 0.1% of the run-out distance and no more than 5.7% of the maximum deposit thickness).
Figure 7-3: Measured and predicted beach profile for fresh deposit at Cell D1 showing good model fit; $Y_s = 18\, \text{Pa}, K=3, n=0.67$
Within the McPhail (1995) model, the calculated bulk yield stress and the yield stress sustainable by the fluid are calculated at each point down the beach according to the calculated flow velocity and shear rate in a laminar channel of assumed geometry. The values shown in Figure 7-4 demonstrate reasonable agreement.

![Calculated vs Sustainable Shear Stress](image)

Figure 7-4: Calculated and sustainable shear stress along beach length.

The McPhail (1995) stream power model provides a good fit with the fully-developed, field-measured profile with reasonable rheological parameters assumed from laboratory and field testing.

### 7.3.5.4 Verification and Validation

To verify the model calibration, another profile (not used in calibration) was selected to assess the goodness of fit. A typical deposit from the System 4 deposition area was selected for analysis as this was the only other fully developed deposit with boundary conditions consistent with ongoing deposition cell construction (i.e. long cells with relatively shallow bed slopes).

The same Herschel-Bulkley model was used and the bed slope and header height parameters were adjusted to reflect the conditions at the System 4 site. The resulting profile is presented in Figure 7-5.
Figure 7-5: Measured and predicted beach profiles for Cell B1 (System 4) for validation of McPhail (1995) model

\[ y = 0.00004x^2 - 0.03493x + 9.98207 \]

\[ R^2 = 0.99993 \]
7.3.5.5 Application to Dewatered Deposits

Due to safe access concerns and the limited availability of remote surveying equipment, many of the deposit profiles were obtained some time after the discharge and deposition period. After periods of days and weeks, the deposits show significant signs of settlement and consolidation due to dewatering and evaporative drying. This change in volume over time must be considered if these dewatered-deposit surveys are to be used for validation of the model.

Using the assumed flow curve from the calibration discussed in Section 7.3.5.3, the following initial deposit profile is generated (Figure 7-6). It should be noted that the bed slope was not known definitively but was assumed to vary between 1% and 3%. During modeling, the most reasonable profile was achieved using a 1% bed slope.
Figure 7-6: Examination of predicted fresh deposit surface vs. the measured profile at Cell 6S. The discrepancy is partially attributed to ongoing dewatering and consolidation; $Y_s = 18$ Pa, $K=3$, $n=0.6$
Once again, the calculated shear stress and sustainable shear stress show reasonable agreement (Figure 7-7)

![Calculated vs Sustainable Shear Stress](image)

**Calculated vs Sustainable Shear Stress**

Upon closer inspection of the profile, the discrepancy between the predicted fresh deposit profile and the as-measured field profile is evident. The date of surveying was approximately one month after deposition of the uppermost 0.5 metres of flocculated MFT (full deposit was placed in lifts of approximately 0.5 metres thickness at the head).

The average settlement across this section is in the range of 10 to 20 centimetres which is reasonable for a deposited layer of approximately 50 centimetres initial thickness (20% to 40% settlement). Note also that the proportion of settlement is greater near the toe of the cell where the deposit thickness decreases. The greater overall volume reduction is likely attributable to evaporative losses and the nearly complete desiccation of the flocculated MFT near the toe as no water was retained at the lower portion of this cell.

### 7.3.6 Results

During the calibration stage, the McPhail profile was successfully fitted to the field-measured profile of Cell D1 using a Herschel-Bulkley rheological model which is considered reasonable when compared to
laboratory and field measurements. A direct comparison of measured and predicted surface elevations are provided in Figure 7-8. The results show good model fit, with all predicted points within 40 cm of the measured elevations. An acceptable error of 10 to 15% of the maximum deposit thickness was deemed acceptable for this exercise.

![Figure 7-8: Calibration results for the McPhail model applied to Cell D1 profile](image)

The stream power model is applicable directly to fresh deposits that have not experienced significant settlement or consolidation due to dewatering. Beyond this timeframe, one should consider consolidation and settlement effects. The applicability of this model to fresh deposits may range from a period of hours in optimal water release material to a period of weeks for sub-optimal water release material. During the validation stage of modeling, the McPhail model was successfully applied to a measured profile of a fresh deposit from the System 4 Cell B1 deposition area. A comparison of the predicted and measured deposit surface elevations is presented in Figure 7-9. There was a local area
where the measured beach profile was more than 50 cm below the predicted profile, but generally the model provides an acceptable fit.

To assess how a dewatered deposit profile compares to a fresh deposit, and whether the McPhail (1995) model could still describe the surface, the model was applied to the Cell 6S profile. The analysis suggests that the profile can still be explained using the McPhail (1995) model and that back-analysis of older deposits may be possible if the effects of dewatering and consolidation are understood. Figure 7-10 illustrates the goodness of fit for this exercise.
Uncertainty and Sensitivity Analysis

As there is some uncertainty regarding the operational parameters assumed in this study, and as the nature of the flocculated MFT could change over time and as the process is developed, a sensitivity analysis was undertaken to evaluate the effect of discharge rate, bed slope, and flocculate MFT yield stress on the beach profile. As the profile presents a complex geometry, a simplification was required to compare the modeled deposits. To achieve this, the run-out distance of the beach was taken as the basis for comparison. For high concavity beach profiles, the run-out distance will tend to be shorter than for beaches of low concavity, owing to the relationship between yield stress and concavity.

The effect of yield stress was first analyzed by systematically changing the yield stress component of the Herschel-Bulkley model used in the McPhail (1995) calculations. The run-out distance was predicted for four different yield stresses over four different bed slopes, producing a total of 16 sensitivity runs. For all runs, the discharge rate was held at 450 m³/hr and the height of the discharge point above ground surface was 3.5 metres. The results of these runs are presented in Figure 7-11.

Figure 7-10: Model fit results for McPhail (1995) model applied to Cell 6S profile
Two main observations are apparent from the compilation of Figure 7-11, namely:

- Predicted run-out distance (and hence beach profile) is strongly influenced by basal slope when the yield stress is less than 50 Pa and this sensitivity increases as the yield stress decreases; and
- Predicted run-out distances for materials with a yield stress above 100 Pa are relatively insensitive to basal slope, and are not predicted to achieve run-out distances greater than 50 m on bed slopes up to an including 3.5%.

In addition to yield stress, the effect of discharge rate was examined with an additional eight sensitivity runs. These run results are presented in Figure 7-12.
The key observations from Figure 7-12 include the following:

- Predicted run-out distance is positively correlated (non-linearly) and highly sensitive to discharge rate; and that
- A theoretical maximum run-out distance at the current operational discharge rate (450 m$^3$/hr) is approximately 400 m on a 3.5% slope.

When the run-out distance is expressed as a function of discharge rate, the utility of the data becomes more apparent (Figure 7-13).
7.4 Discussion

Three full-scale beach profiles were used to calibrate and validate the McPhail (1995) model for flocculated MFT beach profile prediction. All model runs showed good correlation with the field-surveyed beach profiles. The apparent discrepancy in run-out distance is attributable to the author’s observation of errant product filling the lower reaches of the cell, which is not representative of the overall deposit geometry.

The McPhail (1995) model may be used to back-analyze dewatered and consolidated deposits in order to ascertain the original rheology of the tailings; however, fresh deposits should be used for analyses wherever possible.

Furthermore, a sensitivity analysis of key operational parameters has revealed that the dependence of run-out distance on discharge rate and basal slope is strongest when the yield stress of flocculated MFT is below 50 Pa.
Chapter 8 : Application and Discussion of the Results

8.1 Flow Control

8.2.1 General

Flow control refers to the management of discharge rates such that the tailings are deposited to a cell in a manner which precludes unnecessary shearing of the material, erosion of the previous beach surface, or stacking of high viscosity tailings requiring mechanical intervention.

On the basis of the flow map that has been suggested for flocculated MFT in this thesis, guidelines can be established for the effective management of tailings discharge rates to the receiving cell. For example, both stacking flows and turbulent flows are undesirable for everyday operation.

Stacking may be avoided by increasing the energy inputs which can be achieved by increasing the discharge rate at the spigot. This may be achieved in two main ways, namely:

- Increase the flow rate to the entire cell, or
- Increase the flow rate through individual spigots by restricting or preventing flow through neighbouring spigots.

These operational changes could increase the dynamic pressure of the flow and move it into a channel flow regime; however, increases in the pressures for spigots and distribution lines have to be maintained within their safe operating limits and pump capabilities.

For turbulent flows, the solution is more easily achieved. The operator should reduce the flow rate through each spigot such that the velocity of flow on the beach falls back to within the limits established for laminar flow. Reducing the flow rate to the cell may not be desirable for production purposes or for hydraulic reasons; however, additional spigots could be introduced to the system thereby reducing the average flow rate through each outlet. These additional spigots could be opened or closed depending on the requirements of the system.

Laminar flows may be routinely achieved by managing the discharge rate such that it is tailored to the yield stress and density of the material that is produced as a result of the flocculation process.
8.2.2 Sustaining a Laminar Channel Flow

A laminar flow regime will be sustained when the tailings embody sufficient energy to preclude stacking and back-up without exceeding some critical value above which turbulent flow is initiated.

If the flow velocity measurements embodied in the flow map from Section 6.3.2 are assessed directly (Figure 8-1), a range of Froude numbers from 1.11 to 1.36 is computed (assuming a mean flow depth of 10 cm) between the laminar and turbulent observation points. This value range likely exhibits some density dependence, and hence the laminar-turbulent boundary would not be vertical in the flow map, as it is depicted in Figure 8-1 (density effects have been eliminated from this plot by assuming a constant density).

![Observed Velocity Thresholds for Flocculated MFT](image)

For flocculated tailings with a static yield stress equal to or above 100 Pa, the minimum flow velocity required to sustain channel flow (and avoid stacking) is shown to be approximately 0.65 m/s. Assuming a channel radius and depth equal to 15 cm, this equates to a minimum required flow rate of 83 m$^3$/hr supplied by the spigot to the beach channel when the material yield stress is above 100 Pa.
To preclude turbulent flow of materials below 100 Pa, the channel velocity on the beach should not exceed a nominal range of 0.95 to 1.2 m/s. Again, assuming the channel geometry as above, each spigot should supply between 120 and 150 m$^3$/hr to the beach.

For the purposes of flow control, the findings of this thesis would suggest that an ideal operating range for discharge to a deposition cell, as currently configured, would be from 330 to 480 m$^3$/hr. By operating below or above this range, the operator is exposed to risk of frequent back-ups and turbulent channel flows.

8.2 Profile Control

Data presented in Section 7.2.1 suggests that many of the measured beach profiles, when compared on a normalized basis, exhibit the same degree of concavity although the scale of those deposits varies considerably. From an operational perspective, the control of the deposit profile may be practically difficult to achieve given the variability of feed and discharge conditions, and the chaotic nature of beach formation; however, several conclusions may be drawn from this thesis to direct operators in controlling run-out distance and maintaining effective cell coverage.

First, the run-out distance of a tailings beach is shown to be highly sensitive to discharge rate and sensitive to slope when the tailings yield stress is low (below 50 Pa). The higher the slope of the beach, the more prudent the operator must be when regulating the discharge rate. Second, stacking and back-up is nearly inevitable when the tailings yield stress exceeds 100 Pa; a pseudo-uniform sheet flow may be achievable between 50 and 100 Pa on bed slopes between 1 and 3.5%, but this yield stress range may be practically difficult to maintain.

8.3 Design of Deposition Cells

Although sheet flow or pseudo-sheet flow may be considered ideal, predictions based on the McPhail (1995) model show run-out distances (for the yield stress range defined in the flow map, and assuming current discharge practices) no greater than about 100 metres (Figure 7-11). For the design of a deposition cell, the designer should consider selecting the bed slope and cell dimensions that accommodate deposits formed by laminar channel flows.

The sensitivity analysis introduced in Section 7.3.7 suggest that a 3.5% bed slope produces a wide range of deposit lengths and implies that this bed slope is inappropriate for tailings with yield stress values
lower than 50 Pa. A more appropriate bed slope for a robust design would likely lie between 1.5 and 2%.

The length of the deposition cell should be based on the anticipated maximum run-out distance of the tailings. The reason for this is so that the lowest reaches of the cell can be used for the collection and control of water (derived from the dewatered tailings and from surface run-off), and so that this body of water does not adversely impact the dewatering and drying of material near the end of the deposit. Based on an assumed header height of 3.5 metres and a bed slope ranging between 1.5 and 2%, a minimal cell length of between 220 and 270 metres should be adopted (allowing for up to 20 metres of horizontal space for water management).

### 8.4 Storage Estimation

This application provides estimates of cell storage based on various geometries and assumptions regarding beach concavity. Estimates of storage capacity can be made by estimating the area of a longitudinal cross-section and multiplying by the cell width. There are three primary methods for estimating the cross-section of a sloping deposit, namely:

- Assume a monotonic beach slope and approximate the deposit volume using a wedge-shape;
- Assume a concavity index, \( c \), and use Equation 3-22 to estimate the cross sectional area of the deposit (through integration of the exponential function); or
- Integrate a polynomial function that is fitted to the McPhail (1995) beach profile.

Concavity indices typical of flocculated MFT deposits range from approximately 2.0 to 2.5 based on observations presented in Section 7.2.1. This concavity leads to a discrepancy between monotonic storage calculations and those that accommodate concave beaches. This discrepancy is independent of the beach length, bed slope, or header height, and is dependant only on the degree of concavity.
Table 8-1 presents estimates of deposition cell storage based on an assumed length and width, and varying degrees of cell usability (dictated by water control measures), header height, and beach concavity. The measured range of concavity translates into a discrepancy of 14 to 27% when compared to monotonic storage estimates.

Table 8-1: Disposal cell capacity for deposits with monotonic (planar) and concave profiles

<table>
<thead>
<tr>
<th>Cell Length, l (m)</th>
<th>Cell Width, w (m)</th>
<th>Usable Cell Length (%)</th>
<th>Cell Header Height, H (m)</th>
<th>Deposit Concavity Index, c</th>
<th>Concave Fill Capacity (m$^3$)</th>
<th>Monotonic Calc. Capacity (m$^3$)</th>
<th>% Monotonic Over-Estimate</th>
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</thead>
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<tr>
<td>200 50 85 1</td>
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<td></td>
<td></td>
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<td>4,250</td>
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<td></td>
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<td>8,500</td>
<td>14%</td>
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<tr>
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<td></td>
<td></td>
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<td>12,750</td>
<td>14%</td>
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<td>4,323</td>
<td>5,000</td>
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</tr>
<tr>
<td>200 50 100 2</td>
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<td></td>
<td></td>
<td>8,647</td>
<td>10,000</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>200 50 100 3</td>
<td></td>
<td></td>
<td></td>
<td>12,970</td>
<td>15,000</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>200 50 85 1.5</td>
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<td></td>
<td></td>
<td>3,121</td>
<td>4,250</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>200 50 85 2.5</td>
<td></td>
<td></td>
<td></td>
<td>6,242</td>
<td>8,500</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>200 50 85 3.5</td>
<td></td>
<td></td>
<td></td>
<td>9,363</td>
<td>12,750</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>200 50 100 1.5</td>
<td></td>
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<td></td>
<td>3,672</td>
<td>5,000</td>
<td>27%</td>
<td></td>
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<tr>
<td>200 50 100 2.5</td>
<td></td>
<td></td>
<td></td>
<td>7,343</td>
<td>10,000</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>200 50 100 3.5</td>
<td></td>
<td></td>
<td></td>
<td>11,015</td>
<td>15,000</td>
<td>27%</td>
<td></td>
</tr>
</tbody>
</table>
Figure 8-2 illustrates the volume discrepancy in two-dimensions.

Figure 8-2: Two-dimensional volume discrepancy (purple area) between a monotonic beach and a concave beach with a (a) concavity index of 2.0 and (b) concavity index of 2.5.

The apparent increased storage volume in the toe of the deposit (x/H = 0.8 to 1.0) is the result of the exponential representation of the profile and accounts for only 2.5 to 5% of the total volume estimate. It can thus be expected that a monotonic beach profile used for storage estimates will overestimate flocculated MFT capacity by approximately 10 to 20%.
The most accurate estimate of deposition cell capacity may be achieved by examining the volume captured by a McPhail (1995) beach profile. The simplest method for determining this volume is by fitting an appropriate function through the beach profile, integrating that function and evaluating it at the limit of the beach length, correcting for the bed slope, and multiplying by the cell width. Polynomial functions (second-order) are fitted to McPhail (1995) beach profiles in Figure 7-3, Figure 7-5, and Figure 7-6. These functions are easily integrated to determine the cross-sectional area. Table 8-2 presents a comparison of volume estimates for deposits represented by monotonic, concave, and McPhail (1995) model profiles for key study cells in this thesis.

### Table 8-2: Comparison of volume estimates for study cells

<table>
<thead>
<tr>
<th>Study Cell</th>
<th>Monotonic Estimate</th>
<th>Concavity Estimate ((c = 2.0))</th>
<th>Concavity Estimate ((c = 2.5))</th>
<th>McPhail Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>16,625</td>
<td>14,298</td>
<td>12,136</td>
<td>13,957</td>
</tr>
<tr>
<td>6S</td>
<td>8,000</td>
<td>6,880</td>
<td>5,840</td>
<td>4,865</td>
</tr>
<tr>
<td>B1</td>
<td>20,000</td>
<td>17,200</td>
<td>14,600</td>
<td>16,523</td>
</tr>
</tbody>
</table>

This application shows that integration of a McPhail (1995) profile provides a reasonably conservative estimate of storage volume.
Chapter 9: Conclusions & Recommendations

9.1 Hypothesis Outcomes

The flow and deposition of flocculated MFT on a sloping beach can be described in the context of a rheology-energy conceptual model. The conceptual model, or flow map, can provide designers and operators with a useful framework for managing beach development in a sub-aerial deposition cell.

A suite of depositional mechanisms are suggested for integration into the conceptual model for flocculated MFT beaching, including yield stress fluid stoppage for sheet and stacking flows as well as the lateral and vertical aggradation of beaches due to the phenomenon of overbanking.

The database of fully-developed beach surveys presented in this thesis demonstrates the trend of strongly concave beach profiles which has significant repercussions for tailings planning; this geometry cannot be ignored when calculating storage volumes.

Furthermore, the McPhail (1995) stream power model provides a robust tool for estimating final beach profiles developed from the sub-aerial discharge of polymer-flocculated mature fine tailings. The model has been validated against field-scale measurements and is consistent with the rheology-energy conceptual model developed to describe the flocculated MFT beaching behaviour. The entropy-based stream power model is capable of predicting fresh deposit profiles with knowledge of discharge conditions and rheological parameters derived from standard laboratory testing that are validated with field measurements. The model can be used for back-analysis and determination of flow-scale rheological behaviour.

Ultimately, the utility of the flow map conceptual model and the field-validated profile model lays in the efficient design and operation of a sub-aerial disposal cell for flocculated tailings.

9.2 Limitations

The analyses and interpretations presented in this thesis are limited to observations of flocculated MFT; however, it is conceivable that the findings presented here may be applied to other types of thickened tailings.

Furthermore, the author recognizes that numerical boundaries and quantification of some processes described in this thesis could be further refined with additional field and laboratory data. However, the methods and conceptual model presented here serve as a basis for future work in this area.
9.3 Recommendations for Further Research

9.3.1 Confirmation of the Flow Map Conceptual Model Boundaries

Further work should be completed to refine the boundaries or transitional regions between the observed flow conditions and depositional processes. Conceivably, an appropriately sized bench-scale experiment could be developed to verify and augment the observations presented in this thesis under rigorously controlled conditions. The scale of this experiment would have to account for the stacking behaviour which can build deposits to considerable height and lateral extent. Ideally, the experimental set-up would also be capable of replicating the overbanking phenomenon as this is identified as a key depositional mechanism in this thesis.

The flow map concept could also be applied to other tailings which exhibit variable flow behaviours due to flocculation or thickening processes.

9.3.2 Rheology-Distance Correlations for Beach Profile Prediction

While this thesis shows the validity and robustness of the McPhail (1995) model for predicting the beach profiles created by the sub-aerial flow and deposition of flocculated MFT, the model in current form is based on the assumption of a constant rheology over the entire flow length. This thesis has shown that changes in rheology do occur along the flow path.

Further research into the changes of rheology as a function of flow distance would improve the completeness of this model.

9.3.3 Large-Scale Boundary Effects on Beach Profiles

There is some evidence to suggest that slopes near the boundaries of large disposal cells may be influenced by adjacent containment berms. This may be due to wall friction effects at the field scale, changes in dewatering and settlement behaviour near the containment berms, or variability in the discharge quality near the beginning or end of the delivery pipes. The quantitative effect of these boundary conditions was beyond the scope of this thesis; however, this boundary effect could have implications for storage estimates.

Complete surveys over entire deposition areas (containing up to 10 adjacent deposition cells) are scarce, hence further investigation into this phenomenon would be required. Likely, land-based LIDAR would provide valuable data for this research.
9.3.4 Over-Wintering Effects & Long Term Creep of Deposits

Some measured profiles after the first winter were noted to have a remarkably planar surface. Visually, this observation is applicable to other similar deposits on a 4% slope. This may indicate a slow creep phenomenon or differential consolidation as the result of freeze-thaw action on a relatively steep inclination.

It is conceivable that if underlying materials remain at sufficient moisture content on a steep gradient, the deposit could very slowly flow down-gradient, much as a glacier flows down-valley under the influence of gravity. Observations show that freeze depth in these deposits is typically no more than one metre; hence deposits over one metre in thickness could experience creep, even when the deposit pore water is frozen near-surface.

9.3.5 Three-Dimensional Deposit Modeling

It is conceivable that the McPhail (1995) entropy model could be adapted to produce a three-dimensional surface representing the ultimate deposit surface. The model would require an algorithm for lateral distribution of material through channel meandering, an inherently stochastic process. A correction would be required for the reduced gradient as the assumed path of the channel deviates from the discharge centreline (and hence the maximum gradient of gravitational potential). A three-dimensional model would further help determine capacity estimates for containment facilities.
Bibliography


Appendix A – Basic Rheological Concepts

This appendix is intended to provide the reader with a basic background in rheological concepts applicable to this thesis. The information and figures cited are reproduced from Boger (2009) unless produced by the author.

For a fluid undergoing laminar flow, the flow is conceptualized as an infinite number of layers sliding over one another. The force acting between adjacent layers is the shear stress. For open channel flow, the magnitude of the flow velocity decreases with depth until it reaches zero at the base of the channel due to friction and hence the velocity gradient, $\delta u/\delta y$ (which is defined perpendicular to the orientation of the layers) increases with depth (Figure A-1).

![Velocity and shear stress distribution through a laminar flow in an open channel.](image)

The shear stress between layers will be proportional to the velocity gradient at any point in the flow profile. This relationship is expressed as in Equation A-1:

$$\tau = \text{shear stress, } \tau$$

$$\delta u / \delta y$$

$$y$$

velocity, $u$

---

where the coefficient of proportionality, \( \mu \), is referred to as the *dynamic viscosity*\(^4\) and the velocity gradient is synonymous with the term *shear rate* (\( \gamma \)).

Dynamic viscosity is defined then as the shear stress divided by the shear rate and has standard units of Pascal·seconds (Equation A-1).

\[
\tau = \mu \frac{\delta u}{\delta y}
\]

**Equation A-1: Distribution of shear stress through a fluid profile**

Hence, it can be observed that for simple (Newtonian) fluids, the viscosity at any shear rate is simply the ratio of shear stress to the shear rate. These two parameters can be easily measured with the proper instrumentation, and hence the viscosity can be calculated (Figure A-2). Further implied in this formulation is the fact that so long as the shear stress is greater than zero, the shear rate will be greater than zero and the fluid will flow.

\[
\mu = \frac{\tau}{\gamma}
\]

**Equation A-1: Definition of dynamic viscosity**

\(^4\) Less commonly, *kinematic viscosity* is used as a measure of fluidity and is simply the dynamic viscosity divided by the fluid density.
For mineral suspensions, the relationship between applied shear rate and shear stress is generally not constant. That is, the viscosity of the fluid changes as a result of changes in applied shear. This is referred to as a *non-Newtonian* behaviour. Because of this behaviour, viscosity may be referred to as *apparent viscosity* because the ratio of shear stress to shear rate is dependent on the shear rate.

Figure A-3 illustrates a typical flow curve derived from laboratory testing that shows both thixoptropic and shear-thinning behaviour. As both the time under shear and the shear rate are increased, the apparent viscosity of the material (red mud, in this example) is reduced. Thixotropy is reserved to describe the decrease in viscosity of a fluid subjected to a constant shear rate over time, while shear-thinning refers to the decrease in viscosity as a result of increasing the rate of applied shear.

Figure A-4 shows the effect of material breakdown as the time under shear increases and also shows how the material properties approach the initial conditions after some time at rest (re-growth).
To fit curves to empirical data like those shown in Figures A-3 and A-4, mathematical models have been developed. The most common models applied to mineral suspensions are the Bingham and Herschel-Bulkley models (Figure A-5).
Both models are similar in that they include definition of the yield stress ($\tau_y$ or $\tau_0$) that is required to initiate flow. The models differ in that only the Herschel-Bulkley model describes a relationship where viscosity changes as a function of shear rate. The form of the Herschel-Bulkley model is provided in Equation A-2.

$$\tau = \tau_0 + K\gamma^n$$

*Equation A-2: Definition of the Herschel-Bulkley model*

Mathematically, it can be seen that the Bingham model is a special case of the Herschel-Bulkley model where the parameter $n$ is equal to one.

An important rheological parameter for the design of slurry transportation systems and tailings facilities is the yield stress. As described earlier, this constitutes the minimum shear stress required to initiate flow. Boger (2009) shows the influence of the suspension concentration on yield stress for a variety of tailings (Figure A-6).
Determination of the yield stress presents a challenge as one must determine the shear stress in a fluid at a shear rate of zero, by definition. This implies that some extrapolation is required to estimate the shear stress at zero shear rate, as this is not directly measurable. Difficulties in obtaining reliable results at very low shear rates present problems like slip and sedimentation. When a Bingham model is applied to the data, the yield stress may be significantly over-predicted (as shown in Figure A-8) because the intercept is extrapolated from high shear rate data (Boger, 2009).

Figure A-6: The effect of solids concentration on yield stress for various tailings (Boger, 2009).

Figure A-8: Extrapolation to find yield stress using a Bingham and Herschel-Bulkley model (Boger, 2009)
The vane method and slump methods are shown to provide the best estimate of the true yield stress affecting fluid flow (Boger, 2009). A schematic for each method is provided in Figure A-9 and Figure A-10.

Figure A-9: Yield stress measurement using the vane technique (Boger, 2009)

Figure A-10: Yield stress determination from the slump method (Boger, 2009; Pashias and Boger, 1996)

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Appendix B – Description of the McPhail (1995) Algorithm

The following is a general description of the semi-automated spreadsheet algorithm used to calculate the beach profile based on the McPhail (1995) stream power model. The spreadsheet model was developed by G.I. McPhail and was provided to the author for use in this work.

First, an initial guess at the geometry of the flow leaving the plunge pool is made using the inputs of flow rate from the spigot and an assumed flow width. From this, the bulk shear rate in the flow is calculated.

Next, the shear stress is calculated as a function of the Herschel-Bulkley rheological model inputs. From this, the initial slope of the flow is calculated. Using the slope function presented in Chapter 3 – Section 3.6.6 (Equation 3.25), the parameter \( \mu \) is solved iteratively until the calculated slopes at distance zero from the plunge pool are equal.

At the lip of the plunge pool, the stream power is calculated using the \( \mu \) parameter and the expression for stream power as a function of distance (Chapter 3 – Section 3.6.6, Equation 3.24). This establishes the velocity and flow geometry at the beach head.

The fanning friction factor, \( f \), which relates the flow velocity to frictional losses along the channel wall, is calculated. This is used to calculate the bulk shear stress of the tailings mass at that point. Using the Herschel-Bulkley model, the theoretical shear stress is also calculated. These two values are compared to ensure that the flow is hydraulically possible given the fluid characteristics. During the calibration process, fluid parameters can be adjusted within a reasonable range so that these values are in reasonable agreement.

At the next calculation step, a new distance along the beach is chosen (typically the beach length is divided into horizontal intervals of equal spacing) and the calculation of stream power and slope is repeated. The change in slope of the stream power curve dictates the change in elevation across each distance interval, and hence the continuous beach profile is generated when all calculations have been performed across the horizontal extent. The algorithm is complete when the stream velocity (and hence the stream power and beach slope) is zero.

At this point, the operator should verify the goodness of fit (if back-analyzing a measured profile) and ensure that the plots of shear stress over distance coincide.