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Deposition thickness and evaporative drying for oil sands tailings in northern Alberta

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Abstract

Directive 074 issued by Alberta Energy Resources Conservation Board (ERCB) requires that fine tailings materials deposited each year must achieve a minimum undrained shear strength of 5 kPa within one year following deposition. Challenged with this requirement, oil sands owners and operators in Alberta, Canada, are evaluating several opportunities for tailings dewatering. One opportunity is taking advantage of the evaporation potential, following deposition, to assist with dewatering tailings. Three types of tailings, namely, non-segregated tailings (NST), mature fine tailings (MFT), and treated thickened tailings (TT) were generally produced by Shell Canada Limited's Albian Sands Energy operation with different treatment technologies. These three types of tailings have various consolidation behaviours and initial solids contents, which imply that the tailings deposition thickness will be different from each other in order to achieve the ERCB-D 074 requirements while utilising evaporative drying to dewater the fluid tailings. The average annual precipitation and potential evaporation are approximately 470 and 640 mm, respectively in the northern Alberta area. A simplified methodology based on tailings consolidation properties, meteorological data, and initial state of tailings deposits is presented in this paper to determine appropriate fine tailings deposition thicknesses, in the context of the exceedance probability of achieving the desired solids content (and hence undrained shear strength), for different times of the year. The maximum yearly deposition thickness with 80% probability of exceedance is approximately 200 cm for NST with enhanced initial deposition solids content, approximately 160 cm for enhanced TT, and approximately 144 cm for enhanced MFT. The methodology presented in this paper can be used to develop understanding for potential tailings deposition thickness that will have a high probability of achieving the target solids contents and shear strengths due to evaporative drying. Site-specific conditions can then be used to optimise fine tailings management.

1 Introduction

Alberta Energy Resources Conservation Board (ERCB) issued *Directive 074* (ERCB, 2009) to regulate tailings management in order to reduce containment of fluid tailings and create a trafficable landscape at the earliest opportunity to facilitate progressive reclamation in Northern Alberta, Canada. Directive 074 requires the reduction of fluid tailings through fines captured in dedicated disposal areas (DDAs). The deposited fluid tailings in DDAs each year must achieve a minimum undrained shear strength of 5 kPa within one year of deposition. Challenged with this requirement, oil sands owners and operators are evaluating several opportunities for tailings dewatering. One approach being considered to reduce water content of fluid oil sands tailings is by taking advantage of environmental evaporation.

Evaporative drying technology takes advantage of the evaporation potential, following tailings deposition, to assist with dewatering tailings. The evaporative drying rate of fluid tailings is affected by environmental factors, characteristics of the tailings, and tailings depositional conditions/processes. The environmental factors include solar radiation, air temperature and relative humidity, wind speed, and precipitation intensity and duration. Characteristics of the tailings include salt concentration in the pore fluid in the tailings and potential to form a crust (Simms et al., 2009), as well as tailings hydraulic material characteristics. The factors associated with tailings deposition processes/conditions include tailings filling rates (i.e. deposition lift thickness and frequency), capillary barrier effects, and under drainage conditions (Boswell and Sobkowicz, 2010). The tailings deposition thickness satisfying a particular requirement (ERCB-D 074) is a function of the tailings evaporative drying rate and tailings initial and target states (i.e. solids content, or void ratio).

Shell Canada Limited (Shell) produces three major types of tailings at its Albian Sands Energy (ASE) operation located approximately 70 km north of Fort McMurray, Alberta, Canada. The three types of tailings are non-segregated tailings (NST), paste thickener underflow (PTU) or treated thickened tailings (TT), and mature fine tailings (MFT). The enhanced solids contents of the tailings are between 40% and 60%. Evaporative drying rates from deposits of these various tailings materials could be different depending on their geochemical, physical/hydraulic and depositional characteristics. Fort McMurray has a humid continental climate with long, cold winters and warm, short summers. The average annual precipitation is approximately 470 mm, which, in general, is evenly distributed between winter and summer. The potential evaporation (PE) is approximately 640 mm per year.

Tailings management with evaporative drying includes determining the tailings filling rate and then maximising utilisation of environmental evaporation. Seneviratne et al. (1996), at a site in Western Australia, found that a threshold filling rate is 5.3 m/yr for a clayey silt tailings (initial void ratio 4.6) for an annual PE rate of approximately 3,000 mm. The threshold filling rate for a given PE is the fastest rate that the tailings should be deposited while still allowing evaporation to have its full effect. For the climate with a PE of approximately 0.6–0.7 m/yr in Northern Alberta, the threshold filling rate should be much smaller than that in Western Australia for a similar deposit. Although thin lifts (typically less than 20 cm) have substantial benefit in regards to consolidation through self drainage and desiccation (Boswell, 2009), a general description of thin lifts do not satisfy the demands of tailings deposition management due to varied climates.

This paper presents a simplified methodology, based on tailings consolidation properties, meteorological data, and initial state of tailings deposits, to determine appropriate fine tailings deposition thicknesses, in the context of the exceedance probability of achieving the desired solids content (and hence undrained shear strength), for different times of the year. A 100-year climate database was developed for Shell ASE site based on meteorological data measured at the site and climatic data of the surrounding area obtained from Environment Canada. PE is calculated using Penman's equation (Penman, 1948). The tailings deposition thicknesses determined under various scenarios provide guidelines (upper limits) for oil sands tailings management in the Northern Alberta area.

2 Methodology

2.1 Materials

Three types of tailings materials are investigated in the present study; namely NST, TT, and MFT. The tailings initial and final solids contents and voids ratio are listed in Table 1. The final state of the tailings is determined on the basis of its consolidation curve. The tailings have a vertical effective stress of 20 kPa at its final state. If a minimum coefficient of 0.25 (the ratio of undrained shear strength over vertical effective stress) is applied (Hyndman and Sobkowicz, 2010), the undrained shear strength in the tailings is 5 kPa at the selected final state. It should be noted that tailings consolidation (void ratio–vertical effective stress relationship) may vary depending on the tailings' 'type' and solids content. Therefore, characterisation of the site-specific consolidation characteristics of the material is crucial for tailings settlement analysis.

Table 1 Tailings initial and final states (void ratio e_0 or e and solids content S_c)

Tailings Material	k_{sat} (cm/s)	Normal Initial State		Modified Initial State		Final State	
		e_0	S_c (%)	e_0	S_c (%)	e	S_c (%)
NST	9×10^{-7}	2.1	55	1.7	60	0.7	79
TT	8×10^{-8}	3.9	40	2.6	50	0.9	74
MFT	3×10^{-8}	6.1	30	3.2	45	1.0	72

2.2 Calculation of potential evaporation from tailings

The Penman equation (Equation (1)) is employed in this study to calculate PE from tailings surface (Penman, 1948). The parameters used in the Penman equation are meteorological data in a 100-year climatic database developed specifically for the Shell ASE site. In this paper, PE calculated with the measured net radiation and other climatic parameters (e.g. temperature, relative humidity, wind speed) is referred to as the 'normal' PE.

$$E = (H\Delta + E_a\gamma)/(\Delta + \gamma) \tag{1}$$

where:

E	=	Evaporation (potential evaporation).
H	=	Net radiant energy available at the evaporating surface.
γ	=	Psychometric constant ($\gamma = 0.27$, in °F and mm.H_g units).
Δ	=	Slope of the saturation vapour pressure versus temperature curve at the mean temperature of the air.
E_a	=	$(e_a - e_d)f(u)$.
e_a	=	saturation vapour pressure in the air.
e_d	=	saturation vapour pressure at the dew point in the atmosphere above.
f(u)	=	a function of the horizontal wind velocity.

Considering that the tailings surface is different from the ground surface where the weather station is located, net radiation for the tailings can also be re-calculated by using Equation (2) with the measured albedo over tailings surfaces. Allen et al. (1998) provides the calculation procedure in detail. The applied albedo values over the tailings are listed in Table 2. PE obtained with the calculated net radiation and measured climatic parameters is referred to as the 'modified' PE in this paper.

$$R_n = R_{ns} - R_{nl} \tag{2}$$

where:

R_n	=	Net radiation.
R_{ns}	=	Incoming net shortwave radiation.
R_{nl}	=	Outgoing net longwave radiation.

Table 2 Albedo values used in calculation of net radiation over tailings surface

Month	Albedo
January	0.6
February	0.6
March	0.45
April	0.3
May	0.2
June	0.15
July	0.15
August	0.15
September	0.15
October	0.2
November	0.6
December	0.6

2.3 Climatic database development for Shell ASE

A site-specific 100-year (1908–2010 inclusive) climatic database was developed on the basis of the meteorological data collected from three locations: onsite—Shell's ASE site, Mildred Lake area (30 km south of the Shell ASE site), and Fort McMurray area (70 km south of the Shell ASE site). The periods for the collected data in the database are different for the three locations: 2003–2010 from onsite, 1973–2002 from Mildred Lake, and 1908–1972 from Fort McMurray. The onsite measured climate data is directly incorporated into the database without any change. The climate data collected from the Mildred Lake and Fort McMurray areas are corrected before being incorporated into the database. The correction factor for each climate parameter for each day is on the basis of comparing the average value of the parameter at the day over 2003–2010 inclusive, measured onsite, to the average parameter value obtained from Mildred Lake (or Fort McMurray) at the same day over 2003–2010 inclusive. The correction factors are used to adjust recorded climate data in Mildred Lake and Fort McMurray, respectively. Equation (3) provides an example to calculate correction factor for the minimum temperature. The purpose of developing the 100-year climatic database is to predict long-term trends and to provide statistic analysis for PE and tailings deposition thickness.

$$F_i^{Tmin} = \frac{A_i^{Tmin}}{B_i^{Tmin}} \tag{3}$$

where:

F_i^{Tmin} = Correction factor for minimum temperature at i^th day.

A_i^{Tmin} = Average minimum temperature at i^th day onsite during 2003–2010.

B_i^{Tmin} = Average minimum temperature at i^th day at Mildred Lake or Fort McMurray during 2003–2010.

2.4 Calculation of deposition thickness due to evaporative drying

In this paper the tailings deposition thickness due to evaporative drying is referred to as the 'maximum' tailings thickness that can be deposited in a tailings facility in order to achieve a vertical effective stress of 20 kPa after evaporative drying in a certain time. The process of increasing vertical effective stress in the tailings is also the process of releasing water from the tailings and decreasing the tailings deposition height; therefore, the tailings deposition thickness can be calculated based on equation (Equation (4)).

$$H_0 = T_{wr} + H_1 \tag{4}$$

where:

H_0 = Tailings deposition thickness with initial state.

T_{wr} = Thickness of released water from the tailings due to evaporative drying.

H_1 = Tailings thickness at which vertical effective stress is 20 kPa in the tailings (final state).

The tailings deposition thickness (H_0) is obtained through a try and adjustment method. Specifically, H_0 is first assumed and its state (e_0 and S_c) is set as the initial state as shown in Table 1. After water removal (T_{wr}) due to evaporative drying, the tailings thickness becomes H1 and its state should match the final state as stated in Table 1; H_0 is adjusted if the final state of tailings deposit is not achieved after water removal. During calculation, the mass of solids in tailings maintains the same in the tailings initial state and final state. The tailings is assumed to be saturated in its final state.

Ten (10) scenarios are developed to capture a wide range of conditions, including variation of evaporation from oil sands tailings, surface runoff management, and tailings initial solids contents (Table 3). Although under drainage is an important factor for developing consolidation in tailings, it is not included in the scenarios because the amount of under drainage is very site-specific. A simple way to account for the under drainage is to add the water loss through under drainage into the potential evaporation, thus the calculation method of the deposition thickness is the same as the cases demonstrated in the paper.

Table 3 Summary of scenarios evaluated

Items	Cases	Evaporation Applied to Dewater Tailings	Tailings Initial State	Runoff Management
1	Case 1	E-1[a]	TIS-1[c]	RO-1[e]
2	Case 1-1	E-1	TIS-2[d]	RO-1
3	Case 2	E-2[b]	TIS-1	RO-1
4	Case 2-1	E-2	TIS-2	RO-1
5	Case 3	E-1	TIS-1	RO-2[f]
6	Case 3-1	E-1	TIS-2	RO-2
7	Case 4	E-2	TIS-1	RO-2
8	Case 4-1	E-2	TIS-2	RO-2
9	Case 5	E-1	TIS-1	RO-3[g]
10	Case 5-1	E-2	TIS-2	RO-3

[a] E-1: Normal PE, that is, PE is calculated by using measured climate data (including measured net radiation).

[b] E-2: Modified PE, that is PE is calculated by using calculated net radiation and other measured climate data.

[c] TIS-1: Tailings with normal initial state as defined in Table 1.

[d] TIS-2: Tailings with modified initial state as defined in Table 1.

[e] RO-1: All precipitation is considered as runoff.

[f] RO-2: Daily Precipitation larger than specified value (threshold) is considered as runoff. The threshold value is set as 0.8 mm/day for NST and 0.5 mm/day for TT and MFT.

[g] RO-3: No runoff is allowed; that is, all precipitation would consume evaporation energy.

2.5 Exceedance probability

Exceedance probability is the probability that a certain value is going to be exceeded. The following equation (Equation (5)) is used to calculate exceedance probability of tailings deposition thickness.

$$E_p = R/(N+1) \tag{5}$$

where:

E_p = Exceedance probability.
R = Rank of the value (deposition thickness).
N = Total number of values (i.e. 103 in the present paper).

The calculated tailings deposition thickness for each month over the 100-year is first ordered from the largest to smallest, then the rank of each deposition thickness is found and the exceedance probability corresponding to the deposition thickness is calculated.

3 Results and discussion

The average annual precipitation is approximately 470 mm over the climate database developed. PE for the 100-year climate database is approximately 640 mm/yr for the ‘normal’ PE (calculated with measured net radiation) and 800 mm/yr for the ‘modified’ PE (calculated with net radiation values corrected for tailings surface albedo), respectively. Therefore, ‘modified’ PE is 25% larger than ‘normal’ PE. Statistically the largest precipitation and PE occurs in July at the Shell ASE operation site (Figure 1). The major evaporative drying period is between April and September. Snowfall occurs and cumulates in the period of November, December, January, February, which can consume substantial evaporation energy during spring melt in March and April.

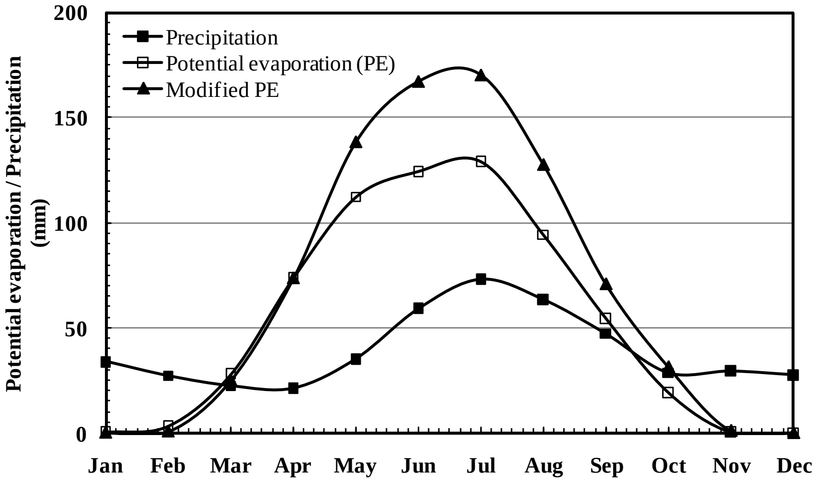

Figure 1 **Average monthly precipitation and potential evaporation (PE) values at Shell ASE operations (modified PE is calculated with net radiation computed with applied albedo)**

Figures 2 to 4 present tailings deposition volume (thickness) against exceedance probability for Case 1 for NST, TT, and MFT respectively. An apparent feature in these figures is that variation of the deposition thickness for each month is small, indicating the consistency of the climate parameters in the database at the study site. In general, the change of the calculated tailings deposition thickness in each month is less than 10 cm. For example, the tailings deposition thickness is in the range of 24–34 cm in July for NST (Figure 2), 17–26 cm for TT (Figure 3), and 15–22 cm for MFT (Figure 4). With 60% probability of exceedance, the largest deposition thickness in July is 28 cm for NST, 21 cm for TT, and 18 cm for MFT. The difference in the tailings deposition thickness under the same climate and surface runoff management conditions is attributed to the tailings deposition initial and final states, particularly the deposition initial solids content. The higher solids content in the deposited tailings, the larger tailings deposition thickness can be achieved. This finding provides one option for oil sands tailings management to satisfy regulatory requirement, such as the requirement of achieving a minimum shear strength of 5 kPa in one year in Alberta ERCB D-074. This option is to increase the initial deposition solids content of tailings through various plant treatment technologies, which are currently being evaluated by oil sands mining operators in Northern Alberta.

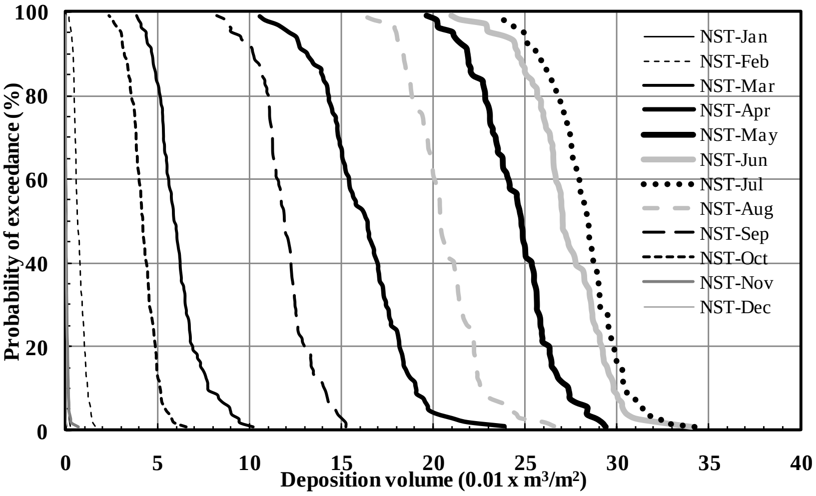

Figure 2 **Deposition thicknesses (volume) of NST for each month for Case 1 (normal PE and initial state, all precipitation for runoff)**

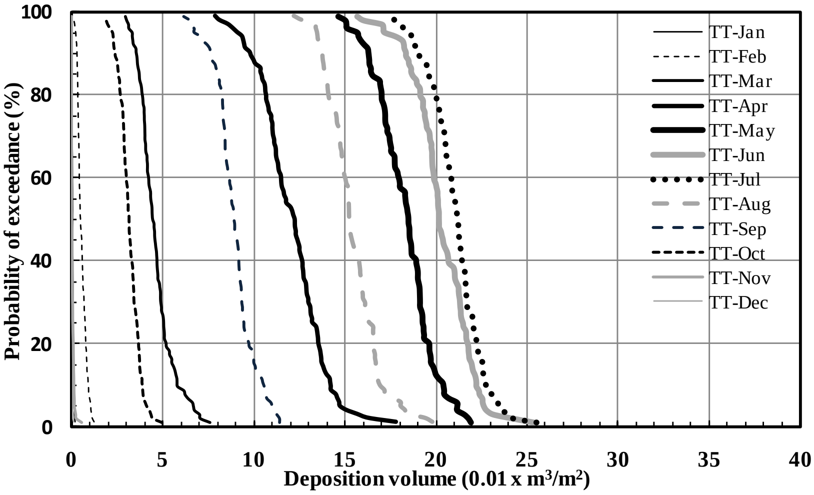

Figure 3 Deposition thicknesses (volume) of TT for each month for Case 1 (normal PE and initial state, all precipitation for runoff)

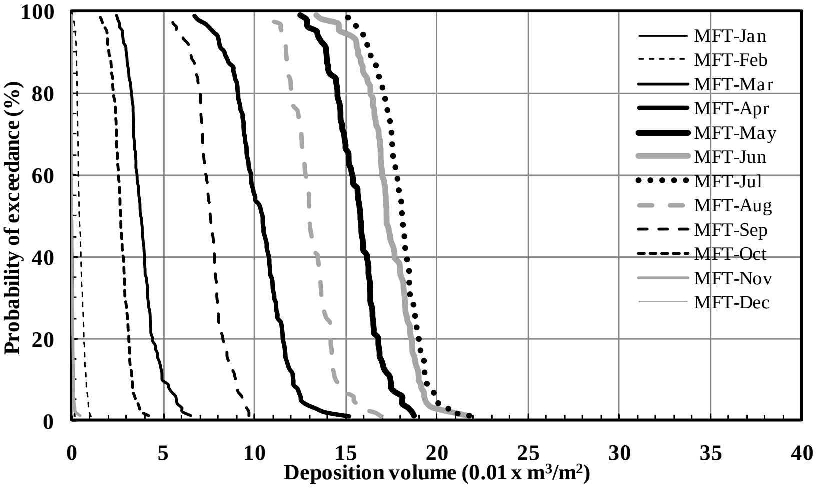

Figure 4 Deposition thicknesses (volume) of MFT for each month for Case 1 (normal PE and initial state, all precipitation for runoff)

The tailings deposition thicknesses with 80% probability of exceedance show only small differences between Case 2 and Case 4, and between Case 1 and Case 3 for all three tailings materials, as shown in Figures 5 to 7 inclusive. This implies that surface infiltration rates less than the tailings saturated hydraulic conductivity is a minor factor affecting the tailings deposition thickness due to the low saturated hydraulic conductivity values of the tailings materials. Similar results are evident when comparing Case 2-1 and Case 4-1, and between Case 1-1 and Case 3-1. In general, the tailings deposition thickness calculated with the modified PE is larger than that calculated with the normal PE for each tailings material. For example, the deposition thickness is approximately 35 cm for NST in June in Case 2 (with the modified PE), while the deposition thickness is approximately 26 cm in Case 1 (with the normal PE) as shown in Figure 5. However, the increase from the tailings deposition thickness calculated with the normal PE to that with the modified PE is not uniform for each month and the largest increase occurs in June and July. If there is no surface runoff management (i.e. ensuring that positive surface gradients are maintained on the tailings surface such that minimal ponding can occur), the evaporative drying can only occur between April and August under the normal PE condition (Case 5 in Figures 5–7) and between April and September under the modified PE condition (Case 5-1 in Figures 5–7). Significant increase in the tailings deposition thickness in June for each tailings material (Figures 5–7) indicates, when comparing Case 5-1 to Case 5, that the combination of the enhanced PE and tailings initial solids content would be a beneficial factor to improve tailings disposal.

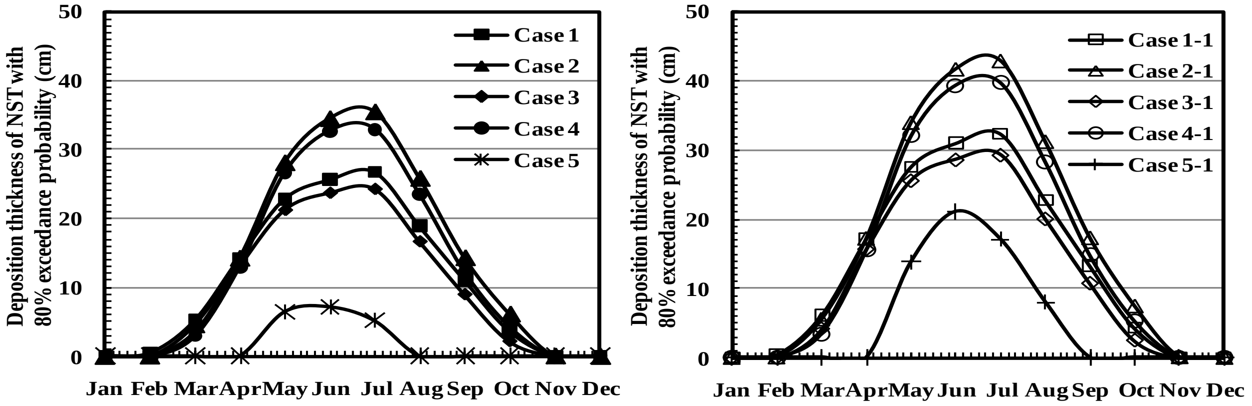

Figure 5 Calculated deposition thickness of NST with 80% exceedance probability for each month (the criteria for the cases are defined in Table 3)

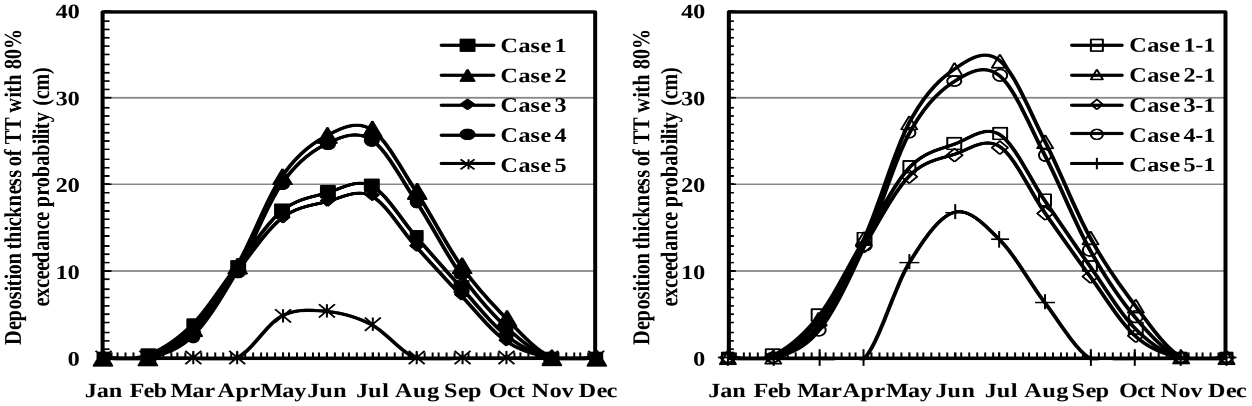

Figure 6 Calculated deposition thickness of TT with 80% exceedance probability for each month (the criteria for the cases are defined in Table 3)

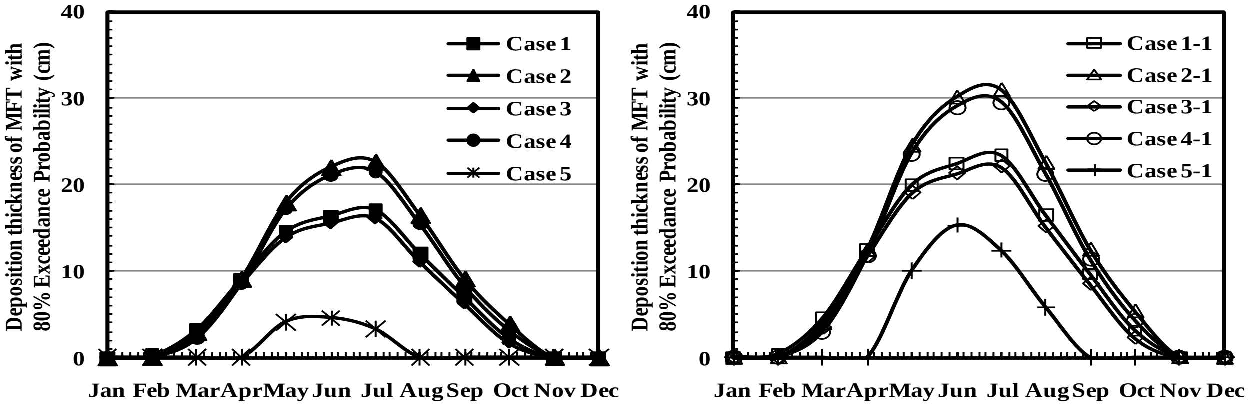

Figure 7 Calculated deposition thickness of MFT with 80% exceedance probability for each month (the criteria for the cases are defined in Table 3)

Figure 8 presents the annual deposition thickness with 80% probability of exceedance for each tailings material type. The largest tailings deposition thickness occurs in Case 2, in which the modified PE and initial state is assumed without water infiltration, i.e. all precipitation is considered as runoff. Based on Case 2-1, the tailings deposition thickness is approximately 200 cm for NST, 160 cm for TT, and 140 cm for MFT, assuming an 80% probability of exceedance.

The lowest annual tailings deposition thickness occurs with Case 5 (the normal PE and initial solids content as well as no runoff) as expected. It should be noted that the yearly tailings deposition thickness calculated in Figure 8 is the sum of the monthly tailings deposition with the same 80% probability of exceedance, it does not necessarily mean that the tailings can be deposited instantaneously to this thickness and achieve a vertical effective stress of 20 kPa through evaporative drying.

It is challenging to choose a case that best represents the field conditions because of the complexity associated with tailings deposition boundary conditions (e.g. under drainage) and surface runoff management. However, the tailings deposition thickness obtained from Cases 3-1 and 4-1 most likely reflect the tailings deposition thickness being achieved at the site. In these two cases, annual tailings deposition thickness (assuming an 80% probability exceedance), ranges from ~140–180 cm for NST, ~115–145 cm for TT, and ~105–135 cm for MFT. A 100 cm thick test deposition of TT at Shell's ASE operation placed in two lifts in November 2009 achieved an average vertical effective stress of 44 kPa at the end of August 2010. In this field test, good runoff management (no ponded water at any time) and under drainage (based on in situ pore-water pressure measurements) were observed.

Figure 8 illustrates the importance of surface runoff management for tailings deposition at the Shell ASE site when the difference between PE and precipitation is not large. The tailings deposition thickness less than 20 cm in Case 5 implies that poor surface runoff management (i.e. allowing for surface water ponding) may result in all evaporative energy being used for evaporating ponded water, rather than dewatering tailings. In situ measurements during a field test of TT material deposited with an initial thickness of 4.5 m in a large test cell (Cell 4) at Shell's ASE site indicates that vertical effective stress in the tailings upper lift was still very low (less than 5 kPa) after over 300 days. This is primarily attributed to continuous ponded water on the tailings surface.

It can be argued that using actual evaporation (AE) in the calculation would more accurately reflect field tailings deposition thickness. However, in the context of the methodology presented in this paper, calculation of AE is more time consuming than calculation of PE. In general, AE is calculated numerically. As a result of AE being influenced by both tailings properties (e.g. moisture retention curve and unsaturated hydraulic function) and meteorological parameters, it does not provide a quick and direct guideline to tailings disposal.

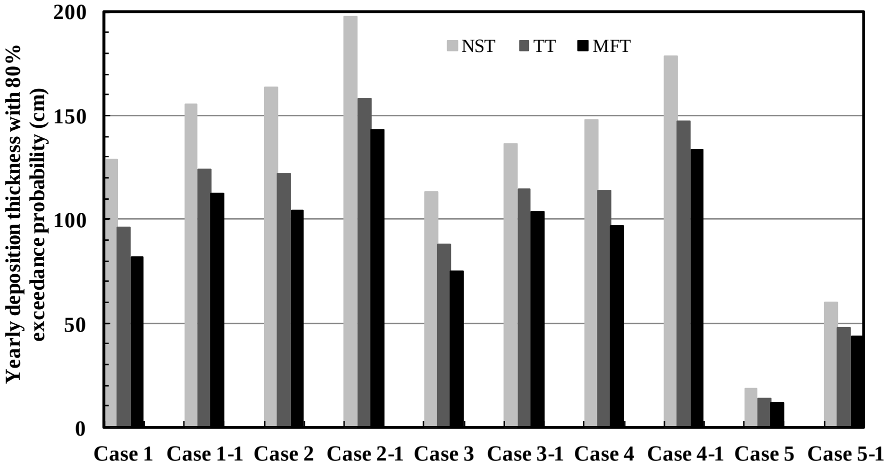

Figure 8 Comparison of tailings deposition thickness with 80% of exceedance probability for various cases. The criteria for the cases are defined in Table 3

Using PE in the present study is not unrealistic because mud-farming can expose saturated and/or near saturated tailings to the atmosphere and maintain PE (or at least evaporation rates near PE) from the tailings. Mud-farming can also minimise the potential for salt accumulation and formation of efflorescent salt crusts at the tailings surface during periods of drying. Accumulation of salts at the surface can drastically reduce evaporation from a soil surface, to less than 10% of PE in some cases (Chen, 1992). The reduction in evaporation is attributed to two factors. First, the presence of dissolved salts in the pore fluid causes the vapour pressure in the tailings to decrease, thereby reducing the 'drying power' of the air above the surface (Fahey and Fujiyasu, 1994). Secondly, the presence of a salt crust increases the albedo (reflectance) of the tailings surface, which means less energy is available to liberate moisture from the underlying tailings (Malek et al., 1990).

The calculated tailings deposition thicknesses with the normal PE (and the modified PE) in the present study provide, most likely, an upper limit at the site for annual tailings deposition thickness. Uncertainties with the data, such as climatic parameters, tailings solids contents and consolidation behaviour, as well as under drainage conditions, would lead to variation of the calculated deposition thickness. However, the method demonstrated in the paper can still be valid when the above parameters and conditions are known.

It would appear that thin lifts may be preferred in order to enhance tailings consolidation. However, tailings deposition thicknesses presented in Figures 2–4 implies that the thickness of each thin lift should change with time and in response to the climatic conditions throughout the year. A single value (e.g. 200 mm) for a thin lift may not effectively and efficiently utilise PE sometimes. Therefore, a proper tailings deposition thickness plan (or management strategy) should be based on the varied time or meteorological parameters.

Summary

The methodology presented in this paper provides a simple and quick approach to calculate potential tailings deposition thickness due to evaporative drying in a year with varied climate. This method is on the basis of measured meteorological data and tailings consolidation behaviour. Under drainage can be incorporated in the method if the seepage value is known. The calculated tailings deposition thickness is considered as an upper limit to the specific site and tailings deposit. The cases presented in the paper reveal the approaches to increase tailings deposition thickness, which includes maximising surface runoff through proper tailings surface slope controls, maximum utilisation of potential evaporation through mud-farming, and maximising solids content of tailings in its initial deposition through plant treatment.

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