Oil Sands composite tailings disposal planning

Samira Kalantari and Hooman Askari-Nasab
Mining Optimization Laboratory (MOL)
University of Alberta, Edmonton, Canada

Abstract

Waste management is one of the critical problems in the current oil sands industry. Linking the long-term production schedule to the produced tailings at the end of the process can lead to valuable developments in the mine planning and waste management. In this paper, the formulations required to link oil sands mine production schedules to the respective amount of composite tailings produced downstream are developed and discussed.

1. Introduction

The mine and tailings long-term plans define the complex strategy of displacement of ore, waste, overburden, and tailings over the mine life. The objective of long-term mine plan is to minimize the environmental footprint and maximize the future cash flows. Limitation of space because of lease conditions, scale of the operations, and construction of external in-pit dyke impoundments adds to the complexity of planning in oil sands mining. Contrary to metal and non-metal mine planning; oil sands long-term mine plans are driven by quantity and quality of mature fine tailings and composite/consolidated tailings produced downstream.

Production scheduling is an important aspect of mine planning and design. Maximizing the net present value (NPV) and considering the sequence of the material that has to be mined over time under the defined constraints is used in order to construct a schedule for long-term production (Dimitrikopoulos et al., 2004).

Not meeting the production target in the early years of a project is one of the main problems in long-term mine planning, and it is due to the geological uncertainties which will also lead to the production shortfalls in the later years of the operation (Goody et al., 2004).

The hot water process that is being used to extract bitumen from oil sands in northern Alberta will result in producing a tailing stream which contains residual bitumen, clays, sand and small amount of soluble organic compounds (Kasperski, 1992).

In oil sands mining, every barrel of oil produces approximately three cubic meters of tailings which contains between 35 and 65% of solids content, with fines content between 8 and 25% and approximately 1% of residual bitumen (Beier et al., 2008). Due to the specific characterization of tailings, it will segregate with the sands going down the water and fines going up. Since it will be harmful for the environment and wild life to dispose tailings to the river system, MFT is stored on site. Therefore this method of tailings disposal will result in a tailings pond with a fine tails zone that will take many decades to fully consolidate (Boratynec, 2003).

In order to increase the tailings dewatering rate and reduce the formation of fine tailings zone, composite tailings (CT) is used to produce non-segregating tailings which is a mixture of coarse sand, gypsum, and MFT. The CT process reduces the storage and tailings management costs, and will decrease the volume of mature fine tailings (MFT) on leases. In addition, the CT process will help to reclaim the distributed areas for terrestrial land use faster (Caughill, 1992).

To produce CT, using the pipelines, coarse tailings are pumped from the extraction plant to the CT plant, where they are cycloned to produce a densified coarse tailings stream. The resulting densified stream is combined with the MFT and gypsum in order to produce CT. The CT produced is transported hydraulically to the specified tailings disposal facility. After deposition of CT in the pond, the dewatering of the mixture starts rapidly which will leave a soft deposit behind (Syncrude, 2009).

The implementation of CT process has a number of benefits such as reducing the existing volumes of the MFT and increasing the percentage of dry landscape. This is a positive response to environmental and regulatory concerns regarding the long term management of fluid fine tailings and also result in reducing the tailings management and storage costs (Matthews et al., 2002).

2. Problem definition

The oil sands long-term mine plans are driven by quantity and quality of the MFT and composite/consolidated tailings produced downstream. Unfortunately, common approaches to mine planning rely on deterministic ore-body models as the basis for the mine tailings long-term plans. The geological uncertainties caused by grade variability, are not considered which may result in not reaching the targets for ore tonnage, grades and cash flow.

Oil sands production leads to the production of waste by-products including waste rock and a finer grained slurry called tailings. Management of tailings results in environmental challenges and financial burdens for operators. One of the mine waste management techniques is to create a non-segregating mixture or composite tailings that will increase the rate of dewatering process resulting in a higher consolidation rate of the fine tailings (Chalaturnyk et al., 2002).

In the oil sands mine planning, developing an optimal risk-based methodology for the oil sands mine and in-pit CT disposal planning is of good interest. The long-term mine plan should minimize and eventually eliminate long-term storage of fluid tailings in the reclamation landscape, and to create a trafficable landscape at the earliest opportunity to facilitate progressive reclamation.

The final mine schedule should relate the mine plan of the oil sands production to the amount of CT which will be produced at the end of the process. The resulting schedule should be mathematically optimal within the practical constraints and should account for the risk and uncertainties associated with the long-term schedule. The overall goal is to assist in progressive reclamation of the mined-out pits and to minimize the lead-time between mining and start of reclamation.

In finding the optimal mine plan the constraints such as production rate, the effect of different uncertainties on the oil sands production and tailings production, rate of gypsum addition to MFT, and the composite tailings production rate should be considered.

At the end of the day, the mine schedule should provide the yearly plan on the quantities of bitumen, fines, overburden and waste, and the final CT produced.

3. Assumptions & definitions of terms

3.1. Mass-volume relationships

Oil sands tailings are composed of four different phases with different characteristics. The four different phases are mineral grains, bitumen, gas and water. Since the viscosity of bitumen is higher than the viscosity of water, it has a really low mobility and can be assumed as a solid phase. The unique characteristics of oil sands tailings, lead to defining some mass-volume relationships which are complicated due to the effects of clay contained within the tailings stream. When the mineral phase split into two phases, the oil sands tailings will become a five-phase material.

Defining the mass-volume relationships for oil sands tailing helps to increase the understanding of the material behavior. The most common mass-volume relationships for the oil sands tailing are sands fines ratio (SFR), fines water ratio (FWR), fines void ratio and sands void ratio (Boratynec, 2003). Fig. 1 shows a schematic diagram of oil sands tailings different phases.

Where:

M : total mass of ore feed

M_g : mass of gas

M_w : mass of water

M_b : mass of bitumen

M_f : mass of fines

M_{sd} : mass of sand

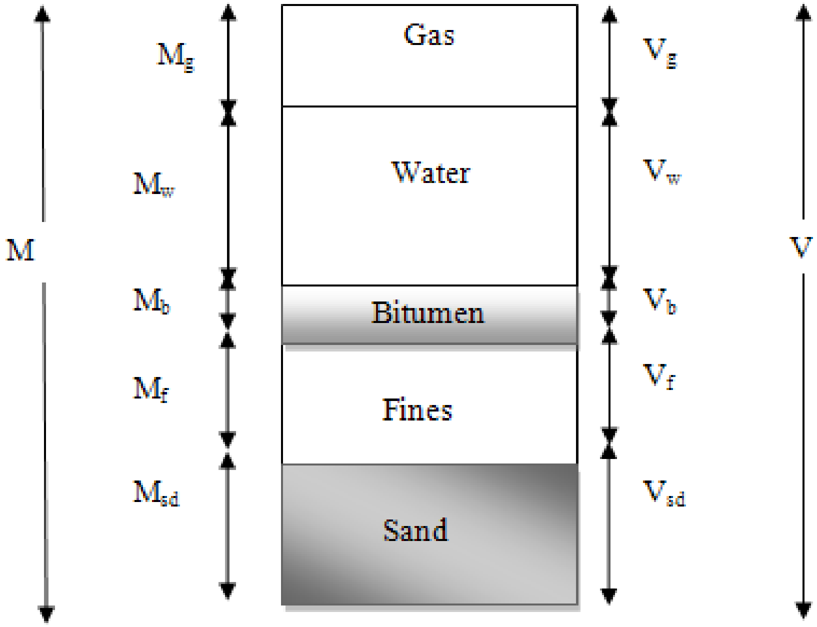

Fig. 1. Schematic diagram of oil sands tailings different phases.

3.2. Definitions of mass-volume relationships

Eqs. (1) to (6) represent the mass-volume relationships for the oil sands ore.

$$\text{Fines content of feed } (F_{feed}) : \frac{\text{mass of fines}}{\text{total mass of feed}} = \frac{M_f}{M} \tag{1}$$

$$Sand\ content\ of\ feed\ (SD_{feed}): \frac{mass\ of\ sand}{total\ mass\ of\ feed} = \frac{M_{sd}}{M} \tag{2}$$

$$Water\ content\ of\ feed\ (W_{feed}): \frac{mass\ of\ water}{total\ mass\ of\ feed} = \frac{M_{w}}{M} \tag{3}$$

$$Solid\ content\ of\ feed\ (S_{feed}) = 1 - B_{feed} - W_{feed} \tag{4}$$

$$Sands\ to\ fines\ ratio\ (SFR): \frac{mass\ of\ sand}{mass\ of\ fines + mass\ of\ bitumen} = \frac{M_{sd}}{M_f + M_b} \tag{5}$$

$RJ\%: reject\ percent$

$RJ_{sd}: sand\ reject$

$U / F: cyclone\ underflow$

$$FR_{sd}: sand\ in\ froth = \frac{Bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \tag{6}$$

4. Mature fine tailings (MFT)

The total tailings will tend to segregate after deposition into the tailings ponds due to its gap-graded characteristics, and high void ratio, therefore tailings is classified as a segregating mixture. In other words, after deposition of the tailings into the tailings ponds, the fines grained material tends to be separated from the coarse-grained material. Near the discharge point, the sands will fall out from the suspension, while most of the water plus approximately half of the fine material (thin tails), will flow towards the pond centre. During the first two years, the thin tails has a high tendency to release water until it reaches a solid content of approximately 30% and it will be known as MFT. As a result of high water release rate during the first two years, the thin fine tails will experience hindered sedimentation followed by consolidation. After the first two years, the dewatering rate of mature fine tailings will be decreased until it reaches zero, and due to its low hydraulic conductivity and thixotropic strength gain, even after hundreds of years, the full consolidation of tailings will not occur. One of the crucial problems in the oil sands mining is the extremely slow rate of consolidation of MFT (Boratynec, 2003).

5. Non-segregating tailings

The MFT with the solid content of more than 30% has an extremely slow rate of consolidation, therefore would take more than several decades to consolidate completely under self weight consolidation. As a result, over the production of oil sands, a large amount of the MFT will be accumulated (Tang, 1997). MFT is harmful for the environment due to its toxic behavior; therefore changing the physical properties of the MFT is required in order to form a mixture which has a low tendency to segregate. Depending upon the solid content and the gradation of the solid material, the segregation of the tailing stream will change (Boratynec, 2003). To produce consolidated tailings, the process should be able to replace the water that is found in tailings with the MFT. As a result of consolidated tailings, the strength of tailings will increase (Mikula et al., 2008).

6. Composite tailings (CT)

To produce a non-segregating tailings, research shows that a mixture of tailings cyclone underflow and MFT, with the addition of lime (CaO) or phosphogypsum ($CaSo_4.2H_2O$) produces composite tailings which is a non-segregating tailings stream (Boratynec, 2003). One important advantage of composite tailings production is that the transportation and pumping of the produced CT is easy. Using MFT to produce CT, the required sand comes directly from the extraction process. Fig. 2 shows a schematic diagram of the CT production process. The ore feed from the oil sands mine is sent to the separation cell (flotation cells) to separate bitumen from the fines using aeration (air flotation) technique. The tailings from the froth treatment will be sent to the ponds. Mature fine tailings will be formed in almost a two year period in the pond. In the hydro-cyclone, coarse solids will be simply separated from fine solids; cyclone over flow contains fine solids whilst the cyclone under flow carries the coarse solids. A portion of cyclone under flow will be sent to cell DT and the remaining portion will be used in the composite tailings production. In order to complete the CT production process, fines and water will be added from the MFT deposit with a solid content of approximately 30%. Finally, Gypsum will be added to MFT to produce the non-segregating tailings.

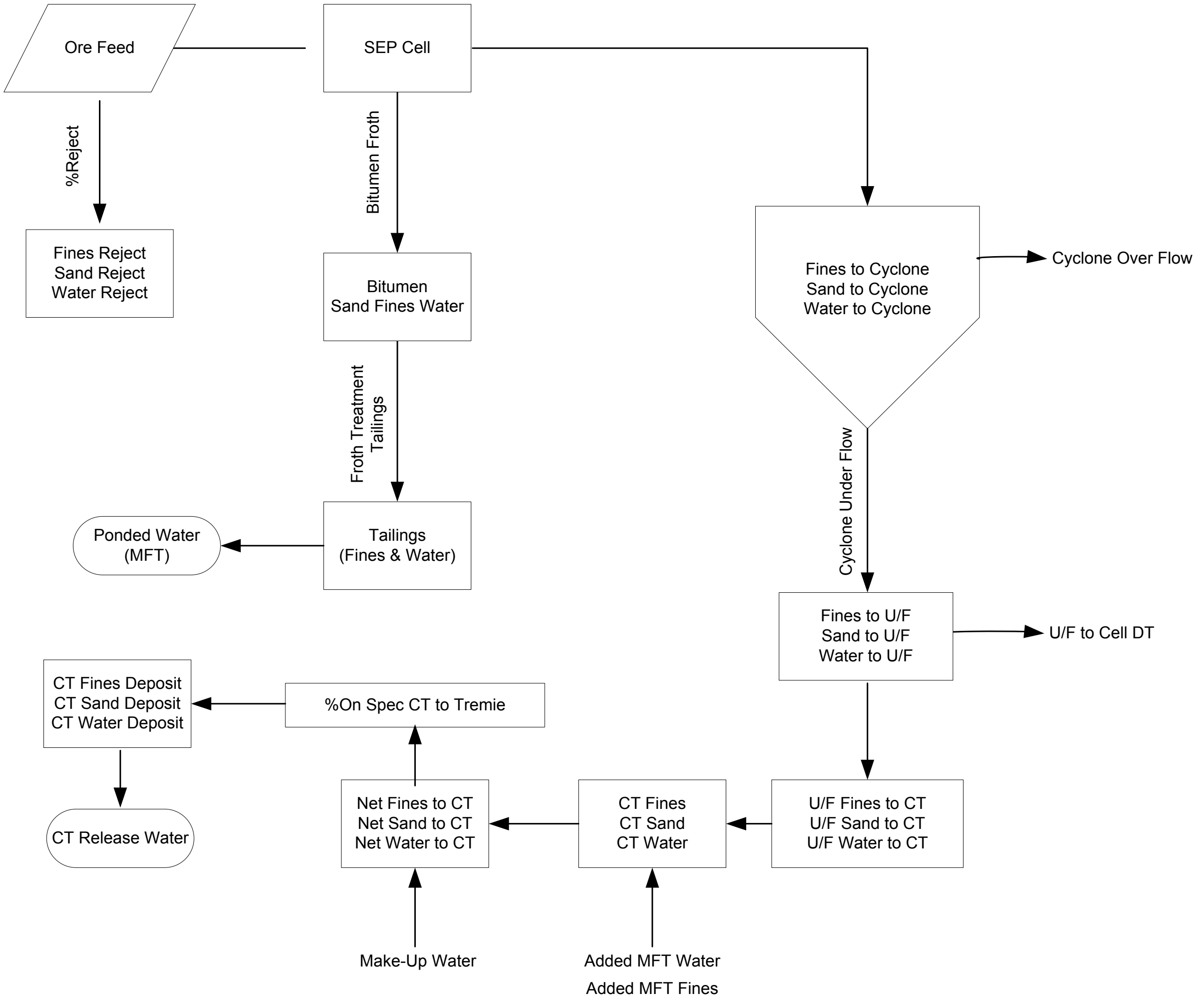

Fig. 2. Mass balance flow diagram for CT production

7. Mass relationship between CT and the ore feed

The ultimate goal of this project is to generate an oil sands mine production schedule according to the limitation of the CT required at the end of the process. In order to find the relationship between CT and the mine plan, first we should find out the relationship between the quantities of the ore tonnage and the produced CT. Eq. (7) shows that the total mass of CT can be calculated by finding the total mass of sand, fines, and water needed to produce CT. Eq. (8) controls the total mass of fines in the CT deposit for a specific ore tonnage. To calculate the CT sand and water deposits, Eqs. (9) and (10) can be used.

$$Total\ mass\ of\ CT = CT\ fines\ deposit + CT\ sand\ deposit + CT\ water\ deposit \tag{7}$$

$$CT\ fines\ deposit = \%\,on-spec\ CT\ to\ Tremie \times \left(added\ MFT\ fines + U/F\ fines\ to\ CT\right) \tag{8}$$

$$CT\ sand\ deposit = \%on-spec\ CT\ to\ Tremie \times U/F\ sand\ to\ CT \tag{9}$$

$$CT\ water\ deposit = \%\,on-spec\ CT\ to\ Tremie \times \left(make-up\ water + added\ MFT\ water + U/F\ water\ to\ CT\right) \tag{10}$$

7.1. CT fines deposit

According to Eq.(8), the total mass of fines in CT can be found by adding the total mass of added MFT fines and the mass of underflow fines to CT. In order to find the total mass of added MFT fines, Eq. (11) should be used. In order to find the total mass of U/F sand used for CT production, Eq. (12) should be used. Eqs. (13) to (17) control the sand content of the cyclone under flow.

The total mass of sand in cyclone under flow which is sent for CT production, can be found using Eqs. (18) to (26). Eqs. (27) and (28) represent the total mass of fines in cyclone under flow which is sent for CT production.

Total mass of added MFT fines is represented by Eq. (29). According to Eq.(8), the total mass of CT fines, can be found by adding the mass of added MFT fines to the mass of fines in U/F which is sent to the CT production process; therefore, using Eqs. (28) and (30), CT fines deposit could be calculated. Eq. (31) represents the total mass of fines used for CT production.

$$Added\ MFT\ fines = \frac{U/F\ sand\ to\ CT}{SFR\ in\ pipe} - U/F\ fines\ to\ CT \tag{11}$$

$$U/F\ sand\ to\ CT = sand\ to\ U/F \times \left(1 - U/F\%\ to\ cell\ DT\right) \tag{12}$$

$$Sand\ to\ U/F = sand\%\ to\ U/F \times sand\ to\ cyclones \tag{13}$$

$$Sand\ to\ cyclones = sand\ feed - sand\ reject - sand\ in\ froth \tag{14}$$

$$Sand\ to\ cyclones = SD_{feed} - RJ_{sd} - FR_{sd} \tag{15}$$

$$Sand\ to\ cyclones = SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \tag{16}$$

$$Sand\ to\ U/F = sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right) \tag{17}$$

$$U/F\ fines\ to\ CT = fines\ to\ U/F \times \left(1 - U/F\%\ to\ cell\ DT\right) \tag{18}$$

$$fines\ to\ U/F = \frac{sand\ to\ U/F}{sand\ in\ U/F} \times fines\ in\ U/F \tag{19}$$

$$U/F\%\ to\ cell\ DT = \frac{sand\ to\ DT}{sand\ to\ U/F} \tag{20}$$

$$Sand\ to\ DT = \frac{sand\ to\ cell}{physical\ capture \times cell\ efficiency} \tag{21}$$

$$Sand\ to\ cell = \left(cell\ volume \times cell\ dry\ density\right) - fines\ to\ cell \tag{22}$$

$$fines\ to\ cell = cell\ volume \times cell\ dry\ density \times fines\%\ in\ solids \tag{23}$$

$$Sand\ to\ DT = \frac{\left(cell\ volume \times cell\ dry\ density\right) \times \left(1 - fines\%\ in\ solids\right)}{physical\ capture \times cell\ efficiency} \tag{24}$$

$$U/F\%\ to\ cell\ DT = \frac{\dfrac{\left(cell\ volume \times cell\ dry\ density\right) \times \left(1 - fines\%\ in\ solids\right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - \left(\dfrac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)} \tag{25}$$

$$U / F\ sand\ to\ CT = sand\%\ to\ U / F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)$$

$$\times \left(1 - \frac{\dfrac{\left(cell\ volume \times cell\ dry\ density \right) \times \left(1 - fines\%\ in\ solids \right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U / F \times \left(SD_{feed} - RJ_{sd} - \left(\dfrac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)} \right) \tag{26}$$

$$fines\ to\ U / F = \frac{sand\%\ to\ U / F \times \left(SD_{feed} - RJ_{sd} - \left(\dfrac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)}{sand\ in\ U / F} \times fines\ in\ U / F \tag{27}$$

$$U / F\ fines\ to\ CT = \frac{sand\%\ to\ U / F \times \left(SD_{feed} - RJ_{sd} - \left(\dfrac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)}{sand\ in\ U / F} \times fines\ in\ U / F$$

$$\times \left(1 - \frac{\dfrac{\left(cell\ volume \times cell\ dry\ density \right) \times \left(1 - fines\%\ in\ solids \right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U / F \times \left(SD_{feed} - RJ_{sd} - \left(\dfrac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)} \right) \tag{28}$$

$$Added\ MFT\ fines = \frac{sand\%toU/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand\right)\right) \times \left(1 - \frac{\frac{\left(cell\,volume \times cell\,dry\,density\right) \times \left(1 - fines\%\,in\,solids\right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\,bitumen} \times SET\ sand\right)\right)}\right)}{SFR\ in\ pipe}$$

$$- \frac{sand\%toU/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand\right)\right)}{sand\ in\ U/F} \times fines\,in\,U/F \times \left(1 - \frac{\frac{\left(cell\,volume \times cell\,dry\,density\right) \times \left(1 - fines\%\,in\,solids\right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - (\frac{bitumen\ in\ froth}{SET\,bitumen} \times SET\ sand)\right)}\right) \quad (29)$$

$$Added\ MFT\ fines + U/F\ fines\,to\,CT = \frac{U/F\ sand\,to\,CT}{SFR\,in\ pipe}$$

$$= \frac{sand\%toU/F \times \left(SD_{feed} - RJ_{sd} - (\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand)\right) \times \left(1 - \frac{\frac{\left(cell\,volume \times cell\,dry\,density\right) \times \left(1 - fines\%\,in\,solids\right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - (\frac{bitumen\ in\ froth}{SET\,bitumen} \times SET\ sand)\right)}\right)}{SFR\,in\ pipe} \quad (30)$$

$$CT\ fines\,deposit = \%on-spec\,CT\ to\,Tremie$$

$$\times \frac{1}{SFR\,in\ pipe} \times sand\%toU/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand\right)\right) \times \left(1 - \frac{\frac{\left(cell\,volume \times cell\,dry\,density\right) \times \left(1 - fines\%\,in\,solids\right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\,bitumen} \times SET\ sand\right)\right)}\right) \quad (31)$$

7.2. CT sand deposit

The total mass of sand used for CT production for a specific ore tonnage can be found using Eqs. (31) and (32). Eq. (33) controls the CT sand deposit.

$$\mathit{CT\ sand\ deposit} = \mathit{CT\ fines\ deposit} \times \mathit{SFR\ in\ pipe} \tag{32}$$

$$\begin{aligned}\mathit{CT\,sand\,deposit} &= \%\mathit{on} - \mathit{spec\,CT\,to\,Tremie} \\ &\times \mathit{sand\%\,to\,U/F} \times \left(\mathit{SD}_{\mathit{feed}} - \mathit{RJ}_{\mathit{sd}} - \left(\frac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}} \times \mathit{SET\ sand} \right) \right) \times \left(1 - \frac{\dfrac{(\mathit{cell\,volume} \times \mathit{cell\,dry\,density}) \times (1 - \mathit{fines\%\,in\,solids})}{\mathit{physical\ capture} \times \mathit{cell\ efficiency}}}{\mathit{sand\%\ to\ U/F} \times \left(\mathit{SD}_{\mathit{feed}} - \mathit{RJ}_{\mathit{sd}} - \left(\dfrac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}} \times \mathit{SET\ sand} \right) \right)} \right)\end{aligned} \tag{33}$$

7.3. CT water deposit

Based on Eq. (10), added MFT water, make-up water, and mass of under flow water sent to the CT production process, are three different water deposits used in the CT production. Mass of the added MFT water can be calculated using Eqs. (34) and (35).

In order to find the total mass of under flow water sent to the CT production, Eqs. (36) to (39) should be used. Eq. (40) controls the mass of make-up water used for CT production for a specified ore tonnage.

Finally, Eq. (41) represents the total mass of water used for CT production for a specified ore tonnage.

$$\mathit{Added\ MFT\ water} = \frac{\mathit{added\ MFT\ fines}}{\mathit{MFT\%\ solids}} - \mathit{added\ MFT\ fines} = \mathit{added\ MFT\ fines} \times \left(\frac{1}{\mathit{MFT\%\ solids}} - 1 \right) \tag{34}$$

$$\mathit{Added\ MFT\ water} = \left(\frac{1-\mathit{MFT\%\ solids}}{\mathit{MFT\%\ solids}}\right)\times\frac{1}{\mathit{SFR\ in\ pipe}}\times\Bigg(\mathit{sand\%\ to\ U/F}\times\left(\mathit{SD}_{\mathit{feed}}-\mathit{RJ}_{\mathit{sd}}-\left(\frac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}}\times\mathit{SET\ sand}\right)\right)$$

$$\times\left(1-\frac{\dfrac{(\mathit{cell\ volume}\times\mathit{cell\ dry\ density})\times(1-\mathit{fines\%\ in\ solids})}{\mathit{physical\ capture}\times\mathit{cell\ efficiency}}}{\mathit{sand\%\ to\ U/F}\times\left(\mathit{SD}_{\mathit{feed}}-\mathit{RJ}_{\mathit{sd}}-\left(\dfrac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}}\times\mathit{SET\ sand}\right)\right)}\right)-\frac{\mathit{sand\%\ to\ U/F}\times\left(\mathit{SD}_{\mathit{feed}}-\mathit{RJ}_{\mathit{sd}}-\left(\dfrac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}}\times\mathit{SET\ sand}\right)\right)}{\mathit{sand\ in\ U/F}}$$

$$\times\,\mathit{fines\ in\ U/F}\times\left(1-\frac{\dfrac{(\mathit{cell\ volume}\times\mathit{cell\ dry\ density})\times(1-\mathit{fines\%\ in\ solids})}{\mathit{physical\ capture}\times\mathit{cell\ efficiency}}}{\mathit{sand\%\ to\ U/F}\times\left(\mathit{SD}_{\mathit{feed}}-\mathit{RJ}_{\mathit{sd}}-\left(\dfrac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}}\times\mathit{SET\ sand}\right)\right)}\right)\Bigg) \tag{35}$$

$$\mathit{U/F\ water\ to\ CT}=\mathit{water\ to\ U/F}\times(1-\mathit{U/F\%\ to\ cell\ DT}) \tag{36}$$

$$\mathit{Water\ to\ U/F}=\frac{\mathit{sand\ to\ U/F}}{\mathit{sand\ in\ U/F}}\times\mathit{water\ in\ U/F} \tag{37}$$

$$\mathit{water\ to\ U/F}=\frac{\mathit{sand\%\ to\ U/F}\times\left(\mathit{SD}_{\mathit{feed}}-\mathit{RJ}_{\mathit{sd}}-\left(\dfrac{\mathit{bitumen\ in\ froth}}{\mathit{SET\ bitumen}}\times\mathit{SET\ sand}\right)\right)}{\mathit{sand\ in\ U/F}}\times\mathit{water\ in\ U/F} \tag{38}$$

$$U/F\ \text{water to}\ CT=\frac{\text{sand\% to}\ U/F\times\left(SD_{feed}-RJ_{sd}-\left(\frac{\text{bitumen in froth}}{SET\ \text{bitumen}}\times SET\ \text{sand}\right)\right)}{\text{sand in}\ U/F}\times\text{water in}\ U/F$$

$$\times\left(1-\frac{\dfrac{(\text{cell volume}\times\text{cell dry density})\times(1-\text{fines \% in solids})}{\text{physical capture}\times\text{cell efficiency}}}{\text{sand\% to}\ U/F\times\left(SD_{feed}-RJ_{sd}-\left(\dfrac{\text{bitumen in froth}}{SET\ \text{bitumen}}\times SET\ \text{sand}\right)\right)}\right) \tag{39}$$

$$\text{if}\ \frac{CT\ \text{fines}+CT\ \text{sand}}{CT\ \%\text{solids}}\times(1-CT\ \%\text{solids})-CT\ \text{water}<0\rightarrow\text{make}-\text{up water}=0 \tag{40}$$

$$\text{if}\ \frac{CT\ \text{fines}+CT\ \text{sand}}{CT\ \%\text{solids}}\times(1-CT\ \%\text{solids})-CT\ \text{water}\geq 0\rightarrow\text{make}-\text{up water}=\frac{CT\ \text{fines}+CT\ \text{sand}}{CT\ \%\text{solids}}\times(1-CT\ \%\text{solids})-CT\ \text{water}$$

$$CT\ \text{water deposit}=\%\text{on}-\text{spec}\ CT\ \text{to Tremie}$$

$$\times\text{sand\% to}\ U/F\times\left(SD_{feed}-RJ_{sd}-\left(\frac{\text{bitumen in froth}}{SET\ \text{bitumen}}\times SET\ \text{sand}\right)\right)\times\left(1-\frac{\dfrac{(\text{cell volume}\times\text{cell dry density})\times(1-\text{fines\% in solids})}{\text{physical capture}\times\text{cell efficiency}}}{\text{sand\% to}\ U/F\times\left(SD_{feed}-RJ_{sd}-\left(\dfrac{\text{bitumen in froth}}{SET\ \text{bitumen}}\times SET\ \text{sand}\right)\right)}\right) \tag{41}$$

$$\times\left\{\left(\frac{1-MFT\ \%\ \text{solids}}{MFT\%\ \text{solids}}\times\left(\frac{1}{SFR\ \text{in pipe}}-\frac{\text{fines in}\ U/F}{\text{sand in}\ U/F}\right)\right)+\frac{\text{water in}\ U/F}{\text{sand in}\ U/F}\right\}+\text{make}-\text{up water}$$

7.4. Total mass of CT

Based on Eqs. (7) and (40), the total mass of the composite tailings depends on whether the make-up water is required for CT production or not. Eq. (42) represents the total mass of CT when make-up water is not added to the CT production process. Finally Eq. (43) controls the total mass of CT in case of adding make-up water to the CT production process.

$$\begin{aligned}
&If\ \frac{CT\ \ fines+CT\ sand}{CT\ \ \%solids}\times\left(1-CT\ \ \%solids\right)-CT\ \ water<0\rightarrow make-up\ water=0\\
&\Rightarrow Total\ \ mass\ of\ \ CT=\%On-spec\ \ CT\ \ to\ \ Tremie\times sand\%\ \ to\ \ U\ /\ F\times\\
&\left(SD_{feed}-RJ_{sd}-\left(\frac{bitumen\ \ in\ \ froth}{SET\ \ bitumen}\times SET\ sand\right)\right)\times\left(1-\frac{\dfrac{(cell\ volume\times\ cell\ \ dry\ \ density)\times(1-\ fines\%\ \ in\ \ \ solids)}{physical\ \ capture\times\ cell\ \ efficiency}}{sand\%\ \ to\ \ U\ /\ F\times\left(SD_{feed}-RJ_{sd}-\left(\dfrac{bitumen\ \ in\ \ froth}{SET\ \ bitumen}\times SET\ sand\right)\right)}\right)\\
&\times\left(\frac{1+SFR}{SFR}+\left\{\left(\frac{1-MFT\ \ \%\ \ solids}{MFT\%\ \ \ solids}\times\left(\frac{1}{SFR\ \ in\ \ pipe}-\frac{fines\ \ in\ \ U\ /\ F}{sand\ \ in\ \ U\ /\ F}\right)\right)+\frac{water\ \ in\ \ U\ /\ F}{sand\ \ in\ \ U\ /\ F}\right\}\right)
\end{aligned}\tag{42}$$

$$\begin{aligned}
&If \quad \frac{CT\ fines + CT\ sand}{CT\ \%solids} \times (1 - CT\ \%solids) - CT\ water \geq 0 \rightarrow make - up\ water = \frac{CT\ fines + CT\ sand}{CT\ \%solids} \times (1 - CT\ \%solids) - CT\ water \\
&\quad \Rightarrow Total\ mass\ of\ CT = \%on - spec\ CT\ to\ Tremie \times \left(\frac{1 + SFR\ in\ pipe}{SFR\ in\ pipe} \right) \\
&\times \left(\frac{1}{CT\ \%solids} \right) \times sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - \left(\frac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right) \\
&\times \left(1 - \frac{\dfrac{\left(cell\ volume \times cell\ dry\ density \right) \times \left(1 - fines\%\ in\ solids \right)}{physical\ capture \times cell\ efficiency}}{sand\%\ to\ U/F \times \left(SD_{feed} - RJ_{sd} - \left(\dfrac{bitumen\ in\ froth}{SET\ bitumen} \times SET\ sand \right) \right)} \right)
\end{aligned} \tag{43}$$

8. Illustrative example

With the calculations discussed in this paper, we can find the mass relationship between the produced composite tailings (CT) and the ore tonnage. Three different blocks from a long-term mine schedule were selected to implement the CT calculations. The inputs for the calculations are represented in Table 1.

Table 1. Inputs for the CT calculations.

Cell volume (m^3)	100
Cell dry-density (kg/m^3)	1.559
Cell efficiency (%)	75
Physical capture (%)	70
SFR in pipe	4
MFT %solids (%)	30
%On-spec CT to Tremie (%)	85
CT %solids (%)	55

Table 2 represents the results of implementing CT production calculations on three different blocks. According toTable 2, the total mass of the produced CT is related to the feed tonnage.

For three blocks with the same ore tonnage, the total mass of the composite tailings depends on the sand content of the input block. As the sand content increases, the total mass of the produced CT will increase for a block with the same ore tonnage. For block #1 with the lowest sand content of 83%, the total mass of CT is 15678 tonnes, whilst for block #2 with the highest sand content of 93%, the total mass of the produced CT is 17752 tonnes.

Table 2. CT calculation results for three different blocks.

Block Number	Ore tonnage (tonne)	Bitumen grade (%)	Fines grade (%)	Water content (%)	Solid content (%)	Sand content (%)	CT produced (tonne)
Block #1	74812	1.050	12.28	4.303	94.651	83.03	15678
Block #2	74812	1.120	3.11	2.583	96.290	93.30	17752
Block #3	74812	0.321	6.83	3.281	96.397	89.81	17068

Fig. 3 shows the relation between sand content of the input blocks and the total mass of the CT which is produced at the end of the process. From this figure it can be seen that the fines content of the block has a direct impact on the total mass of CT produced at the end of the process.

Based on the information represented in Table 2, when fines grade increases in the blocks with the same ore tonnage, the total mass of the CT will decrease. According to Table 2, block #2 with the lowest fines content will lead to the maximum mass of CT produced, whilst block #1 with the highest fines content will result in producing 15678 tonnes of CT which is the lowest amount of CT amongst three different blocks with the same ore and feed tonnage.

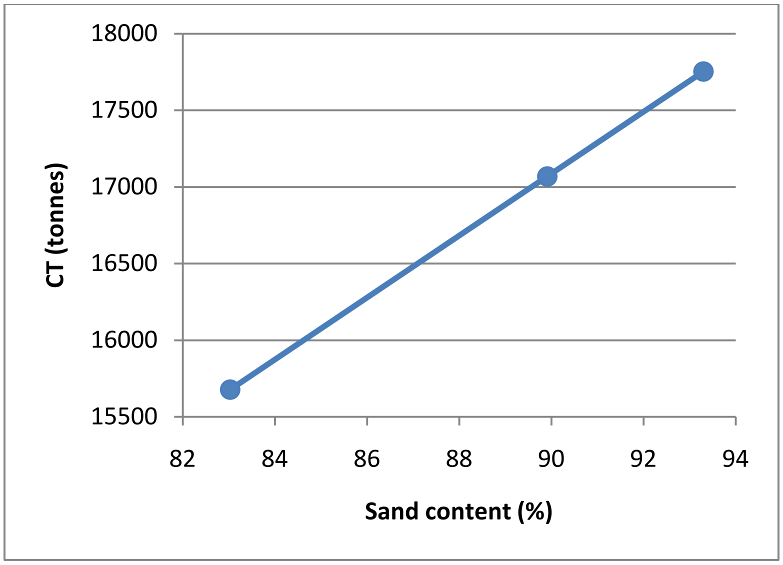

Fig. 3.Relation between sand content and CT.

Fig. 4 represents the inverse relation between fines content of the block and the total mass of composite tailings produced at the end of the process.

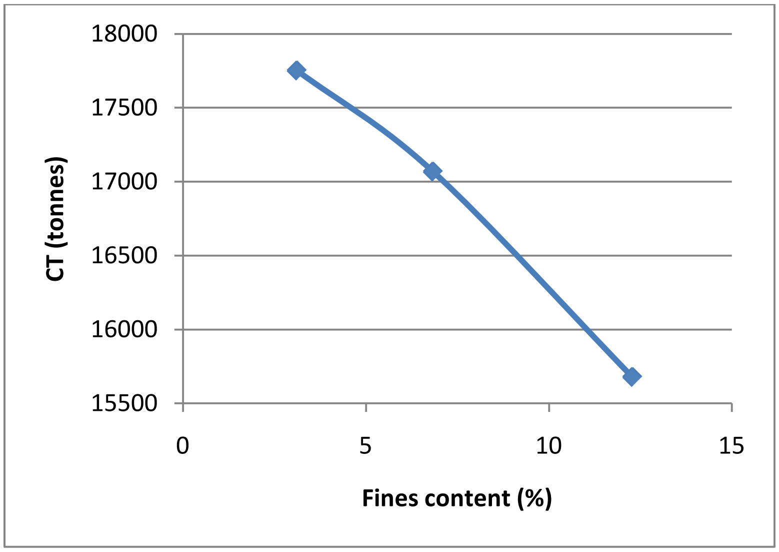

Fig. 4. Relation between fines content and CT.

9. Conclusions and future work

In this paper the mass relation between the ore feed and the quantity of the total composite tailings produced at the end of ore processing was calculated. The final equation, Eq. (43), represents the total mass of CT produced for a specified ore tonnage, and it is the linkage between the mine plan and the final product. This relationship can lead to proper tailings management. In other words, the mass relation between the final CT product and the ore feed can help in developing a disposal planning strategy for the produced composite tailing .The yearly mine plan will be the input for CT calculations in order to link the mine plan of the oil sands production to the amount of CT which will be produced at the end of the process.

Based on these calculations, the long-term mine plan can be optimized according to the storage area limitations for the disposal of tailings. In other words, in case of having limitations on the tailings disposal areas, these calculations can lead to optimizing the long-term mine schedules based on the disposal restrictions.

In the future steps of this project, the CT calculations will be implemented on a realistic long-term mine schedule from an oil sands mine.

The main goal of this project is to consider the uncertainties associated with the long-term mine schedule in relating the mine plan to the final CT. Probability distributions which will capture the uncertainties associated with oil sands production process, will be defined as the inputs for CT calculations.

10. References

[1] Beier, N. and Sego, D. (2008). The Oil Sands Tailings Research Facility. *Geotechnical news*, 72-77.

[2] Boratynec, D. J. (2003). Fundamentals of Rapid Dewatering of Composite Tailings. Master Thesis, University of Alberta, Edmonton, Alberta, Pages 280.

[3] Caughill, D. L. (1992). Geothecnics of Non-Segregating Oil Sand Tailings. Master Thesis, University of Alberta, Edmonton, Alberta, Pages 262.

[4] Chalaturnyk, R. J., Scott, J. D., and Ozum, B. (2002). Management of oil sands tailings. *Petroleum science and technology*, *20*, 1025-1045.

[5] Dimitrikopoulos, R. and Ramazan, S. (2004). Uncertainty-based production scheduling in open pit mining. *Society for Mining, Metallurgy, and Exploration*, *316*, 106-112.

[6] Goody, M. and Dimitrikopoulos, R. (2004). Managing risk and waste mining in lokg-term production scheduling of open-pit mines. *Society for Mining, Metallurgy, and Exploration*, *316*, 43-50.

[7] Kasperski, K. L. (1992). A review of properties and treatment of oil sands tailings. *AOSTRA Journal of Research*, *8*, 11-51.

[8] Matthews, J. G., Shaw, W. H., Mackinnon, M. D., and Cuddy, R. G. (2002). Developement of Composite Tailings Technology at Syncrude. *International Journal of Mining, Reclamation and Environment*, *16*, 24-39.

[9] Mikula, R. J., Munoz, V. A., and Omotoso, O. (2008). *Water use in bitumen production: Tailing management in surface mine oil sands*. Paper presented at Canadian International Petroleum Conference, Calgary, Alberta. pp. 8.

[10] Syncrude (2009). 2009 Annual tailings plan submission Syncrude Mildred Lake (Leases 17 and 21). Syncrude Canada Ltd., Fort McMurray, Alberta, September 30, 2009, 39.

[11] Tang, J. (1997). Fundamental Behaviour of Composite Tailings. Master Thesis, University of Alberta, Edmonton, Alberta, Pages 224.