Simulation of Oil Sands In-Line Thickened Tailings Disposition

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ABSTRACT
In this paper a finite strain consolidation theory is used to simulate field deposition of in-line thickened tailings (ILTT), sheared in-line thickened tailings, cyclone overflow fine tailings (COF) and composite tailings made from ILTT (ILTT-CT). It is important in these simulations to determine whether a deposit develops a minimum undrained shear strength of 5 kPa for a material deposited in the previous year as required by Directive 074 (ERCB 2009). This Directive requires this minimum shear strength in order that the deposit can be considered reclaimable and no longer considered a semi-liquid fine tailings. Six scenarios were selected for this investigation. Scenarios 1 to 4 are depositions of cyclone overflow tailings, in-line thickened tailings, sheared in-line thickened tailings and ILTT-CT by depositing the materials for 3 months in a disposal area and allowing them to settle under self-weight for 9 months. This method allows consolidation by an upward single drainage condition. Alternatively, Scenarios 5 and 6 utilize a double drainage condition: sand sandwiching and sand columns. In Scenario 5, the same amount of the fine tailings is also divided into three ponds; each pond is filled for 2 months then 20 kPa of sand cap is applied during the 3^{rd} month. At the start of the 4^{th} month a new tailings layer is deposited and the process is repeated. For Scenario 6, ILTT-CT is deposited in a single pond with the same filling strategy as that of Scenario 5. The simulation results of the different tailings materials and strategic deposition methods show that even though the in-line thickened tailings provide a significant improvement in sedimentation and consolidation characteristics of the fine tails, the possibility of reclaiming the land can only come by combining good deposition techniques, external stresses, environmental conditions and good strategy.

RÉSUMÉ
En ce document une théorie finie de consolidation de contrainte est employée pour simuler le dépôt de champ des produits de queue épaissis intégrés (ILTT), des produits de queue en ligne épaissis cisaillés, des produits de queue d'amende de débordement de cyclone (COF) et des produits de queue composés (CT) faits à partir d'ILTT. Il est important dans ces simulations de déterminer si un dépôt développe une résistance au cisaillement undrained minimum du kPa 5 pour un matériel déposé par année précédente selon les exigences de la directive 074 (ERCB 2009). Cette directive exige cette résistance au cisaillement minimum pour que le dépôt puisse être considéré reclaimable et n'être plus considéré les produits de queue fins semi-liquides. Six scénarios ont été choisis pour cette recherche. Les scénarios 1 4 sont des dépôts des produits de queue de débordement de cyclone, des produits de queue épaissis intégrés, des produits de queue en ligne épaissis cisaillés et d'ILTT-CT en déposant les matériaux pendant 3 mois dans un secteur de disposition et en leur permettant d'arranger sous l'individu-poids pendant 9 mois. Cette méthode permet la consolidation par un état simple ascendant de drainage. Alternativement, les scénarios 5 et 6 utilisent un double état de drainage : serrage de sable et colonnes de sable. Dans le scénario 5, le même montant des produits de queue fins est également divisé en trois étangs ; chaque étang est rempli pendant 2 mois puis de 20 que le kPa du chapeau de sable est appliqué pendant le 3ème mois. Au début du 4ème mois par nouvelle couche de produits de queue est déposé et le processus est répété. Pour le scénario 6, ILTT-CT est déposé dans un étang simple avec la même stratégie remplissante que celui du scénario 5. Les résultats de simulation des différents matériaux de produits de queue et des méthodes stratégiques de dépôt prouvent que quoique les produits de queue épaissis intégrés apportent une amélioration significative des caractéristiques de sédimentation et de consolidation des queues d'amende, la possibilité de reprendre la terre peuvent seulement venir en combinant de bonnes techniques de dépôt, efforts externes, conditions environnementales et bonne stratégie.

1 INTRODUCTION

In-line thickened oil sand tailings (ILTT) is tailings produced by the addition of flocculants and coagulant in three consecutive stages into a modified tailings pipeline to improve the dewatering behavior of oil sands cyclone overflow tailings. The development of the in-line thickened tailings presents an alternative promising solution to the fine tailings problem for the oil sands industry.

A detailed laboratory study of the in-line thickened tailings sedimentation and consolidation behavior is given by Jeeravipoolvarn (2010). It was shown that the in-line thickening process increases hydraulic conductivity of the cyclone overflow fines by more than three orders of magnitude during sedimentation. Compressibility of the in-line thickened tailings indicates that the tailings is more difficult to compress due to a stronger floc structure. The stronger floc structure in the in-line thickened tailings also provides a higher undrained shear strength at the same void ratio compared to that of the cyclone overflow tailings. It was also found that shearing due to tailings transportation damages some of the floc structure in the in-line thickened tailings but does not cause the material to fully return to the original state of the cyclone overflow.

An investigation of the use of the ILTT to create composite tailings (ILTT-CT) at a sand to fines ratio of 4:1 was given by Jeeravipoolvarn et al. (2010). Similar to the in-line thickened tailings, ILTT-CT was found to have high hydraulic conductivity and high undrained shear strength inherited from the flocculated fines. Static segregation for this composite tailings is comparable to that of the gypsum treated composite tailings made from mature fine tails.

Based on the above findings in the ILTT research, the behavior of the various tailings materials during deposition was modeled. The laboratory determined sedimentation, consolidation and undrained shear strength characteristics of cyclone overflow tailings (COF), in-line thickened tailings (ILTT), sheared in-line thickened tailings and composite tailings made from in-line thickened tailings (ILTT-CT) was used to investigate how these tailings are likely to perform under field conditions. Since different deposition techniques and boundary conditions can yield different dewatering behavior, two tailings deposition schemes, namely a conventional deposition and a sand sandwich with sand column deposition, were investigated. A conventional deposition scheme refers to a deposition of tailings material into an open pond surrounded by impermeable boundaries. The sand sandwich scheme with sand or wick drain columns is a deposition of tailings with layers of sand separating layers of the tailings and with columns of sand forming vertical drainage passages. These particular investigations are focused on the development of the undrained shear strength with time. The performance of each tailings was investigated to determine if 5 kPa undrained shear strength can be obtained after a one year deposition period of the material as required by Directive 074 for a acceptable reclaimed deposit (ERCB 2009).

2 TAILINGS CONSTITUTIVE RELATIONSHIPS

In order to simulate field tailings behavior, a consolidation model based on finite strain consolidation theory (Gibson et al. 1967) is used. To perform this analysis, the constitutive relationships void ratio - effective stress and hydraulic conductivity - void ratio, are required. A full range of constitutive relationships for each tailings material was obtained by utilizing a test program to measure a wide range of compressibility and hydraulic conductivity functions (Scott et al., 2008). Compressibility, hydraulic conductivity and undrained shear strength properties of all the tailings materials were determined by Jeeravipoolvarn (2010) and are shown in Figures 1, 2 and 3 respectively.

Cyclone overflow, in-line thickened tailings and sheared in-line thickened tailings have a fines content (< 45 μm) of about 94% and a specific gravity of 2.46 and ILTT-CT has a fines content of 20% and a specific gravity of 2.59.

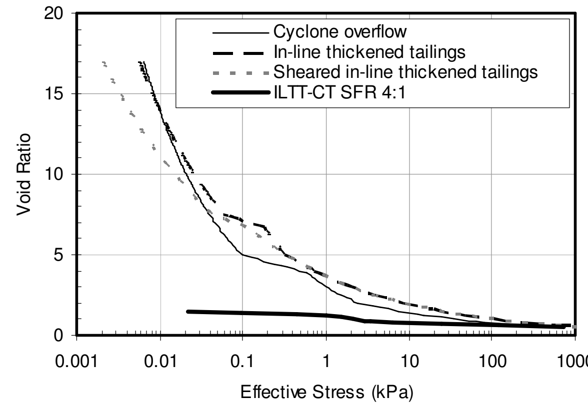

Figure 1. Void ratio – effective stress relationships

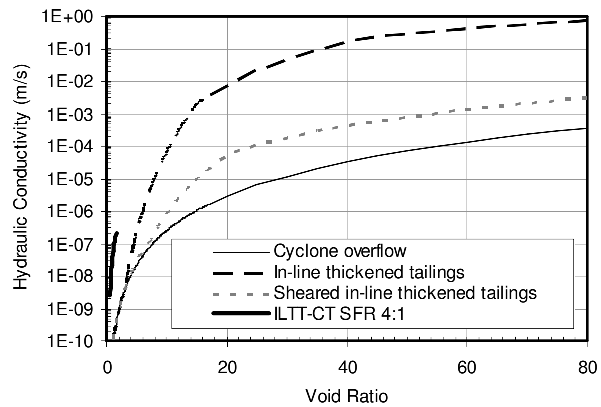

Figure 2. Hydraulic conductivity – void ratio relationships

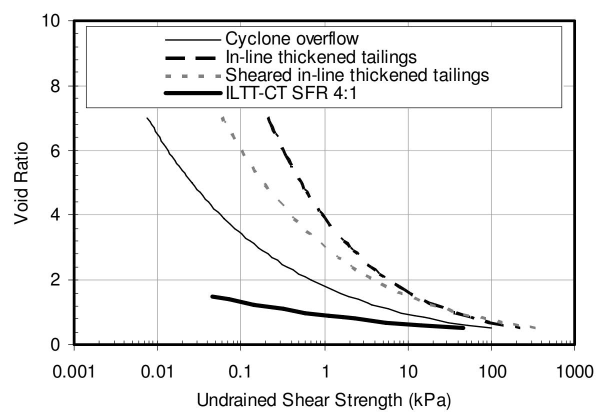

Figure 3. Void ratio – undrained shear strength relationships

3 TAILINGS PLACEMENT SCHEMES

In these particular simulations, it is desired that a deposit develops a minimum undrained shear strength of 5 kPa for a material deposited in the previous year as required by Directive 074 (ERCB 2009). Therefore the pond's life is assumed to be 1 year. For these simulations, a quiescent model is used and a filling period is determined by a method given by Carrier et al. (1983). The initial fill height for the quiescent model was assigned as 50 m or a total of about 50 tonnes of total mass per square meter of fine tailings at an initial solids content of 5%. This initial solids content is used as an initial solids content for the in-line thickened tailings, the sheared in-line thickened tailings and the cyclone overflow tailings. The ILTT-CT at a sand to fines ratio of 4:1 was created by a mix of 3 month old ILTT and cyclone underflow. Three month old in-line thickened tailings has an average solids content of approximately 34.5% with a fines content of about 94% and the cyclone underflow is assumed to have a solids content of 73% and a fines content of 5%. The mix of the two streams will create nonsegregating composite tailings at 61% solids content with a 20% fines content. It is noted that the assumptions and conditions used in the simulations do not reflect any particular operation. They are utilized to produce a comparative study between each tailings material and the strategic deposition scheme.

Six scenarios were selected for this investigation. Scenarios 1 to 4 are depositions of cyclone overflow tailings, in-line thickened tailings, sheared in-line thickened tailings and ILTT-CT by filling the materials for 3 months and allowing them to settle under self-weight for 9 months. Alternatively to the single application of a self-weight stress in Scenarios 1 to 4, Scenarios 5 and 6 utilize a double drainage condition, sand sandwiching and sand columns. In Scenario 5, the same amount of in-line thickened tailings is divided into three ponds; each pond is filled for 2 months then 20 kPa of a sand layer is applied during the 3rd month. It is assumed that the full load from the layer instantaneously begins at the beginning of the 4th month. At the start of the 4th month a new layer is placed during the next two months and the process is repeated. Half of the load from the new layer is assumed to be fully activated at the end of each month. For Scenario 6 with ILTT-CT, the same filling strategy as in Scenario 5 is used. In both Scenarios 5 and 6, a two way drainage condition is assumed as each layer of new fill is bounded at both top and bottom by sand layers and sand columns or wick drains are assumed to connect the sand layers to the surface. Therefore each of the new fill layers one year after its deposition are assumed to behave the same. The summaries of each step occurring in each scenario are given in Table 1.

4 SIMULATION RESULTS

Simulated interface settlement, average fines-bitumen void ratio and projected undrained shear strength in a hypothetical pond for all scenarios are shown in Figures 4, 5 and 6 respectively. It is noted that fines-bitumen void ratio is a ratio between a volume of voids and a volume of fines with bitumen. Viscous bitumen exists in the voids between mineral solids is treated as a part of the total solids. Fines-bitumen void ratio indicates remaining water in the fines matrix.

In Figure 4, required pond heights to store the tailings for Scenarios 1 to 4 are 36.6 m, 5.9 m, 11.4 m and 14.2 m for cyclone overflow, in-line thickened tailings, sheared in-line thickened tailings and ILTT-CT respectively. Scenario 2 with the in-line thickened tailings performed the best by providing the smallest required containment height followed by the sheared in-line thickened tailings, the ILTT-CT and the cyclone overflow. For Scenarios 5 and 6, a minimum required height to accommodate the first layer is 5.4 m and 14.1 m respectively. The in-line thickened tailings in Scenario 5 requires the smallest pond height amongst all the cases.

The average fines-bitumen void ratio shown in Figure 5 is an indication of rate of dewatering. For Scenarios 1 to 4, the average fines-bitumen void ratio of in-line thickened tailings shows the smallest value followed by ILTT-CT, sheared in-line thickened tailings and cyclone overflow. The in-line thickened tailings performs the best amongst Scenarios 1 to 4 and even if the tailings is poorly deposited and behaves as a sheared in-line thickened tailings, it still releases more water compared to that of cyclone overflow during a period of 1 year. In Scenarios 5 and 6, due to the additional sand surcharge and tailings layers on top of the tailings and a double drainage condition, the average fines-bitumen void ratios are 1.94 and 2.7 respectively. Significantly lower fines-bitumen void ratios in the last two cases indicate a fast release of water and a rapid increase of undrained shear strength.

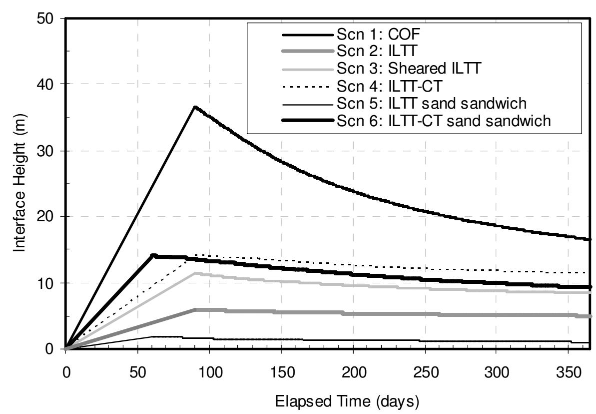

Figure 4. Interface settlement comparison for all simulations

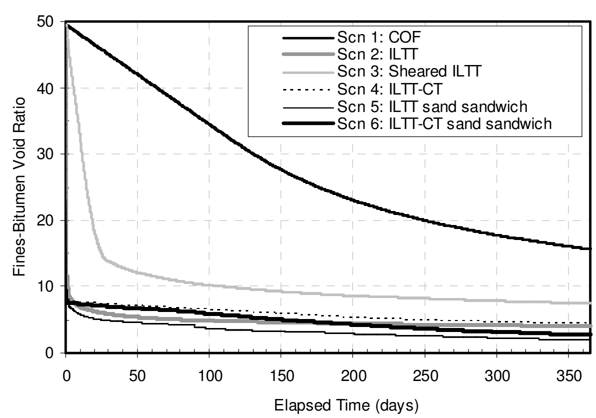

Figure 5. Average fines-bitumen void ratio comparison for all simulations

Table 1. Six simulated scenarios

Scenarios	1	2	3	4	5	6
Tailings	COF	ILTT	Sheared ILTT	ILTT-CT	ILTT	ILTT-CT
Initial height (m)	50.0	50.0	50.0	15.5	16.7	15.5
Numbers of pond	1	1	1	1	3	1
Start of 1st month	Filling	Filling	Filling	Filling	Filling	Filling
Start of 2nd month	Filling	Filling	Filling	Filling	Filling	Filling
Start of 3rd month	Filling	Filling	Filling	Filling	Start installing 20 kPa sand cap	Start installing 20 kPa sand cap
Start of 4th month	End of filling	End of filling	End of filling	End of filling	Sand cap is complete start filling a new layer	Sand cap is complete start filling a new layer
Start of 5th month	-	-	-	-	A new layer is half filled	A new layer is half filled
Start of 6th month	-	-	-	-	End of filling	End of filling
Start of 7th month	-	-	-	-	Start installing 20 kPa sand cap	Start installing 20 kPa sand cap
Start of 8th month	-	-	-	-	Sand cap is complete start filling a new layer	Sand cap is complete start filling a new layer
Start of 9th month	-	-	-	-	A new layer is half filled	A new layer is half filled
Start of 10th month	-	-	-	-	End of filling	End of filling
Start of 11th month	-	-	-	-	Start installing 20 kPa sand cap	Start installing 20 kPa sand cap
Start of 12th month	-	-	-	-	Sand cap is complete start filling a new layer	Sand cap is complete start filling a new layer

Average undrained shear strengths developed in the hypothetical pond for each scenario are shown in Figure 6. After 1 year, cyclone overflow, in-line thickened tailings, sheared in-line thickened tailings and ILTT-CT in Scenarios 1 to 4 develop average undrained shear strengths of 0.00 kPa, 0.92 kPa, 0.05 kPa and 1.09 kPa respectively. The ILTT-CT developed an averaged undrained shear strength close to the in-line thickened tailings. ILTT-CT in Scenario 4 shows a faster rate of increase in undrained shear strength compared to the ILTT in Scenario 2. At the end of 1 year, the slope of the shear strength-time plot of ILTT-CT is significantly greater than that of in-line thickened tailings. This is due to the higher applied internal surcharge of the ILTT-CT, the higher global hydraulic conductivity provided by the sand and the probable synergistic strength contribution of the sand in the composite tailings. Without a consideration of other external application of stress, all tailings in Scenarios 1 to 4 are unable to obtain the target undrained shear strength of 5 kPa based on these specific hypothetical deposition conditions.

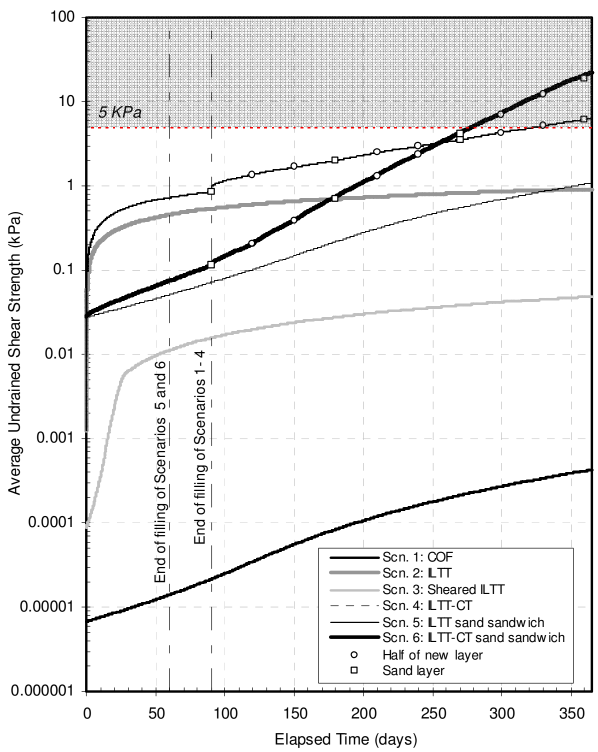

Figure 6. Average undrained shear strength comparison for all simulations

With an application of a sand sandwich, a sand column and the addition of new tailings layers in Scenarios 5 and 6, the target undrained shear strength of 5 kPa is possible. In Scenario 5, the in-line thickened tailings is deposited into 3 ponds for 2 months, the average solids content of the material at this time is about 33% with an average undrained shear strength of about 0.46 kPa. A sand layer is then placed on the top of the material during a one month period. A new in-line thickened tailings layer is then filled on top of the sand. The applied stress from the new layer is about 15 kPa at the end of filling. It can be seen in Figure 6 that the combination of a thin lift of in-line thickened tailings, the applied stresses from the sand and the drainage condition gives the in-line thickened tailings an undrained shear strength of 6.39 kPa at 365 days. For Scenario 6, similar conditions to Scenario 5 are applied with the exception that the applied stress from the new layer is 90 kPa. The average undrained shear strength developed at the end of 1 year is found to be 22.27 kPa for Scenario 6. It is noted that even though the ILTT-CT has a higher fines bitumen void ratio, it has a higher undrained shear strength than that of the in-line thickened tailings due to the sand.

Void ratio and undrained shear strength profiles for all cases at 365 days are shown in Figures 7 and 8. The application of sand surcharges in Scenarios 5 and 6 decreases the void ratio and increases the undrained shear strength near the surface substantially. This decrease of void ratio contributed to surface undrained shear strengths of more than 5 kPa for both cases. It is noted that for the in-line thickened tailings in Scenario 5, the tailings in the middle can have an undrained shear strength lower than 5 kPa as shown in Figure 8.

Summary of the critical outputs for all six scenarios is given in Table 2. The examples of the tailings behavior and strategic deposition techniques analyzed in this paper indicate that even though the in-line thickened tailings provide a significant improvement in sedimentation and consolidation characteristics of the oil sands fine tails, the possibility in reclaiming the land can only come by combining good deposition techniques, external stresses, environmental conditions and good strategy.

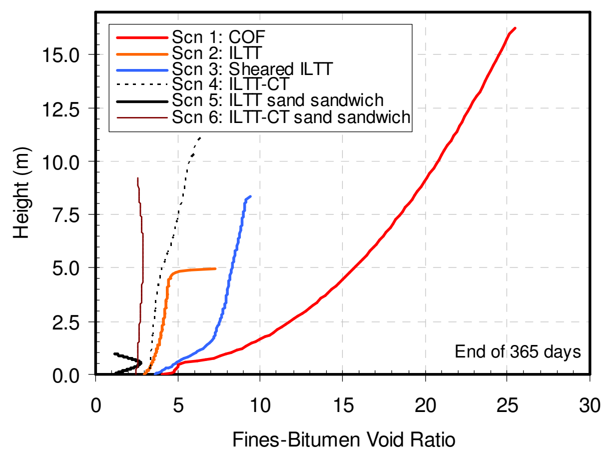

Figure 7. Simulated fines-bitumen void ratio profiles at 365 days

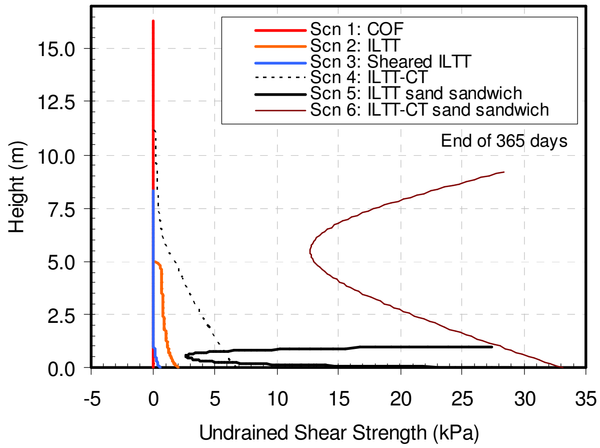

Figure 7. Projected undrained shear strength profiles at 365 days

Based on the above simulations in a hypothetical pond, advantages and disadvantages of the in-line thickened tailings can be drawn as follows.

Advantages

- The ILTT deposits require a relatively small containment area to release sufficient water to reach an average solids content of about 34.5% within 3 months due to its very high initial hydraulic conductivity.
- The high solids content of the settled in-line thickened tailings can be used as a high solids content fines feed for the production of composite tailings. Nonsegregating composite tailings can be made with in-line thickened tailings and cyclone underflow at a solids content of about 52% with a sand to fines ratio of 4:1 or a fines content of 20% (Jeeravipoolvarn et al., 2010). The composite tailings made with the in-line thickened tailings will inherit a high permeability and high undrained shear strength from the ILTT's fines.
- The undrained shear strength of the in-line thickened tailings is considerably higher than that of cyclone overflow or mature fine tailings. The combination of the high hydraulic conductivity and the high undrained shear strength means that the material will develop an undrained shear strength of 5 kPa much more quickly. This statement is also true for the ILTT-CT.
- The superior in-line thickened tailings properties opens up other possible dewatering techniques.

Disadvantages

- The in-line thickened tailings requires slightly higher effective stress to compress to the same void ratio as cyclone overflow.
- The advantage of being more permeable can disappear at a solids content of about 46% or a void ratio of about 3 as shown in Figure 2.
- As can be seen from the simulations, in-line thickened tailings released more than 90% of its initial water volume very quickly. The release water from the in-line thickened tailings must be recycled, treated and released otherwise a large water containment pond will be required to store the water. This may contribute to the operational cost.
- Poor deposition techniques resulting in floc disruption during the deposition of the in-line thickened tailings can reduce its high hydraulic conductivity and undrained shear strength. Its properties, however, are still much better than those of the cyclone overflow.

Table 2. Summarized simulated results on a hypothetical pond

Scenario	Min. required height (m)	1 year avg. solids content (%)	1 year e_{avg}	1 year e_{fb}	1 year avg. τ_u (kPa)
1	36.6	14.3	14.78	15.66	0.00
2	5.9	39.2	3.81	4.04	0.92
3	11.4	25.9	7.04	7.46	0.05
4	14.2	74.0	0.91	4.29	1.09
5	1.8 x 3 = 5.4	57.4	1.83	1.94	6.39
6	14.1	81.9	0.57	2.70	22.27

5 SUMMARY

Different deposition schemes are available for different tailings management plans. The selection of a deposition scheme for a specific type of tailings needs to be evaluated case by case based on factors such as availability of water, material behavior and site conditions. An important aspect of tailings planning is the use of existing theory, material properties and numerical capability to explore all possible deposition schemes to optimize each option and guide engineering practice. The numerical model has to be constructed with the best determined material behavior and possible field conditions.

In this paper, examples of strength projection for in-line thickening related materials are given and the results indicate that an average undrained shear strength of 5 kPa after one year deposition as required by ERCB (2009) for a reclaimable condition is possible for oil sands tailings by combining good deposition techniques, external stresses, environmental conditions and good strategy.

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