Coarse Tailings Sand Densification By Dozer Packing

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ABSTRACT
Upstream construction tailings dams in the oil sands mining industry rely on a compacted shell and beaches of non-liquefiable sand to contain the pond and internal loose beach deposits. Compaction energy to densify the sand in the shell is provided by dozers which densify the sand through the vibration of trafficking repeatedly across the sand surface, together with the downward drainage of construction water through the sand. This paper updates previous published data on dozer track-packing effectiveness, based on operational experience and addresses the influences of: dozer size, tailings sand gradation, and sand moisture content. Observations on equipment productivity are given in terms of cubic metres of densified sand per operating hour. The effectiveness of the densification was assessed using cone penetration testing, surveys of the surface settlement, and visual observations of water liberated from the beach.

RÉSUMÉ
La méthode de construction par l'amont des parcs de résidus miniers de l'industrie des sables bitumineux comprend des sections de sable compacté par étages et des plages de sable non-liquéfiable. L'énergie pour compacter et densifier le sable est fournie par des bulldozers qui densifient le sable par vibrations en roulant à plusieurs reprises à sa surface. Le processus est facilité par l'écoulement de l'eau à travers le sable. Cet article met à jour des données publiées antérieurement sur l'efficacité de cette méthode de compactage en fonction de l'expérience opérationnelle et tient compte des facteurs suivants: la taille du bulldozer, la gradation des résidus de sable et l'humidité dans le sable. Les observations sur la productivité des équipements sont données en mètres cubes de sable densifié par heure de fonctionnement. L'efficacité de la densification a été évaluée à l'aide d'essais de pénétration au cône, de mesures du tassement et d'observations visuelles de l'eau libérée de la plage.

1 INTRODUCTION

Upstream construction tailings dams in the oil sands mining industry rely on a compacted shell of coarse tailings sand and beaches of non-liquefiable sand to contain the pond and internal loose beach deposits. A typical section illustrating the zonation of an upstream-construction oil sand tailings dam is shown in Figure 1. Compaction energy to densify the sand in the shell (cell sand and beach above water; BAW) is provided by dozers which compact the sand through the vibration of trafficking repeatedly across the sand surface, together with the downward drainage of construction water through the sand. The cell sand compaction occurs during deposition in hydraulic cells, whereas BAW is typically compacted after deposition.

Martens et al. (2008) published the results of a track packing trial at the Albian Sands Muskeg River Mine in May 2006, where CAT D7R dozers were used to compact upstream coarse tailings sand (CST) beaches. The objective of the trial was to determine the depth that could effectively be compacted with the dozers, and the level of effort required to achieve sufficient compaction that the sand would not be vulnerable to static liquefaction.

Since the trial reported by Martens et al. (2008) was completed, track packing to compact beach sand has been used extensively in tailings operations at the Albian Sands Muskeg River Mine (MRM) and Jackpine Mine (JPM) External Tailings Facilities (ETFs). This paper extends the results reported in that study to a variety of operational conditions, and reports more information on typical track packing productivity experienced with the CST beaches at Albian Sands.

2 MRM ETF SOUTH EXPANSION AREA

Track-packing has been used operationally to densify the beaches of the South Expansion Area (SEA) of the MRM ETF using D8T dozers, starting in 2012. A photo of the SEA with the beaches is shown in Figure 2.

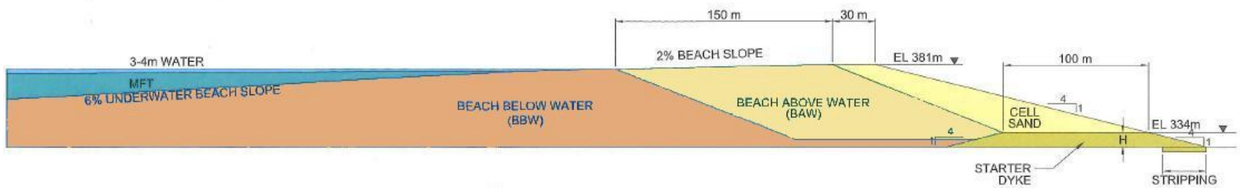

Figure 1. Upstream construction tailings dyke

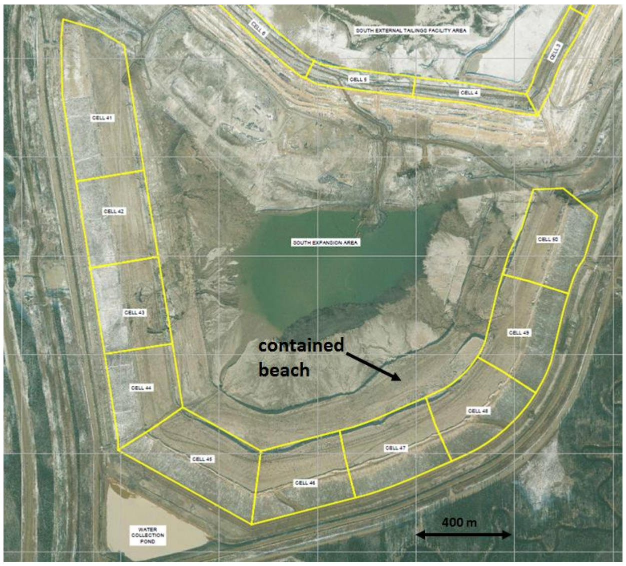

Figure 2. MRM External Tailings Facility South Expansion Area showing construction cells (November 2015).

The average characteristics of the Albian Sands' beach sands are listed in Table 1. These were measured at the MRM ETF from a detailed beach investigation in 2005, the MRM SEA in cell construction/contained beach area, and from two beach test locations at the JPM ETF.

Table 1. Characteristics of Albian Sands' beach sands

Site	Fines (% < 75 μm)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	Moisture (%)
MRM ETF	7	0.09	0.16	0.36	19
MRM SEA*	7	0.08	0.16	0.28	7
JPM SC1	3	0.20	0.24	0.39	6
JPM SC2	4	0.11	0.20	0.29	25

*cell construction/contained beach

Results from an investigation of track-packing effectiveness at the SEA in 2012 are shown in Figure 3. Pre-packing results are dashed lines, and post-packing are solid lines.

In 2013, a track packing program was carried out in the SEA where the beach was divided into 30 segments so that the dozer effort can be tracked over a defined area of the beach. The area of each beach segment varied between 6,100 m^2 and 36,000 m^2. Dozer time was recorded and CPTs were performed to assess the optimal method specification for the SEA beach track packing given that the tailings characteristics remain similar to those shown in Table 1. The beach density was assessed using CPT for dozer efforts ranging between 90 m^2/hr (high effort) to 1000 m^2/hr (low effort) (i.e. repeated trafficking in just this area for an hour). Based on observations of track-packing effort and effectiveness at the MRM SEA between May and September 2013, the typical productivity that achieved the compaction requirement was approximately 150 m^2/hr. In this case, the compaction requirement was defined as a CPT normalized equivalent clean sand tip resistance ($Q_{tn,cs}$) > 70, after Robertson (2010). The actual effort required can vary depending on the initial density, the moisture content of the sand, and other factors such as drainage conditions and gradation. In some cases, double the standard effort was used and there were still some areas identified with insufficient compaction. In general the track packing was found to be most effective if done immediately after pouring. Operational constraints resulted in some longer delays between pouring and track-packing, and this resulted in reduced compaction effectiveness.

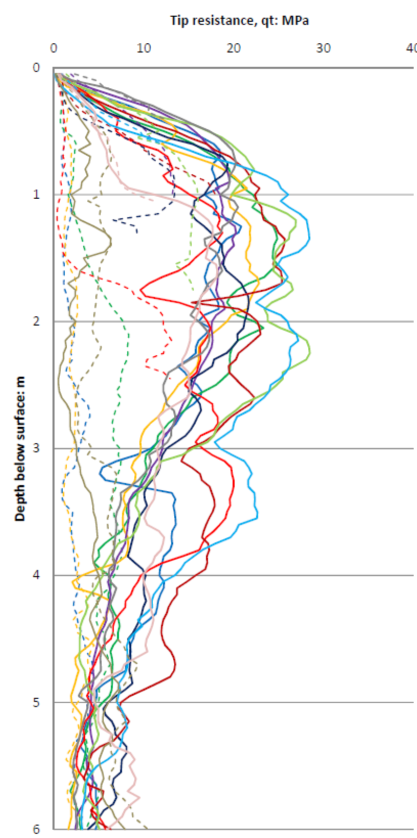

Figure 3. MRM ETF SEA 2012 track packing results.

A photo of the beach track packing in 2013 is shown in Figure 4. The area being packed had water flow to the beach surface due to the densification of the sand.

Figure 4. Track packing in the SEA in 2013.

The operational methodology was changed to contained beaching in 2014, where the dozer track-packing was done during pouring within an area contained between dry dykes. This methodology is similar to hydraulic cell construction used for the cell sand, except that one end of the hydraulic cell containment dykes is left open to decant into the impoundment.

CPTs in the SEA determined that densification was possible to between 4 and 5 m, but was most effective in the upper 3 m.

3 JPM EXTERNAL TAILINGS FACILITY

Track-packing at the JPM ETF has been done under varying conditions in Sand Cell 1 (SC1) and Sand Cell 2 (SC2). The locations of specific events and trials described in the following sections are shown in Figure 5.

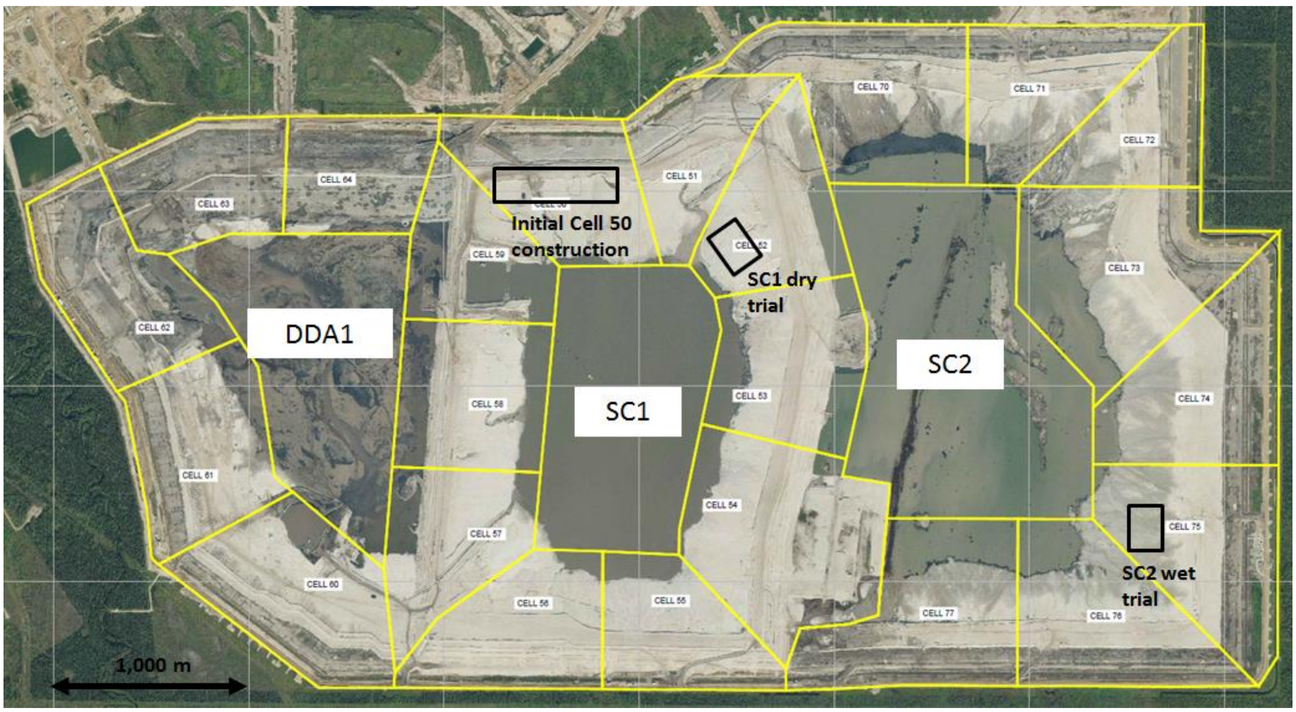

Figure 5. JPM External Tailings Facility showing initial deposit track-packing and trial locations (September 2015)

3.1 JPM Initial Construction

In November 2010, the first lift of CST was deposited in the north area of JPM SC1. The initial lift was 4 to 8 m thick. This was thicker than previous testing (Martens et al., 2008) and experience had shown that this could not be compacted to the full depth by D7R to D8T dozers (25 tonne and 39 tonne, respectively), and therefore much heavier D11T dozers (104 tonne) were used to attempt to pack the full thickness of the lift. It was anticipated that the additional vibrational energy from the heavier dozers would result in a greater depth of compaction.

A comparison of nearby CPTs done after the initial packing with D8 dozers and after the second round of packing with D11 dozers show that the D11 dozers were not successful in advancing the depth of compaction beyond what had been achieved by the D8 dozers (Figure 6). A comparison of the CPT tip resistance for the D8 and D11 dozer compaction shows the same pattern of maximum CPT tip resistance between 1 and 2 m depth, diminishing to no improvement beyond about 4 m depth. The ground surface elevation was lower for the attempt with the larger dozers as it was cut down to attempt compaction to a lower elevation. In both cases, the target zone for compaction was 2 to 3 m below the pond level and the sand was saturated, as the beach had been poured into approximately 3 m of standing water. The contractant-dilatant boundary (purple vertical line) on these figures is from Fear and Robertson (1995) as presented by Olson and Stark (2003). In Figure 6, the original ground elevation (OG, green line) represents the pre-construction ground surface elevation, and the muskeg interface identified in the CPT (red line) is lower due to the settlement from the weight of the fill. The groundwater table is shown by the blue (GWL) line.

The results may have been influenced by the proximity of the underlying muskeg layer, which could have absorbed vibrational energy from the dozers and prevented compaction of the sand immediately overlying the muskeg. So while no increase in depth of compaction was observed in the CPTs after using the D11 dozers, this issue would warrant further study before it can be conclusively stated that the D11 dozers are not more effective than the D8 dozers in compacting the beach sand.

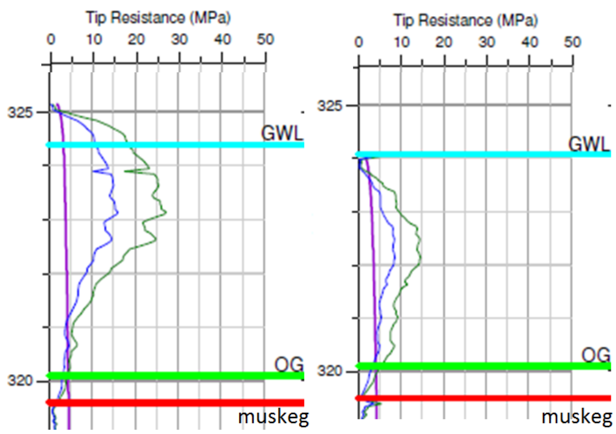

Figure 6. Comparison of compaction depth by D8 (left) and D11 (right) dozers. Blue line is CPT tip resistance q_t, green is stress normalized CPT tip resistance q_{t1}, purple is the contractant-dilatant boundary

3.2 JPM SC1 beach compaction trial

Track packing was attempted on the upstream beaches at Sand Cell 1 (SC1) JPM ETF using D8 dozers.

The tailings sand gradation at JPM to date has been slightly coarser than at MRM, with a lower fines content. The JPM CST gradations are listed in Table 1 and shown in Figure 7.

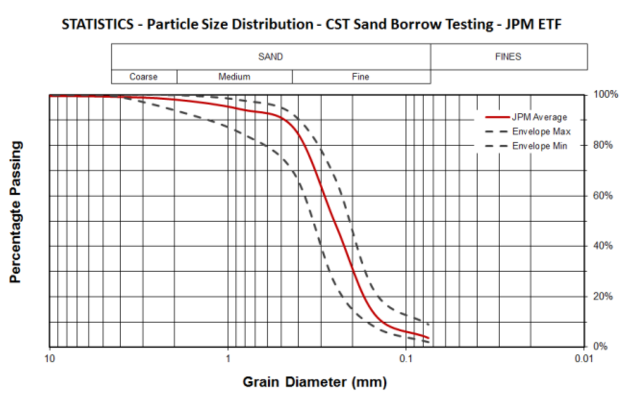

Figure 7. JPM CST gradation

Early attempts to track pack the beach sand at JPM were found to be ineffective, with little to no difference in the CPT $Q_{tn,cs}$ values before and after packing, despite considerable dozer effort. Visual observations were that there was little or no water expelled to the surface during packing, in contrast to the significant water release described by Martens et al. (2008) at the MRM ETF, and observations from the MRM SEA discussed earlier in this paper. The cleaner, coarser sand at JPM was found to drain faster than the MRM CST, and the window of time after deposition of the beach, when packing would be effective, was suspected to be small.

A "dry" trial was performed in September 2014 in Cell 52 of the JPM SC1 to investigate if drainage was the reason for the limited effectiveness. This trial involved track packing a beach after it had drained for a period of about 5 months. The location of the dry beach trial at JPM is shown in Figure 8, with segments A and B each having an area of 15,000 m^2. The two segments averaged 4.8 m and 2.7 m above the pond elevation, and used 4 and 6 shifts of D8 dozers packing in pairs, respectively. This translates to track-packing productivity of 190 m^2/hr and 125 m^2/hr for segment A and B, respectively.

The fines content (75 μm) of the sand typically ranged from 2% to 4% with an average of 3%. The average moisture content was 6%. The characteristics of the beach sands from the MRM SEA operations, and the JPM SC1 (dry) and SC2 (wet) trials are compared in Table 1.

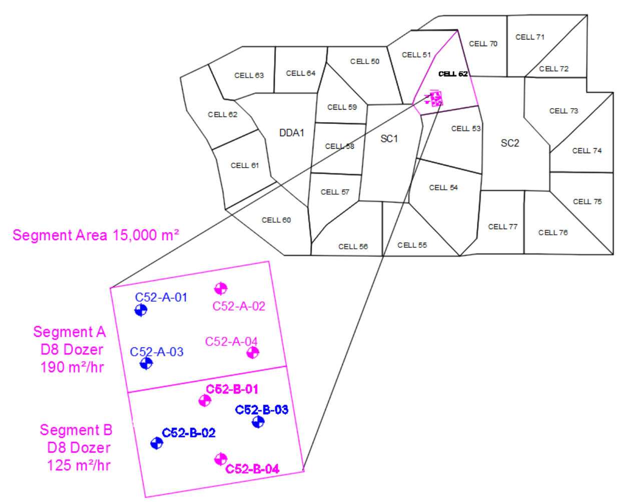

Figure 8. Dry beach trial CPT locations. (CPT plots for locations highlighted in blue are provided in Fig. 9 and 10)

The susceptibility to static liquefaction was evaluated using the methodology of Robertson (2010). A normalized, equivalent clean sand CPT tip resistance $Q_{tn,cs}$ of 70 was taken as the boundary between liquefiable and non-liquefiable sand.

Typical results from the JPM dry beach trial are shown in Figures 9 and 10, and demonstrate that there was very little difference between the pre-packing (blue line) and post-packing (brown line) results, for either Segment A or B. The contractant-dilatant boundary is shown as the red vertical line. For conditions where the sand was too dry to effectively pack, increasing the effort was not found to improve the density.

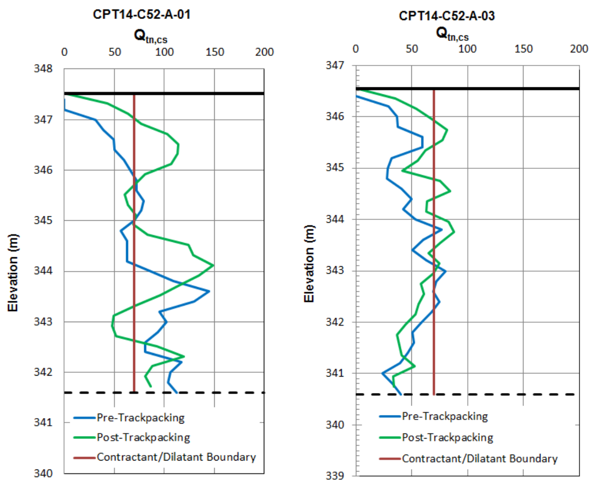

Figure 9. Segment A dry beach typical CPT results

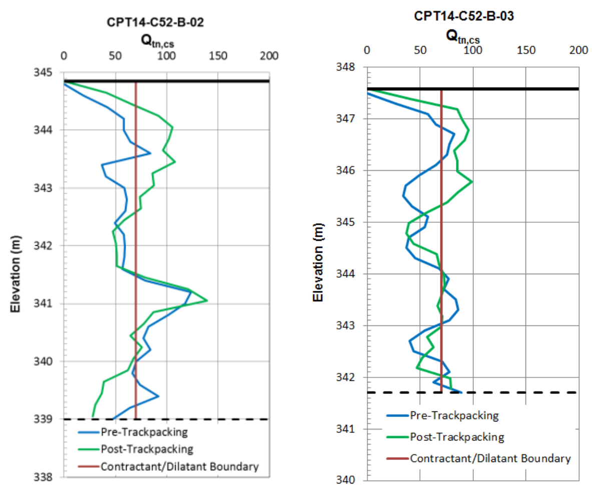

Figure 10. Segment B dry beach typical CPT results

3.3 JPM SC2 beach compaction trial

A second "wet" trial was performed at Cell 75 in JPM SC2 in May 2015 to evaluate the effectiveness of packing the beaches while still wet, shortly after deposition. The trial was performed on three segments each with an area of 10,000 m^2 that were track-packed with two D8 dozers over several shifts, which was equivalent to three levels of productivity: 320, 200 and 130 m^2/hr (productivity estimated per one dozer). The location of the wet beach trial is shown in Figure 11.

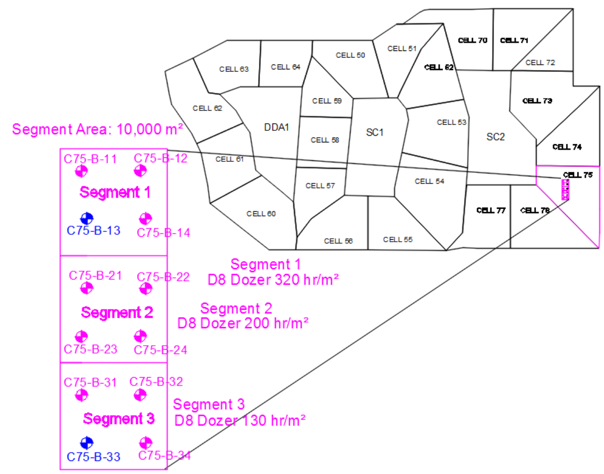

Figure 11. Wet beach trial CPT locations. (CPT plots for locations highlighted by blue are provided in Fig. 12.)

For this trial, track packing was done within approximately 2 weeks of pouring.

The standard Proctor maximum dry density for the sand was 1620 kg/m^3 with an optimum moisture content in the range of 12-15% (average 13%). Fines contents (75 μm) were 2-7% (average 4%).

Measured field moisture contents prior to track packing were 18-32% (average 25%), with samples taken at 1, 2 and 3 m depths. This was substantially wetter than the standard Proctor optimum moisture content. The beach was 4-5 m above the pond elevation at the time of the wet beach trial.

The depths of improvement over 12 test locations in the three segments ranged from 3.6 to 5.9 m with a median of 4.5 m and an average of 4.8 m. Settlements in the track packing area ranged from 0.2 to 0.6 m with an average of 0.3 m over 8 measurement points, with larger average settlements in the areas of higher packing effort. Comparing the average settlement to the average depth of improvement, the beach settled by about 7% of the thickness within the zone of improvement. This is consistent with the medium effort zone from the MRM ETF trial described by Martens et al. (2008), but less than the average settlement (0.6 m) in the high effort zone from that study. There were also no visible signs of settlement and tension cracking in the JPM trial, such as those observed in the MRM trial (compare to Figure 13 of Martens et al. (2008)).

The 2006 MRM ETF trial from Martens et al. (2008) used 25 tonne D7R dozers while the JPM standard dozers are 39 tonne D8T. In comparing the 2006 MRM ETF and 2015 JPM SC2 results, there was no apparent correlation between the dozer mass and depth of compaction.

Example results are shown in Figure 12, which demonstrate that packing the wet beaches is effective in densifying the sand.

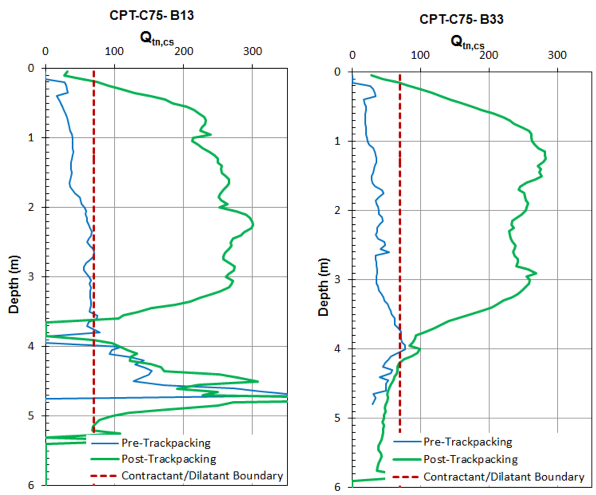

Figure 12. Wet beach trial typical results

Comparing the results in the three test segments, the segment with the least dozer effort (320 m^2/hr) produced an average depth of compaction of 3.4 m, whereas the other two were 5.4 m and 4.8 m respectively. Some of the difference may be attributable to other factors that were not controlled such as variations in the gradation or water content of the tailings, however, it does not appear that increasing the effort beyond about 200 m^2/hr results in additional benefit. The optimum packing productivity was about 200 m^2/hr, and for a typical depth of improvement of 4.5 m, equates to 900 m^3/hour.

A photo of the dozers packing the SC2 beach is shown in Figure 13. The visible water was produced by the track packing. A general observation is that effective track packing will liberate water from the surface of the beach. If the track packing does not produce water, it is likely not effective in densifying the sand.

Figure 13. Dozers packing the SC2 beach during the wet beach trial.

4 JPM CONTAINED BEACH OPERATIONS

Attempting to compact the fast-draining beaches at JPM was found to be too operationally challenging, and so Tailings Operations proposed an alternative method whereby the width of beach that was required to be non-liquefiable for the structural stability of the dyke was poured as a contained beach rather than an overboarded discharge. The cell was widened to 100 m, and a contained beach of 100 m width was poured upstream of the cell for each lift of the dyke, to satisfy the total structural requirement of 200 m (cell plus beach). Typical contained beach segment widths range from 40 to 60 m for a one-leg pour. Usually the contained beach is advanced in a two-leg (2 tailing pipes) set up. A schematic figure of the contained beach operation is shown in Figure 14.

Contained beaching is a modified form of cell construction with one end dyke and using the upstream edge of the existing cell for downstream containment. The tailings lines discharge parallel to the dyke axis, rather than perpendicular as during overboard beaching. Separation dykes are built up as sand is deposited in the cell. Beach sand builds up at the open end of the cell. The key difference between contained beaching and track packing is that compaction occurs while the tailings are discharged in contained beaching, whereas compaction occurs after discharge in track packing.

The dozers usually travel perpendicular to the separation dykes to push sand and track-pack the deposited sand. Occasionally, track-packing parallel to the cell is required to squeeze water out. The contained beach has the benefit of holding some water on the beach while the dozer packing is ongoing, which also facilitates downward drainage and may aid in effective compaction.

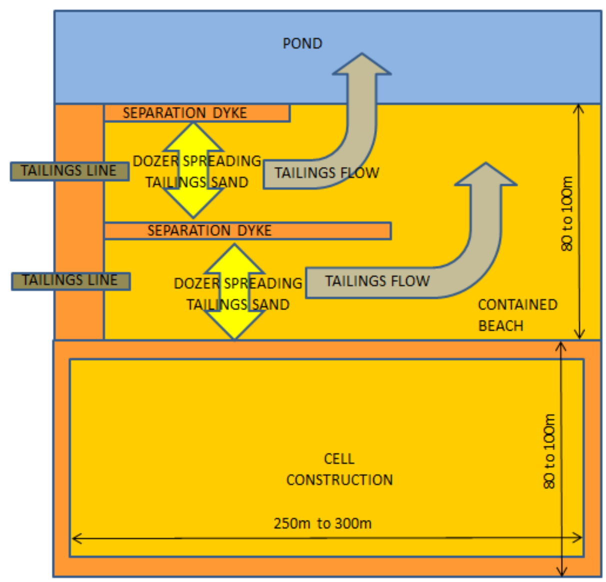

Figure 14. Plan view of contained beach construction methods.

Because the construction progress in contained beaching varies with the quality of feed (slurry density and gradation), it is difficult to draw a direct comparison with regular beach track-packing effort since the total dozer time in contained beaching is affected by factors in addition to the minimum time required to obtain the required sand density. For planning purposes, an average advance of 100 m per day is used. Assuming 75% of shift time is dedicated to track-packing, the productivity is approximately 125 to 170 m^2/hr (per one D8 dozer). CPT testing found that the beach was typically compacted to 2 to 5 m below the base of the contained beach, plus the thickness of the contained beach lift (3-4 m). This translates to an average productivity of 500 to 700 m^3/hr based on the contained beach lift thickness of 4 m.

The contained beach methodology leads to an increased total thickness of compacted sand because the sand is compacted as it is poured. As the tailings slurry is introduced into a new contained beach area, the previous beach under the step-over is saturated, and the dozers are able to compact that material during the initial pour, before the accumulated thickness of new contained beach sand prevents the vibrational energy from reaching the lower beach material below the step-over. In this way, a 4 m lift that steps out over previously uncompacted beach can produce an 8 to 9 m thickness of compacted, dilatant beach material.

The track-packing effort to compact the contained beach was similar to the wet beach compaction trial with 4 and 6 shifts compacting time. However, contained beach construction method offers several advantages: more consistent results, greater thickness of the dilative sand zone, and it is less time-sensitive as the sand is saturated during the compaction work.

A cross section through the dyke, showing the outer cell (orange) and the inner contained beach (yellow) is shown in Figure 15. CPT results in terms of $Q_{tn,cs}$ are shown on the section, demonstrating that CPT tip resistances much in excess of the minimum criteria of 70 were readily achieved.

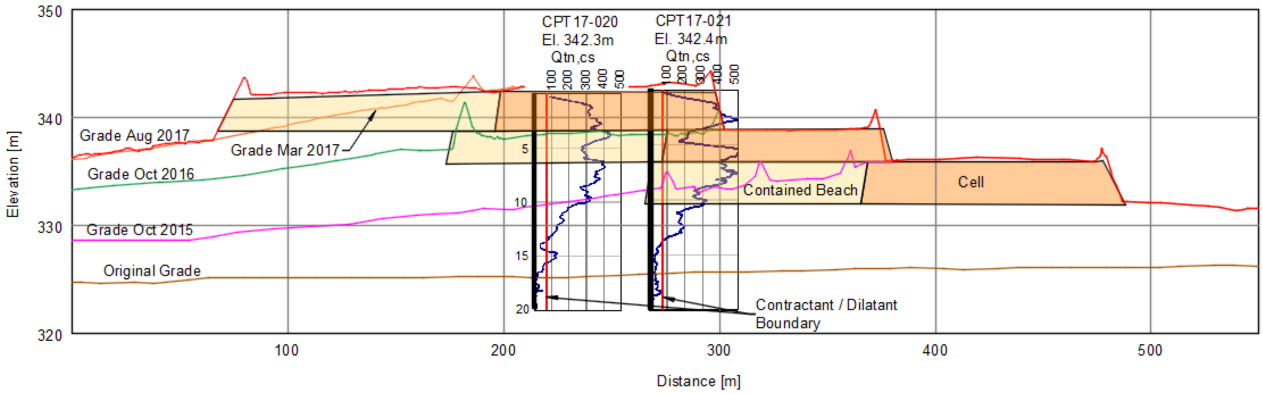

Figure 15. Cross section through an area of contained beach.

5 QUALITY CONTROL AND ASSURANCE

A custom-built Automated Dynamic Cone Penetration rig (ADCP) was developed at the Albian Sands mines to provide a rapid and cost effective means of verifying track packing compaction, and has been used to assess the density of the upper 5 m to 6 m of beach deposits following compaction (Figure 16). The test is performed by advancing a 16 mm (5/8”) diameter rod with a tip trimmed at 60 degrees. The rod is advanced by an automated hammer and numbers of blow counts per 150 mm of penetration are recorded. The results have been calibrated to CPT data using paired ADCP/CPT results. A representative test result is shown in Figure 17.

Figure 16. Automated Dynamic Cone Penetration rig

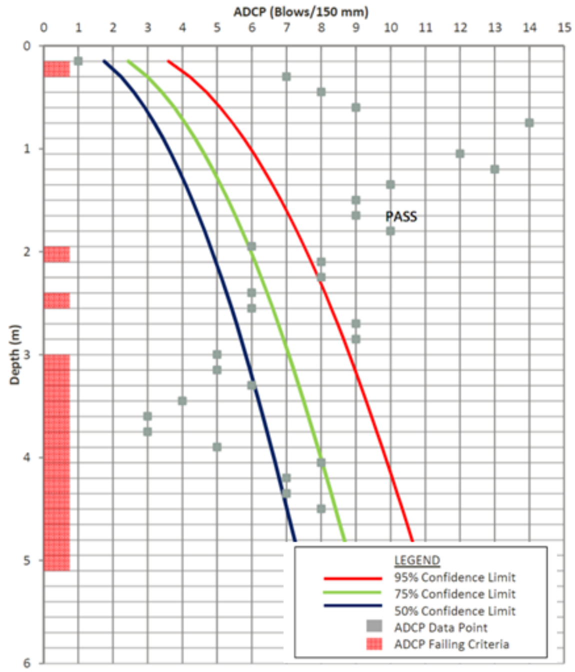

Figure 17. ADCP data showing compaction results.

The quality assurance program using the ADCP is often complemented by nuclear field density tests performed at surface and up to 1 m depth, in addition to CPT soundings to obtain density profiles for greater depths.

The testing program indicates that generally high densities are achieved within the cell construction and contained beach. On occasions where a field density or dynamic cone penetration test fails, additional tests are performed around the test location to delineate the defect area, which was then remediated if found to be larger than a localized area.

6 CONCLUSIONS

The following observations were made from the operation track-packing experience:

- Dozer compaction can be a very effective method of densifying oil sand coarse tailings sand if the sand is saturated.
- The typical range of densification was 3 to 5 m.
- Beaches with low fines content drain quickly and have a limited window of opportunity for packing before they become too dry.
- If the beach is too dry to pack, adding additional dozer effort did not improve the results.
- Where the beach conditions are amenable to packing, typical productivity is about 150-200 m^2/hr, or 600-1000 m^3/hr. Under these conditions, dozer packing is the most cost-effective method for densifying oil sand tailings sand, likely by a substantial margin.
- Based on a non-rigorous assessment, it appeared that using larger dozers did not increase the effective depth of compaction, however, further testing would be needed to validate that conclusion.
- The contained beach method of depositing coarse tailings sand allows for effective compaction and provides an opportunity to also compact the upper portion of the previous beach lift if there is a large stepover onto uncompacted beach. After attempting to compact the overboarded beaches, Tailings Operations at both MRM and JPM switched to contained beaching as this allowed for more consistent density improvement. Typical contained beaching packing productivity was 500-700 m^3/hr per dozer.

7 REFERENCES

Fear, C.E. and Robertson, P.K. 1995. Estimating the Undrained Strength of Sand: a Theoretical Framework, *Canadian Geotechnical Journal*, 32: 859-870.

Klohn Crippen Consultants, 2005. *Muskeg River Mine External Tailings Facility Liquefaction Investigation Program – Data Report.* Report prepared for Albian Sands Energy Inc., November 21.

Martens, S., Lappin, T., and Godwaldt, R. 2008. Compaction of upstream construction tailings dam beaches using dozers. *Canadian Geotechnical Conference*, Edmonton, 746-752.

Olson, S.M., and Stark, T.D. 2003. Yield Strength Ratio and Liquefaction Analysis of Slopes and Embankments, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 129: 727-737.

Robertson, P.K. 2010.“Evaluation of flow liquefaction and liquefied strength using the cone penetration test. *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 125(6): 842-853.