Blast densification trials for oilsands tailings

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ABSTRACT
This paper describes a blast densification trial program that was performed in 2006 at Shell Canada Energy's Muskeg River Mine External Tailings Facility (ETF) near Fort McMurray, Alberta to assess the effectiveness of blast densification. At the test location, the tailings were about 25 m thick, overlying several metres of bitumen-tailings mixture, overlying native foundation soils. The main intent of the test program was to determine the effectiveness of blast densification in tailings containing layers and zones of bitumen.

RÉSUMÉ
Cet article décrit un programme expérimental de compactage aux explosifs qui eu lieu en 2006 sur le site du barrage de la mine Muskeg River de Shell Canada Energy près de Fort McMurray en Alberta, afin de déterminer l'efficacité du compactage aux explosifs. Sur le site testé, les résidus miniers étaient d'environ 25 m d'épaisseur, reposant sur plusieurs mètres de résidus et de bitume, surimposés sur une fondation de sol local. Le but principal du programme d'expérimentation était de déterminer l'efficacité de la technique de compactage aux explosifs dans des résidus miniers contenant à la fois des couches et des zones de bitume.

1 INTRODUCTION

The Shell Canada Muskeg River Mine External Tailings Facility (ETF) is an upstream constructed tailings dam near Fort McMurray, Alberta. Following construction of the starter dam, raises have incrementally stepped out over the beach. Deposition within standing water has resulted in some parts of the beach being in a loose state.

The dam is stable in its current configuration even if the loose zones in the beach deposits liquefy. However, the dam designers were concerned that further dam raises could be unstable in the event that the loose beach sand, beneath the dam raises or in the adjacent beach, were to liquefy under either static or dynamic conditions.

Shell Canada reviewed several options to increase the long term stability of the dam prior to additional significant raises. Options included toe berm construction, blast densification and dewatering.

To assess the effectiveness of using explosive compaction to densify the upstream tailings, an explosive compaction trial program was conducted between July 17 and August 5, 2006. During the trial program, 35 holes were drilled and blasted using a total of 1132 kg of explosive contained in 100 separate charges. The program progressed from a single hole blast with a single charge, through single hole blasts with multiple charges, to multiple hole blasts with multiple charges.

The blasting was monitored through the use of 3 seismographs, 29 high pressure electric piezometers connected to two high speed data acquisition systems, 16 low pressure electric or vibrating wire piezometers in the surrounding tailings and dam foundation, and 4 inclinometers.

Cone Penetration Tests (CPT) and topographic surveys were conducted before and after the trial program to document the change in ground conditions due to blasting.

Figure 1. Upstream tailings beach (pre-blast)

2 SITE CHARACTERIZATION

At the time of the test, the ETF tailings dam was approximately 30 m high. Contained behind the dam are loose tailings about 25 m thick, overlying several metres containing thin layers of bitumen-tailings mixture, overlying native foundation soils. The CPT tip resistance of the tailings is typically about 5 MPa to 10 MPa, and the fines content is about 10% to 15%. The CPT tip resistance of the tailings-bitumen mixture is about 2.5 MPa to 5 MPa and the fines content is up to 40%.

Prior to the explosive compaction (EC) trial program, fourteen CPT tests were performed at the trial area. All CPT testing was performed by ConeTec Investigations of Richmond, British Columbia, using a track mounted drill rig. A typical pre-blast CPT result is presented in Figure 2.

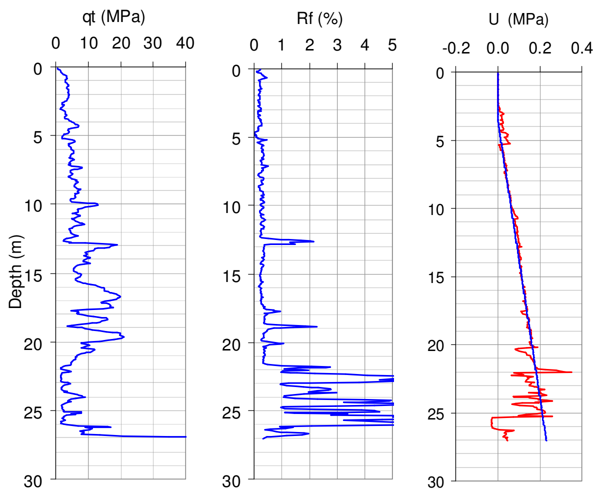

Figure 2: Pre-blast CPT plot

3 EXPLOSIVE COMPACTION TRIAL PROGRAM

3.1 Test Layout

The explosive compaction trial area was located on the upstream tailings beach. The test was split into two trial areas separated by about 200 m. Twenty holes were drilled in one area, while 15 were drilled in the second area. The main purpose of the split trial was to allow drilling and post-blast monitoring to continue in one area, while loading and blasting was proceeding in the other area. Splitting the trial into two areas reduced delays and allowed drilling to continue uninterrupted throughout the program.

A total of ten blasts were conducted over the approximate 3 week trial period. The first four blasts were single-hole blasts with one, two or three decks of explosives. The fifth blast consisted of 3 holes at 18 m spacing and the sixth blast consisted of 3 holes at 14 m spacing. The last four blasts each consisted of 6 holes at 11 m spacing. In the first test area, a 6-hole grid at 11 m spacing was first detonated and an adjacent 6-hole grid was detonated 4 days later. In the second test area, a 6-hole grid at 11 m spacing was first detonated and a second overlapping pass was detonated 4 days later. Table 1 summarizes the explosive compaction trial.

Table 1: Explosive Compaction Trial Summary

Blast	Area	Hole Pattern	Charge Pattern
1	1	Single	10 kg at 12 m
2	1	Single	12 kg at 23 m
3	1	Single	10kg at 15 m 12 kg at 23 m
4	1	Single	8 kg at 9 m 10kg at 16 m 16 kg at 26 m
5	2	Row - 3 at 18 m	Same
6	1	Row - 4 at 14 m	Same
7	2	Grid – 11 m	Same
8	1	Grid – 11 m	Same
9	2	Grid – 11 m	Same
10	1	Grid – 11 m	Same

Charge weights and patterns varied in the single, 3-hole and 4-hole tests. In general, charge weights and the number of holes detonated in each test were progressively increased as the trial progressed. The intentions of this incremental approach were to gain a better understanding of the tailings response to blasting and to monitor the stability and response of the dam prior to progressing to larger charges.

For the final four blasts, 6 holes were detonated at once with 8 kg, 10 kg and 16 kg charges placed at about 9 m, 16 m and 26 m depth, respectively.

3.2 Drilling Methodology

A total of 35 blast holes were installed using a track-mounted auger drill rig operated by Mobile Augers of Edmonton, Alberta. A hollow stem auger casing (107 mm ID, 127 mm OD, approximately 200 mm flight diameter) with a wooden plug tip was first advanced to a depth of about 23 m to 27 m. The hollow stem auger casing was then withdrawn about 0.3 m, the auger casing filled with water, and the wooden plug driven out of the tip using AW drill rods. After the wooden plug was driven out, 76 mm, glued, bell-and-socket, PVC pipe (90 mm OD, 83 mm ID) was installed to the bottom of the hole in 6 m lengths. As each length was installed, it was filled with water to counteract buoyancy. Once the PVC pipe was to the bottom of the hole, the top of the pipe was capped and the hollow stem auger casing withdrawn, which allowed the tailings sand to collapse around the PVC pipe.

In general, drilling would proceed at one test area while loading and blasting proceeded at the other test area. The drill rig was left on the beach during the blast; however, drilling would stop during the actual blast. Typically, three holes were drilled in a 10 hour day by a 2 or 3 person crew.

3.3 Blasting and Timing Sequence

Once the PVC was installed, the holes were loaded with explosives, detonators, boosters and stemming material by Explosives Ltd. of Calgary, Alberta. The explosives consisted of high-strength micro-balloons in 2 kg charge weights. Each 2 kg charge was packaged in a rigid plastic shell, 600 mm long by 60 mm diameter. Multiple shells were screwed together to produce different total charge weights. During the trial program, total charge weights varied from 8 kg (4 coupled shells) to 16 kg (8 coupled shells).

One cast booster was threaded onto the bottom of each group of coupled shells. A detonator with a wire length of 6 m, 40 m or 60 m was then inserted into the cast booster.

The explosives, boosters and detonators were lowered into the hole by the detonator wire. The PVC was then stemmed with 12 mm, crushed and washed gravel to the underside of the next charge. Stemming between the bottom and middle decks was typically about 4 m to 5 m, stemming between the middle and upper decks was typically about 2 m to 4 m, and stemming between the upper deck and surface was typically about 6.5 m.

A bottom-up blasting sequence was used for the first four blasts, with varying charge and deck delays. A top-down blasting sequence was used for the final six blasts, with delays of 500 ms between charges and 3500 ms between the end of one deck and beginning of the next.

From visual and audible observations of the blasts and observation of the high pressure piezometer and seismograph responses, there was no indication that sympathetic detonation or misfires occurred during the blasts. Water was often ejected from inside the PVC pipe during the blast, but no ejection of stemming material or jacking of the PVC out of the ground was observed.

4 INSTRUMENTATION

4.1 Seismographs

Vibration levels on the surface during each blast were measured simultaneously by three seismographs, at horizontal distances varying from 9 m to 120 m from the blast area. The seismographs measured the three perpendicular components of particle velocity and the peak particle velocity (PPV) was calculated as the square root of the sum of the squares of the three components.

4.2 High Pressure Electric Piezometers (Beach Area)

Thirty high pressure electric piezometers and two high speed data acquisitions systems were supplied and installed by ConeTec. One piezometer did not function properly after installation. The remaining 29 piezometers survived the trial blasting and all functioned as intended for the duration of the program.

Fifteen piezometers were installed at five locations in each test area. At each location, three piezometers were installed at nominal depths of about 7 m, 15 m, and 22 m. Separation between blast holes and piezometers varied from a minimum of 3 m to a maximum of 40 m.

The piezometers were pushed to the target depth using threaded cone rod fitted with an adaptor to push the piezometer tip. The piezometer installations were not grouted; the tailings sand was allowed to collapse around the tip and cable.

The high pressure piezometers had a 3.5 MPa range, with 7 MPa over-range. The piezometers were connected to a data acquisition system and were sampled at a rate of 32 Hz for approximately 6 to 10 minutes during the initial part of the blast. The sampling rate was then reduced to once every 3.2 seconds for the remainder of the monitoring period. The monitoring period depended on the individual blast, but was generally in the range of 12 to 24 hours.

4.3 Low Pressure Electric Piezometers (Shell Area)

Four low pressure electric piezometers were installed in the compacted dyke shell. The installation procedure was identical to that described above for the high pressure piezometers. However, the low pressure piezometers had a range of only 0.7 MPa and were monitored manually by a hand-held PiezoWatch unit.

4.4 Vibrating Wire Piezometers (Foundation)

Twelve existing vibrating wire piezometers, consisting of three in the compacted shell, seven in the foundation and two in the starter dyke were monitored manually during the trial program. Part way through the trial program, three of the piezometers were connected to a data logger, recording at 5 minute intervals.

4.5 Inclinometers

Four inclinometers were installed prior to the EC trial program. One inclinometer was installed as part of the general dam monitoring program, while the other three were installed specifically for the EC trial program. Two inclinometers were installed in the compacted dyke shell, while two were installed on the upstream beach.

4.6 Settlement Gauges

Two deep settlement gauges were installed. They consisted of 19 mm steel pipe inside a surrounding 52 mm ID steel pipe. The inner pipe was mounted on a circular base plate and the annulus was filled with bentonite slurry to allow the pipes to move independently. The settlement gauges were installed at a depth of approximately 12 m.

4.7 Survey

A topographic survey of both areas was performed on a 5 m grid prior to the start of the EC trial. However, beach erosion from surface water and deposition of sand due to blasting made the general topographic survey unreliable. Settlement points consisting of short lengths of rebar or spikes were subsequently established at selected locations prior to each blast, and monitored for the duration of the EC trial program. Surveying was carried out using a GPS backpack unit with a vertical accuracy of approximately 20 mm.

5 TRIAL OBSERVATIONS

5.1 Visual Observations

Visual observations and instrumentation readings were taken after each blast. In general, water would be ejected vertically out of the PVC pipe typically about 30 seconds after the blast. About 10 to 20 minutes after the blast, water would appear at the surface, flowing around the outside of the PVC casings. Water flow would typically continue for about 1 to 2 hours. Figure 3 shows erosion around the PVC pipe after a blast.

After the blast, bitumen would sometimes flow from the inside of the PVC pipe as shown in Figure 4. The bitumen would usually become visible several hours after the blast.

Figure 3: Erosion around PVC after blast


Figure 4: Bitumen flowing from PVC after blast

5.2 Peak Particle Velocity (PPV)

A typical waveform example from Blast 8 is presented in Figure 5. The seismograph was located 22 m from the nearest charge.

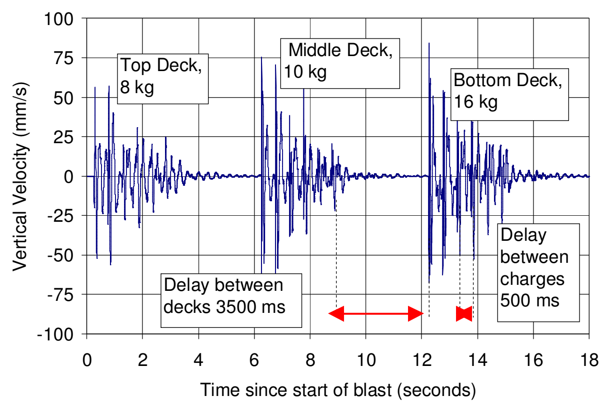

Figure 5: Peak Particle Velocity

The recorded PPV ranged from about 11 mm/s to 140 mm/s. By observing the seismograph waveform, it was possible to determine when the maximum PPV occurred and which charge weight contributed to the maximum PPV. Peak particle velocity was plotted against the scaled distance parameter $R/W^{0.333}$, where R is the hypocentral distance from the seismograph to the influencing charge and W is the influencing charge weight in kilograms.

A plot of all PPV results vs. scaled distance is presented in Figure 6.

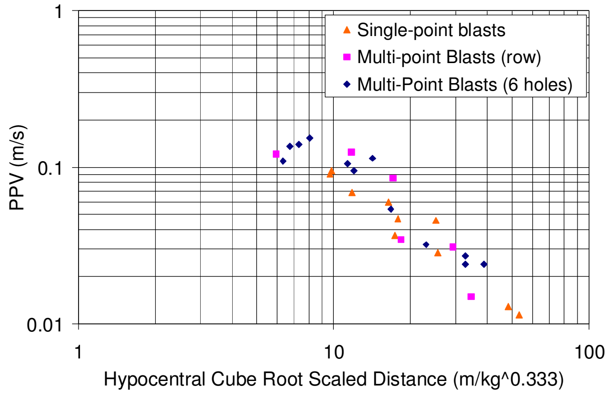

Figure 6: PPV vs. Scaled Distance

5.3 High Pressure Electric Piezometers (Beach Area)

The high pressure piezometers connected to the data acquisition system were able to record the spiky nature of the pore pressure immediately following the blast. Figure 7 shows a typical example from Blast 8. The plot shows excess or relative Ru with time, where excess or relative Ru is the increase in water pressure divided by the initial effective stress. An excess or relative Ru value of zero indicates static, pre-blast conditions, and an excess or relative Ru value of one indicates full liquefaction.

Very short-duration pressure peaks were recorded as each charge detonated. However, the peak pore pressure value determined for each blast did not include these spikes.

All 15 piezometer response traces are shown on Figure 7. For clarity, Figure 8 shows only 3 piezometers, at shallow (7 m, green), middle (15 m, purple) and deep (22 m, blue) depths. Figures 7 and 8 show that an Ru value of 1.0 can be achieved for shallow or nearby piezometers after detonation of the first upper deck. Achieving an Ru value of 1.0 for deeper or more remote piezometers requires more time or subsequent detonation of the middle or lower decks.

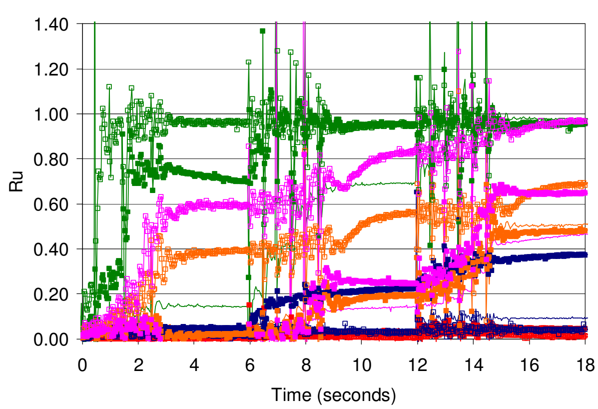

Figure 7: Ru vs. time (all 15 piezometers)

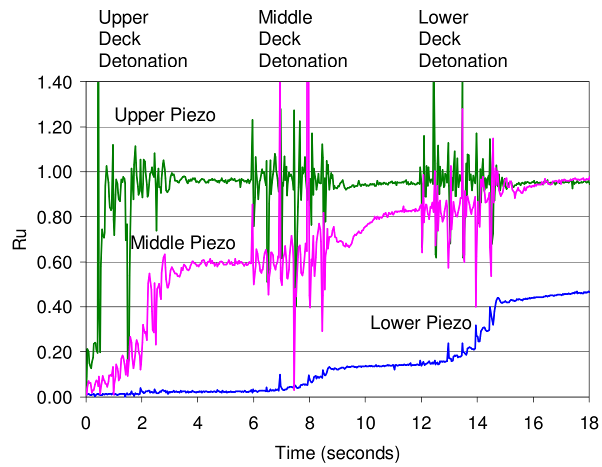

Figure 8: Ru vs. time (selected piezometers)

Pore pressure was generally measured for about 6 to 24 hours following each blast. Figure 9 shows the decrease in Ru over a 6 hour period for Blast 8. Compared to explosive compaction results at other sites (Ashford 2004, Rollins 2004, Handford 1988), the drop in pore pressure with time was quite slow. Some piezometers would still show Ru values in excess of 50% after 2 to 3 hours, and Ru values of 20% after 10 hours were observed.

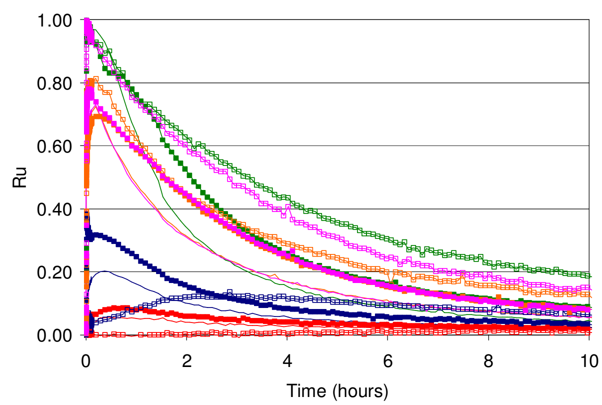

Figure 9: Ru vs. time

Figure 10 presents maximum Ru vs. scaled distance for the six multihole blasts. Figure 11 presents maximum Ru vs. distance from nearest charge. These plots show that Ru of 1.0 could be achieved at a distance of about 10 m, while Ru of 0.8 (the target of the test program, since it was estimated that an Ru value of 0.8 would be sufficient to cause liquefaction and improve density) could be achieved at a distance of about 12 m.

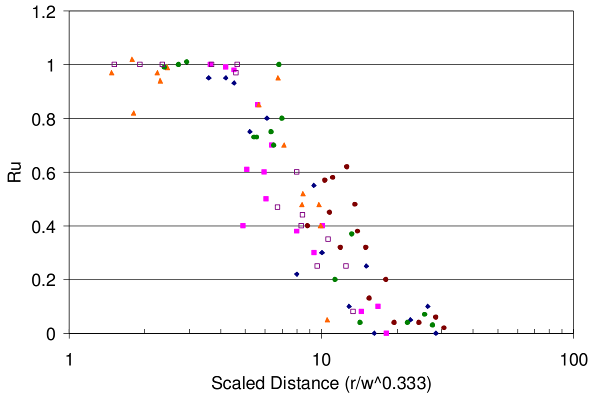

Figure 10: Ru vs. scaled distance

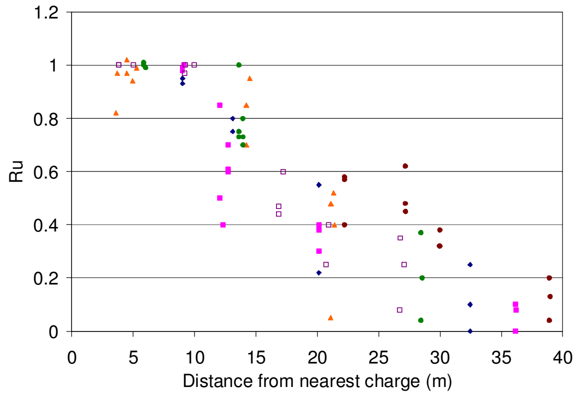

Figure 11: Ru vs. distance to nearest charge

5.4 Vibrating Wire Piezometers (Foundation)

The foundation piezometers connected to data loggers showed a pressure increase of about 0.1 m after each blast. This occurred almost immediately after the blast for the two piezometers in the native foundation, about 140 m and 170 m away from the trial area. The increase occurred about 30 minutes after the blast for the piezometer in the starter dyke, about 250 m away from the trial area. Even though the piezometers responded to the blasting, the pressure increase was within the historical fluctuation range, and below the past maximum.

5.5 Inclinometers

No measurable movement of the dam was detected after any of the blasts; however, some of the plots showed minor fluctuations within the precision of the inclinometer probe.

5.6 Low Pressure Electric Piezometers (Shell Area)

The four low pressure electric piezometers within the compacted shell of the dyke were read by hand approximately one hour after most blasts. No significant change in pressure was observed during any of the readings. However, due to the infrequent reading of these piezometers, temporary increases in water pressure could have been missed.

5.7 Settlement Gauges

It is likely that the settlement gauges did not work as intended. There was no measurable differential movement between the outer and inner rods at either of the settlement gauges, indicating that the inner rod may have been jammed inside the outer rod.

5.8 Survey

Two adjacent 6-hole blasts were conducted in the first trial area. After the first blast, settlement averaged about 480 mm, with a maximum of 650 mm. A second 6-hole blast was subsequently done adjacent to the first grid. Settlement of the second blast grid averaged about 470 mm, with a maximum of 790 mm. Additional settlement of the first grid area, as a result of the second blast, averaged about 70 mm, with a maximum of 180 mm.

Two overlapping 6-hole blasts were conducted in the second trial area. Settlement after Pass 1 averaged about 570 mm, with a maximum of 760 mm. Additional settlement after Pass 2 averaged 410 mm, with a maximum of 550 mm. The resulting total settlement averaged 1050 mm, with a maximum of 1280 mm. Assuming a 25 m thickness of tailings, this corresponds to an average vertical strain of about 4.2% and a maximum vertical strain of about 5.1%.

Figure 12 shows the upstream tailings beach after blasting, where the depression formed by blasting, filled with water, is clearly visible.


Figure 12: Upstream tailings beach after blasting

6 POST-EC TRIAL OBSERVATIONS

This section presents the results of observations made after the EC trial program was finished. In particular, CPTs were conducted before the trial program and two weeks and six weeks after the trial program to document the change in ground conditions due to blasting.

6.1 Cone Penetration Testing

The first round of post-EC tests, consisting of 28 CPTs, was conducted approximately 2 weeks after the final blast. Findings from blasting trials at other sites have shown a time-dependent improvement in sand density following blasting (Ashford et al. 2004). To check for this effect, a second round of post-EC tests, consisting of 20 CPTs, was conducted approximately six weeks after the final blast, however, no significant increase was observed between the 2 week and 6 week results.

Summary plots showing average pre-EC and 6 week post-EC CPT results for the two trial areas are presented in Figures 13 and 14. The equivalent corrected Standard Penetration Test $(N_1)_{60}$ was calculated after Lunne et al. (1997).

Figures 13 and 14 show the contractant / dilative boundary based on Fear and Robertson (1995). Approximately 49% of the Area 1 tailings profile was originally dilative. After the EC trial blasting, this had been increased to 86%. Approximately 51% of the Area 2 tailings profile was originally dilative, while after EC trial blasting this had increased to 81%.

No significant increase in tip resistance was observed below about 21 m in Area 1. This was not unexpected, since the bottom several metres of tailings in Area 1 contain high fines content as a result of previous use of this area as a localized waste dump during construction of the dyke.

Area 2 showed only a small increase in tip resistance below about 20 m depth. Soils above 20 m generally interpret as clean sand to silty sand based on CPT data, while soils below 20 m generally interpret as silty sand to sandy silt.

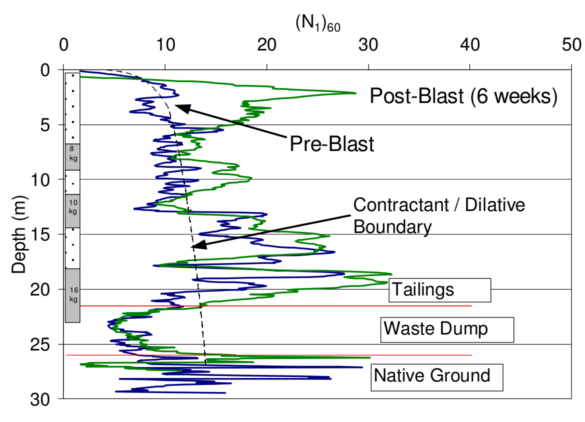

Figure 13: Area 1 (single pass) Pre- and Post-EC CPT

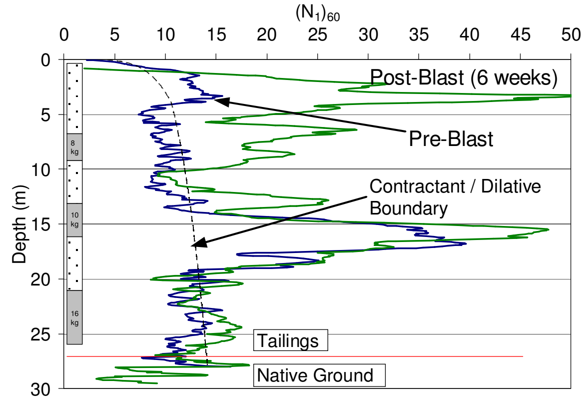

Figure 14: Area 2 (double pass) Pre- and Post-EC CPT

7 DISCUSSION OF RESULTS

Based on the explosive compaction trial program carried out at the Muskeg River Mine External Tailings Facility, the following conclusions can be drawn.

1) Controlled blasting techniques can be used to safely induce liquefaction in localized areas within the tailings deposit, with a resulting increase in the tailings density. During the test program, no dam movement or unexpected pore pressure response in the dam or foundation was observed.

2) Blasting can be used to induce liquefaction within a limited distance from the blast. Excess pore pressures of 100% were generated within a distance of about 10 m, and excess pore pressures of 80% were generated within a distance of about 12 m.

3) Excess pore pressures generated during the blast varied linearly with the cube root scaled distance. The correlation for single charge and single hole blasts was quite good. Multiple charge and multiple hole blasts produced a larger scatter in results, likely due to different blasts affecting a single piezometer.

4) Peak particle velocity generated during the blast varied linearly with the cube root scaled distance.

5) Settlement of up 1280 mm, or a vertical strain of about 5.1%, was observed. Settlement typically averaged about 1050 mm or 4.2 %.

6) CPT testing after the blasting indicated an increase in tip resistance and density. Prior to blasting, about 50% of the tailings was estimated to be dilative, while after blasting this increased to about 81% to 86%. The increase in density was most noticeable above 10 m depth.

7) No significant increase in CPT tip resistance was observed in the bitumen rich tailings below about 20 m depth.

8) Pore pressure response to the blasting in some of the piezometers was quite slow. In some cases, pore pressures did not reach peak values until about 15 minutes after the blast, and stayed elevated for several hours.

9) Bitumen was observed flowing from some of the PVC pipes after blasting. This observation, in combination with the slow pore pressure response of some piezometers and the lack of improvement in CPT tip resistance below about 20 m depth, may indicate that the bitumen content of some parts of the tailings decreases the effectiveness of using explosive compaction for these types of deposits.

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