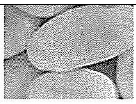
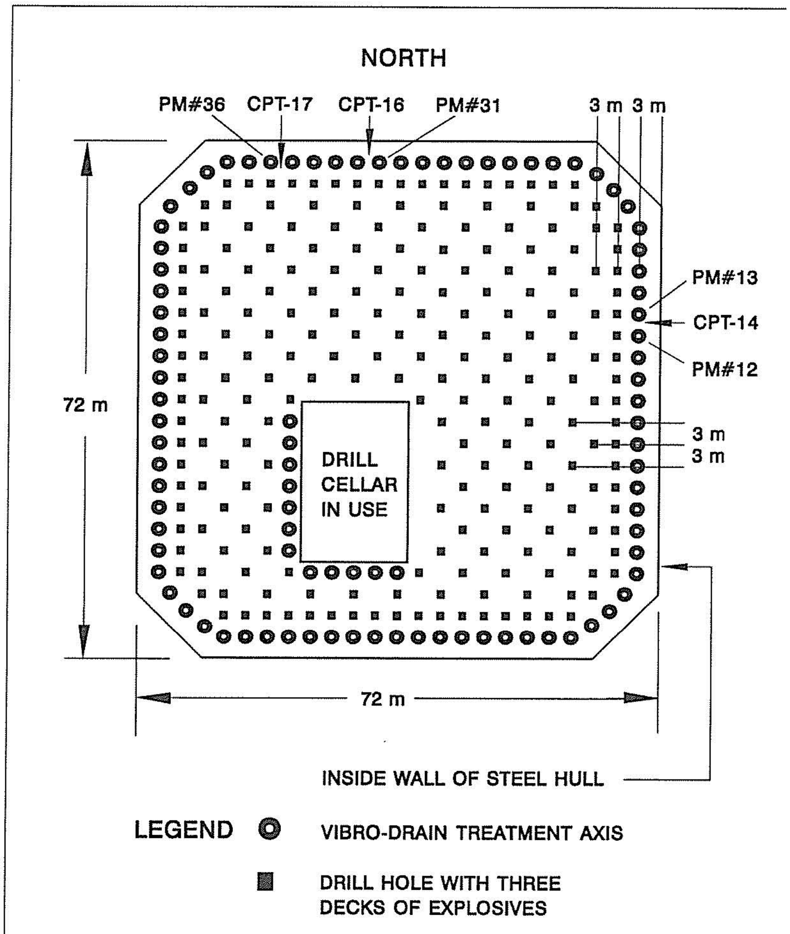


Molikpaq Field Performance

The Vibro-Drain was first used to densify sandfill inside the Molikpaq platform while it was engaged in hydrocarbon exploration drilling in the Mackenzie Delta, 100 km north of Tuktoyaktuk in the Canadian offshore Arctic. This original platform concept was principally the idea of John Bruce; the author was responsible for the geotechnical aspects of the design which are described in McCreath et al (1982). The densification work which was the source of the data presented here is described in Stewart & Hodge (1988). Photo 2 shows the platform under ice attack.

The Molikpaq is a steel vessel which was floated onto location and then the hull ballasted down with seawater to rest on a previously prepared earthfill base. The area directly beneath the deck was open, with the deck carrying the drilling rig and gear being simply supported on the annular hull. The design called for the platform to resist horizontal ice loads created by wind blowing the ice pack against the stationary structure. The critical horizontal loading conditions included ultimate static and peak impact loads of 900 MN, and pulsating loads between 300 MN and 535 MN at a period of between 5 seconds and 25 seconds, persisting for a duration of up to 2 hours. The design was based on these loads being resisted by the frictional forces which could be developed by filling the core (the open space beneath the deck) with dredged sandfill. This core sandfill was designed to rest on, and be in direct contact with, the sandfill of the foundation berm. The closest analogy to the resisting mechanism is laboratory direct shear box testing.



NOTE REFER TO TABLE 1 OF TEXT FOR DISTANCES BETWEEN CPT & CLOSEST VIBRO-DRAIN TREATMENT AXES

Figure 2. Molikpaq Core Plan showing Treatment Arrays and CPT Locations

To prevent liquefaction of the sandfill, the original design called for the lower half of the core fill to be compacted to about 70% relative density. For various reasons this was not done, and subsequently, during operation, the platform was subjected to heavy pulsating ice loading similar to those anticipated at the design stage. The untreated sandfill within the core failed as had been predicted. Fortunately, there were no human casualties and no environmental damage was done. The following winter Phoenix Engineering Ltd won a competitive bid to carry out the densification of the core (as was recommended in the original design) for the subsequent year's deployment of the platform. The majority of the work was accomplished by sequenced detonations of chemical explosive charges within the body of the sandfill. Details of treatment are shown in Figure 2.

Because structural limitations on vibrations (330 mm/s) were being exceeded by explosive charges placed at 6 m from the hull, a 6 m annular space around the perimeter of the core sandfill could not be densified by blasting. This annulus was the part of the sandfill closest to the ice loading and was therefore the most vulnerable, and in need of treatment. The Vibro-Drain, which had been mobilized as a backup in case of such a contingency, was put into service to complete the job. Because each of its modules and extension rods was no more than 1.5 m long the Vibro-Drain equipment was capable of being deployed in the 3.4 m space between the deck ceiling and the top of the core sandfill. Photo 3 illustrates the deployment arrangement within the confined headroom.

The vibro-draining array was dictated by the owner. It consisted of a treatment interval of 3 m in the middle of the 6 m wide annulus around the full perimeter, as shown in Figure 2. This meant that each Vibro-Drain was called upon to densify an 18 m^2 plan area. The depth range of treatment was between 6.1 m and 19.8 m below sand surface level inside the core; the upper 6.1 m was left untreated. The gradation of the dredged sand was uniform with a D_{50} size of 350 microns (Jeffries et al 1988). Apart from occasional lenses of gravel the core was apparently all sand. The mean sea level, and therefore the average depth to the phreatic surface within the sand core, was 5 m.

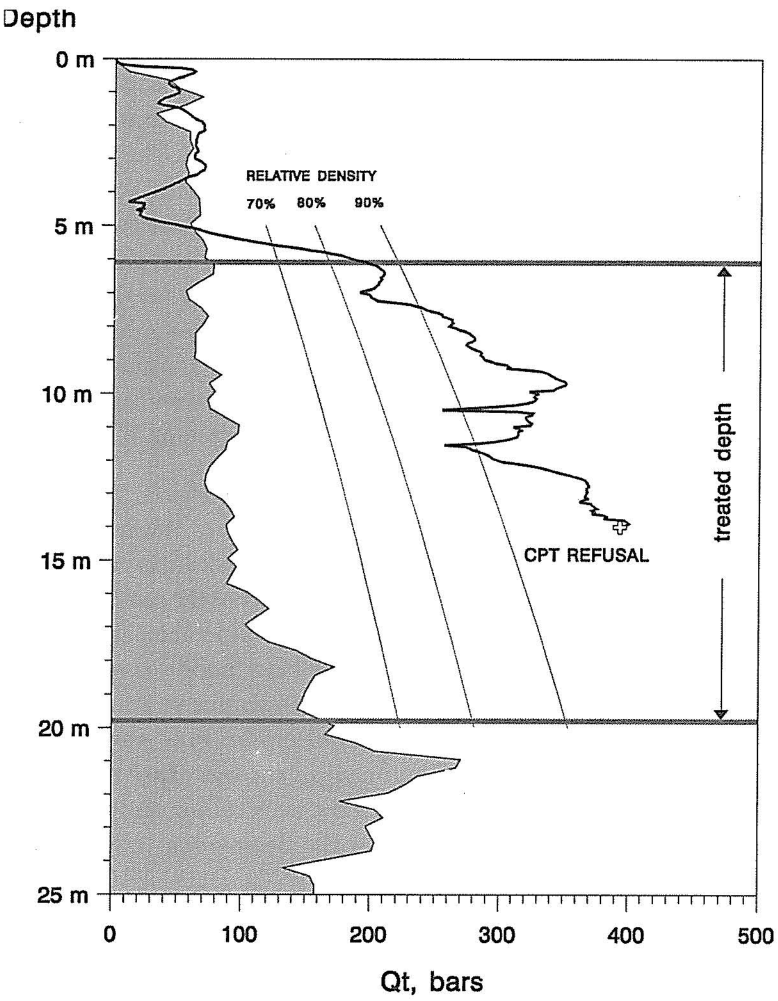


Figure 3. Molikpaq CPT-14 Tip Resistance

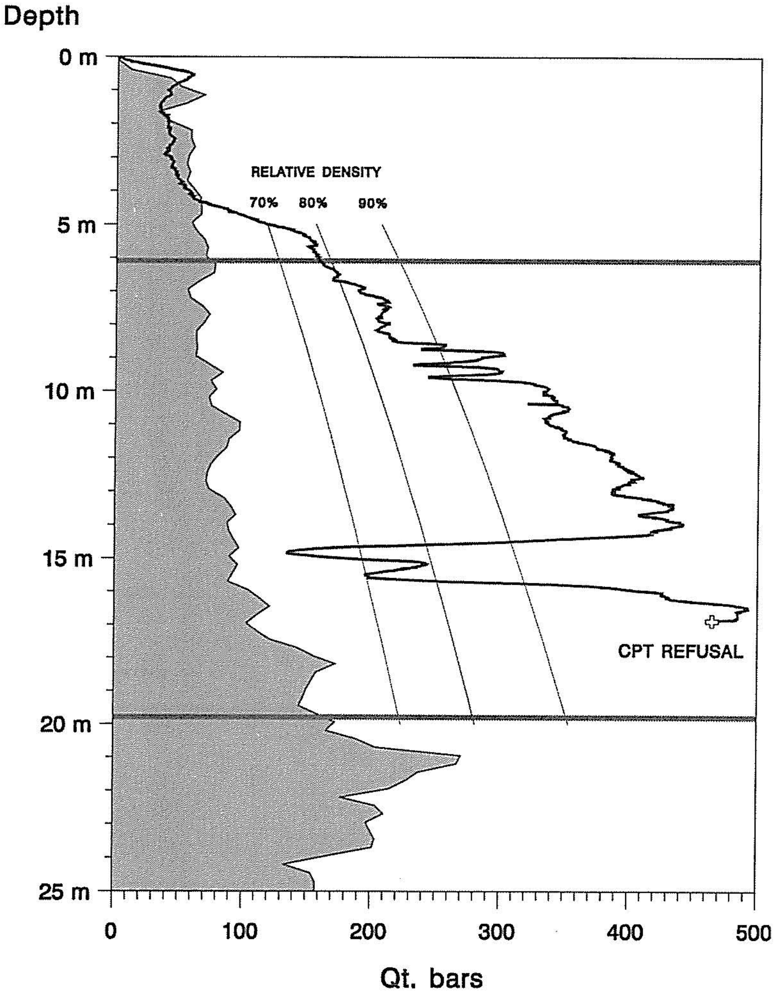


Figure 4. Molikpaq CPT-16 Tip Resistance

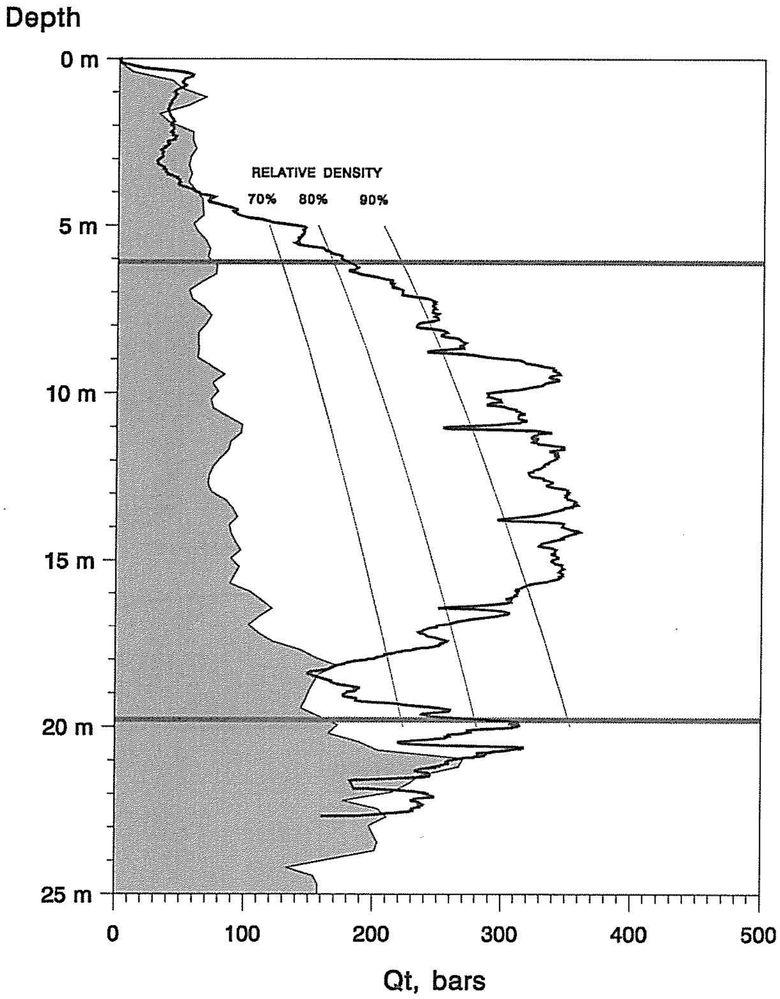


Figure 5. Molikpaq CPT-17 Tip Resistance

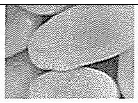
Cone Penetration Testing ("CPT") was used as a measure of the density change in the sandfill. Figures 3, 4, and 5 show the tip resistance traces for three CPTs which were carried out following vibro-draining. The positions of these soundings are marked in Figure 2, and Table 1 lists the horizontal distances between the CPTs and the Vibro-Drain treatment axes on either side. In the plots the shaded area to the left is the average trace of two earlier CPTs, and is intended to depict the sand condition after blasting, and before vibro-draining. The depth interval over which treatment was enacted is indicated by horizontal lines at the upper (6.1 m) and lower (19.8 m) limits. The three curved lines represent three levels of relative density for this type of sand within the core environment, as calculated by the relationships proposed by Baldi et al (1982). Photo 4 is a picture of the water discharge from the Vibro-Drain during the course of treatment at depth.

Probe	Separation	Treatment	Separation	Treatment
CPT-14	2.50 m	PM#12	0.62 m	PM#13
CPT-16	1.88 m	PM#31	1.33 m	PM#32
CPT-17	2.11 m	PM#35	1.14 m	PM#36

Table 1. Distance of Molikpaq CPT soundings from nearest Vibro-Drain treatment axes

The general indication from these plots is that relative densities in excess of 90% are achievable with this equipment. The density loss above 4 m or 5 m is presumably due to collapse of the untreated fill following compaction of the sands below. The CPT probe could not penetrate beyond 14 m in CPT-14 (Figure 3), nor beyond 17 m in CPT-16 (Figure 4), because the sand density caused the cone equipment tolerances to be exceeded. In both cases the tip resistance was apparently continuing to increase with depth. The reason for the failure to densify around the 15 m depth in CPT-16 is not known, perhaps it was due to operator error at a rod change, where one rod length (1.5 m) was inadvertently left untreated. In CPT-17 (Figure 5) the cone succeeded in penetrating the full treated depth and here it can be seen that once into untreated ground the CPT trace realigned itself with the background density. Also obvious in the CPT-17 trace is a drop-off in resistance below 15 m. This may have been due either to the array spacing being too wide to allow complementary interaction (handshaking) between neighbouring stinger axes, or alternatively, the CPT probe may have glanced off the densified column and drifted off-vertical into the less compact zone closer to the centre of the structure.

The time interval between completing the vibro-draining treatment and the subsequent CPT probing was 3 days in the case of CPT-14 and 16 days in the cases of both CPT-16 and CPT-17. There does not seem to be a radical difference between the results from the two time intervals, and this implies that the Vibro-Drain improvements are not time dependent, an indication which has been the experience with this equipment.



Myra Falls Field Performance

Myra Falls is an underground copper mining operation on Vancouver Island. The tailings is impounded against one wall of the valley by a rockfill dyke. Over the years the dyke has been increased in height using the upstream construction method and now retains 18 m of tailings. Mining projections called for a doubling of the height of the dyke, and apart from the engineering problems associated with further construction, the design was to attend to seismic concerns related to the close proximity of the Nootka fault zone which was credited with producing a Magnitude 7.3 earthquake fifty years ago. To deal with these problems the geotechnical consultants (Knight Piésold of Vancouver) undertook a field trial to investigate different methods of strengthening, or stabilizing, the tailings on which the upper berms of the dyke partially rest. One of the methods selected for evaluation was the Vibro-Drain; the other methods eventually proved ineffective.

At the planning stage it was believed that the tailings consisted of interlayers of coarse to fine sands and silts, with the sands forming the thicker seams. The stated objective of the work was to densify the sand lenses only, since the prevailing opinion was that the post-liquefaction strength of the silts was already adequate. Nevertheless, the author was of the opinion that apart from densifying the sands, however fine, some improvement in the coarser silts would turn out to be an additional byproduct of the effort. This opinion was based on observations made at Blackdome gold mine "where the ore is ground to between 85 and 90 percent minus 200 mesh", see Eivemark & Robinson (1989). Photo 5, taken at Blackdome, shows a light-weight probe being driven through a sheet of plywood between

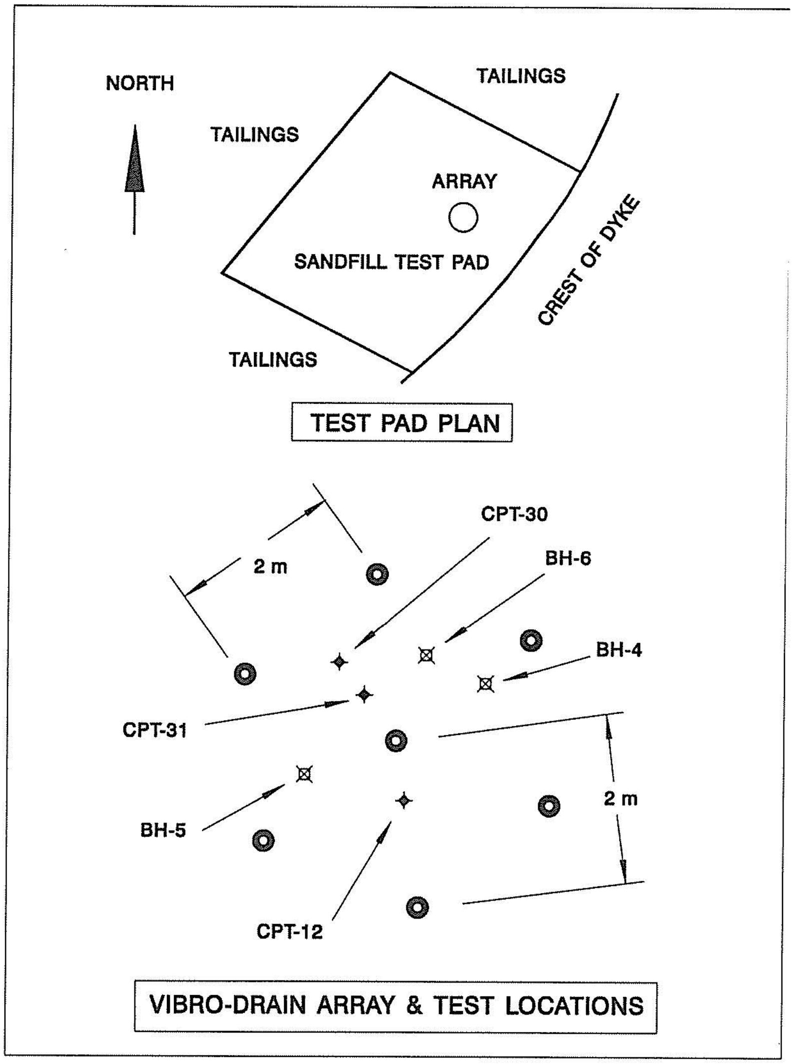


Figure 6. Myra Falls Test Pad showing Test Array, Borehole and CPT Locations

two craters which formed during vibro-draining. These two separate insertions of the Vibro-Drain penetrated the tailings to a depth of 7 m (23 ft) after going through the surficial access fill.

At Myra Falls, a sandfill working pad, about 21/2 metres thick, was placed over the tailing pond surface at the site chosen for the trial, see Figure 6. Geogrid was incorporated within the pad to spread equipment loads. It was not until after this pad had been built that access was available for drill rigs inside the rockfill berms, and it was only then that the true nature of the deposits was revealed. The majority of the tailings to be treated turned out to be slimes. As can be seen from the grain size distribution curves shown in Figure 7, all but one of the samples recovered in the subsequent investigations identified the material as being essentially a silt with from 10% to 30% clay sizes. A visual impression of the general nature and consistency of the tailings can be seen in Photo 6 which shows one of the vibro-draining extension rods after withdrawal.

The densification string was deployed by Nilex Inc of Denver, using one of their standard Wick-Drain masts mounted on a backhoe. Photo 7 shows the equipment in operation while working on the pad. Several array spacings and rates of withdrawal were attempted. The one reported here was the most successful result. The array shape, together with the locations of boreholes and CPT soundings, are shown on Figure 6. This array consisted of seven Vibro-Drain treatments in a triangular pattern of 2 m spacing.

Photo 8 shows the vicinity of the test array after treatment was completed. It may be seen that the surface of the pad was locally depressed with a drop in surface elevation near the centre of the array of 0.68 m (21/4 ft). The amount of settlement was somewhat constrained by the Geogrid mesh, and although cavities were observed beneath the mesh, no Blackdome-like craters appeared at the surface. Apart from masking surface deformations, it is likely that the Geogrid mat also lessened the overburden pressure on the underlying tailings by preventing the sandfill from fully conforming with the settling surface at the tailings interface.

Figure 8 is a summary of the Standard Penetration Test ("SPT") blow counts

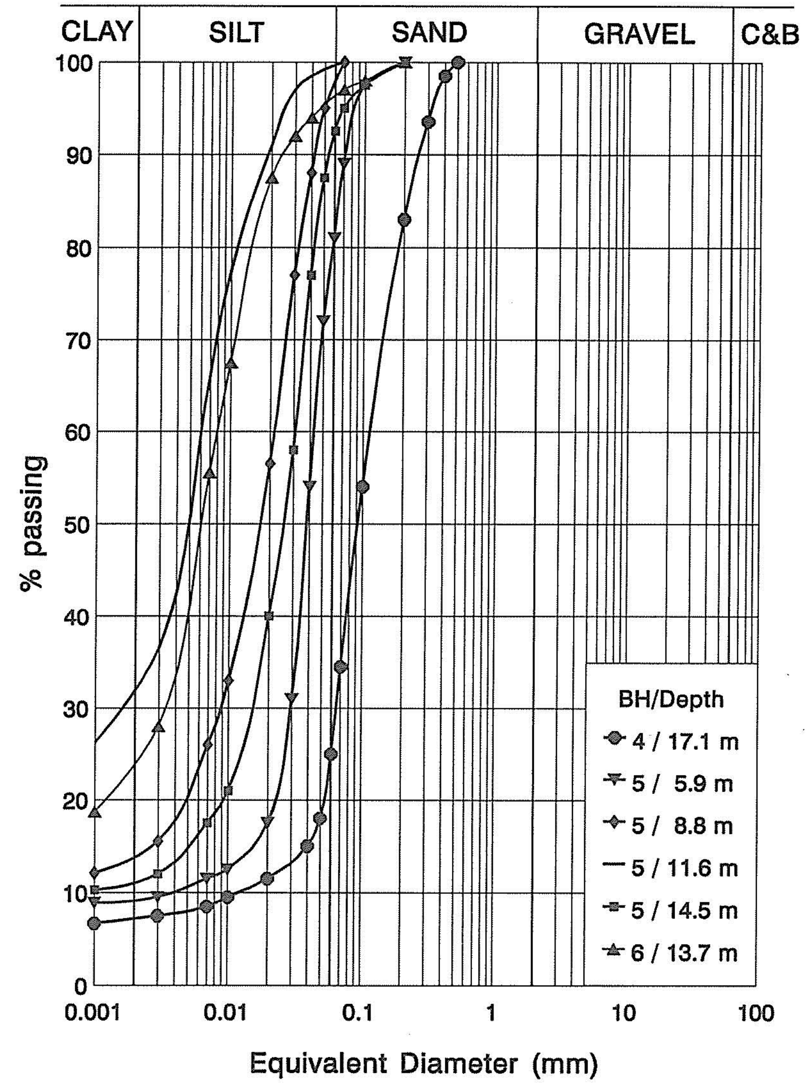


Figure 7: Grain Size Distribution of Myra Falls Tailings

from the one borehole (BH-4) drilled before vibro-draining and the two boreholes (BH-5, BH-6) drilled 12 days afterwards. The SPTs were driven a total of 610 mm (24 inch) with counts being taken for each 152 mm (6 inch); the N-values shown here were calculated by discarding the first 152 mm (6 inch), and prorating the remaining 458 mm (18 inch) to the standard 305 mm (12 inch). The horizontal lines at 2.5 m and 18.3 m demarcate the extent of the column which was treated. Comparison of the plotted N-values show a noticeable overall improvement in the behaviour of that part of the column which was vibro-drained, and no real difference is detectable outside the treated depth.

Figure 9 shows the comparison between CPT tip resistances for the pre-treatment condition (shaded area to the left), and the results obtained six days after vibro-draining (individual data points). The locations of the soundings relative to the treatment array are shown in Figure 6 where it may be seen that CPT-30 is at the centroid of the grid, which is normally considered the most definitive test. Figure 10 is a similar presentation of the CPT friction sleeve resistances. In both cases an improvement is discernable, but because of the high degree of interlayering in the tailings, it is difficult to appreciate the amount in quantitative terms; consequently, an "Improvement Factor" ("I_F") was devised. This I_F is simply the ratio between the pre-treatment and post-treatment data, calculated by dividing the average of the penetration resistances "after" by the average of the "before" values, within the treatment limits. The values of I_F for the soundings are listed in Table 2, and show a 273% improvement in SPT N-values, a 162% increase in CPT tip resistance, and a 172% increase in frictional resistance.

What is believed to be the most significant change in behaviour was noted in the dynamic pore pressure response of the tailings. This is depicted in Figure 11, where the shaded area is the pre-treatment condition, and the individual points are post-treatment readings. Here it may be seen that prior to treatment the entire column of tailings displayed significant pore pressure increases as the cone tip penetrated the tailings, indicating contractive soil behaviour. The post-treatment response is distinctly different, especially in the 11 m to 18 m depth range, where negative pore pressures approach complete

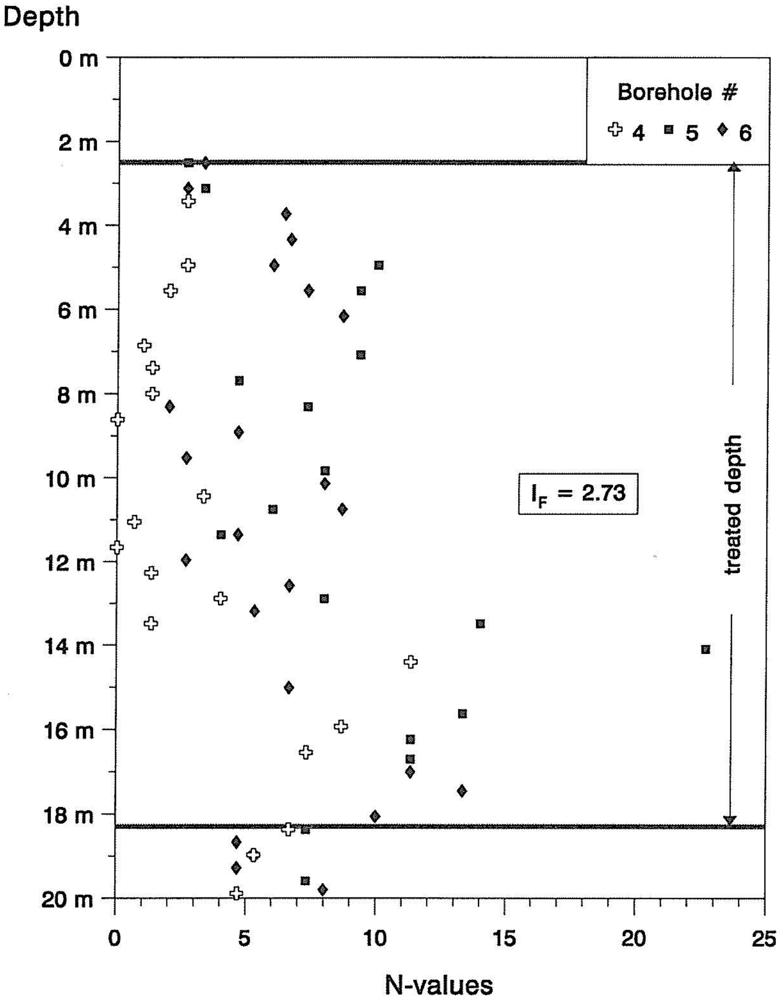


Figure 8. Myra Falls SPT Blow Counts

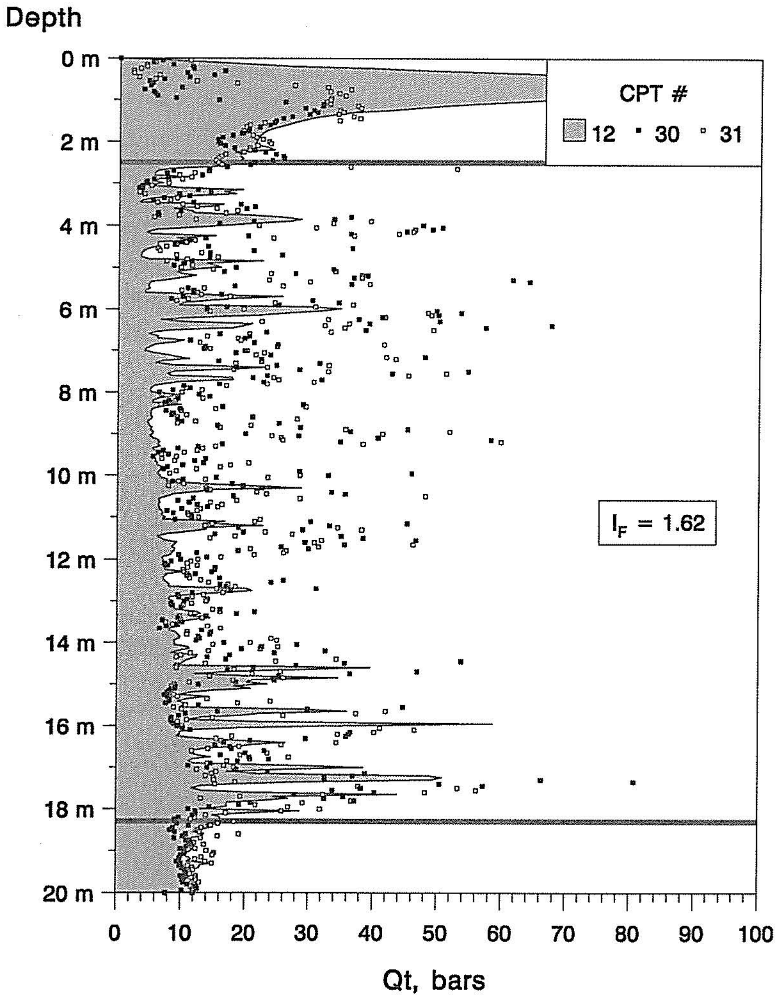


Figure 9. Myra Falls CPT Tip Resistance

vacuum (10.35 m). This indicates that after treatment the tailings were responding to shear distortion by dilating, thus suggesting that their internal structure had been reorganized into a denser/stronger packing arrangement. Below the treated depth (18.3 m) the tailings show no change in pore pressure response to penetration, and this serves to validate the alteration indicated in the treated column.

The above data appears internally consistent, and seems to paint a credible picture of soil improvement. The fact that there has been a significant beneficial change in the behaviour of the tailings seems clearly evident from the field data, but two things are not immediately obvious:

(a) what fundamental alteration in the soil structure occurred to cause this improvement; and,

(b) is this degree of improvement adequate for stability during a strong earthquake?

Sounding Type	Measurement	Location	Improvement Factor	
			individual	average
Standard Penetration Test	N-value	BH-5	3.25	2.73
		BH-6	2.21	
Cone Penetration Test	Tip Resistance	CPT-30	1.67	1.62
		CPT-31	1.57	
	Friction Sleeve Resistance	CPT-30	1.85	1.72
		CPT-31	1.60	

Table 2. Improvements in Myra Falls SPT and CPT Soundings due to Vibro-Drain treatment

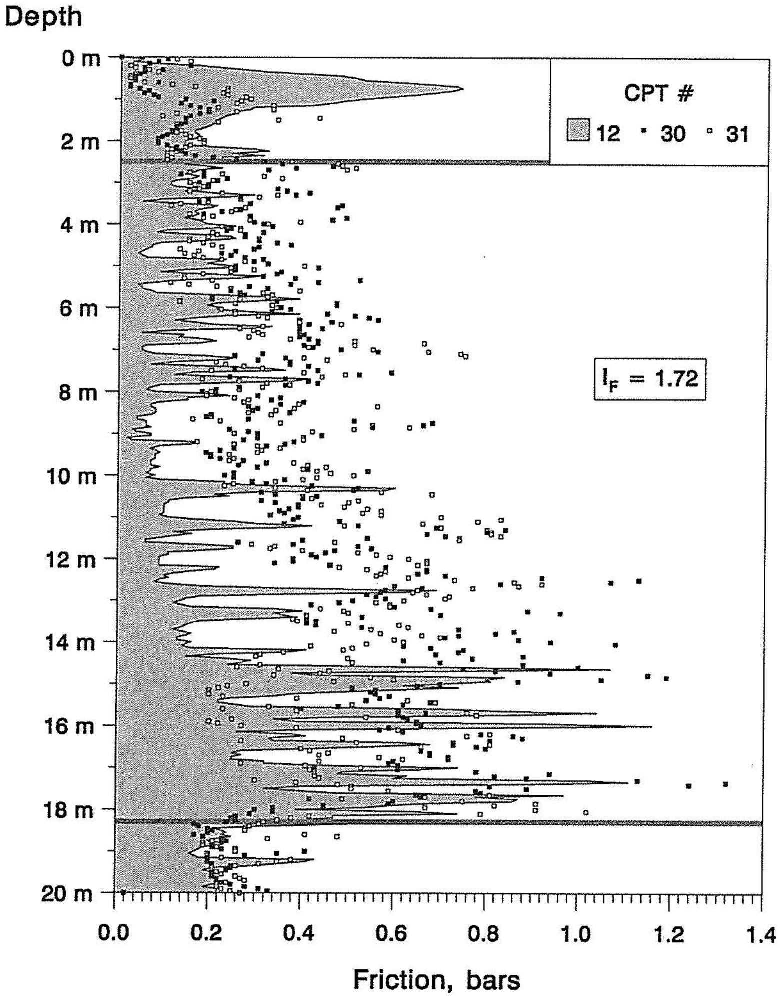


Figure 10. Myra Falls CPT Friction Sleeve Resistance

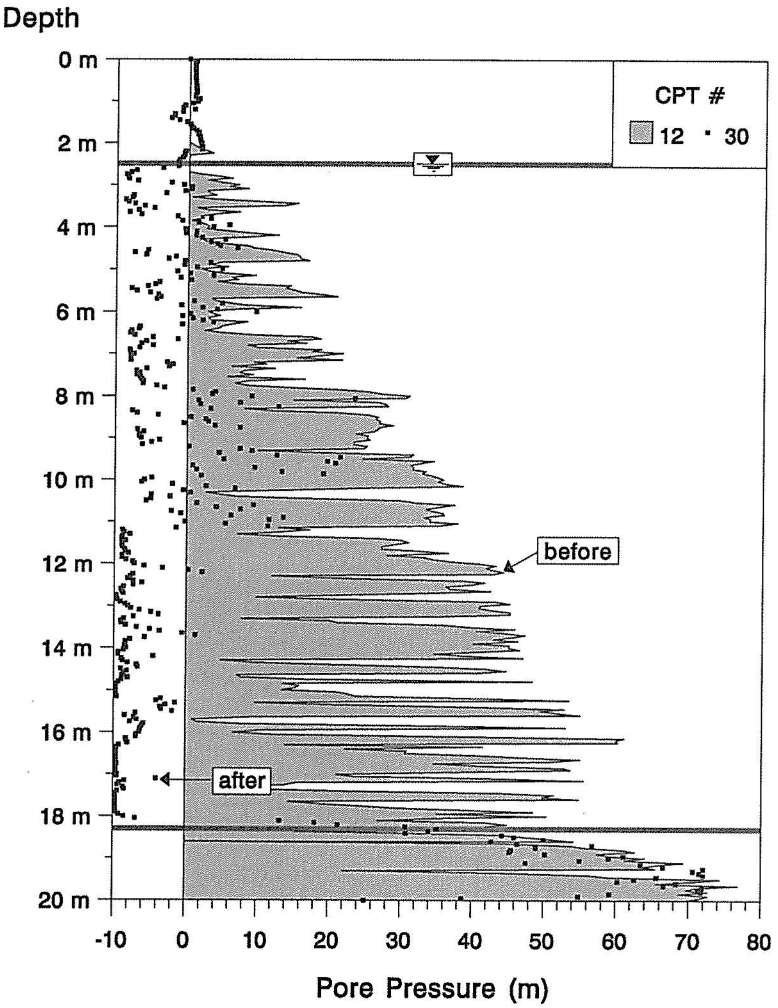


Figure 11. Myra Falls Dynamic Pore Pressure Response