GN Online
www.geotechnicalnews.com
Volume 37 • Number 3 • September 2019

GEOTECHNICAL news

Upstream face of tailings dam at Black Dome

The Phoenix Ground Improvement Machine

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My purpose in writing this article is to bring to the attention of the geotechnical fraternity the fact that we now have at our disposal a tool which can turn loose saturated granular materials into highly competent foundations. Using this hardware, materials such as sands, silts, and rock flour (slimes) can be compacted into a highly dense and dilative aggregation at depths of up to about 20m below ground level. Field records from three different sites are presented below to substantiate this claim. It is by combining into a single poker both vibration and water drainage that this is accomplished.

During the 1980s the petrochemical industry was anxious to tap into the Amauligak oil fields beneath the Mackenzie Delta in the Canadian offshore Arctic.

Gulf Canada Resources [*GCR*] was the oil company who initially engaged me to see if there was a sand island solution to getting their rigs into deeper water. Before finishing that work *GCR* made a decision to switch their focus to a hybrid steel vessel called the Molikpaq and asked me to attend to the geotechnical side of things. It consisted of a 70m square annular hull with an enlarged moon pool into which sandfills would be dredged; the idea being that the platform would gain its lateral stability by virtue of the frictional resistance between the underlying deltaic sand and that within the open-bottomed moon pool.

The design criteria involved a horizontally applied ice loading (70,000 ton, pulsating monotonically at 2Hz), see Fig 1. Because of this my main precondition for the vessel's deployment

Figure 1: Molikpaq under ice attack.

was that the sandfill be densified to prevent subsequent liquefaction of the core. This was an unpopular requirement as it added a time consuming complication. As it turned out, unbeknownst to me, the Molikpaq went to work for a couple of years without its core having been densified. Apparently this was on the advice of a third party who based his judgement on centrifuge model testing. That is until 1986 when the core did in fact liquefy under ice-loading while the platform was drilling on location. Then *GCR* asked Phoenix Engineering Ltd [*PEL*] if we could fix it.

Restabilization of Molikpaq

Blast densification was an obvious option. But detonating multiple charges of TNT inside the core of an offshore platform while it was drilling into an oil field cause some safety and environmental concerns with the regulating authority, Canadian Oil and Gas Lands Administration [*COGLA*]. So while licensing discussions went on *PEL* looked for a mechanical solution. Since there was only 2.5m (11ft) of height between the surface of the sandfill and the underside of the platform's steel deck (see Fig 2), the standard deep compaction pokers such as Vibroflots were ruled out.

It was then that the idea of the vibro-drain, hereinafter referred to as the Phoenix Machine [*PM*], occurred to me. By simply combining the benefits of the seepage forces (Ref 1) we knew about from our earlier research at the hydraulic laboratories of NRC in Ottawa had examined at NRC with some sort of vibrator seemed to be worth trying; vibration being the best approach to improving the density of granular (non-cohesive) loose materials. The mechanical device we came up with to produce vibrations was an eccentric weight rotated by a custom

Figure 2: Work space under Molikpaq deck.

designed air-vane motor. The drainage element which was attached above the vibrator consisted of a structurally supported Johnson Well Screen. The exhaust from the air motor was used to blow seepage water out of the system. Both elements measured about 1.5m (5ft) in length and were 190mm (7½") outside diameter. The deployment method involved pushing these elements and similarly sized extension pipes into the ground using a drill rig. Then, when the assembly reached the required depth to be densified, the air motor was activated and the string gradually withdrawn to the surface again.

COGLA preference was for the *PM* idea, whereas *GCR* wanted to use blasting because it could be done more quickly. It was during this period of hesitation that *PEL* built a prototype of the *PM* described above and field tested it on the ship-impact sand berm protecting the north pier of Annacis bridge in Vancouver. The results were good.

In the event, we mobilized what was necessary to perform the work using either explosives or vibro-drainage. By then *COGLA* had been talked into the blasting option and therefore that is how the work began, all going smoothly until instrumentation showed that vibrations in some steel members were exceeding their structural limit (13"/s) as soon as charges were detonated within 3.7m (12ft) of the core walls. That prohibition meant the sandfill most vulnerable to the effects of ice pounding would be left untreated. It was at this stage *GCR* asked us to deploy the *PM* to finish the densification job. This extra work went without a hitch, with large volumes of seepage water being discharged from the machine. At the few locations where CPT probes made a direct hit on the top, buried 7m (23ft) down, of one of the sand columns created by the *PM* the results showed relative densities generally exceeding 90% (Ref 3). One of these traces is shown in Fig 3, where the background shaded area shows the condition achieved by blasting.

Black Dome Mine

During our field work on the upstream face of the tailings dam at the Black Dome goldmine in the Chilcotin area of BC we observed something new.

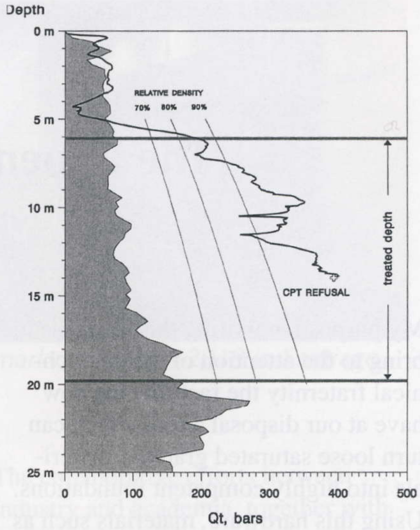

Figure 3: CPT trace of PM results at Molikpaq.

Cylindrical holes appeared around each location at which the *PM* was activated, see Fig 4.

The tailings grind was 95% passing the #200 sieve and accordingly its permeability was quite low; in consequence, there was very little seepage water discharge. It is a geotechnical fact that the quantity of flow is dependent upon permeability, whereas the magnitude of seepage forces is not. Therefore, the amount of water discharge at ground level is no indicator of the effectiveness of the *PM* at depth.

Figure 4: Craters at Black Dome.

The centrifugal vibrations emanating from the poker generate water pressure escalation in the surrounding ground as they dissipate their energy; this excess pore water pressure [***epwp***], diminishes with distance as does the amplitude of the vibrations.

What we learn from the craters at Black Dome is the limiting radius at which the lateral strains caused by the *PM*'s vibrations, at the particular frequency used there, were still just enough to result in structural collapse into a denser soil structure. The *epwp* on both sides of the perimeter of these holes is the same, and is the highest in the vicinity of the *PM*. So this radius demarcates the divide between pore water flowing in opposite directions, something that seemed paradoxical before now. At one and the same time the *epwp* with respect to the draw-down pressure within the poker causes flow towards the poker, and yet has the required differential with respect to the pond's hydrostatic head to cause flow away from the poker.

From seismology we know that higher frequencies attenuate more quickly with distance than do low frequencies, while from mechanics we know that eccentric weights generate centrifugal forces which increase with the square of the rotation rate; the downside of high frequencies is that they don't travel far. So in the case of the PM interacting with a particular soil type there will always be an optimal drive shaft speed. Therefore, field trials are necessary to find out the best frequency for that material type by trying out a few different drive rod speed at separate spots.

Myra Falls very fine tailings

The tailings in the pond at the Myra Falls zinc and copper mine on Vancouver Island turned out to be a very fine tailings comprised of silts with up to 30% clay sizes (slimes). Nevertheless a large surface depression developed in the area of treatment while the work was

Figure 5: Myra Falls showing water discharge haze.

in progress, the true magnitude of which was masked by the presence of a geotextile mat within the test pad fill. Because of the low permeability of the tailings there was very little pore water discharge as can be seen in Fig 5. Fig 6 shows the data comparison between the CPT's Dynamic Pore Pressure Response [***DPPR***] readings taken in probe#12 "before" treatment with probe#30 taken "after" *PM* treatment. The credibility of the data is attested to by the fact that the "before" and "after" data coalesces below the treatment depth.

The upper boundary of the *DPPR* trace for the "before" case shows a response which is about 80% higher than that which could be attained by the full depth of the tailings collapsing into suspension; the surplus can be attributed to energy transfer from the deformation of the solid phase. The most extraordinary data is that from below the 11m depth in probe #30: The black dots show the *DPPR* values recorded after treatment. These are virtually all in the negative range,

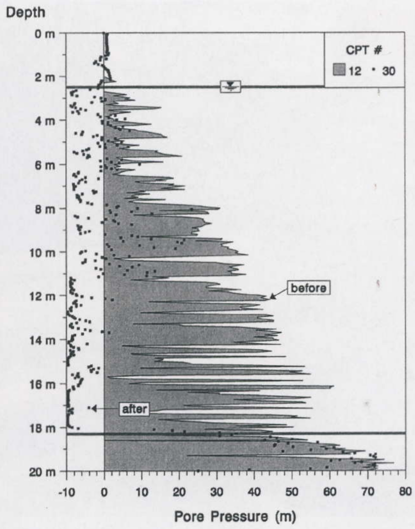

Figure 6: Myra Falls dilatancy results.

and mostly very close to the absolute limit of negative pore water pressure, that is, full vacuum (minus 10.3m). Negative pressures are triggered when the demand for water inflow cannot be supplied by seepage flow from the surrounding ground at the rate the tailings wants to dilate.

There can be no doubt whatever that the tailings in its untreated condition was liquefiable, but it is manifestly impossible for a mass in its highly dilative post-treatment state to liquefy: Liquefaction requires the soil structure to collapse into a suspension which can flow as a fluid. In short, the treated slimes could have safely supported an upstream lift.

So how did this great change in consistency come about? I believe it is simply this: Typical tailings deposit, like deltas, consists of loose inter-layered seams of uniformly sized particles.

It is therefore only a matter of disturbing this metastable soil structure enough to cause the individual seams to become mixed into a far denser aggregation. The *PM*, with its adhered seepage mass, created enough local commotion/agitation to do that.

And that brings us to where we are now . . .

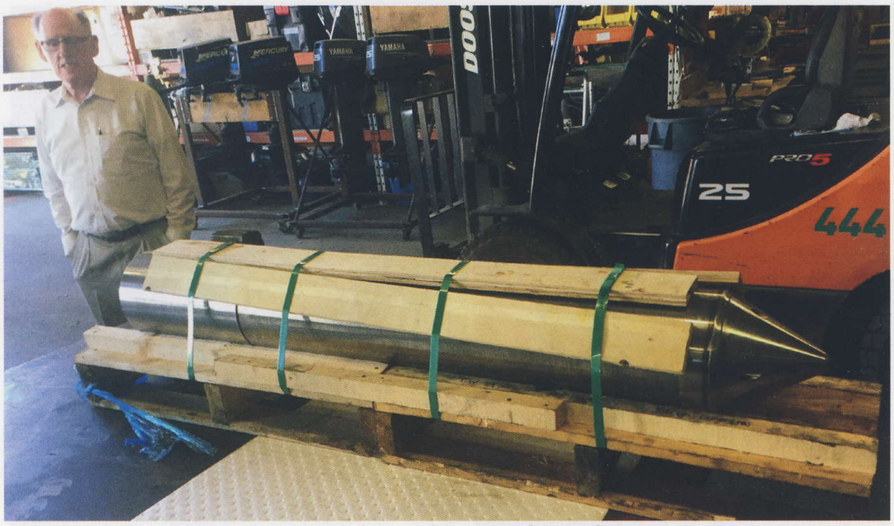

Figure 7: The current PM as delivered by machine shop.

Improvements in the *PM*'s design

Fig 7 shows the current *PM* as it is comes from the machine shop. It differs from the machine used at Molikpaq and at the two mine sites discussed above. In the earlier models the filter/drain stood above the air-motor and eccentric, making the overall machine length 2.9m (9.4ft). In this case the seepage intake section is wrapped around the vibrator thereby reducing the overall length to 5ft (1.5m); the OD in both cases is the same 190mm (7½"). The power source will now be top-drive using the contractor's choice of engine.

Apart from that there have been two recently patented additions to the *PEL* toolkit :

1. In weaker ground environments, such as deltaic deposits and mine tailings of various gradations, the filter of the well screen could become impervious if the open spaces between its helically wound wire became plugged by cohesive layers existing within the material being treated. A newly devised module (US patent 10240314), capable of rectifying this situation will henceforth become a standard part of the *PM*. Of practical importance is that this capability to remove such smearing can be activated remotely while the machine is still at depth.
2. What we call our Trident deployment array (US patent 8419316) consists of three separate *PM* strings structurally harnessed together so that their long axes are vertical and are spaced apart laterally in an equilateral configuration. The mere fact that there are three excitable tools in the ground at the same time, and in close proximity, opens a whole new prospect in ground improvement technology. This is because each of the three neighbouring machines can be made to perform their functions independently, leading to many combinations of their vibratory and hydrodynamic forces. Two applications of this configuration come to mind:

a. The soil within the compass of the three separate prongs could be made into a very dense column which would provide seismic-resistant deep foundations capable of carrying heavy structural loads.

b. Water could be pumped into, or sucked out of, the ground by each poker either in tune with its partners, or in a cooperative manner such as to create a flow in any lateral direction between them. This procedure could be enacted in order to clean up polluted groundwater in the soil between the pokers.

Summing up

My hope is that what is presented above, from field observations and data recorded at three distinctly different sites, is sufficient to convince the reader that the Phoenix Machine hardware and our procedures, are worthy of consideration when geotechnical engineers and ground improvement contractors are faced with the problems arising out of loose or weak foundation conditions. And, to quote Ralph B. Peck: "Whatever the explanation, I think your idea of simultaneous vibration and drainage has a lot of promise in practice" (Ref 4).

Please note: More detail and data than can be printed here can be found at *http://www.phoenix-hodge.com/index.php*

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