Vibro-Replacement and Dynamic Compaction Ground Improvement for a Marine Container Terminal Berth Expansion – A Case History

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ABSTRACT
The Berth 3 expansion at the Deltaport Marine Container Terminal has been undertaken off the coast of Greater Vancouver, British Columbia. Extensive land reclamation was required to create the new facility. Both Vibro-Replacement and Dynamic Compaction methods were applied to densify the berth's loose landside reclamation fills. The overall size and location of the site, low initial densities of the reclamation fills, stringent performance specification, demanding schedule and late completion penalties characterize this project as a unique and challenging ground improvement application.

RÉSUMÉ
La construction d'un 3ème quai au terminal à conteneurs de Deltaport a été entreprise au large des côtes du Grand Vancouver en Colombie-Britannique. L'installation d'un vaste remblai hydraulique était nécessaire à la création de ce nouvel aménagement. Les méthodes de Vibro-Remplacement et de Compactage Dynamique ont été utilisées pour densifier le remblai hydraulique lâche composant le quai. La taille et l'emplacement du site, des densités initiales faibles dans le remblai, des spécifications techniques strictes, un planning chargé et l'application de pénalités de retard caractérisent ce projet d'amélioration de sol unique et exigeant.

1 INTRODUCTION

Deltaport, also referred to as Roberts Bank Marine Terminal, is the location of Port Metro Vancouver's largest sea container handling facility. This 200 hectare parcel of reclaimed land stretches west 5 km into the Straight of Georgia from the City of Delta shoreline, approximately 30 km south of the City of Vancouver as illustrated in Figure 1. Historically, the port was created for the export of coal by Canadian National Railway in the 1960's. With the addition of the container facility consisting of Berths 1 and 2 in 1997, Deltaport is now one of the busiest import/export ports in North America and a major hub for container handling companies (PMV 2009).

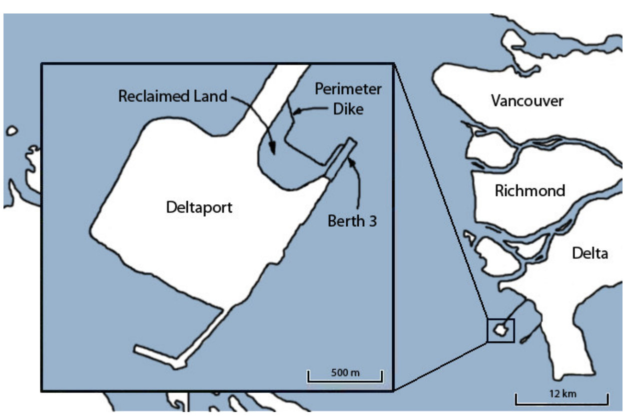

Figure 1. Location of Project Site

As part of an initiative to accommodate consumer and business-driven demand for increased Canadian trade through the West Coast of Canada, the Vancouver Fraser Port Authority is expanding its existing Deltaport Container Terminal with the construction of Berth 3 (PMV 2009). The 430 m long Berth 3 expansion will increase capacity by up to 600,000 TEUs (twenty foot equivalent units) plus the addition of 20 hectares of container storage facilities. Berth 3, estimated at a capital cost of $400 million and expected to be completed in late 2009, will be able to accommodate the largest container ships afloat and feature Super Post-Panamax container cranes (TSI 2009).

Geopac West Ltd. was awarded the Deltaport Berth 3 Marine Works Landside Soil Densification subcontract by General Contractor Deltaport Constructors Ltd. with work to start mid September 2008. Among the ground improvement methods evaluated for the project, Geopac's proposed combination of Vibro-Replacement and Dynamic Compaction techniques was selected/accepted to compact the Berth 3 apron landside reclamation fills.

This paper describes the site setting, soil conditions and the configuration/stratigraphy of the imported engineered fills. It further outlines the design objectives, the soil improvement techniques and methodologies used and the site sequencing required to achieve those objectives. The execution of the ground improvement work is described along with the quality control monitoring. Comparative before and after CPT results are presented as well as an assessment of overall soil volume reduction achieved.

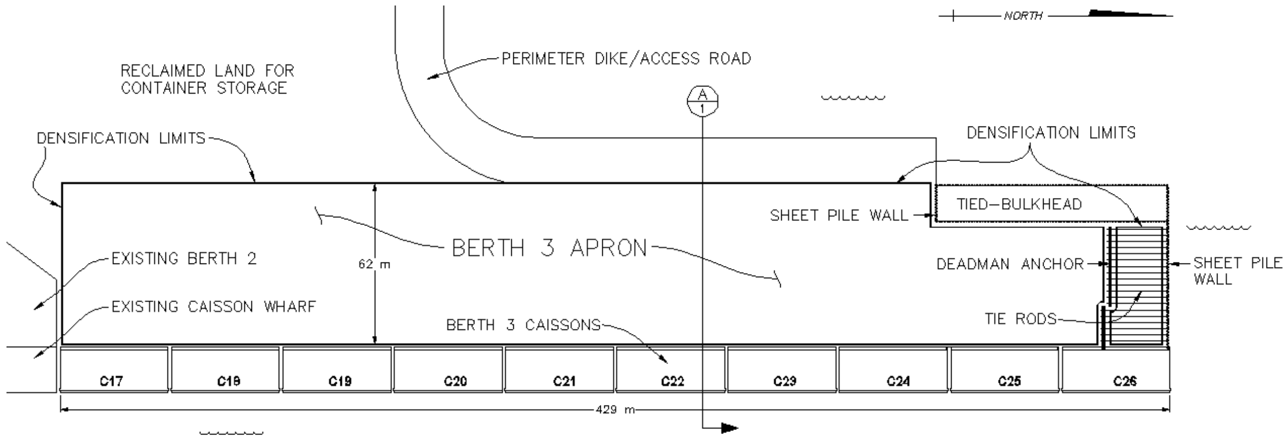

Figure 2. Berth 3 Expansion Plan

2 SITE DESCRIPTION AND BERTH DEVELOPEMENT

The native marine soils at the site are distributary channel sands and silts, and intertidal/overbank silts and sands, part of the offshore Fraser River Delta subtidal flats (Christain et al. 2008). The stratigraphy consists of 6 to 19 m thickness of soft to firm silty soils, over 28 to 40 m thickness of compact to dense fine sand interbedded with silt to sandy silt seams, over stiff sandy silt interbedded with silt seams exceeding depths of 60 m.

The Berth 3 expansion extends north off the existing Berth 1 and 2 facilities. As shown on Figure 2, the Berth 3 reclamation fill is retained by a sequence of ten 40 m long, 15.5 m wide and 20 m high concrete caissons. The ± 62 m wide strip of reclaimed land west of the Berth 3 caisson structures, referred to as the Berth 3 apron, represents an area of 34,000 m^2 and involved the placement of some 1,000,000 m^3 of engineered fill onto the seabed. At the north end, Berth 3 is terminated and enclosed by a sheet pile retaining structure. A cast in place concrete deadman provides anchorage for the 20 m long tension tie rods. A perimeter containment dike and tied-bulkhead structure, constructed prior to Berth 3 dredging and filling, confined the western side of the berth apron and also provided alternate access to the site.

Development of the off-shore site involved marine dredging for removal of the upper seabed under the caisson structures to create a marine trench. A substantial 14 m thickness of coarse Replacement Fill and Mattress Rock was then placed to raise the bottom to the design underside of caisson foundation elevation and provide adequate support for the caisson structures. Marine Vibro Compaction densification of this material was carried out by others prior to placing of the caissons and is not discussed in this paper.

Land reclamation of the Berth 3 apron west of the caissons proceeded concurrent with and following the placing of the caissons from south to north. The Berth 3 apron land reclamation work consisted of backfilling with Rock Berm (RB) (90,000 m^3), Berm Filter (BF) (35,000 m^3) and General Fill Type 1 (GF1) (361,000 m^3) materials, referred to collectively as General Fills. Figure 3 illustrates a typical apron cross section behind the caissons. After the sequential installation of each caisson, a sloping zone of coarse clean Rock Berm material was first placed landside of the caisson to provide efficient drainage and reliable lateral support for

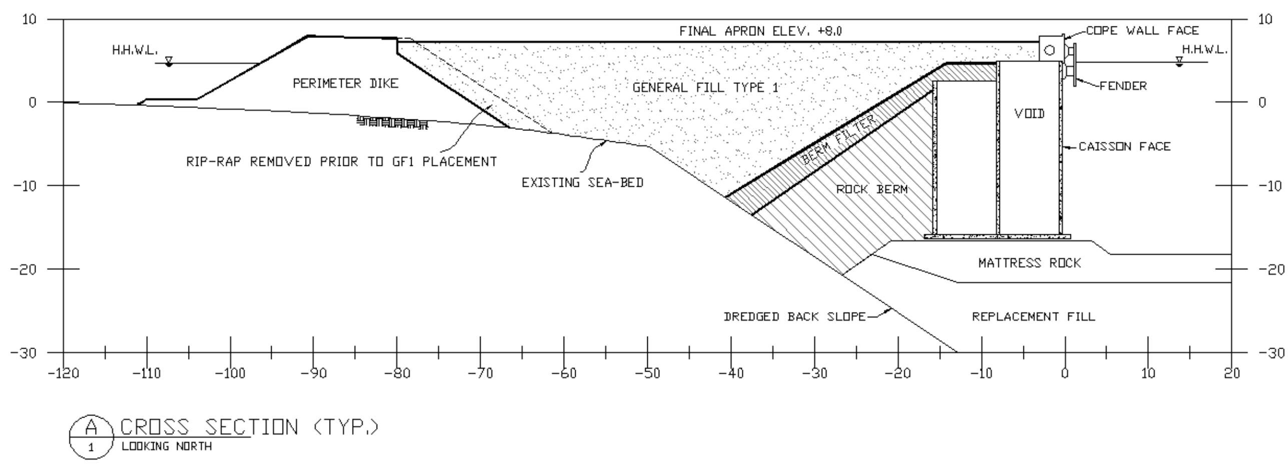

Figure 3. Berth 3 Expansion Reclamation Fill Profile

the caisson wall. The bulk filling over the majority of the apron area was done using clean GF1 sand material placed up to elevation +6.5 m (behind caissons 17 to 19) and +7.5 m (behind caissons 20 to 26) for ground improvement operations. Prior to placement of the GF1 material, a ±3 m thick 2" minus gradation Berm Filter blanket was placed over the Rock Berm to prevent migration of the finer GF1 sand into the coarse Rock Berm. Rock Berm and Berm Filter materials were primarily placed from the water using marine equipment. The GF1 sand was placed from land by end dumping with 25 tonne off road haulers advancing in stages as the caissons, Rock Berm and Berm Filter were extended northward.

3 DESIGN REQUIREMENTS

The subtidal flats of Roberts Bank is in an area with exposure to potentially large earthquakes, particularly from the release of stresses induced in the Cascadia Fault by the collision of the offshore Pacific plate with the American continental plates. Seismic considerations are therefore a key factor in foundation design within the area (Christain et al. 2008). The very loose, water deposited Berth 3 reclamation fills were not only susceptible to significant total and differential settlement due to self weight and imposed loads but were also extremely vulnerable to loss of shear strength due to liquefaction under the design earthquake motion considered in BCBC 2006 and NBCC 2005. To address design and performance concerns for both static and seismic conditions, ground improvement was required to increase the relative density of the loose granular fills.

Ground improvement of the Berth 3 apron reclamation fills had to be developed to meet the tender CPT performance specification. Acceptance of all densification work was strictly based on the graphical comparison of the individual test results against the acceptance criteria. No individual test result was to be less than 90% of the specified value for each elevation interval, and the thickness of any zone which showed a test result less than the 100% specified value was not to exceed 0.61 m. The CPT performance specification criteria applied only to the GF1 sand fills below elevation +5.0 m. No testing was required in the Berm Filter or Rock Berm materials. The specification stipulated that the same Vibro methodology that successfully achieved the CPT criteria in GF1 sand was to be strictly followed in the Rock Berm and Berm Filter zones.

Treatment depths extended to the original sea-bed or to the dredged back-slope, whichever bottom condition applied to the area of work. At its deepest limit, the treatment depth extended to elevation -21.0 m representing a maximum treatment depth of 27.5 m (90') from initial working site grades.

4 DEVELOPMENT OF THE DENSIFICATION PROGRAM

The 'as tendered' ground improvement approach was based on using wet top-feed Vibro-Replacement techniques for treatment of all fill types across the entire apron area. As an alternative to the 'all Vibro' approach, Geopac successfully proposed the integration of Vibro-Replacement and Dynamic Compaction. Figure 4 illustrates the general densification scheme adopted at Deltaport with the deeper fills improved using Vibro-Replacement methods and the fill materials above approximate elevation -1.5 m being improved with Dynamic Compaction. The bid team recognized the significant efficiencies that were available in compacting the upper fill using Dynamic Compaction. Dynamic Compaction not only reduced the length of Vibro-Replacement stone columns by some 20,000 lineal metres, but also eliminated the need for imported stone backfill for a significant portion of the work and reduced the overall ground improvement schedule by approximately two months.

Wet top-feed Vibro-Replacement (VR) is a deep densification method capable of treatment depths over 35 m. VR utilizes a powerful vibrating probe (Vibroflot) to penetrate the ground with the aid of water and/or air jetting. Crushed rock backfill is typically fed from the surface using a wheel loader. The rock backfill flows

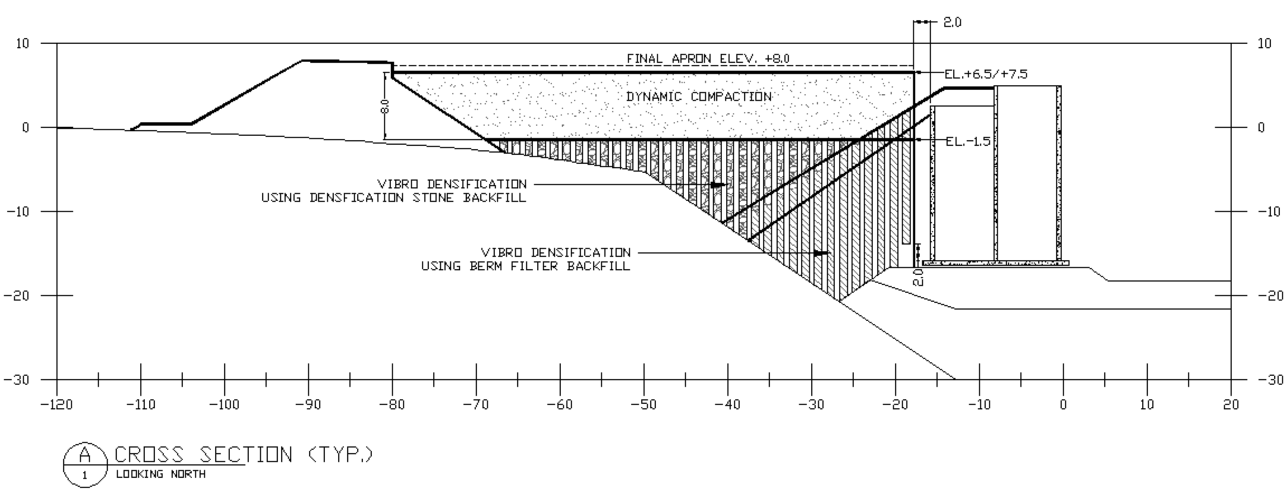

Figure 4. Densification Scheme

down the annulus formed between the soil and the Viboflot. Efficient flow of backfill material is enhanced by the agitating action of air/water jetting. Working the Vibroflot in half metre increments from maximum depth upwards results in the construction of discrete stone columns at each compaction point. Compaction of the host fill is primarily driven by powerful centrifugal forces and lateral stresses imparted to the soil by horizontal movements of the vibrator created by the rotation of an eccentric mass within the Vibroflot. The resulting overall improvement is twofold, significant densification of the reclamation fills in combination with reinforcement and stiffening from the stone column elements.

Dynamic Compaction (DC) is a deep soil improvement method suitable for treatment depths of 10 to 12 m. DC applications involve the dropping of large mass tampers, typically 10 to 20 tonnes, from heights of 15 to 25 m using specially modified crawler crane lifting plants. The high energy impacts locally compress/displace the ground, as well as generate powerful short duration vibrations, shear stresses and pore pressure increases which result in rearrangement of soil particles into a more compact configuration. Dynamic Compaction is a 'phased' method requiring multiple passes over the entire treatment area.

4.1 Vibro-Replacement Methodology

Wet top-feed Vibro-Replacement was selected as a suitable densification method for the Deltaport Berth 3 treatment depths and fill material gradations. The specification required improvement in all landside GF1/Berm Filter/Rock Berm materials to a maximum depth of 27.5 m (90') below working site grades. Wet Vibro-Replacement methods are well suited to such depths provided the Vibro equipment is capable of penetrating the full soil profile. To mitigate potential penetration difficulties, Geopac stipulated the maximum grain size of the coarsest and deepest fill, Rock Berm material, at 3" (75 mm).

The Vibro-Replacement densification program and methodology had to be designed to not only achieve the specified CPT criteria in the GF1, but also to provide effective settlement control within the Berm Filter and Rock Berm materials. Grid spacing, stone column installation methodology and stone backfill quantities were determined based on Geopac's extensive experience with its electrically powered V23 Vibroflot equipment in clean granular soils. The compaction design had points spaced 3.0 m on-center in an equilateral triangle grid pattern except at the north end retaining structure where stone columns were placed at points between the buried tie rods.

Two distinct types of stone column backfill were required on this project which represented a significant added logistical and operational challenge relative to typical stone column applications. Well graded 3" minus clean crushed rock was used as general stone column backfill in all GF1 sand fills. However, in order to ensure the integrity of the Berm Filter zone, two types of material were specified as stone column backfill in treatment areas underlain with Berm Filter/Rock Berm material. Consequently, in the eastern portion of the apron where Berm Filter and Rock Berm zones occur, 2" minus Berm

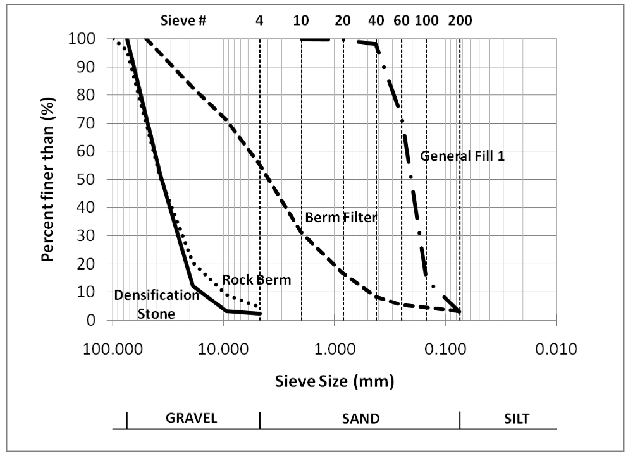

Figure 5. Gradation Curves

Filter material was used as Vibro backfill from the maximum penetration depth to an elevation 2.0 m above the sloping Rock Berm/Berm Filter interface. On applicable compaction points, the backfilling operations would switch from Berm Filter material to general stone column backfill for the remaining length of column above the Berm Filter cut-off elevation and up to the elevation of the Vibro/Dynamic Compaction interface (i.e. elevation -1.5 m). By utilizing Berm Filter backfill in this way, the continuity and integrity of the critical Berm Filter layer was maintained with no adverse effect on the ground improvement work. Typical gradation curves for the various General Fills and stone column backfill are shown in Figure 5.

The free-draining characteristics of the clean imported General Fills generated no spoil making the wet Vibro operation environmentally benign and did not require special controls/measures while working within this sensitive marine ecosystem. The diesel driven jet pump which supplied marine water to the two Vibro rigs was fitted with an intake fish screen to ensure an effective barrier for marine life and low velocity flows at the screen surface.

4.2 Dynamic Compaction Methodology

The Dynamic Compaction program (i.e. weight of tamper, drop height, number of drops and grid spacing) was developed based on experience with similar soil types, treatment depth and the specified CPT performance criteria. The phasing and total energy applied per phase were determined based on the degree of improvement required from initial conditions.

The Berth 3 apron DC work was designed to target a depth of 8.0 m and was conducted in three high-energy phases following completion of the Vibro work in a given area. A 16 tonne steel tamper and 22 m drop height were selected for the high energy phases. Phase 1 compaction points were spaced on an 8.0 m square grid, Phase 2 was on an 8.0 m square grid centered between the first phase points and Phase 3 was a staggered double 8.0 m square grid located at points equidistant from the first two phases. A final low-energy ironing phase consisted of a contiguous pattern of impacts using an 8.6 tonne ironing tamper and an 11 m drop height. An average DC energy input of 220 tonne-m / m^2 was applied over the entire treatment area.

No Dynamic Compaction was allowed within 10 m of the deadman anchor or north of the deadman within the retaining wall tie rod area. DC was also limited to a 4.0 m setback from all caisson structures. Only Vibro methods were allowed in these DC restricted areas. DC only methods were employed along the western slope of the perimeter containment dike, where the maximum improvement depth was less than 8.0 m. In this area DC energy was adjusted to accommodate the reducing treatment depth profile above the sloping embankment.

5 VERIFICATION TRIAL

A full and extensive Verification Trial represented a key and fundamental aspect of the Engineer's QA/QC program. Since the specifications required treatment of the Rock Berm and Berm Filter using the same methods that successively achieved the CPT criteria in the GF1 sands, the effectiveness of the proposed techniques and methodologies had to be demonstrated and approved prior to production work proceeding. The trial area formed part of the final work and consisted of 68 Vibro stone columns and 35 DC compaction points. The location chosen for the verification trial was situated behind caisson 18 in an area where deeper Vibro penetration depths occurred and both of the typical fill profiles would be encountered; the profile containing GF1 sand only (typically occurring on the west side of the densification envelope) and the profile containing the combination of GF1 sand, Berm Filter and Rock Berm materials (typically occurring on the east side of the densification envelope). The trial area was carried out utilizing the Vibro and DC methodologies indicated previously.

The improvement achieved in the Verification Trial was evaluated using Cone Penetration Tests (CPT). In addition to the six specified trial area acceptance CPTs, Geopac carried out one before CPT and three additional interim CPTs following completion of the Vibro portion of work to assess the effectiveness of the Vibro densification below the Vibro/DC interface due to Vibro-Replacement methods only (i.e. prior to application of DC energy), and to allow implementation of changes to the Vibro methodology below elevation -1.5 m for future work in the event that the Vibro only testing did not satisfy the specification. As shown in Figure 6, the CPT results verified that the Vibro only methodology achieved the performance specification requirements below the target -1.5 m elevation. Dynamic Compaction was then applied within the limits of the previously completed Vibro trial area targeting the fill above the Vibro/DC interface. Final acceptance CPT testing of the total fill profile was performed following three high-energy phases of DC energy. Figure 7 shows the average CPT profile for the six Verification Trial acceptance tests. The specified performance criterion was successfully met without any

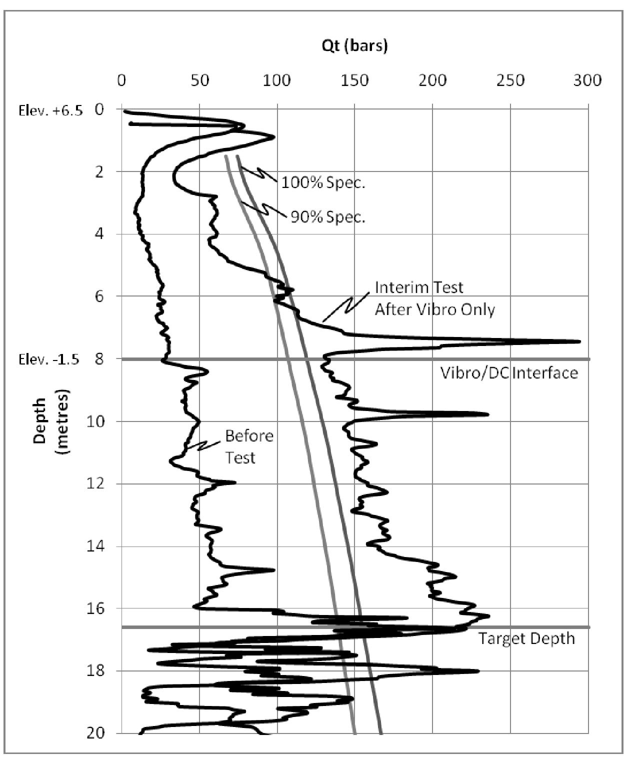

Figure 6. Typical Verification Trial Vibro only CPT prior to DC

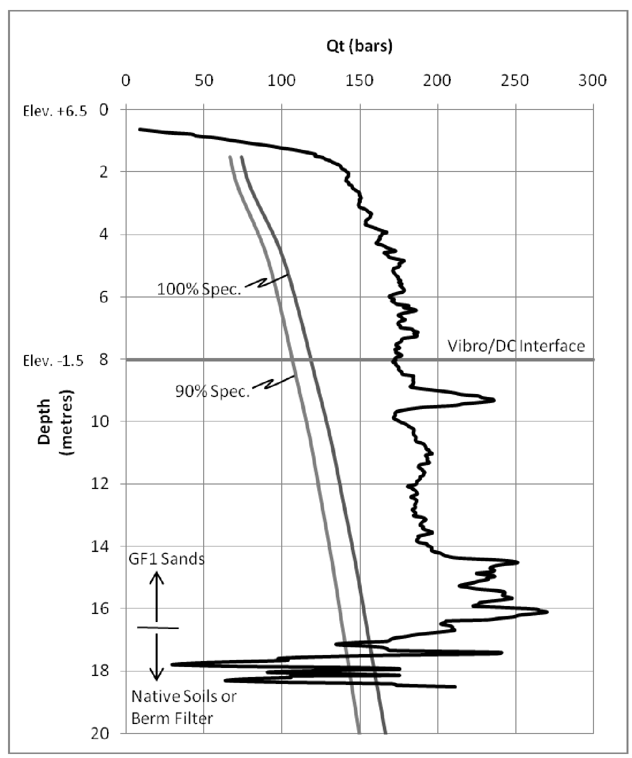

Figure 7. Average of Six Verification Trial CPT Acceptance Tests following Vibro and DC

Table 1. V23 Vibroflot Specifications

Specification		
Manufacturer	Vibro Services AG - Germany	
Type	Electric	
Power	130 (175)	kW (HP)
Eccentric Force	300 (67,000)	kN (ft-lbs)
Amplitude	23 (0.91)	mm (in)
Frequency	30 (1,800)	Hz (RPM)
Voltage	440	Volts
Current (max)	300	Amps
Current (in air)	85	Amps
Diameter	350 (14)	mm (in)
Length	3.5 (11.5)	m (ft)
Weight	2.2 (2.4)	tonne (ton)

modification to the initially proposed ground improvement techniques or methodologies. Comparison of Figure 6 and 7 would suggest that DC had a favourable effect well below the -1.5 m elevation target.

6 PRODUCTION WORK

Completion of the Verification Trial Area marked the beginning of the production work on September 29, 2008. The compaction rigs consisted of two 125 ton crawler cranes and one 100 ton crawler crane. One specially modified 125 ton crane was rigged for DC application and was sequenced behind the two Vibro rigs which were set up for wet method stone column installation. The Vibro rigs were equipped with electric V23 Vibroflots. The manufacturer specifications for this equipment are provided in Table 1. The larger capacity Vibro rig was capable of penetrating to 30 m and the lesser capacity rig to 24 m depth. Consequently, the larger rig operated primarily on the east side of the site where penetration depths through the Rock Berm were the greatest, while the smaller rig worked primarily on the west side of the site in the shallower GF1 sand fill. Two 2 m^3 capacity front-end wheel loaders were used for transporting stone/Berm Filter backfill from stockpile to the operating rigs. With the favourable marine access, all stone column backfill was transported by barge and off-loaded with clamshell and 25 tonne off road haulers to appropriate stockpile locations on the site.

Vibro penetration depths varied in both the north-south and east-west directions due to the varying elevations of the existing seabed and/or dredged back-slope. Furthermore, due to the depth variation of the sloped Rock Berm/Berm Filter interface, different quantities of Berm Filter and general stone backfill material were required for each compaction point which encountered the Rock Berm zone. Detailed site mapping was performed in advance of the work using initial ‘as built’ bottom/dredged elevation data together with the design fill profiles for the Berth 3 apron General Fills. This information was used to establish elevation contours for determining maximum penetration depth and, for compaction points on the east side of the apron treatment area, the intermediate Rock Berm/Berm Filter interface depths. Pertinent data was then transferred to the Vibro grid site plan for use by site supervisors and the Vibro equipment operators. Each of the Vibro compaction points was labelled with its penetration depth and, where applicable, its top of Berm Filter backfill cut-off depth. Detailed layout drawings and corresponding detailed charts were provided to the site crews so that both Vibro-rig and front-end loader operators could follow a compaction point installation sequence that ensured the proper penetration and intermediate depths were achieved and the correct proportion of backfill material was used for each stone column. Site records were maintained of the penetration depth and the quantity of each backfill type.

Besides the replacement volume achieved through the installation of the Vibro backfill, the overall site elevation dropped an average of 1.6 m during Vibro operations, resulting in initial average DC work surface elevation of ±5.7 m (average for both +6.5 and +7.5 m initial Vibro area work surface elevations).

Vibro stone column locations were maintained a minimum 2.0 m distance from sheet pile walls and concrete caissons to mitigate development of high local stresses on the retaining structures during the work. At the north end sheet pile retaining structure, stone columns were installed between buried tie rods spaced 2.4 m apart. With the specification requiring a minimum of 600 mm clearance from all buried tie rods, accuracy of the stone column placement was critical. The locations of all tie rods were marked in advance of the work and the retaining structure (sheet pile wall and deadman anchors) were monitored as the work proceeded. Settlement of up to 700 mm was measured on the concrete deadman. No significant lateral or vertical movement was noted in the sheet pile wall.

Tidal fluctuations had to be considered when scheduling Dynamic Compaction operations. Typically a 1.5 to 2.0 m freeboard must be maintained above the ground water level to ensure efficient energy transfer and a safe work surface condition. Two standpipe piezometers were installed to monitor the ground water levels during tidal cycles. The site ground water levels presented in Figure 8 indicated that adequate freeboard

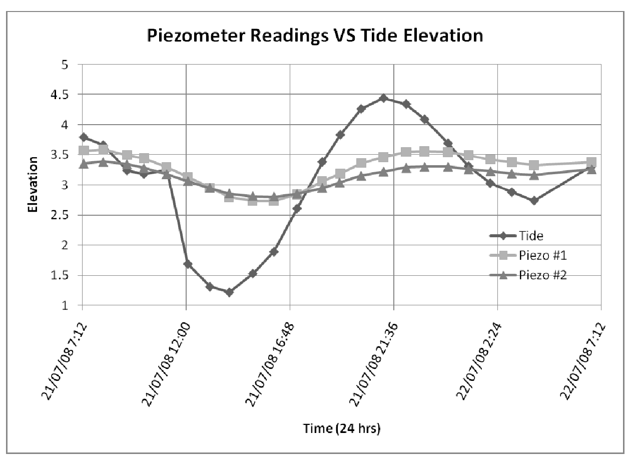

Figure 8. Ground Water Fluctuations

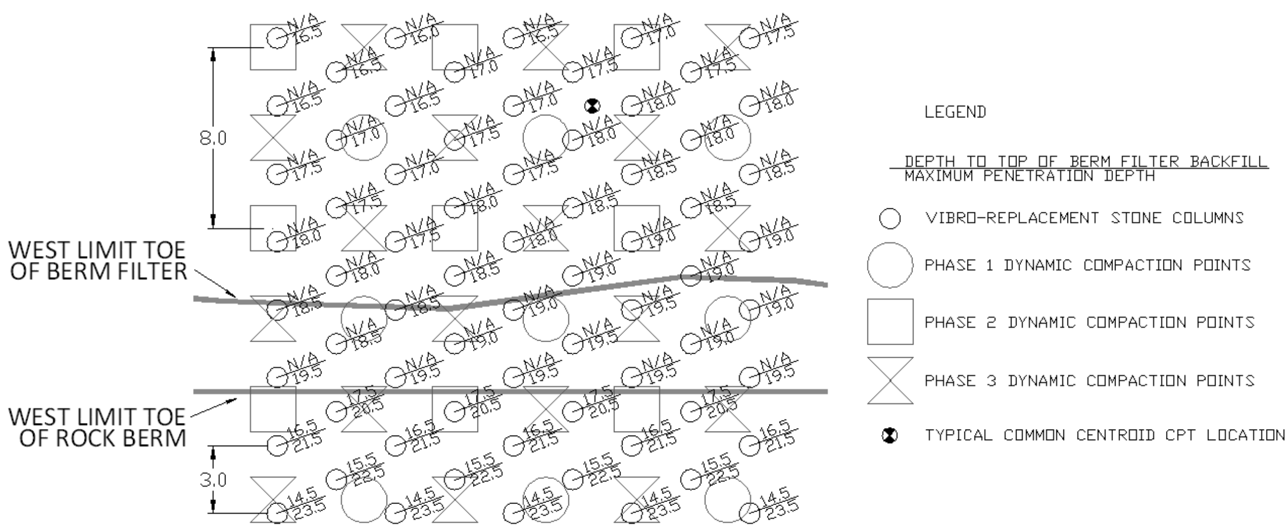

Figure 9. Typical Vibro and DC Layout

was available even during high tide.

Sustained elevated pore water pressures did not affect the scheduling nor sequencing of DC work since the free-draining reclamation fills did not retain residual pore pressures. Regrading between DC phases was done by cutting the GF1 sand work platform with a bull dozer resulting in a lowering of the site. Final average site grades following DC were ±5.4 m.

The General Contract ground improvement schedule allowed 26 weeks for completion of the Landside General Fills densification. The work was completed, including the Verification Trial, within 20 weeks, finishing on February 23, 2009.

7 EFFECTIVENESS OF THE GROUND IMPROVEMENT

All production work QA/QC testing was carried out using the Cone Penetration Test. An electronic 20 ton compression type cone supplied by ConeTec Investigations with a tip area of 15 cm^2 and a friction sleeve area of 225 cm^2 was used for all of the soundings. As stipulated in the specification, Geopac carried out four sets of CPTs for the production work, with each set consisting of four tests (16 test locations total). In addition to the 16 specified test locations, a fifth set of two tests was performed in the DC only area along the perimeter dike. The 18 production CPTs were in addition to the 6 acceptance CPTs carried out in the Verification Trial Area behind caisson 18.

Figure 9 shows a typical superimposed treatment area layout for Vibro and DC compaction points. CPTs were typically located at the centroid of the combined Vibro-Replacement and Dynamic Compaction grid spacings (centered between stone column locations where they coincide with DC compaction point centroids). Each CPT was pushed to initial bottom (i.e. to the existing sea-bed or the dredged back-slope), or to non-GF1 sand materials (i.e. Berm Filter or perimeter dike), depending on the test location.

Prior to ground improvement proceeding, Geopac performed 12 'before' CPTs to assess the initial condition in terms of relative density and to establish a 'before' CPT profile for elevation and use in compaction design and comparison with post treatment CPT results. In several cases, the location of the final production tests were in close proximity to 'before' CPTs allowing a reliable site specific comparison of pre- and post-treatment conditions. Figure 10 shows such a test pairing. A comparison of 'average' before and after results for all CPT tests in GF1 sand is presented in Figure 11. The plot clearly shows that substantial increase in relative density was achieved over the full treatment depth and that the improvement program was very effective in satisfying the performance specification criteria.

Total volume reduction is an alternate reliable indicator of the degree of improvement achieved in terms of the overall increase in bulk density. The density of the treated soil mass in comparison to the density of the untreated soil mass was evaluated by way of the induced settlements caused by the ground improvement work. The total induced settlement volume was determined by measuring the average change in the before and after working platform elevations and then adding the total volume of stone column backfill that was consumed.

These combined volumes taken over the entire densification envelope amounted to an average volume reduction of 12.9 %, when expressed as a percentage of the total initial volume of the Berth 3 apron material prior to Vibro/DC treatment. This percentage value is roughly double the typical volume reduction percentage for ground improvement of similar effort under normally consolidated conditions and was anticipated given the low initial densities resulting from land reclamation through water.

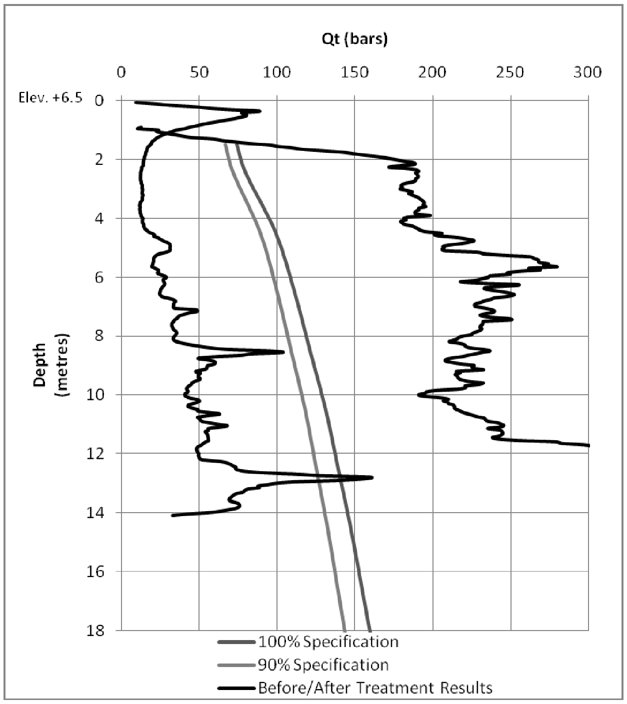

Figure 10. Typical Before and After Comparison for Specific Location behind Caisson 24

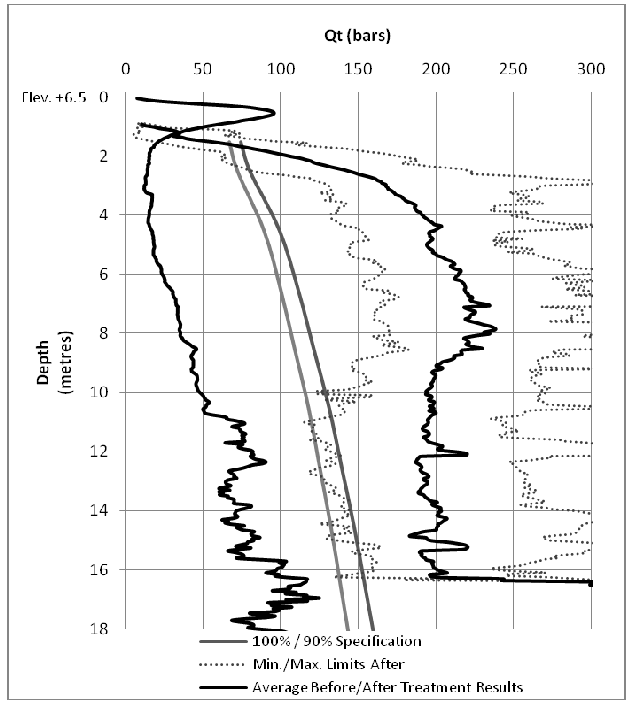

Figure 11. Average Before and After Production Testing Comparison for GF1 Sand Fills for Entire Site

8 CONCLUSIONS

Ground improvement for the Deltaport Berth 3 marine container terminal expansion project demonstrated that densification of extremely loose marine reclamation fills can be successfully and efficiently achieved by integrating wet top-feed Vibro-Replacement and Dynamic Compaction methods. This application further demonstrated that, where required, stone columns can be constructed using more than one type/gradation of stone column backfill without sacrificing quality, productivity or performance characteristics. Cone Penetration Testing verified that the ground improvement approach not only met the demanding performance specification requirements, but generally significantly exceeded them. Post treatment measurements showed an average bulk volume reduction of 12.9 %, roughly double what is typically seen in normally consolidated soils. The success of the overall landside reclamation fill densification program was directly related to the implementation and integration of two traditional ground improvement methods which proved to be an economical, efficient and technically effective solution. Close coordination with the sequential advancement of caisson placement and reclamation works by the General Contractor, together with timely interfacing of related aspects of the overall densification scope of work, such as QA/QC testing, importing/stockpiling of stone column backfill materials and site management between Vibro, DC and subsequent final site filling operations by the General Contractor, greatly contributed to the efficiency and overall success of the work. Achievement of the specified technical requirements will contribute to the overall quality of the marine installation and the satisfactory long term performance of the Berth 3 facility.

ACKNOWLEDGEMENTS

The authors wish to thank Brian Atwell and Dave Basnett of Deltaport Constructors Ltd. for their cooperation and assistance throughout the work as well as their review and data contributions to this paper. Thanks also to the office and field staff of Klohn Crippen Berger for their attention to detail and cooperation with the specified field testing and monitoring program. Finally, we thank Vancouver Fraser Port Authority for the opportunity to contribute to the construction of this world class port facility.

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