Vibro Replacement, Dynamic Compaction & Vibro Compaction Case Histories for Petroleum Storage Tank Facilities

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ABSTRACT
Three tank farm ground improvement case histories are presented illustrating the benefits and effectiveness of ground improvement for foundation support of petroleum storage tank facilities. Each case history is unique in terms of initial site conditions, soil type, performance criteria and the ground improvement techniques utilized to meet the required post treatment foundation performance. The three case histories include a Vibro Replacement stone column application in Richmond BC, a Dynamic Compaction/Preload application in Edmonton AB and a Vibro Compaction application near Fort McMurray AB. Each application exceeded its objectives in terms of specified in-situ testing requirements and returned exceptional performance results.

RÉSUMÉ
Les avantages et l'efficacité de l'utilisation des techniques d'amélioration des sols pour supporter des réservoirs de produits pétroliers sont illustrés au travers de trois différents chantiers. Chaque chantier est unique en termes de conditions initiales des sols, de types de sols, de critères de performance à obtenir et de technique d'amélioration des sols utilisée pour obtenir le bon comportement de la fondation après traitement. Le premier chantier consiste en un chantier de Vibro Remplacement à Richmond, BC, le second détaille un chantier de Compactage Dynamique à Edmonton, AB alors que le dernier se situe à Fort McMurray, AB où la Vibro Compaction a été utilisée. Chacune de ces applications a dépassée ses objectifs et a démontrée un niveau exceptionnel de performance.

1 INTRODUCTION

Soil reinforcement and ground improvement offer economical solutions to foundation design challenges and can be attractive alternatives to more time consuming and costly options such as excavate and replace or deep foundations. There are several innovative ground improvement techniques available that can provide distinct advantages when applied to specific soil and structural loading conditions.

Industrial tank farm construction is one of many development sectors that can benefit from the application of soil improvement. Heavy storage tanks generate large uniform loads that require effective support and load distribution within the foundation soils. Ideally, storage tanks would be founded on dense soil strata, however tank farms can be located along waterways or on sites where loose or soft soils are present. Supporting heavy loads on poor or marginal soils while maintaining total and differential settlements within acceptable limits is one of the main geotechnical design challenges. Storage tank ground improvement applications are designed to improve the poor initial ground conditions in order to deliver reliable and maintenance free foundation performance over time.

This paper presents three Canadian ground improvement case histories for petroleum storage tank facilities: 1) Vibro Replacement techniques applied at YVR Jet Fuel Tank Farm #2 in Richmond BC, 2) Dynamic Compaction and surcharge techniques applied at Petro-Canada #400 Tank Farm in Edmonton AB and 3) Vibro Compaction techniques applied at CNRL Horizon Oil Sands SE Tank Farm near Fort McMurray AB. Each case history highlights the project's geotechnical information and foundation design loading conditions, the ground improvement methodologies utilized based on soil, structure and performance requirements and the QA/QC programs with their results.

2 YVR JET FUEL TANK FARM # 2

The Vancouver Airport Fuel Facilities Corporation (VAFFC) is constructing a second jet fuel tank farm, YVR Jet Fuel Tank Farm #2, at Vancouver International Airport (YVR) in Richmond, British Columbia. The project consists of developing an approximate 6.0 acre parcel of land located adjacent to the YVR north runway and close to the existing jet fuel tank farm in the northeast corner of Richmond Sea Island, as shown in Figure 1. Phase 1 of the development will accommodate four new fuel tanks, each measuring an approximate 31 metres diameter and 15 metres height, as well as relatively small and lightly loaded ancillary structures along the eastern edge of the tank farm site. Consideration was given to allow for the expansion of two additional fuel tanks to be constructed as Phase 2 at a future date.

2.1 Site Conditions

The Vancouver International Airport is situated on Sea Island in Richmond BC, within the estuary of the Fraser River. Sea Island is a typical Fraser River Delta soil profile, characterized by saturated alluvial deposits. These deposits are considered to be young from a geological perspective (Ji et al, 2009).

A site specific soil investigation showed the native soil stratigraphy to be relatively uniform in terms of thickness

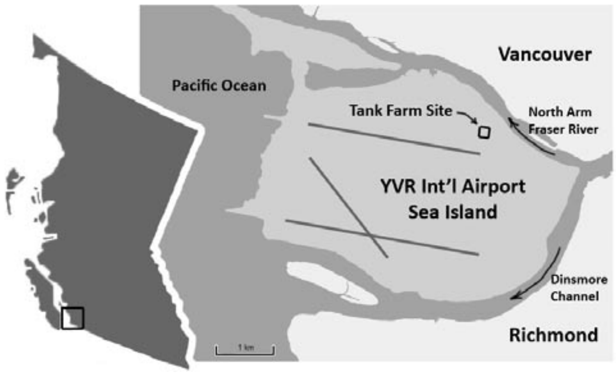

Figure 1. YVR Jet Fuel Tank Farm #2 Site Location

and elevation of the major soil units across the project site, and can be summarized as follows:

Unit A - A layer of soft to firm clayey silt about 1.5 to 2.5 m in thickness overlying;
Unit B - Interbedded silty sand and sandy silt about 1.8 to 2.6 m in thickness overlying;
Unit C - A layer of relatively clean fine to medium sand about 7.5 to 9.5 m in thickness overlying;
Unit D - Inter-bedded silty sand and sandy silt about 1.5 to 4.8 m in thickness overlying;
Unit E - A thick layer of soft to stiff marine clayey silt to silt extending to considerable depths.

2.2 Design Requirements

The Fraser River Delta is located in a zone considered to have a high level of seismic hazard (Ji et al, 2009). Seismic design in the Fraser River Delta is based on the 2006 British Columbia Building Code (BCBC 2006), which accepted the 2005 National Building Code of Canada (NBCC 2005) seismic design guidelines. These stringent seismic design provisions considers, in part, ground motions with a return period of 2,475 years (2% probability of exceedence in 50 years) and includes explicit consideration of an offshore subduction earthquake event.

Based on results of a site specific ground response analysis, the risk of liquefaction of the loose to compact sandy soil Units B & C were considered very high under the design seismic event. In order to reduce the potentially severe negative impacts of earthquake induced soil liquefaction on the proposed fuel tank foundations, it was recommended that ground improvement measures be implemented in the area within the tank farm footprint and extend to the surface of the marine silt, +/- 17 metres below the existing ground surface elevation.

2.3 Ground Improvement Solution

Vibro Replacement (VR) stone column installation using wet top-feed methods was selected as the most efficient and cost-effective ground improvement technique to treat the interbedded and clean sandy soil units. Preloading the tank foundation areas was not considered viable due to constraints related to the tight project schedule as well as cost. Instead, the 2.5 metre highly compressible upper silt layer was stripped from the site and replaced with clean granular fill prior to the ground improvement work proceeding to reduce future foundation settlements resulting from the consolidation of this shallow clayey soil unit.

The Vibro Replacement stone column treatment program was developed to meet the tender's stringent Cone Penetration Test (CPT) performance specification. Acceptance of all densification work was based on the graphical comparison of individual test results against the minimum required post-improvement CPT tip resistance criteria.

The extent of the ground improvement treatment envelope covered a total area of 11,200 square metres. Stone column installation was required from the initial site grade of elev. +1.0 m to elev. -16.0 m, a full treatment depth of 17.0 metres. Grid spacing, stone column installation methodology and stone backfill quantities were determined based on extensive experience with electric V23 Vibroflot equipment in granular soils. The uniform stone column layout had compaction points arranged in an equilateral triangular grid pattern.

2.4 Execution

An initial trial area was required to demonstrate the effectiveness of the Vibro Replacement program in meeting the CPT performance specification. The trial area formed part of the final work and consisted of 23 compaction points. Three CPT soundings were carried out upon completion of the trial area to confirm the improvement achieved by the proposed Vibro Replacement methodologies was generally achieving the specified criteria.

Stone column installation was carried out utilizing two Vibro Compaction rigs.

The project site was located adjacent to an operating airport, +/- 100 metres north of the primary runway. Airport regulations imposed height restrictions during designated periods on the tank farm construction activities to satisfy flight airspace regulations adjacent to the runway. Accordingly, one Vibro rig was setup with a shorter boom length and was employed solely on the southern quarter of the densification area closest to the active runway. In addition, special signal lighting and flagging were required on the Vibro rigs as part of the flight safety protocol measures.

Environmental considerations played an important role in the construction of YVR Jet Fuel Tank Farm #2. An extensive Environmental Control Plan was developed and enforced to ensure the 'wet-method' Vibro Replacement operations continuously monitored for signs of potentially contaminated soils to meet strict air and water quality guidelines. The Sea Island location allowed for the densification stone to be efficiently transported by barge to a nearby riverside bulkhead, loaded by conveyor into tandem trucks and hauled a short distance to site. This stone delivery approach restricted idling times between transfers and minimized the output of atmospheric emissions from both marine tug boats and onshore haul equipment.

The ground improvement schedule allowed 8.5 weeks for completion of the densification work. The work was completed, including the trial area, within 7 weeks, finishing in December, 2009.

2.5 Quality Control & Results

Acceptance of the ground improvement program was based on review by the Engineer of the field testing results in conjunction with the daily site record sheets indicating compliance with the CPT performance criteria. Like the trial area testing, field verification testing was conducted using the electric Cone Penetration Test. CPTs were carried out in the centroid of the stone column pattern, and pushed to 1 m below the depth of Vibro Replacement treatment. The CPT performance specification is dependent on the soil's fines content and stipulated that the CPT resistance at any test location shall not be less than 90% of the specified resistance and the thickness of any zone less than the specified resistance shall not exceed 300 mm.

A total of 36 CPTs were carried out as part of the field verification testing. Figure 2 shows a plot of the averaged results of all 39 tests (3 trial area plus 36 field verification CPTs) with comparison to the CPT performance specification. The plot clearly indicates the effectiveness of the ground improvement program in satisfying the stringent CPT performance criteria within the liquefiable clean sandy soils.

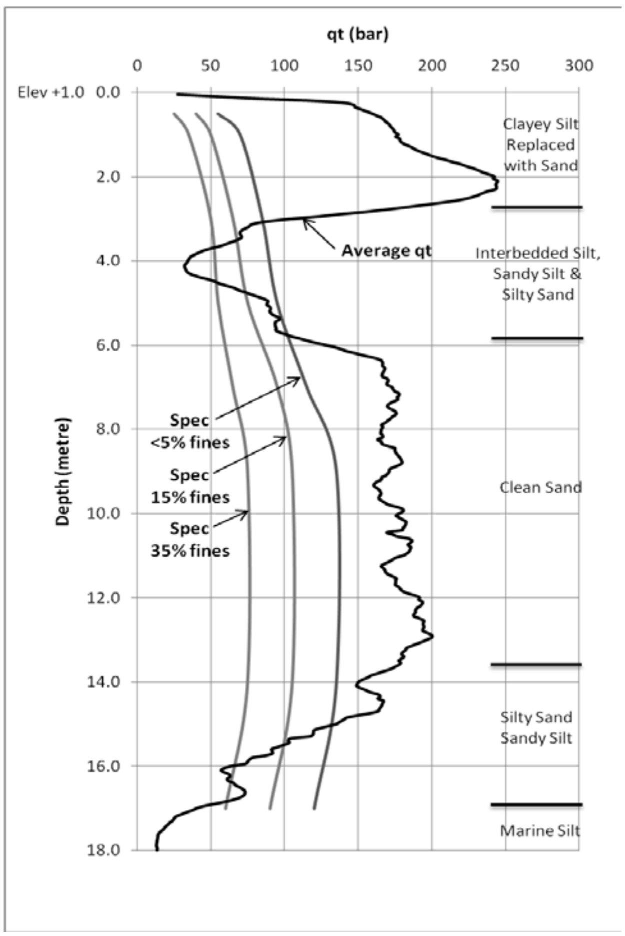

Figure 2. Average of 39 YVR Jet Fuel Tank Farm #2 post-treatment CPT results

3 PETRO-CANADA # 400 TANK FARM

Site preparation for the #400 Tank Farm began in the year 2000 as part of an expansion to Petro-Canada's Edmonton based refinery. The tank farm site is located on previous Lafarge Canada property situated west of Petro-Canada's Edmonton refinery, in the County of Strathcona, Alberta. Included with the proposed tank farm development of approximately 22 acres were twelve tanks varying from 12 m diameter x 15 m height to 24 m diameter x 17 m height. The tanks were to be surrounded by perimeter containment berms and serviced by numerous pipelines supported on piperacks. The tank farm design also provided for a storm pond and a pump area.

3.1 Site Conditions

The native soils found at the tank farm site were consistent with typical geological soil horizons for this north eastern Edmonton area. A thin surficial topsoil layer is underlain by a +/- 1.5 m thickness of very stiff lacustrine clay deposits, underlain by a 2 to 23 m thickness of stiff to very hard, medium plastic clay till, underlain by a 2 to 8 m thickness of compact to very dense medium grained sand containing occasional pockets or layers of gravel (Empress Sand), overlying bedrock predominately composed of clay shale and coal seams.

At the north half of the site, the native soil strata were intercepted by a former gravel pit resulting from extensive mining of the sand and gravel deposits. The pit had been backfilled with on-site and off-site waste soil, which was predominately firm to hard, medium to high plastic clay fill. The clay fill contained numerous topsoil and peat pockets, sand and gravel fill pockets, and layers of construction rubble consisting mainly of concrete fragments with occasional brick pieces, wood fragments, steel pieces, rubber and plastic. The fill is the deepest over the former pit, where it varies from 9 to 17 m in depth. Along the south edge of the pit, the fill varies from 2 to 5 m in depth, and thins to 1.5 m thick outside the pit boundaries to the east.

3.2 Design requirements

The main geotechnical constraint for the proposed tank farm development was the significant depth of variable fill within the former gravel pit. The uncontrolled fill was not considered suitable for grade support of the tank structures due to anticipated large total and differential settlements. Even under no additional loading, the clay fill was expected to continue to settle for the next several years as a result of the long term consolidation under its self weight, settlements from migration of soils into possible voids present around construction rubble and/or the long term degradation of organic material (Proudfoot et al, 2000).

Given the site is a reclaimed gravel pit consisting of varying fill depths and widely ranging fill types, ground improvement was required to improve the quality of the fill within and along the edge of the pit in such a manner as to increase the design bearing capacity and reduce short and long term total and differential settlements to acceptable levels for loaded storage tanks and ancillary structures and services.

The ground improvement performance specification was detailed in terms of meeting minimum bearing capacity values and maximum total and differential settlement criteria. Treatment areas for the various proposed structures and utilities required varying degrees of improvement, with the critical foundation soils directly below the tank structures requiring the highest order of quality and consistency. Tanks within the deep pit area were able to tolerate up to 150 mm of total settlement. However, the tanks were designed to a low tolerance for differential settlement with a maximum of 1/360 specified across the tank base and a maximum of 1/960 for the tank perimeter.

3.3 Ground Improvement Solution

3.3.1 Dynamic Compaction

Due to the highly variable depths, fill types and inconsistent nature of the foundation soils, Dynamic Compaction (DC) was identified as the most effective ground improvement technique for this application. The compaction program was designed to accommodate the varying performance specification criteria that required dividing the site into areas and applying several distinct levels of improvement. To specifically segregate and define these areas, the site was divided into three zones; Zone A for the six tank areas situated over the former pit, Zone B for the general deep pit area exceeding 10 metres of fill in depth, and Zone C for the shallower transitional area along the southeast edge of the former pit. A plan of the site illustrating the three zones is shown in Figure 3.

Production work began in July of 2000 with Zone A, the tank foundation soils. Geopac proposed carrying out Dynamic Replacement (DR) ground improvement under the tank foundation areas using Select Fill Displacement techniques. This method of work is generally used where heavy loads and tight differential settlement criteria impose requirements which demand the highest quality foundation improvement using Dynamic Compaction methods. Select Fill Displacement involves the application of higher than normal DC energy levels in the initial phases of treatment and the importing of granular backfill during the work to provide feed material for the subsequent DC phases and maintain adequate confinement. Using these methods, large 2.5 to 3 metre diameter columns of high quality material are created immediately below the foundation level. These columns can reach depths of some 5 to 6 metres below initial site grades and result in enhanced compaction of surrounding host soils and a dramatic improvement in stiffness and uniformity. The resulting stiffened raft of foundation soil provides a condition which is effective in increasing

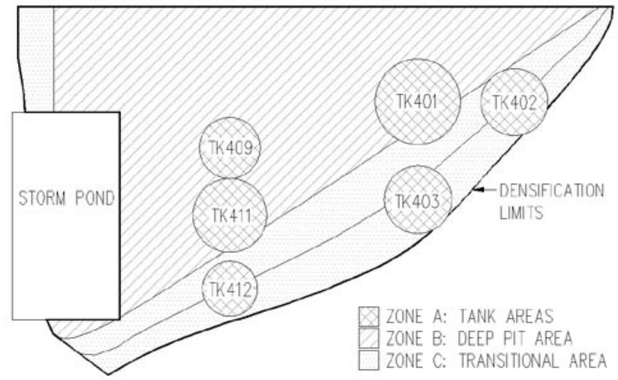

Figure 3. Petro-Canada #400 Tank Farm Site Plan

bearing capacity and reducing both total and differential foundation movement.

Select fill columns were installed in Phase 1 and 2 of treatment. Each phase had multiple passes and return time intervals of adequate duration to allow for porewater pressure dissipation. The return time of various phases and passes were determined based on the observed pore pressure response as monitored by pneumatic piezometers installed to various depths prior to treatment.

The layout of the tank foundation impact points fell on a radial grid pattern extending outside the tank footprint a peripheral distance dependent on tank diameter and magnitude of loading. A third high energy phase was carried out on a staggered double grid between the select fill columns to further compact the soils in between the Phase 1 and 2 treatment. A final low-energy ironing phase consisting of a contiguous pattern of impacts finished the ground improvement application by compacting the near surface soils.

Following completion of Zone A, production work moved to Zone B, the deep pit area outside the tank foundations. Here, conventional Dynamic Compaction techniques were utilized to densify the fill to a target depth of 10 metres. Similar to the treatment methods employed in Zone A, a specially rigged DC plant was used to deliver high energy impacts to the in-situ soils by repeatedly dropping a 16.5 tonne steel tamper from a 24 metre drop height. Compaction points were arranged on a square grid pattern and DC energy was distributed over three high energy phases. Available site soils were utilized for regrading following each phase of treatment.

As production work moved from Zone B to the transitional area Zone C, the number of phases and the magnitude of energy applied were reduced to accommodate the decreasing depth of fill along the southeast edge of the pit. The transitional area was again divided length-wise into two strips, where the deep transitional area targeted an average treatment depth of 3.5 metres and the shallow transitional area targeted an average treatment depth of 2.0 metres. Completion of Zone C in September, 2000 marked the end of the Dynamic Compaction portion of the work.

3.3.2 Preloading

Even after the Dynamic Compaction ground improvement, the stringent tank perimeter differential settlement criteria of 1/960 could not be reliably guaranteed without some type of secondary surcharge treatment. With settlement over a moderate term considered as the governing factor in tank design, preloading was required to consolidate the deeper clay fill profile not effectively treated with DC. A static preload surcharge was applied to the three tanks situated within the deep pit area. Pressuremeter testing at Tank 401 and 402 in the northeast corner of the site confirmed the need for preloading by showing post densification limit pressure values consistant with that of a soft compressible organic clay layer. Preloading was not required for tanks situated within the transitional zone boundaries since the shallow fills in this area experienced high and adequate levels of DC improvement over the entire fill depth.

The preload height was designed to approximate the actual tank loads when full. For the design bearing stress of 215 kPa, a design preload height of +/- 10 metres was applied over the three tank foundation footprints. The preload was installed in lifts commencing in September of 2000.

3.4 Quality Control & Results

3.4.1 Dynamic Compaction

Several testing methods were used to evaluate the effectiveness of the Dynamic Compaction treatment program. Standard Penetration Testing (SPT) and Spectral Analysis of Shear Waves Testing (SASW) were carried out as comparative "before and after" evaluation and Pressuremeter Testing (PMT) was carried out to assess the bearing capacity and settlement characteristics of the treated foundation soils.

Review of the pre and post-compaction SPT profiles indicated (not surprisingly) significant scatter in the penetration results. A large number of the values had clearly been affected by obstructing debris within the clay fill mass while other areas where the saturated clay fill had not yet dissipated pore pressures showed lower values than the longer term values. In general, it was not considered possible to draw any firm conclusions from the SPT penetration profiles.

PMT data was of good quality and was considered the most relevant information for the elastic stress/strain behavior of the clay fill mass (Ryan et al, 2000). A total of 22 PMTs were carried out, 16 within Zone A tank areas, and the remaining 6 within Zone B. Respectively, Figure 4 and 5 show the averaged Limit Pressure and Modulus results for each treatment zone, obtained from PMT data collected at 1.5 metre depth intervals. The interpretation of the raw PMT data and design calculations followed that recommended in the Canadian Foundation Engineering Manual (CFEM). Based on the design calculations, the allowable bearing capacity values in Zone A ranged from 240 to 510 kPa, exceeding the specified tank base bearing pressure of 215 kPa. Similarly, allowable bearing capacity values in the general deep pit area ranged from

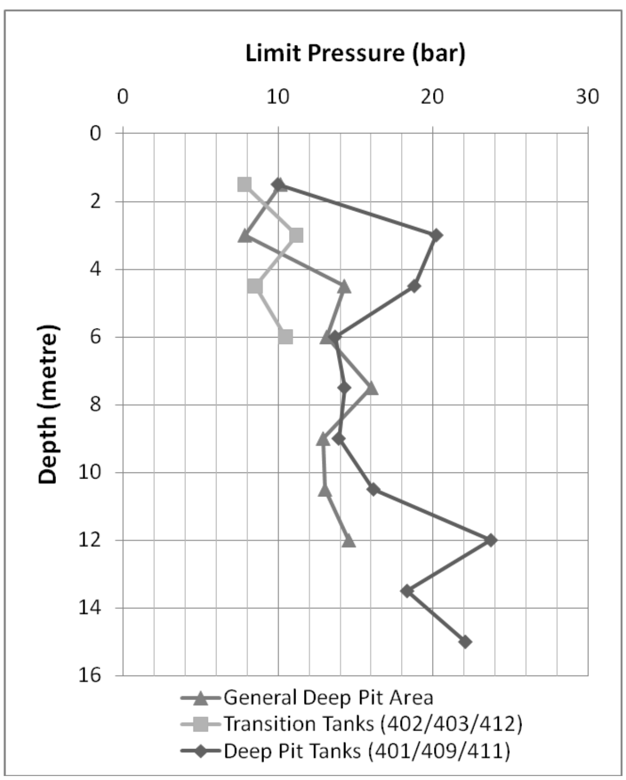

Figure 4. Petro-Canada #400 Tank Farm averaged PMT Limit Pressure results

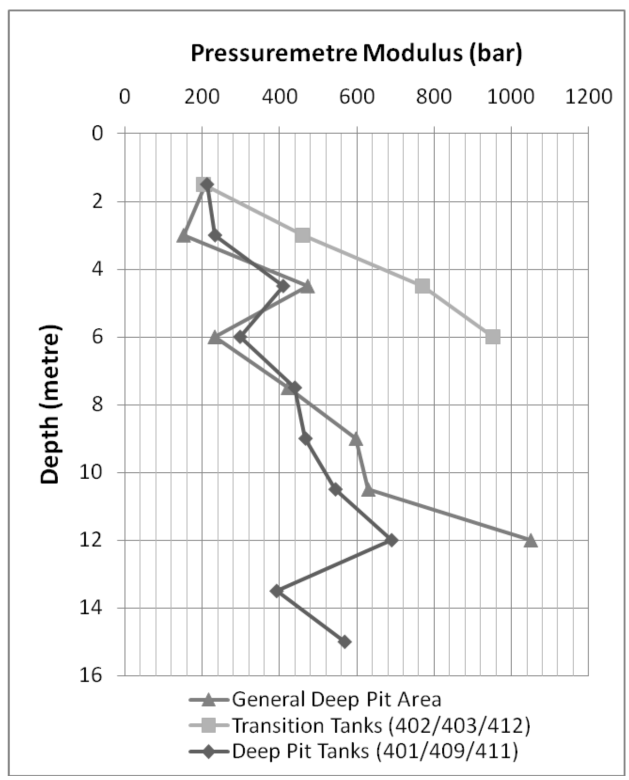

Figure 5. Petro-Canada #400 Tank Farm averaged PMT Pressure Modulus results

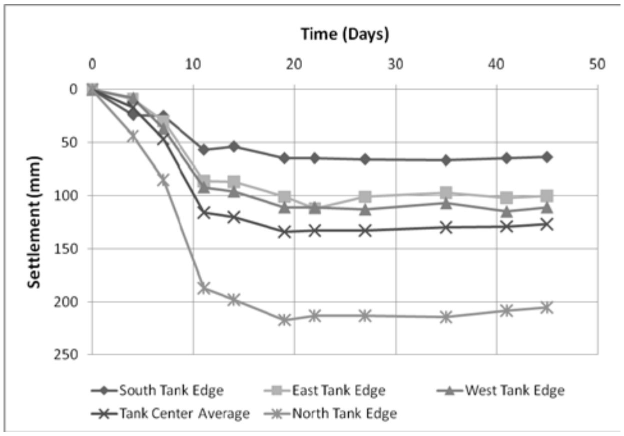

Figure 6. Petro-Canada Tank 411 time rate of settlement profile

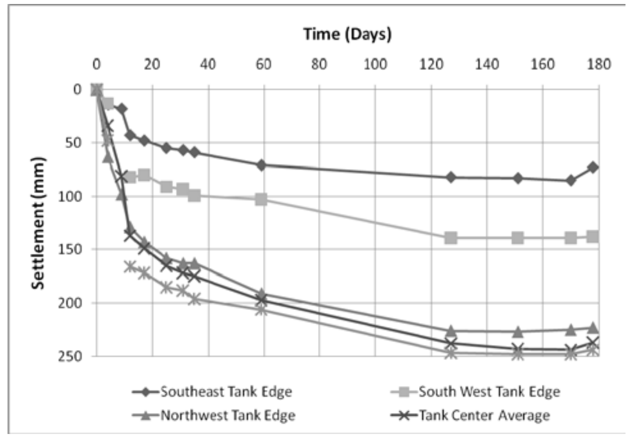

Figure 7. Petro-Canada Tank 401 time rate of settlement profile

190 to 570 kPa, meeting the required 96 kPa design criterion.

3.4.2 Preloading

Horizontal Slope Indicator (HSI) instrumentation was chosen as the most reliable and practical method for preload settlement monitoring as it avoided the risk of instrumentation damage and interference by construction equipment during the preloading. Two HSIs were installed perpendicular to each other (i.e. cross hairs) at the base elevation of each of the three tank preloads, with six points selected on each to assess the general settlement trends.

The time rate of settlement curves for Tank 409 and 411 indicated that uniform consolidation occurred within a relatively short period of time, and the preload as removed after 45 days to allow for accelerated tank construction schedules. Very little elastic rebound, in the order of 5 to 10 mm, was measured during the preload removal. This was considered a very favourable response indicating that the large settlements measured during preloading, ranging from 60 to 220 mm, were primarily the result of permanent consolidation of the soil mass.

The settlement profile trend for Tank 401 took longer to reach a uniform consolidation state. During the early stages of preloading, Tank 401 experienced an increase rate of settlement in the northwest relative to the south, which was attributed to the sloping fill depth profile underlying the tank footprint. The preload was left in place for an extended period and removed after 170 days. The maximum induced settlement on Tank 401 was in the order of 250 mm.

The predicted long term differential settlements for the tank circumferences were below the allowable 1/960 criteria and it was concluded the preload performance was satisfactory. Time rate of settlement profiles for Tank 411 and 401 are provided in Figure 6 and 7 respectively.

4 CNRL HORIZON OIL SANDS SE TANK FARM

Canadian Natural Resources Ltd. (CNRL) have extensive oil sand leases in the regional Municipality of Wood Buffalo Alberta, approximately 75 km northwest of Fort McMurray, near Fort McKay. The owner intends to develop the available bitumen reserves by installing facilities to mine the oil sands and then extract and upgrade the bitumen to generate synthetic crude oil to be sold as a product. As part of the proposed Horizon Oil Sands development, three grade supported tanks will be erected in the “East Tank Farm – South” area of the facilities site. The three tanks, labelled Tank 2, 3 and 4, vary in size, measuring 33, 52 and 52 metres in diameter respectively.

4.1 Site Conditions

The subsurface conditions at the sites of Tank 2, 3 and 4 were investigated in October 2005. The typical soil profile consists of sand fill, overlying native sand, underlain by clay till.

The sand fill extends to variable depths ranging from 4 to 8 metres and is fine-grained with the minus 0.075 mm sizes typically less than 5% by weight. A typical sand fill gradation is shown in Figure 8. The fill was placed in the fall of 2005 and subsequent testing revealed SPT N values ranging from 3 to 67, indicating highly variable initial relative density conditions. The water table was within the sand fill at a depth of 2 to 3 metres.

Underlying the sand fill were the native soil strata, consisting up to a 1 metre thickness of coarse grained sand, underlain by very stiff, medium to high plastic clay till reaching the limits of the investigation.

Several of the investigation test holes encountered ice crystals within the sand fill and native sand soil layers. The ice crystals were found scattered over the full depth of the sand profile, an indication of possible frozen seams and of the sand’s susceptibility to freezing during colder weather periods.

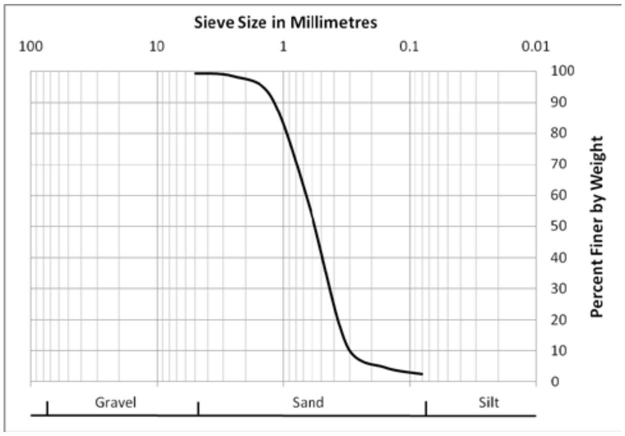

Figure 8. Horizon Oil Sands typical sand fill gradation

4.2 Design Requirements

Remediation treatment of the loose clean sand fill below each of the three subject tanks was required so that adequate bearing support and satisfactory settlement performance was provided for the fully loaded tanks. The designated treatment limits extended radially beyond the tank's foundation footprint by 10 to 16 metres. The treatment diameters for Tank 2, 3 and 4 were 43, 66 and 68 metres respectively.

Treatment was required over the full depth of the sand fill. Average sand fill depths of 5, 7 and 8 metres were measured below Tank 2, 3 and 4 respectively.

The ground improvement plan was designed and developed to meet specified performance criteria. The performance criteria required that the sand fill be densified such that the average Cone Penetration Test (CPT) tip resistance (q_c) over the full fill depth is greater than 95 bar with a minimum CPT tip resistance over the full fill depth not less than 80 bar.

4.3 Ground Improvement Solution

The 'as tendered' ground improvement approach was based on using Dynamic Compaction (DC) techniques for treatment of the loose, clean sand fill. As an alternative to the DC approach, the use of Vibro Densification using Vibro Compaction methods was successfully proposed.

Unlike Vibro Replacement (VR) stone column methods, Vibro Compaction (VC) does not require the addition of imported backfill. With VC the sand fill undergoes an increase in relative density from powerful shaking forces created by the Vibroflot. This shaking induces soil volume reduction and self feeding in the clean sands which results in significant surface settlement around each compaction point. The work platform is then releveled and surface cavities formed by VC operations are backfilled with surrounding on-site sand material.

Although both Dynamic Compaction and Vibro Compaction would have been effective in achieving the desired level of improvement in the clean sand fill, several conditions led to the use of VC over DC. A maximum allowable vibration level (i.e. maximum peak particle velocity) of 20 mm/sec was specified within 10 metres of existing facilities. Maintaining this level of vibration would not be possible using DC, but could easily be satisfied using VC methods. Additionally, VC not only lessened the risk of vibration induced damage to existing plant facilities but also allowed for the concurrent construction of new facilities to proceed in areas within and surrounding the Southeast Tank Farm which proved beneficial to the overall construction schedule.

4.4 Execution

During the winter months, the upper 1.5 to 3.0 metres of surface soils had froze, making an unfavourable ground condition for ground improvement operations. Frozen ground can greatly reduce the efficiency and effectiveness of ground improvement by not allowing for the proper dissipation of pore water within the soil mass, imposing unpredictable future settlements upon thawing, significantly impairing the efficiency of the Vibro equipment to penetrate the host soil resulting in premature wear & tear and possible damage to the Vibro unit. The quality of the CPT data and the safety of CPT equipment used to assess the adequacy of the improvement was also a concern.

To address this condition, the frozen surface soils were thawed by laying large heated glycol industrial blankets over the tank foundation treatment areas.

The ground improvement program arranged compaction points on an equilateral triangular grid pattern at a grid spacing designed to meet the performance criteria. Vibro Compaction work began in March 2006 with completing and testing a 90 m^2 trial area to verify the treatment objectives were being met. The trial area was carried out within the treatment limits of Tank 4 and formed part of the final work. Following completion of the trial area, two CPT soundings were done to confirm the adequacy of the compaction program's grid spacing and compaction procedures. Production proceeded with work within the Tank 4 treatment area, followed by Tank 2 and Tank 3.

Each compaction point required a volume of make-up sand backfill. Approximately 3,000 m^3 of off-site sand backfill of similar gradation to the on-site sand fill was used in backfilling compaction point depressions and to maintain original site grades. The sand backfill was stockpiled adjacent to the work areas and protected from freezing so that it was available on a continuous basis.

Despite the heated blanket ground thawing procedures, a 0.9 to 1.2 metre thickness of frozen soil approximately 0.9 metres below working grades was encountered within the Tank 3 treatment area. In the earlier Tank 4 work, only the jetting action of pressurized air from the Vibro nose was needed to aid with the penetration of the Vibroflot through the loose sand soil stratum. With Tank 3, it was necessary to use the combined jetting action of air and water in order for the Vibro to penetrate the difficult frozen soil condition. Water was supplied by tanker truck and high pressure pump and was used on an as-needed basis wherever frozen soil conditions were encountered. A 1300 cfm volume air compressor was utilized to minimize water usage since the addition of water presented an additional freezing hazard during periods of colder weather.

Production work was completed mid April 2006, on schedule.

4.5 Quality Control & Results

The quality control and testing program was developed to monitor the soil improvement work and demonstrate the specified objectives were being met. The quality control program consisted of CPT testing, daily on-site record keeping and Vibro Compaction installation logs to ensure procedures remained consistent with the procedures initially proven and approved during the trial.

After the completion of the ground improvement program, a total of 24 CPT soundings were conducted with a minimum of 6 CPTs at each tank treatment area. Figure 9 shows the average of 24 production CPT soundings for all three tank areas. The plot clearly demonstrates the effectiveness of the ground improvement effort in meeting the specified performance criteria.

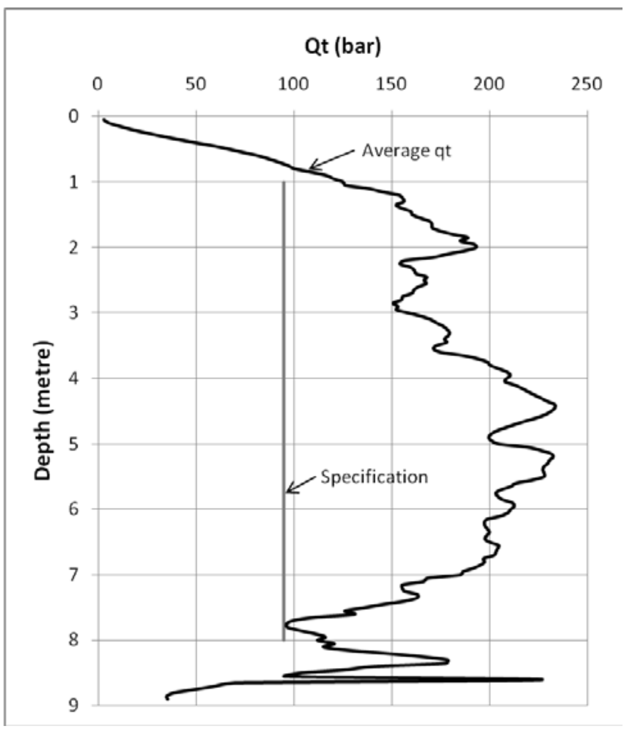

Figure 9. Horizon Oil Sands average of 24 CPT results

5 CONCLUSIONS

There are a wide variety of time-tested soil reinforcement and ground improvement technologies that can be utilized to treat loose and soft soils below heavily loaded storage tanks. Whether the tank foundation soils are susceptible to liquefaction under the design seismic event or excessive total/differential settlements, there are ground improvement techniques to mitigate such foundation design concerns. For storage tanks, ground improvement technologies can often offer the quickest and most economical means of mitigating poor/marginal ground conditions, compared to installing piles, removing and replacing soft ground or relocating the tanks to less desirable locations.

As demonstrated by these three case histories, ground improvement not only met the demanding performance specification requirements, but generally significantly exceeded them. The success of the ground improvement applications were directly related to selecting proper methods and designing densification programs which were tailored to the specific subsurface conditions and design requirements of each project. Successful achievement of the specified foundation design requirements ensure satisfactory long term storage tank performance.

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