A Comparative Study of Targeted Ground Improvement Alternatives during Site Reclamation

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ABSTRACT

A feasibility study was conducted to assess various ground improvement alternatives and their implementation during site reclamation for the construction of a petrochemical plant on a highly compressible ground. The plan dimensions of the offshore area to be reclaimed were approximately 675 m by 265 m. The ground improvement alternatives included: excavation of the clay layer and replacing it with sand fill; deep soil mixing; jet grouting; prefabricated vertical drains (PVDs) with preload fill; and sand drains with preload fill. In addition, vibro-compaction and deep dynamic compaction methods were considered for densifying the new fill to be placed below water level in the case of excavating and replacing the soft clay layer. The purpose of the study was to evaluate the ground improvement measures that could be used to limit future settlements of the portion of reclamation area where critical structures of the plant will be constructed. Strengths, weaknesses, opportunities and threats of each alternative were evaluated and analyzed. Additionally, cost and schedule analyses were performed to determine the suitability of each ground improvement method. Excavation and replacement approach was found to be the most expensive option, while PVDs with preload fill method was shown to be the least costly ground improvement alternative.

KEYWORDS: Ground improvement, Targeted ground engineering, Site reclamation, Feasibility analysis, Offshore construction.

INTRODUCTION

This paper presents the results of a feasibility study conducted to assess various ground improvement alternatives and their implementation during site reclamation for the construction of a petrochemical plant on a highly compressible ground. The plant and associated facilities are planned on a footprint area of about 825 m by 1295 m (Figure 1). This area has both an onshore portion, where limited fill thickness will be placed to bring the site to a desired grade elevation of about El. +2.5 m and a substantial offshore portion, with an average seabed level of El. -1.5 m, where the desired eventual grade elevation will be El. +3.5 m LAT. A substantial quantity of fill, in the order of 7 to 8 million m^3, will be required to bring the site to the desired grade elevations. The fill will be pumped into place by dredging clean sand from an offshore source nearby the reclaimed site. However, with placement of the fill, the site is likely to experience intolerable consolidation settlement due to a very soft layer of clay that underlies

Received on 21/6/2018.
Accepted for Publication on 7/1/2019.

the site. The magnitude- and time-dependent nature of the expected settlement will have a huge impact on the project schedule.

The compressible clay layer is present in most of the site. In general, this layer is thickest on the western portions of the site and thinner on the eastern portions of the site. The thickness of the soft clay layer ranges between 14 m on the western side and 2 m on the eastern side. The upper portions of this clay layer offshore appear to be normally consolidated, while its deeper portions appear to be slightly over-consolidated. Based on the exact degree of over-consolidation interpreted for this layer, it would be subject to substantial consolidation under the new fill load. Where the layer is thickest, anticipated consolidation settlements are in the order of 4.7 m. For petrochemical facilities, typically, the total settlement should not exceed 100 mm (Ramasamy and Kalaiselvan, 1998). Additionally, the differential settlement of petrochemical tanks should be limited to 0.5% to 2.5% of the diameter of the tank (D'Orazio and Duncan, 1987; Ramasamy and Kalaiselvan, 1998). Therefore, the anticipated settlement magnitudes without improving the problematic soil are substantially beyond the settlements that can be tolerated by critical petrochemical facilities. This requires consideration of the following three broad alternatives:

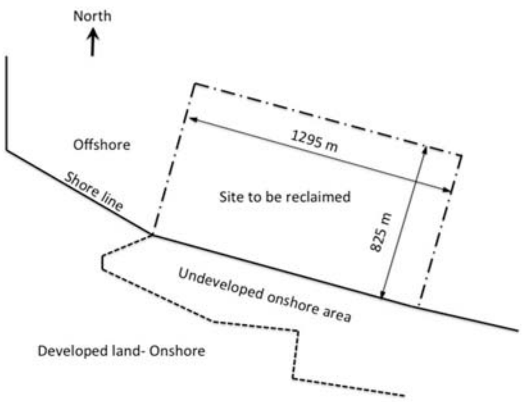

Figure (1): Site to be reclaimed (not to scale)

1. Placing critical facilities on foundations that will transmit loads to deeper less compressible geologic units and allow site grade to settle relative to the facilities, or
2. Improving the soft clay layer under and in the immediate vicinity of critical facilities, so that critical facilities can be placed on shallow foundations, or
3. Stilling place facilities on deep foundations, but improving the clay layer under and in the immediate vicinity of critical facilities sufficiently, so that eventual site grade settlement relative to the deep foundation-supported facilities would be of acceptable magnitudes.

The aim of this feasibility study is to evaluate the third alternative and in particular whether ground improvement could be successfully applied during the site reclamation period, without impact on schedule. In particular, the portion of the site where critical facilities of the plant are to be located is the main focus of this study.

The ground improvement alternatives (Bell, 1993; Hausmann, 1990) considered for improvement of the highly compressible clay unit included: (i) excavation of the clay layer and replacing it with sand fill; (ii) deep soil mixing; (iii) jet grouting; (iv) prefabricated vertical drains (PVDs) with preload fill; and (v) sand drains with preload fill. In addition to the methods considered for improving the clay unit, two ground improvement methods were considered if it became necessary to increase the density of the new fill placed below water level. These methods were (a) vibro-compaction; and (b) deep dynamic compaction.

Evaluation of Targeted Ground Improvement

Area of Consideration

The focus of this feasibility study is the area where critical facilities are planned to be located. This area (hereafter referred to as TGI-A implying targeted ground improvement area) is situated along the western portion of the projected land reclamation area as shown in Figure 2. TGI-A is rectangular with dimensions of approximately 675 m x 265 m, resulting in a plan area of 179,000 m^2.

The feasibility of implementing the ground improvement options listed above is evaluated herein. For each option, strengths, weaknesses, opportunities and threats were considered and analyzed (SWOT analysis). A summary of these analyses is presented in Tables 1 through 4; these tables will be collectively referred to as SWOT tables. The objective here is to identify the ground improvement options that, based on an evaluation of technical feasibility (i.e., effectiveness), constructability and cost, warrant further/more detailed evaluation.

Excavation and Replacement

This option includes removal of the soft clay layer within the TGI-A limits. The excavation will be made using hydraulic dredging equipment. Sand fill from the dredging operation will be placed in such a way as to minimize mud waves (Kwong et al., 2001). Following completion of the excavation and replacement activity within TGI-A, the remainder of the offshore reclamation area and onshore area will be raised to turnover elevations (i.e., +2.5 m LAT for onshore area and +3.5 m LAT for offshore area).

Based on information provided in the SWOT tables, the excavation and replacement option is technically feasible (see Table 1). The key issues affecting further consideration of this option include:

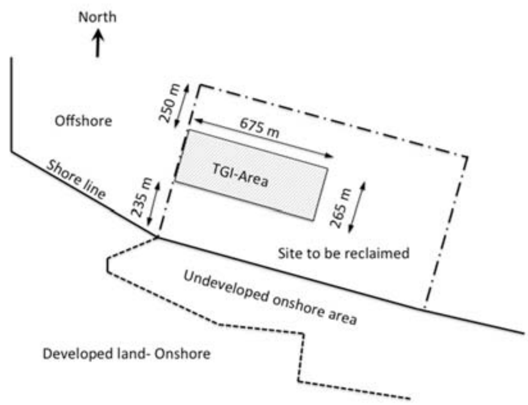

Figure (2): The area of targeted ground improvement (TGI)

Table 1. Analysis of strengths of TGI options

APPROACH	STRENGTHS
EXCAVATION AND REPLACEMENT	Established, well known procedure with successful track record Anticipated easy acceptance by EPC
DSM	Accepted method worldwide Quantifiable design Eliminates liquefaction potential Has been successfully used under petrochemical /LNG plants Quality control essential during installation
JET GROUTING	Quantifiable design Can readily verify strength of material Eliminates liquefaction potential Quality control essential during installation
PVDs WITH PRELOAD	Proven track record worldwide Use at this site would follow conventional application
SAND DRAINS WITH PRELOAD	Used worldwide Drains, if installed correctly, can be more reliable than PVD Improves the stiffness (modulus) of the soft clay layer
VIBRO-COMPACTION	Appropriate method to remediate liquefaction potential Improves overall foundation stiffness Reduces liquefaction potential Reduces settlement
DEEP DYNAMIC COMPACTION	Can eliminate liquefaction potential Relatively easy/unsophisticated method that does not require highly specialized equipment Reduces settlement

Table 2. Analysis of weaknesses of TGI options

APPROACH	WEAKNESSES
EXCAVATION AND REPLACEMENT	May require densification/ improvement to preclude liquefaction Additional dredging equipment required to meet schedule
DSM	Limited previous experience in petrochemical plants/LNG tanks to improve clay soils Acceptance by LNG tank vendors would have to be assured
JET GROUTING	Size of column variable with soil profile Potential to generate significant spoils Requires post construction verification program Acceptance by EPC and tank vendors would have to be assured
PVDs WITH PRELOAD	Some uncertainty in time rate of settlement PVDs need to be stored away from sunlight Requires reliable instrumentation and monitoring Potential impact on foundation construction start date Requires additional site investigation to verify goals having been achieved
SAND DRAINS WITH PRELOAD	As for PVDs
VIBRO-COMPACTION	Requires post-construction verification Results sometimes erratic
DEEP DYNAMIC COMPACTION	May not improve entire targeted depth Requires experimentation to minimize variability in results Requires post-construction verification program

Table 3. Analysis of opportunities of TGI options

APPROACH	OPPORTUNITIES
EXCAVATION AND REPLACEMENT	Provides opportunity to utilize shallow foundations
DSM	Provides opportunity to utilize shallow foundations Can be used easily in other targeted areas if needed to optimize site layout Can do selected vertical (of discrete depth intervals) and areal improvement Do not need the world's largest DSM equipment (depths required < 20m)
JET GROUTING	Provides opportunity to utilize shallow foundations Can be used easily in other targeted areas if needed Can do selected vertical (of discrete depth intervals) and areal improvement
PVDs WITH PRELOAD	Provides opportunity to utilize shallow foundations if preload height and duration are sufficient as verified by careful instrumentation and monitoring
SAND DRAINS WITH PRELOAD	As for PVDs
VIBRO-COMPACTION	Would allow plant to be placed on shallow footings Reduces risk of liquefaction Could allow sourcing of all sand from turning basin, reducing reclamation cost
DEEP DYNAMIC COMPACTION	Would allow plant to be placed on shallow footings Reduces risk of liquefaction Could allow sourcing of all sand from turning basin, reducing reclamation cost

Table 4. Analysis of threats of TGI options

APPROACH	THREATS
EXCAVATION AND REPLACEMENT	Potential side slope failures and mud flows into excavated area Potential liquefaction risk if adequate placement density is not achieved Soft soils may remain at base Silt and mud in water may settle out to bottom of excavation while open Silt and mud in water may be trapped in sand placed
DSM	May end up with unacceptable product if not installed by experienced specialty contractor High organic content may require special cement/mixing
JET GROUTING	May end up with unacceptable product if not done by experienced specialty contractor
PVDs WITH PRELOAD	Rate of primary consolidation may be slower than expected, requiring more fill Risk of disturbance and slower drainage with improper mandrel May require post-construction densification program to mitigate liquefaction potential (only in reclaimed soils)
SAND DRAINS WITH PRELOAD	Rate of primary consolidation may be slower than expected, requiring more fill Risk of necking of sand drains if installed without proper sleeve May require post-construction densification program to mitigate liquefaction potential (only in reclaimed soils)
VIBRO-COMPACTION	Ineffective if fines /silt content in fill is higher than ~15%
DEEP DYNAMIC COMPACTION	May be slow if old equipment used Risk of uneven improvement Ineffective if fines /silt content in fill is higher than ~25%

- A specific weakness of this option (see Table 2) is that additional dredging equipment (above that currently anticipated for the Dredging and Land Reclamation (DLR) contract) may be required to implement this option within the available schedule, which is discussed further under schedule analysis.
- Complete removal of the soft clay layer is required to mitigate potential future differential settlements.
- It is possible that the soil fill placed below the water may not achieve the target density required to preclude liquefaction of this layer during the design earthquake event and minimize immediate settlements in the fill layer resulting from shallow footing loads. If relative densities less than approximately 30 percent are measured (or evaluated) in the soil fill after placement, it is likely that additional measures will need to be implemented to increase the relative density of the material. The feasibility of deep dynamic compaction and vibro-compaction in TGI-A towards this objective is described subsequently.

Deep Soil Mixing (DSM)

Deep soil mixing is usually preferred, as it provides friendly economical and environmental solutions when compared with other traditional ground improvement methods (Spagnoli et al., 2016; Topolnicki, 2004). For this method, fill from the dredging operation is assumed to be placed to an approximate elevation of + 1.5 m LAT over the TGI-A area, the minimum reasonable elevation allowing construction trafficability. This elevation represents the top of the working platform for the DSM operation. DSM is anticipated to be performed using a triple auger system to construct DSM columns. The minimum compressive strength of the soilcrete (i.e., material comprising mixed in place soil and grout), DSM column size and column layout will be evaluated as part of a detailed design should this method be selected; however, the target minimum compressive strength is likely to be in the order of 700 kPa. During DSM column construction, spoil material is generated at the ground surface (Bruce, 2000). This material, consisting of soil thoroughly mixed with cement, comprises soilcrete with the consistency of stiff clay and may be used for structural fill if properly compacted. Fill from dredging operations will be used to raise the site grade to the turnover elevation of + 3.5 m LAT. With proper planning, the spoils could be compacted above the DSM columns and form a "mat" up to the bottom elevation of shallow footings. Formwork for footings can be placed directly on this mat and fill to bring the site to + 3.5 m needs not be placed before the footings are poured.

Based on information provided in the SWOT tables, the DSM option is technically feasible. It will allow shallow foundation support and mitigate liquefaction potential (Nguyen et al., 2013). The key issues affecting further consideration of this option include:

- DSM is a specialized construction technique requiring specialty equipment and specialized labor; moreover, a specific weakness of DSM (see Table 2) is that there is limited previous experience for use of DSM as a foundation improvement measure for petrochemical /LNG plants.
- Equipment availability could be an issue, since multiple rigs will be required to be operating to satisfy schedule constraints.
- Some parts of the soft clay soils have relatively high organic content. While DSM may be used in such soils, it will be necessary to perform a laboratory study to evaluate optimal cement/ cement additives (potentially)/ soil mix designs and mixing procedures using the soft clay soil.
- DSM can be effectively used at discrete locations. This represents an opportunity to perform selected area improvement for critical facility locations only (see Table 3).

Jet Grouting

Many of the design features for DSM are similar for jet grouting (Schaefer, 1997). A working platform will be established at +1.5 m LAT. Careful control and monitoring of grout injection pressures, turning speed of the monitor and withdrawal rate of the monitor are required to achieve a repeatable diameter of a jet grout column.

Based on information provided in the SWOT tables, jet grouting is technically feasible. The key issues affecting the further consideration of this option include:

- Jet grouting is a specialized construction technique requiring specialty equipment and specialized labor; moreover, the use of jet grouted columns as a foundation improvement measure for LNG tanks has not to our knowledge been previously used.
- Jet grouting represents one of the most sophisticated ground improvement measures available on the market and is generally most cost-effective when used to improve ground that cannot be treated by other methods. For this reason, the jet grouting technique may be cost-prohibitive for this project.

PVDs with Preload

For large-scale land reclamation, PVDs with preload method is known to provide a very economical solution (Chu and Raju, 2012). For the PVDs with preload approach (Schaefer, 1997), the improved area is anticipated to undergo secondary settlements of less than 10 cm over 20 years. For this approach, to expedite the consolidation of the soft clay layer, PVDs will be installed from a working platform level at about El. +2.0 m LAT to the bottom of the soft clay layer. The plan area to be improved with PVDs should extend to at least three times the thickness of the soft clay layer on each side of TGI-A (i.e., a larger area than TGI-A has to be treated with PVDs). The PVDs will be installed in a triangular pattern with a spacing of approximately 1.5 m. Once the drains are installed, a surcharge load will be applied over the area covered with the PVDs to allow water to drain more rapidly from the clay layer, so that sufficient consolidation can be achieved prior to handover to EPC. After the preloading period, a portion of the surcharge load will be removed. This removal of the surcharge causes the underlying soft clay soil to become over-consolidated such that future foundation loads will result in only relatively small additional settlements in the clay layer.

For the PVDs with preload option, analyses have been performed to evaluate surcharge fill heights, required time period for preloading and amount of surcharge removal required to minimize post-site turnover settlements to acceptable levels. The primary design objective is to design the preload-surcharge fill such that a post-construction settlement due to secondary compression of no more than 5 cm will occur over a period of 20 years. The analysis considers the fact that the average degree of consolidation of the soft clay layer will be less than 100% when the surcharge fill is removed. Table 5 presents the results of analyses conducted for TGI-A during the feasibility study. As can be seen, if the target post-construction settlement is set to 5 cm, the required surcharge fill height will be in the order of 7.3 m in TGI-A-1 and 6.4 m in TGI-A-2 (see Figure 3). The surcharge (preload) volume required in this case will be about 1,651,000 m^3. If the target post-construction settlement is increased to 10 cm, then the surcharge fill height will be 6.5 m and 5.6 m for TGI-A-1 and TGI-A-2, respectively, resulting in a total surcharge volume of 1,353,000 m^3.

The PVDs with preload approach, as presented in the SWOT tables, is appropriate and technically feasible for the site. However, the success of this method is highly dependent on reliable instrumentation and monitoring. A monitoring program for the PVDs with preload option should, at minimum, provide the following information:

- Pore pressures in the soft clay layer.
- Settlement profiles at the surface and in the clay layer.
- Inclinometers and alignment stakes at fill edges to monitor edge stability through evaluation of lateral soil movement.
- Surface monuments outside the targeted area to evaluate the impact in the rest of the reclamation area.

Instrumentation needs to be installed by a suitably experienced specialty contractor and the results should be interpreted by geotechnical engineers who are familiar with site improvement design and experienced in interpreting field data during soft ground construction.

Table 5. Preload volumes required for the PVDs with preload option

Area	Sub-area	Seabed Elevation (m)	Initial thickness of the soft clay layer (m)	Case a: Fill height (preload) above El. +3.5m to get Ss<=5cm	Case b: Fill height (preload) above El. +3.5m to get Ss<=10cm	Preload Volume for Case a (m^3)	Preload Volume for Case b (m^3)
TGI-A	TGI-A1	-1.00	14	7.3	6.5	**1,651,000**	**1,353,000**
	TGI-A2	-1.00	10	6.4	5.6		

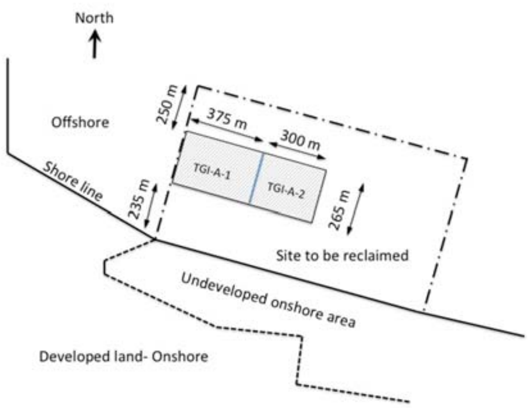

Figure (3): Sub-areas of TGI for PVDs with preload option

Sand Drains

Sand drains are a viable vertical drain option. As for PVDs, the successful implementation of this approach requires a geotechnical instrumentation and monitoring program.

Densification of Sand Fill below Water

An important consideration for the development of this site is the quality of suitable material for land reclamation. The placement density of the sand will depend on the deposition method as well as the grain size distribution of the material. Relative densities of soil fill under water may reach 40 percent for the coarsest material; however, relative densities less than 30 percent should be expected for finer material (i.e., with fines more than about 10 percent).

For the purposes of this feasibility study, it is assumed that adequate relative densities can be achieved for the underwater placement of soil fill associated with all ground improvement options, except for the excavation and replacement option. For options other than the excavation and replacement option, soil fill is placed from the elevation of the current seabed, thus limiting the thickness of placed material (below water) to approximately less than 3 m. The excavation and replacement option requires the removal of 2 to 14 m of the soft clay layer, thus requiring a relatively substantial thickness of soil fill (on average) to be placed under water.

As part of the excavation and replacement option, piezocone penetration testing (CPTu) will likely need to be performed at selected locations following underwater fill placement. If this option is selected, a minimum tip resistance and/or friction ratio could be developed for the soil fill to evaluate in place relative density. Areas which do not meet minimum relative density requirements will likely be subject to additional densification procedures, as described below.

Vibro-compaction

Vibro-compaction is a viable option to densify the sand fill, because it is effective to the depths being considered and is not detrimentally affected by the presence of a high water table (Wightman, 1991). The process may result in the overall grade of the site being reduced by 5 to 15 percent; that is, expected settlements resulting form densification may be in the order of 5 to 15 percent of the thickness of the layer being densified. Penetration points for the vibrator are typically spaced between 1.8 and 4.4 m.

Vibro-compaction, however, may not be effective in densifying granular materials if the fines content is greater than 15 percent and the clay content is greater than 2 percent (Elias et al., 2001). Should relative densities of placed soil fill be deemed too low, it will be necessary to collect placed soil fill samples for laboratory grain size and hydrometer analysis to evaluate the potential effectiveness of vibro-compaction.

Deep Dynamic Compaction (DDC)

Deep dynamic compaction is a viable densification option for this project. DDC is best-suited for deposits with fines contents less than about 25 percent (Lukas, 1995), which is the case for the sand fill to be placed as part of the excavation and replacement option. The maximum depth of improvement that can generally be achieved for tamper weights and drop heights that can be lifted with conventional equipment is in the order of 11 m. For greater improvement depths, such as may be required in the western portions of TGI-A, specialized equipment would be required and even then, maximum depths of improvement of no more than 14 m should be expected. It is likely, however, that an improvement depth of 11 m would be sufficient to increase the "overall" relative density of the sand fill to an appropriate level. Moreover, the confining stresses in the soil itself should be sufficient to mitigate potential liquefaction for layers deeper than approximately 10 m.

RESULTS AND ANALYSES

All ground improvement options considered to this point are technically feasible and the elimination of an option will be based on construction schedule, equipment availability (i.e., number of rigs required to implement a specific option) and/or cost considerations.

The primary driver for the successful implementation of any ground improvement option for this site is the ability to implement the option within an approximate 44-week period of time, which will commence immediately after an 8-week start-up period for the dredging contractor. The estimated volume of material to be dredged/filled as part of the reclamation efforts is 7.6 x 10^6 m^3 of soil if the additional excavation and replacement volume is not considered. This volume is based on the likely fill quantities required to establish post reclamation grades of +3.5 m LAT in the offshore reclamation area and +2.5 m LAT in the onshore area.

Considering that this volume of soil would need to be placed in a 44-week period, the resulting average dredging/filling production rate is 173,000 m^3 per week. For this feasibility study, an average dredging/filling production rate of 175,000 m^3/week is used.

Quantities of Targeted Ground Improvement

Specific work element quantities were estimated for each ground improvement option. These quantities are provided in Table 6. The following clarification on quantities should be noted:

Excavation and Replacement: The volume of 2,360,000 m^3 of cut volume was developed by projecting an 8H:1V slope from the bottom of the soft clay layer to the mud line elevation. This volume is also assumed to represent the amount of fill material to be replaced in the excavation.

Deep Soil Mixing and Jet Grouting: The volume to be improved by DSM or jet grouting in TGI-A was developed assuming an area of improvement of 685m x 285 m at the mud line and projecting vertically down to the elevation of the soft clay layer over this area. This plan area includes an additional improvement depth of 10 m along the edges of TGI-A. For an estimated volume to be improved of 1,850,000 m^3, an average depth of improvement of 9.5 m is estimated. For scheduling and cost evaluation, it is assumed that DSM or jet grouting columns would constitute 33 percent of this volume.

Table 6. Summary of quantities for the ground improvement options considered

APPROACH	QUANTITY	HOW THIS QUANTITY WAS ESTIMATED:
EXCAVATION AND REPLACEMENT	2.36 Mm^3	675 m x 275 m improvement area was considered. Soft clay layer to be removed and replaced with sand considering 1V:8H side slopes.
DSM	1.85 Mm^3 *	685 m x 285 m improvement area was considered. Depth of improvement: average 9.5 m.
JET GROUTING	1.85 Mm^3 *	685 m x 285 m improvement area was considered. Depth of improvement: average 9.5 m.
PVDs WITH PRELOAD	1,800 km	PVDs extend from bottom of the soft clay layer to El. +4.5 m with 1.5 m triangular spacing. Improvement area (675 m x 275 m) increased by 3 x thickness of the soft clay layer on N, S and E sides.
SAND DRAINS WITH PRELOAD	1,350 km	Sand drains extend from bottom of the soft clay layer to El. +4.5 m with 2 m triangular spacing. Improvement area (675 m x 275 m) increased by 3 x thickness of the soft clay layer on N, S and E sides.
VIBRO-COMPACTION	1.85 Mm^3	685 m x 285 m improvement area was considered. Depth of improvement: average 9.5 m.
DEEP DYNAMIC COMPACTION	196,000 m^2	685 m x 285 m improvement area was considered.

PVDs with Preloading: PVDs are assumed to extend from a working platform elevation of +2 m to the bottom of the soft clay formation and are placed with a 1.5 m triangular spacing. The area of improvement includes the plan area of TGI-A plus approximately three times the thickness of the soft clay layer along the north, south and east sides of TGI-A. For the specific evaluations performed herein, the platform elevation is reduced to facilitate early-on placement of the PVDs.

Sand Drains with Preloading: Quantities for sand drains were developed similarly as for PVDs, except that the assumed triangular spacing of the sand drains is 2 m.

Vibro-compaction: Where additional methods are considered to densify soil fill placed under water, it is assumed that the entire thickness of material from the bottom of the soft clay layer (i.e., the bottom of the excavation) to water elevation requires densification. The volume described above for the excavation and replacement option is only up to mud line and, as previously indicated, results in an average depth of 9.5 m. Herein, an average mud line elevation of -1.5 m LAT and an average water surface elevation of +1 m LAT are assumed, thus an additional volume of soil equivalent to a 2.5 m thickness over the plan area of TGI-A is used for estimating purposes for this option, resulting in a total thickness for vibro-compaction of 12 m.

Deep Dynamic Compaction: As for vibro-compaction, the assumed total depth of improvement for DDC is 12 m. The area for improvement is the same as for vibro-compaction.

Cost Analysis

Table 7 provides a summary of estimated costs for construction for the ground improvement options being considered for TGI-A. Unit cost and quantities used for making the estimate are also provided. These costs do not include costs associated with the reclamation of the onshore and offshore portions of the site. It is noted that equipment availability will be a key issue. Unit costs used in this estimate are U.S. costs, rather than local costs for the site area.

The following observations are drawn:

- DSM and jet grouting are similar technologies providing a reasonably similar product. They both require specialized equipment and labor and it is reasonable to remove jet grouting from further consideration, because it is cost-prohibitive as compared to DSM.
- PVDs and sand drains (in conjunction with a preload) would strengthen the soft clay soil by accelerating consolidation, thus allowing the soil to become denser, less compressible and stronger. According to Elias et al. (2001), PVDs are almost exclusively used on U.S. projects where both PVDs and sand drains would be technically feasible. Limitations which may make sand drains more feasible for a specific project include constraints related to limited headroom, near-surface obstructions, extreme depth or site accessibility; none of these restrictions are present in this project. Also, Table 7 indicates that PVDs are less expensive than sand drains. This information indicates that sand drains with preloading should no longer be considered in the feasibility study and that PVDs should be exclusively considered for a vertical drain option for the project.
- Vibro-compaction appears to be cost-prohibitive compared to DDC.

Schedule Remarks

The dredging/filling activities are scheduled to take no longer than 52 weeks with an initial period of 8 weeks required for site preparation activities, leaving 44 weeks for actual dredging and filling operations. As a result, an additional project constraint is that any soil improvement option of the soft clay layer would need to be completely implemented within the available 44-week period where active dredging/filling is taking place.

Table 7. Estimated costs for the ground improvement options

APPROACH	UNIT COST	QUANTITY	COST IN BASELINE US$ (MOB/DEMOB NOT INCLUDED)
EXCAVATION AND REPLACEMENT	$30-$45/m^3	2.36 Mm^3	$71,000,000-$107,000,000 (Assumes satisfactory relative density obtained below water)
DSM	$75-$90/m^3	1.85 Mm^3 *	$47,000,000-$56,000,000
JET GROUTING	$130-$150/m^3	1.85 Mm^3 *	$80,000,000-$93,000,000 (More work to be done but high end of range is most likely for very high quality columns not needed for this project)
PVDs WITH PRELOAD	$1.5-$2/lm	1,800 km	$3,000,000-$4,000,000 (1. PVDs only; preload removal not included; 2. Allow additional $3 million for instrumentation and post- improvement site investigation)
SAND DRAINS WITH PRELOAD	$3-$4/lm	1,350 km	$4,000,000-$6,000,000 (1. Drains only; preload removal not included; 2. Allow additional $2 to $3 million for instrumentation and post- improvement site investigation)
****VIBRO-COMPACTION**	$7-$10/m^3	1.85 Mm^3	$13,000,000-$19,000,000 (Applies to precluding liquefaction)
****DEEP DYNAMIC COMPACTION**	$10-$22/m^2	196,000 m^2	$2,000,000-$5,000,000 (Applies to precluding liquefaction)

* Actual cement columns ≈ 1.85/3 Mm^3.

** One of these methods may need to be added to the excavation and replacement option if the reclamation method does not yield minimum relative density of 30 percent for sand fill below water.

The remaining ground improvement options to be considered for TGI-A include: (i) excavation and replacement; (ii) excavation and replacement with vibro-compaction; (iii) excavation and replacement with DDC; (iv) DSM; and (v) PVDs with preload. Analyses indicated that any of these alternatives can be implemented in the available 44-week period. The following remarks are to be made:

Excavation and Replacement Option without Densification

For this option, to meet the schedule requirement, two dredgers are required. The first dredger begins excavation at the western limit of TGI-A. While this excavation is occurring, the second dredger is filling in areas of the site away from TGI-A (as part of the overall reclamation of the site). When the excavation of the soft clay has proceeded sufficiently eastward (away from the western limit), it is assumed that the second dredger is deployed to TGI-A to begin backfilling operations at the western limit and to progressively follow the first dredger. Herein, it is assumed that after 8 weeks of excavation have occurred (resulting in an excavated volume of 8 weeks × 175,000 m^3/week = 1,400,000 m^3), the backfilling operations would begin. The total time required to complete the reclamation activities, based on an assumed dredge/fill production rate of 175,000 m^3/week, is 44 weeks.

Excavation and Replacement Option with Densification

For this option, it is assumed that when 10 weeks of backfilling have occurred in TGI-A, additional filling is performed over TGI-A to bring the grade to El. +1.5 m LAT. This elevation represents the working platform elevation for both vibro-compaction and deep soil mixing. As soon as the platform elevation is established, either vibro-compaction or DDC commences. 23 weeks are available to implement the vibro-compaction option or the DDC option. Calculations indicate that 1,704 rig days and 220 rig days, respectively, are required to implement the vibro-compaction or DDC option. For 23, 6-day workweeks (i.e., 138 workdays), this would require that 13 vibrators be available to perform the work for vibro-compaction and 2 cranes and tampers be available to perform the work for DDC over the entire 23-week period.

Deep Soil Mixing

After initial preparations, 40.5 weeks are available to implement DSM for the project. Immediately following the construction of the soil platform to El. +1.5 m, DSM can begin. For improvement of TGI-A, 2,056 rig days are required to implement DSM. Therefore, 9 DSM rigs operating throughout the 40.5-week period would be required. It is possible to use a smaller number of rigs earlier in the project (i.e., less than 9 rigs) and to later be operating with more rigs (i.e., more than 9 rigs) to meet the schedule.

Based on an anticipated spoil volume of 20 to 25 percent of the theoretical volume of a DSM column, approximately 123,000 m^3 of spoil soilcrete will be generated. This quantity of spoil is sufficient to provide a 0.7-m thick layer over TGI-A. This fill could be placed using conventional earthwork equipment in approximately 1 week.

PVDs with Preload

For the PVDs with preload option, the targeted area (TGI-A) is divided into two sub-areas (TGI-A-1 and TGI-A-2), as shown in Figure 3. The available time period for the preload application is 4 months (i.e., the maximum time that preload can be in place) and after this period, the preload is to be removed and used as fill material in other portions of the reclamation area. The fill height and fill volume for each of the sub-areas were calculated and are presented in Table 5. For the purposes of this feasibility study, the following construction sequence is recommended:

1. Fill area TGI-A-1 with dredged material to El. +2.0 m LAT and continue dredging and filling in other portions of the reclamation area to establish a working platform at El. +2.0 m LAT.
2. Install PVDs in sub-area TGI-A-1. Note that this area is critical, as it is underlain by the thickest layer of the soft clay. Dredging and filling continue in the rest of reclamation area.
3. Installation of PVDs in area TGI-A-1 will be immediately followed by placement of preload.
4. Start the consolidation time of 4 months for area TGI-A-1.
5. There will be no pause in the installation of PVDs. As soon as installation in TGI-A-1 is complete, installation in TGI-A-2 will commence.
6. While area TGI-A-1 is preloaded, PVDs will be installed in area TGI-A-2.

7. Installation of PVDs in area TGI-A-2 will be immediately followed by placement of preload.
8. Continue dredging and filling in the rest of the reclamation and onshore areas.
9. Remove preload of TGI-A-1 and use it in other portions of the site as fill material at a rate of 30,000 m^3/day.
10. Remove preload of TGI-A-2 and use it in other portions of the site as fill material at a rate of 30,000 m^3/day.
11. Handover site to EPC.

SUMMARY AND CONCLUSIONS

The purpose of this feasibility study was to evaluate various ground improvement measures that could be used to limit future settlements of the portion of reclamation area where critical structures of a petrochemical plant will be constructed. The presence of the soft clay layer poses significant challenges. If the layer is not improved and facilities are placed on deep foundations, site grade will settle substantially relative to facilities over much of the site. To eliminate or reduce this concern, a design criterion has been considered which would limit future (i.e., post-site handover) settlements of areas where foundations are to be constructed to less than 50 cm. Detailed evaluation of reasonably achievable site improvement methods has shown that once ground improvement is undertaken, the cost and schedule impact to improve this criterion to less than 10 cm over a 20-year period is not prohibitive.

Several options were considered in this feasibility study with technical feasibility (i.e., effectiveness), construction schedule and cost, being the primary criteria used to judge such options.

Options which were shown to be technically viable include: (1) excavation and replacement; (2) deep soil mixing; and (3) prefabricated vertical drains (PVDs) with preload. These options were found to limit future settlements to less than 10 cm following the site handover.

The excavation and replacement option is the most expensive option with estimated costs ranging from $71 to $107 million. This option can be implemented within the available 44-week period. In general, risks associated with this option are minor; however, for this project, a significant portion of the work will require underwater fill placement. Unless specific measures are implemented, the density of the fill placed under water may be relatively low and, since the potential for liquefaction under the safe-shutdown earthquake (SSE) is a potential concern at this site, it is important that a certain minimum threshold density be achieved for the sand fill (i.e., replaced soil). This concern can likely be mitigated if clean and coarse sand fill is used exclusively. If needed, additional densification measures, such as deep dynamic compaction or vibro-compaction, could be used. Both of these options are expected to improve the underwater sand fill to an acceptable minimum density that would preclude liquefaction during the design earthquake event. The additional costs associated with these options are $2 to $5 million for deep dynamic compaction and $13 to $19 million for vibro-compaction.

The deep soil mix option ranges in cost from $47 to $56 million. With this option, cement would be mixed into the soft clay layer, resulting in a gross sense in a stiffer and stronger “soil-cement” layer capable of supporting shallow foundations within the previously described settlement tolerances. With DSM, the ability to achieve the required strength and stiffness of the soil-cement reduces as the clay content increases. It is noted that 9 DSM rigs would be required to perform the work. This equipment is highly specialized and equipment availability would need to be absolutely understood before this option is selected.

The PVDs with preload option ranges in cost from $3 to $4 million (instrumentation is not included and may be assumed to add further $2 to $3 million) for the improvement area considered. This option requires a continuous process of soil filling, PVD installation, preload installation, consolidation under the preload loading and preload removal. The vast majority of these costs is associated with earthwork operations. The PVDs with preload option may be used without any impact on schedule for site handover. Since approximately 3 m of soil fill will be placed below water to establish the working platform for PVD installation, it is necessary that clean sand be used. To implement additional densification measures (as may be required for the excavation and replacement option) would likely result in a schedule increase and logistical difficulties which would make the implementation of this option impractical. The largest uncertainty for the successful implementation of this option is the time required to allow the soft clay to undergo sufficient consolidation. If this period were to double from 4 months (assumed herein) to 8 months, the net effect on schedule would be an increase of about 4 months. It is noted that there seems to be no merit to the concept of installing PVDs without preload, other than that most or all of the fill-induced settlements would have occurred by the time the site handover takes place.

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