Intrafor is a leading ground improvement specialty contractor, providing ground treatment for different types of constructions including mega civil engineering and infrastructure projects around the world. With a reputation for reliability and innovation, our experienced design engineers and workforce deliver cost-effective and constructible solutions to our clients’ most complex foundation and geotechnical engineering challenges.

Intrafor specialises in all aspects of ground engineering projects by employing specialists and innovative construction techniques. Intrafor is capable of performing ground improvement work associated with retaining structures, soil improvement and environmental protection.

A ground improvement specialist, Intrafor has in-house resources and expertise to design and implement optimal ground improvement technologies to complement virtually any ground conditions. Intrafor’s track record has delivered highly reliable ground improvement solutions for projects such as communication networks (roads and highways); industrial buildings and platforms; commercial buildings and storage areas; harbour platforms; reclamation projects and airport construction projects.
Vibratory Ground Improvement

All successful civil and structural engineering projects depend on sound and solid foundations. The design process initiates detailed geotechnical engineering evaluation to determine the most appropriate and cost-efficient design solution. Ground improvement is one of the many forms of ground engineering options available to circumvent weak foundation materials such as soft and compressible soils, peaty clay and organic soils, under-consolidated ground conditions and newly reclaimed land. Intrafor is capable of integrating different types of ground improvement options into the overall final design and construction schemes of any project. Frequently, Intrafor provides value engineering alternatives and viable cost-effective ground treatment solutions to strengthen poor ground conditions. With in-house design capabilities, Intrafor offers a wide range of ground improvement techniques to overcome problematic soil formations associated with unsuitable weak foundation materials and compressible ground conditions.

Intrafor offers the following Ground Improvement techniques:

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<th>Techniques</th>
<th>Vibratory</th>
<th>Cementitious Grouting</th>
<th>Other Methods</th>
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<tr>
<td>Vibro Compaction</td>
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<tr>
<td>Vibro Stone Columns</td>
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<tr>
<td>Permeation</td>
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<td>Hydrofracture</td>
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<td>Jet Grouting</td>
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<td>Compaction Grouting</td>
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<tr>
<td>Ground Freezing</td>
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<tr>
<th>Benefits</th>
<th>Improve bearing capacity</th>
<th>Overcome differential settlements</th>
<th>Increase settlement time</th>
<th>Groundwater control</th>
<th>Minimize liquefaction potential</th>
<th>Increase erosion resistance</th>
<th>Improve base / slope stability</th>
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<tr>
<td>Improve bearing capacity</td>
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<td>▼</td>
<td>▼</td>
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<tr>
<td>Accelerate settlement time</td>
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<td>Minimize liquefaction potential</td>
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<td>Increase erosion resistance</td>
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<tr>
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</tbody>
</table>

The different types of ground improvement techniques shown in the previous page can be applied to many civil and structural engineering projects involving bearing capacity requirements; settlement control associated with soft ground formations and seismically active ground conditions; minimising liquefaction potential; groundwater control; cut-off barrier wall and excavation bottom plug; foreshore stability and erosion resistance; excavation and lateral support and improving shear resistance requirements.

**Applicability of foundation soil improvements to different structures and soil types**

<table>
<thead>
<tr>
<th>Category of Structure</th>
<th>Structure</th>
<th>Permissible Settlement</th>
<th>Usual pressure required kPa</th>
<th>Loose cohesionless soils</th>
<th>Soft alluvial deposits</th>
<th>Old, uncontrolled inorganic fills</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office / Apartment</td>
<td>High-rise; more than 6 stories</td>
<td>Small; &lt;25-50mm</td>
<td>&gt;300</td>
<td>High</td>
<td>Unlikely</td>
<td>Low</td>
</tr>
<tr>
<td>Frame or load-bearing construction</td>
<td>Medium-rise; 3-6 stories</td>
<td>Small; &lt;25-50mm</td>
<td>&lt;200</td>
<td>High</td>
<td>Low</td>
<td>Good</td>
</tr>
<tr>
<td>Frame or load-bearing construction</td>
<td>Low-rise; 1-3 stories</td>
<td>Small; &lt;25-50mm</td>
<td>100-200</td>
<td>High</td>
<td>Good</td>
<td>High</td>
</tr>
<tr>
<td>Industrial</td>
<td>Frames warehouses and factories</td>
<td>Moderate</td>
<td>100-200</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Industrial</td>
<td>Storage tanks</td>
<td>Moderate</td>
<td>&lt;300</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Industrial</td>
<td>Embankments and abutments</td>
<td>Moderate to high</td>
<td>&lt;300</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

The effect of different ground improvement techniques can be classified by the type of change they deliver to the ground: *change of state, nature or response.*

- **Change of state:** the same ground is made stronger, stiffer and more durable, e.g. vibro compaction
- **Change of nature:** the ground becomes a different material by inclusion of other materials, e.g. jet grouting, permeation grouting
- **Change of response:** the incorporation of other materials transforms the ground into a composite material with enhanced load-carrying or deformation characteristics, e.g. vibro stone columns

The challenges linked to ground variability drive constant discovery and innovation in ground engineering. To measure the success of ground improvement measures, existing ground properties must be known from the outset. Effects of the chosen method are then evaluated during and after treatment. Control testing and assessment of the effectiveness of the treatment are essential in any ground improvement project.
Vibro Compaction

Developed in the 1930s, vibro compaction was the first vibratory ground treatment method used for stabilisation of deep granular soils. Inserting a vibratory probe into the treatable area, the method increases the density of in-situ soils. It is a rapid, economical and sustainable method of ground improvement. Vibro compaction increases bearing capacity [enabling shallow foundation construction], reduces settlement under individual or area loads and mitigates liquefaction potential. Intrafor’s engineers and technicians apply their know-how and experience to select the best equipment and methods to achieve the degree of compaction required by clients for various ground conditions.

Using powerful vibro probes, vibro compaction optimally rearranges cohesionless soil particles. Aided by water jets, a vibro probe is inserted into the soil. Sustained vibration and the constant addition of water reduce the inter-granular forces between the soil particles. This causes soil surrounding the vibro probe to temporarily liquefy and the grains to rearrange into a denser configuration with improved engineering properties.

The Vibro Probe

- Follow-up Tubes
- Vibration Damper
- Electric Motor
- Water Jet Pipe
- Eccentric Weight
- Nose

Vibro Probe Motion

- Circular movements

Effective in
- Sands with fines content < 10%
- Silty Sands < 2% clay
- Hydraulic fill, depending on fill nature
- Marine spoils, if clean and granular

Effect of increasing fines content on effectiveness of vibro compaction after Suzuki, 1995

Vibro compaction is a vibratory ground improvement technique used to densify granular soils with limited fines content by rearranging their particles into a denser state.

Before Vibro Compaction

Loose Original State

After Vibro Compaction

Dense Final State

Top | Vibro compaction in progress
Bottom | Ground subsidence after vibro compaction
Range of treatable soils for vibro systems

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
<th>Gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Passing</td>
<td>Sieve No.</td>
<td>200</td>
<td>100</td>
</tr>
</tbody>
</table>

- **Vibro Replacement / Displacement - Stone Columns**
- **Most Liquefiable Soils**
- **Vibro Compaction**

*Vibro compaction works for Dubai Electricity and Water Authority [DEWA] Substation*

*Vibro compaction was used as a soil improvement method at Tuen Mun – Chek Lap Kok, Hong Kong*

The Vibro Compaction Process

**Penetration**
Aided by water and/or air pressure at the vibro probe’s nose cone, the vibro probe is steadily lowered into the ground to the final design depth. Simultaneously, the side jets are working with a water/air mixture to agitate the sand above, removing fines and forming an annular gap around the vibro probe. Upon reaching design depth, the water/air at the nose cone is reduced or switched off.

**Compaction & Refilling**
The lateral forces around the vibro probe cause the soil to rearrange into a denser formation. The vibro probe is raised in stages and held at each stage whilst compaction takes place. As the vibro probe is raised and compaction happens, coarse granular material is introduced to fill the annular gap during the densification process.

**Completion**
The surface of the compacted area is levelled and densified with a surface compactor. In non-cohesive granular soils, the compacted area may be lowered by 5% to 15% of the overall compacted depth.
Vibro Compaction

Vibro compaction is one of the most commonly used methods to densify hydraulic fills in large reclamation projects around the world. It is a technically proven and cost-effective ground improvement method that enables the construction of buildings without the need for deep foundations.

Applications

Vibro compaction is particularly well adapted to solving ground improvement problems for the construction of:

- Communication networks: roads and railways
- Industrial buildings and platforms
- Commercial buildings and warehouses
- Ports and harbour platforms
- Airports
- Industrial treatment plants and hydraulic works

Design Considerations

Prior to commencing a vibro densification program, Intrafor engineers evaluate the following information pertinent to the project:

- Design loads (structure, surcharge, live, wind and seismic)
- Ground conditions (soil types, properties, groundwater level)
- Foundation type (spread footing, deep foundation)
- Displacement tolerance (vertical and horizontal settlement)
- Site constraint and accessibility

Following the assessment of the above engineering data, Intrafor engineers and technicians can determine the vibratory equipment and resources best suited to the project. Prior to full production work, compaction trials with different grid spacing are often performed to confirm the equipment and method chosen for the project will meet and exceed the project specification requirements.

The following working parameters can be optimised from the compaction trials based on the equipment selected for the site-specific ground conditions:

- Grid spacing
- Lifting
- Holding time
- Backfill material
- Feeding method

The compaction trial is used to demonstrate the construction techniques and equipment selected are capable of meeting the project acceptance criteria. The compaction trial location should be representative of the anticipated production contract work. Pre-compaction trial CPT or borehole investigation is performed to establish the initial soil conditions for comparison with post trial CPT or borehole testing. These are essential for confirming the effectiveness of the compaction trial.

Trial Grid for Vibro Compaction

Legend
- Pre Trial CPT
- Post Trial CPT Pattern A
- Post Trial CPT Pattern B
- Post Trial CPT Pattern C
- Vibro Compaction Point

Top & Bottom
Vibro compaction in progress
Quality Control and Quality Assurance

Prior to any ground treatment works, Intrafor engineers will carry out pre-construction testing to study the site-specific ground conditions of the project. Pre-construction testing includes survey of existing site grade, soil sampling of reclaimed fill with Standard Penetration Testing (SPT) and Cone Penetration Testing (CPT). The determination of the vibration method and working parameters, such as holding time and grid spacing, will be based on the pre-construction test results.

In addition to the initial soil densities, inclusion of silt layers and pockets of silt lenses/soft zones for the entire area will be taken into consideration for the ground treatment method.

Typical Results of Pre and Post CPT of Vibro Compaction with Fines Content Assessment

![Graph showing tip resistance and fines content as a function of depth with various CPT readings and boring points indicated.](image-url)
Typical Printout of Quality Control Monitoring Data for Vibro Compaction Work

Vibro Compaction Record

Job No.:  
Client:  
Project No.:  
Operator:  
Base machine:  MC 64  
ID No.:  296  
Vibro-Tip:  # 53  
ID No.:  

Introduced material:  
2 / 250  
Grain size:  2 / 250 mm  
Density:  2.25 t/m³  

Time:  
Start time:  11:40:41  
Start compaction:  11:50:41  
Total elapsed time:  00:44:26  
Time to bottom:  11:50:20  
End compaction:  12:26:07  

Column-No.:  554  
Date:  14.12.2008  
Location:  
Elevation MSL:  16 m  
Max penetrometer depth:  23.35 m  
Column length:  23.35 m  
Material Consumption:  It. Lieferschein  
Uncompacted Volume:  12.00 m³  
Weight:  27.00 t  

Soil Profile No.:  
Remarks:  
Superintendent:  
Client:  

Post Construction Testing

A Post-Trial Compaction Report with a site specific Method Statement describing the proposed execution of the vibro compaction program will be submitted to the Engineer or the Client for review and approval. The proposed working parameters, such as grid spacing, holding time and lifting steps, will be based on the evaluation of the compaction trial results so that the most economical and constructible ground treatment method can be selected for the project.

The before and after verification testing determines the success of a ground treatment project.

During the vibro compaction work, Intrafor engineers and technicians will perform on-site evaluation of the compaction works using real-time monitoring equipment to gauge the compaction depth and energy input; assess the quality of backfill material; perform post compaction testing by SPT / CPT and ground settlement survey to determine the overall compaction effort for the project.

Typical Post Construction Quality Assurance Verification Testing includes the following:

- Standard Penetration Testing (SPT)
- Cone Penetration Testing (CPT)
- Dilatometer Testing (DMT)
- Pressuremeter Test (PMT)
- Full Scale Load Test
- Shear Wave Velocity Profiling (SASW)
Vibro Stone Columns

Vibratory ground improvement equipment is most suitable for granular soils with less than 10% fines content. The densification of the sandy soils reacts to the vibratory action by shaking and rattling, re-arranging soil grains into a tighter pattern. Hence, the relative density changes from loose to dense state. However, soft and compressible soils, especially interbedded layers of silt and clay with sand deposits, are usually more cohesive in nature. The complex deposits do not react well to the vibratory motion and tend to synchronise with the vibration.

Treatment of these mixed deposits can only be achieved by introducing backfill into the annular space created by the vibro probe. Consisting of coarse aggregate or crushed stone, the backfill forms a dense and stiff reinforcing element. The coarse aggregate/crushed stone within the stone column provides a higher shear resistance to sustain the required bearing capacity of the proposed structures. Sometimes, concrete can be introduced to make the reinforcing elements even stronger to carry much heavier loads.

In summary, vibratory ground improvement includes the following processes to deal with much wider engineering applications in different types of soil conditions:

- Vibro compaction
- Vibro replacement wet top feed stone columns
- Vibro displacement dry bottom feed stone columns
- Vibro concrete column (wet concrete
- Vibro concrete column (dry concrete

As a ground improvement specialist, Intrafor has many years’ experience in vibratory ground treatment techniques and the necessary personnel and resources to design and construct vibro stone column projects to meet our client’s challenging requirements.

**Effective in**
- Interbedded silt and clays
- Silt, sandy silt
- Fine sand, uniform graded
- Sand with fines content >10%
- Depth up to 40m

**Range of treatable soils for vibro systems**

The vibratory compacted crushed stone forming the stone column improves bearing capacity, reduces unacceptable settlement and mitigates the liquefaction potential of the interbedded soil conditions.
The Vibro Stone Columns Process

There are two principal systems for installing stone columns: vibro replacement wet top feed stone columns and vibro displacement dry bottom feed stone columns. Both systems will form a higher carrying capacity stone column element within the soft and compressible ground conditions.

**Penetration**
The jetting action of the water; the probe’s vibratory action and sometimes compressed air from the nose jets help ease the probe to the required treatment depth in the ground. The water jets create an annular space around the probe.

**Replacement**
Stones are fed from the top as the vibro probe lifts. The repenetration of the vibro probe and lateral forces it creates compact the gravel. The vibro probe then lifts in stages. The filling and compaction cycle is repeated in upward increments up to the working platform. Gravel is added as required to form a stone column of dense granular materials.

**Completion**
The process is completed when ground level is reached, forming a well compacted stone column surrounded by densified soil.

**Penetration**
The probe’s vibratory action combined with compressed air from the nose jets help ease the probe to the required treatment depth in the ground.

**Displacement**
The stone column is installed by adding gravel from the bottom through a separate gravel duct alongside the vibroprobe. The filling and compaction cycle is repeated in upward increments up to the working platform. Gravel is added as required to form a stone column of dense granular materials.

**Completion**
The process is complete when the column reaches ground level. The result is a well compacted stone column surrounded by improved soil.

**Wet Top Feed:**
The wet top feed system is mainly used for the treatment of cohesive soils below the water table or in weak silts and clays. Using its own weight, and aided by water jetting and vibrations, the vibro probe penetrates the ground to the required depth. The water jetting flushes loose soil particles out of the bore, forming an annular space around the vibro probe. Following the formation of an open hole, the vibro probe is kept in the ground and the water flow reduced to maintain circulation and to stabilise the bore. Stone is introduced from ground level to the base of the hole via the annulus around the vibro probe and compacted in short lifts.

This is the most common and cost-effective method. However, handling of the spoils generated by the process may make this method more difficult to use, especially in environmentally sensitive areas.

**Dry Bottom Feed:**
The introduction of a bottom feed vibro probe has extended the range of practical applications of vibro methods, including the use of a dry construction technique below the water table. This system uses a stone supply tube attached down one side of the vibro probe to deliver stone to the tip of the vibro probe. The vibro probe penetrates the ground and the supply tube is loaded with stone before continuing down to the required depth under the combined action of the vibrations and self-weight, assisted by compressed air. Additional stone is fed to the top of the vibro probe by a skip bucket system. The stone column is formed and compacted by lifting the vibro probe, repenetrating into the stone backfill and allowing the stone to radially displace the surrounding subsoil to create circular stone columns. This is repeated until the compacted stone column is formed up to the ground surface. The elimination of flushing water in turn reduces the generation of spoil, extending the range of sites that can be treated.
Vibro Stone Columns

Vibro Stone Columns are a technically proven, easy to implement and cost-effective method to increase bearing capacity allowing shallow foundation construction. This is particularly useful for higher load areas on new rejections, such as tanks or infrastructure buildings that are typically designed for piles, but can often be realised using vibro stone columns.

Applications

Vibro stone columns are mainly used for buildings and light industrial development projects. Warehouses, oil tanks, buildings of up to four storeys and, less often, rigid multi-storey buildings have been built on ground improved by vibro stone columns. Increasingly, the vibro stone column method is used to reduce the liquefaction potential of loose fine sands in layered deposits. The method is also used to improve the foundation stability of embankments on soft soils, as well as increasing the shear resistance by the inclusion of stronger material. The stone columns may also act as vertical drains, speeding up the consolidation of the soft soil under the embankment.

Design Considerations

The design approach for vibro stone columns is linked to at least one of the major benefits of site improvement: increased shear resistance, settlement control and/or mitigation of liquefaction potential. Prior to starting any ground treatment works, Intrafor engineers perform pre-construction testing including ground levelling, Cone Penetration Testing (CPT) and soil samplings to understand the project's soil conditions. This initial site investigation helps Intrafor engineers calculate the predicted improvements and establish requirements for actual treatment (settlements, etc…).

To provide an economic design, the following production parameters are determined for vibro stone columns: the number, spacing and diameter of each column and the depth of the columns below the working platform. These parameters must account for the thickness, depth and tip resistance dependent soil modulus of the non-compactable layers. This information is then presented to clients in a trial and zone specific method statement.

The success of vibro stone columns treatments is evaluated during and after the treatment.

Area Replacement Ratio

The Area Replacement Ratio $A_r$ represents the ratio of tributary area influenced by a stone column. The degree of ground improvement can be estimated from the design chart as shown below.

### Example 1:

- **Stone Column Backfill Material:** Friction Angle, $\phi = 40^\circ$  
  - **Stone Column Diameter:** $D = 1.0m$, thus $A_s = 0.785 \times 1^2 = 0.785m^2$  
  - **Spacing of Grid Pattern:** $S = 1.9m$ where $A = 0.866 \times 1.9^2 = 3.13m^2$  
  - **Area Replacement Ratio:** $A_r/A_s = 0.785/3.13 = 25\%$

From the chart above, the basic improvement factor, $N = 2.5$

- **Area of stone column:** $A_s = \pi D^2/4$  
  - **Area of tributary area:** $A = 0.866 S^2$
During the ground treatment work, Intrafor engineers routinely carry out production monitoring to confirm the depth of treatment, energy input and compaction effort, quality and quantity of backfill material, working efficiency of the vibrator, verticality and positional accuracy of the compaction point. Field adjustment of working parameters is also evaluated to accommodate the soil conditions in which the equipment is working at its maximum benefit for the project. Upon completion of the work, field verification testing follows to determine the effectiveness of the ground improvement treatment. Intrafor utilises applicable field verification testing methods mentioned below to prepare a post improvement report for submission to the Engineer and the Client.

### Post Construction Testing

In situ tests are commonly required to measure the improvement and changes in lateral pressure of the soils surrounding the compaction point or stone column. The following available site investigation techniques are applicable:

- Standard Penetration Test (SPT)
- Cone Penetration Test (CPT)
- Flat Plate Dilatometer Test (DMT)
- Pressuremeter Test (PMT)

### Typical soil property changes before and after stone columns

<table>
<thead>
<tr>
<th>Soil data input</th>
<th>Load project</th>
<th>Save project</th>
<th>Report header info</th>
<th>View results</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>Bottom level (m)</td>
<td>Diameter (m)</td>
<td>A/Ac</td>
<td>Ds (MPa)</td>
</tr>
<tr>
<td>1</td>
<td>1.00</td>
<td>0.80</td>
<td>16.17</td>
<td>39.00</td>
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<tr>
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<td>18.00</td>
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<tr>
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<td>11.00</td>
<td>0.80</td>
<td>16.17</td>
<td>27.00</td>
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<tr>
<td>6</td>
<td>12.00</td>
<td>0.80</td>
<td>16.17</td>
<td>75.00</td>
</tr>
</tbody>
</table>

**Column material**
- Dry unit weight: 21,000 kN/m³
- Sat. unit weight: 18,000 kN/m³
- Friction angle: 45.00 Degrees

**Additional notes**
- Settlements calculation according to "Soil API" software
- Effective overburden pressure: 0.00 kPa

**Typical stone column design**

- Bearing Pressure q = 250 kPa
- Shallow Concrete Foundation
- Crushed Rock / Gravel Base
- Stone Columns

**Typical stone column grid and foundation properties**

- Foundation pressure: 80.00 kPa
- Grid type: Triangular
- X column distance: 3.00 m
- Y column distance: 5.57 m
Penny’s Bay Reclamation Disneyland Hong Kong

Phase 1: Vibro Compaction
- Sand compaction and testing
- Compaction volume: 41.5 million m³
- Depth: up to 38m

Phase 2: Vibro Stone Columns & Vibro Compaction Vibro Compaction
- Compaction volume: 600,000m³
- Depth: 12m

Vibro Stone Columns
- Number of columns: 7,500
- Depth: 19m
- Volume of stones: 78,000m³
- Triangular grid-spacing

One of the largest vibro projects ever undertaken, the Penny’s Bay land reclamation for Hong Kong Disneyland comprised about 280 hectares of land. The first two phases of the project were fast track, high priority land formation and infrastructure development contracts essential to the successful and punctual completion of the Disneyland Theme Park.

Challenge

The works had to provide the necessary engineering conditions for the Disneyland Theme Park’s foundations. Tight project timelines were directly tied to the theme park’s opening schedule. The newly formed and treated land had to meet the long-term total and differential settlement criteria and was to be delivered on or before a contractually set deadline. Given the fast-track construction period, acceleration to consolidate the soft and compressible soil could not be achieved by normal means. Time was of the essence and the schedule to complete was critical with no margin for error. A suitable ground treatment option had to be chosen to eliminate unacceptable settlement and to meet the project requirements. Failing this, the land parcel could have been refused for the operations.

Design Solution

Phase 1: Vibro Compaction
To meet requirements relating to strength and settlement, Intrafor carried out vibro compaction and testing works. Stringent amp-depth logs, duration of point, CPT, SPT testing and measurements of settlements carried out before, during and after vibro compaction enabled and confirmed the quality of the works.

Phase 2: Vibro Stone Columns and Vibro Compaction
To accelerate the consolidation process and reduce settlements of reclamation built over soft muds, Intrafor adopted a design approach using vibro stone columns. The vibro stone columns were used to disperse excess pore pressure from the muds and helped consolidate the ground.

Construction

Phase 1: Vibro Compaction
The sand fill was placed 15m above water level to provide a temporary load of 4m above the finished level, with vibro compaction works being carried out from the top of the load to depths reaching 38m. Intrafor achieved the compaction of 41.5 million m³ within the tight 1.5 year deadline by deploying as many as 160 workers operating up to 16 rigs, 24 hours a day.

Phase 2: Vibro Stone Columns and Vibro Compaction
Using the dry bottom feed method, Intrafor installed 78,000m³ of stones and delivered 7,500 columns of 1m in diameter to a maximum depth of 19m. A triangular grid spacing was adopted. An additional 600,000m³ of reclaimed sand was compacted above the head of the stone columns.
The development of Ghantoot Naval Base into a world class facility required substantial land formation to construct all necessary wharfing and berthing requirements for the navy’s operations. The land reclamation necessitated hydraulic filling with a large amount of sand.

Challenges
Sheet piles installed by another sub-contractor retained the fill in the finger piers area. This new hydraulic fill was composed of sand fill - 10m to 11m thick - overlaying the existing ground stratum, itself consisting of loose soil, underlain by layers of decomposed rock and siltstone. The sub-contractor was experiencing difficulties installing the sheet piles to the design toe level.

Design Solution
To enhance the density and mechanical properties of the hydraulic fill, Intrafor designed a Vibro Compaction programme. The sheet piles issue was addressed by improving the properties of the reclaimed fill behind the sheet pile wall down to seabed level. Vibro Stone Columns were required to achieve this goal.

In consideration of movement or vibration of the existing structure, Intrafor designed a square grid pattern of 2.1m spacings for vibro stone columns and 4.1m spacings for vibro compaction.

Construction
Vibro stone columns and vibro compaction points were installed at depths of 9m to 12m from ground level. The project required the construction of 506 vibro stone columns and 306 vibro compaction points of a 1000mm diameter each.

A selected trial area was defined to confirm the design criteria for the vibro stone columns. Post-CPTs were performed to determine the compliance to project specifications.

Other project references for stone columns wet top feed
DEWA Substation – Dubai Marina, UAE
Al Mamara Villa – UAE
Dubai Police Forensic Facility – UAE
KITAF (Trade Center) – UAE
Extension of port de la Condamine – MONACO
The State of Qatar’s steadfast economic growth required the development of the Old Doha Port to meet demand for business and pleasure purposes. The Old Doha (the Big Tree) Port is situated along the Corniche in Doha Bay. The completed redevelopment along with upgraded facilities would provide additional berthing capacity and quayside access for fishing and other water sport recreational use. The soft and compressible foundation soils below the proposed quay wall required major improvement prior to construction.

**Challenge**

Intraor was awarded the ground improvement works to treat the foundation soils below the new quay wall. The seabed of Old Doha Port consisted of layers of very soft sandy silt and silty sand deposits. The subsoils required ground treatment to increase bearing capacity to support the new imposed loadings from the gravity retaining wall structure.

**Design Solution**

Intraor examined and studied the site-specific soil information and decided to improve the foundation soils using a **dry bottom feed vibro displacement method**. The chosen method densified and replaced the loose sandy soils. It also consolidated the soil between the vibro stone columns.

**Construction**

Using the **Dry Bottom Feed method**, Intraor engineers designed a foundation system consisting of vibro stone columns installed in an equilateral triangular spacing of 2.25m. A total of 666 stone columns were completed offshore. The vibro stone columns were 900mm in diameter and about 11.5m below the bay bottom. Aggregate size of 20mm crushed rock was used as backfill material for the vibro stone columns. A “long reach” excavator was employed to deliver the stone backfill to the hopper out in the water. Global Positioning System was installed at the top of the vibro unit for control of the stone column locations.
Reference list of articles for vibro stone column design


10. Duzceer, R. (2003), "Ground Improvement of Oil Storage Tanks using Stone Columns"