Concept and Parameters related to ground improvement illustrated by Case Histories

by

Serge VARAKSIN

Chairman T.C. Ground Improvement (TC 211)
State of the Art Report

17th International Conference on
Soil Mechanics & Geotechnical Engineering

State of the Art Report

Construction Processes
Procédés de Construction

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Alexandria, Egypt
5-9 October 2009
<table>
<thead>
<tr>
<th>Category</th>
<th>Method</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Ground improvement without admixtures in non-cohesive soils or fill materials</td>
<td>A1. Dynamic compaction</td>
<td>Densification of granular soil by dropping a heavy weight from air onto ground.</td>
</tr>
<tr>
<td></td>
<td>A2. Vibrocompaction</td>
<td>Densification of granular soil using a vibratory probe inserted into ground.</td>
</tr>
<tr>
<td></td>
<td>A3. Explosive compaction</td>
<td>Shock waves and vibrations are generated by blasting to cause granular soil ground to settle through liquefaction or compaction.</td>
</tr>
<tr>
<td></td>
<td>A4. Electric pulse compaction</td>
<td>Densification of granular soil using the shock waves and energy generated by electric pulse under ultra-high voltage.</td>
</tr>
<tr>
<td></td>
<td>A5. Surface compaction (including rapid impact compaction)</td>
<td>Compaction of fill or ground at the surface or shallow depth using a variety of compaction machines.</td>
</tr>
<tr>
<td>B. Ground improvement without admixtures in cohesive soils</td>
<td>B1. Replacement/displacement (including load reduction using light weight materials)</td>
<td>Remove bad soil by excavation or displacement and replace it by good soil or rocks. Some light weight materials may be used as backfill to reduce the load or earth pressure.</td>
</tr>
<tr>
<td></td>
<td>B2. Preloading using fill (including the use of vertical drains)</td>
<td>Fill is applied and removed to pre-consolidate compressible soil so that its compressibility will be much reduced when future loads are applied.</td>
</tr>
<tr>
<td></td>
<td>B3. Preloading using vacuum (including combined fill and vacuum)</td>
<td>Vacuum pressure of up to 90 kPa is used to pre-consolidate compressible soil so that its compressibility will be much reduced when future loads are applied.</td>
</tr>
<tr>
<td></td>
<td>B4. Dynamic consolidation with enhanced drainage (including the use of vacuum)</td>
<td>Similar to dynamic compaction except vertical or horizontal drains (or together with vacuum) are used to dissipate pore pressures generated in soil during compaction.</td>
</tr>
<tr>
<td></td>
<td>B5. Electro-osmosis or electro-kinetic consolidation</td>
<td>DC current causes water in soil or solutions to flow from anodes to cathodes which are installed in soil.</td>
</tr>
<tr>
<td></td>
<td>B6. Thermal stabilisation using heating or freezing</td>
<td>Change the physical or mechanical properties of soil permanently or temporarily by heating or freezing the soil.</td>
</tr>
<tr>
<td></td>
<td>B7. Hydro-blasting compaction</td>
<td>Collapsible soil (loess) is compacted by a combined wetting and deep explosion action along a borehole.</td>
</tr>
<tr>
<td>C. Ground improvement with admixtures or inclusions</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------------------------------------------------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>C1. Vibro replacement or stone columns</td>
<td>Hole jetted into soft, fine-grained soil and back filled with densely compacted gravel or sand to form columns.</td>
<td></td>
</tr>
<tr>
<td>C2. Dynamic replacement</td>
<td>Aggregates are driven into soil by high energy dynamic impact to form columns. The backfill can be either sand, gravel, stones or demolition debris.</td>
<td></td>
</tr>
<tr>
<td>C3. Sand compaction piles</td>
<td>Sand is fed into ground through a casing pipe and compacted by either vibration, dynamic impact, or static excitation to form columns.</td>
<td></td>
</tr>
<tr>
<td>C4. Geotextile confined columns</td>
<td>Sand is fed into a closed bottom geotextile lined cylindrical hole to form a column.</td>
<td></td>
</tr>
<tr>
<td>C5. Rigid inclusions (or composite foundation, also see Table 5)</td>
<td>Use of piles, rigid or semi-rigid bodies or columns which are either premade or formed in-situ to strengthen soft ground.</td>
<td></td>
</tr>
<tr>
<td>C6. Geosynthetic reinforced column or pile supported embankment</td>
<td>Use of piles, rigid or semi-rigid columns/inclusions and geosynthetic girds to enhance the stability and reduce the settlement of embankments.</td>
<td></td>
</tr>
<tr>
<td>C7. Microbial methods</td>
<td>Use of microbial materials to modify soil to increase its strength or reduce its permeability.</td>
<td></td>
</tr>
<tr>
<td>C8 Other methods</td>
<td>Unconventional methods, such as formation of sand piles using blasting and the use of bamboo, timber and other natural products.</td>
<td></td>
</tr>
<tr>
<td>D. Ground improvement with grouting type admixtures</td>
<td>D2. Chemical grouting</td>
<td>Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate to either increase the strength or reduce the permeability of soil or ground.</td>
</tr>
<tr>
<td>D3. Mixing methods (including premixing or deep mixing)</td>
<td>Treat the weak soil by mixing it with cement, lime, or other binders in-situ using a mixing machine or before placement</td>
<td></td>
</tr>
<tr>
<td>D4. Jet grouting</td>
<td>High speed jets at depth erode the soil and inject grout to form columns or panels</td>
<td></td>
</tr>
<tr>
<td>D5. Compaction grouting</td>
<td>Very stiff, mortar-like grout is injected into discrete soil zones and remains in a homogenous mass so as to densify loose soil or lift settled ground.</td>
<td></td>
</tr>
<tr>
<td>D6. Compensation grouting</td>
<td>Medium to high viscosity particulate suspensions is injected into the ground between a subsurface excavation and a structure in order to negate or reduce settlement of the structure due to ongoing excavation.</td>
<td></td>
</tr>
</tbody>
</table>

| E. Earth reinforcement | E1. Geosynthetics or mechanically stabilised earth (MSE) | Use of the tensile strength of various steel or geosynthetic materials to enhance the shear strength of soil and stability of roads, foundations, embankments, slopes, or retaining walls. |
| E2. Ground anchors or soil nails | Use of the tensile strength of embedded nails or anchors to enhance the stability of slopes or retaining walls. |
Why Soil improvement?

- To increase bearing capacity and stability (avoid failure)
- To reduce post construction settlements
- To reduce liquefaction risk (sismic area)

Advantages / classical solutions

- avoid deep foundation (price reduction also on structure work like slab on pile)
- avoid soil replacement
- save time
- Avoid to change site
- Save money!
### Soil Improvement Techniques

<table>
<thead>
<tr>
<th>Cohesive soil</th>
<th>Without added materials</th>
<th>With added materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat, clay ...</td>
<td>1 Drainage</td>
<td>4 Dynamic replacement</td>
</tr>
<tr>
<td></td>
<td>2 Vacuum</td>
<td>5 Stone columns</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 CMC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 Jet Grouting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Cement Mixing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Soil with friction</th>
<th>Without added materials</th>
<th>With added materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand, fill</td>
<td>3 Dynamic consolidation</td>
<td>4 Vibroflotation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- Soil characteristics
  - Cohesive or non cohesive
  - Blocks?
  - Water content, water table position
  - Organic materials
  - Soil thickness
  - Structure to support
    - Isolated or uniform load
    - Deformability

- Site environment
  - Close to existing structure
  - Height constraints
  - Time available to build
Preloading with vertical drains

$\sigma = \sigma' + u$

high fines contents soils
Radial and Vertical consolidation

(A) VERTICAL DRAINAGE ONLY

\[ t = \frac{T_v (H_d)^2}{c_v} \]

\[ \bar{U}_v = f(T_v) \]

IMPERVIOUS BOUNDARY

VERTICAL SEEPAGE ONLY

(B) RADIAL DRAINAGE ONLY

\[ t = \frac{T_h D^2}{c_h} \]

\[ \bar{U}_h = f(T_h, \frac{D}{d_w}) \]

\[ n = \frac{D}{d_w} \]

COMBINED VERTICAL AND RADIAL DRAINAGE

\[ \bar{U} = 1 - (1 - \bar{U}_v)(1 - \bar{U}_h) \]

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Vertical drains: material

High fines contents soils

Flat drain

Circular drain

5 cm, PVC
vertical drain + geotextile

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Vertical Drains
### Vertical drains

<table>
<thead>
<tr>
<th>CONCEPT</th>
<th>PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Stable subsoil for surcharge</td>
<td>1 – Depth</td>
</tr>
<tr>
<td>- Soil can be penetrated</td>
<td>2 – Drainage path</td>
</tr>
<tr>
<td>- Time available is short</td>
<td>3 – Cohesion</td>
</tr>
<tr>
<td>- Some residual settlement is allowed</td>
<td>4 – Consolidation parameters</td>
</tr>
</tbody>
</table>

(oedometer, CPT)

\[ e_0, C_C, C_V, C_R, C_\alpha, t, \]

CPT dissipation test
Vacuum Consolidation (high fines contents soils)

VACUUM (J.M. COGNON PATENT)

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**Vacuum Consolidation**

### Concept

- Soil is too soft for surcharge
- Time does not allow for step loading
- Surcharge soil not available
- Available area does not allow for berms

### Parameters

<table>
<thead>
<tr>
<th>1</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Drainage path</td>
</tr>
<tr>
<td>3</td>
<td>Condition of impervious soil</td>
</tr>
<tr>
<td>4</td>
<td>Watertable near surface</td>
</tr>
<tr>
<td>5</td>
<td>Absence of pervious continuous layer</td>
</tr>
<tr>
<td>6</td>
<td>Cohesion</td>
</tr>
<tr>
<td>7</td>
<td>Consolidation parameters (oedometer, CPT)</td>
</tr>
<tr>
<td></td>
<td>$e_\text{O}$, $C_C$, $C_V$, $C_R$, $C_\alpha$, $t$,</td>
</tr>
<tr>
<td></td>
<td>CPT dissipation test</td>
</tr>
<tr>
<td>8</td>
<td>Theoretical depression value</td>
</tr>
<tr>
<td>9</td>
<td>Field coefficient vacuum</td>
</tr>
<tr>
<td>10</td>
<td>Reach consolidation to effective pressure in every layer</td>
</tr>
<tr>
<td>11</td>
<td>Target approach</td>
</tr>
</tbody>
</table>
Case history – EADS Airbus Plant, Hamburg

General overview of Airbus site
Basic design and alternate concept of Moebius–Menard

Temporary sheet pile wall – in 5 month – dyke construction in 3 years

Dyke construction to +6.5 in 8.5 month and to +9.00 in 16 month

Settlement ≥ 2.0 – 5.5 m

Settlement 0.7 – 1.84 m
## Subsoil characteristics

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Water content</th>
<th>Density</th>
<th>Shear strength</th>
<th>Deformation Modulus (under $\sigma_z = 100$ kN/m$^2$)</th>
<th>Coefficient of consolidation</th>
<th>Coefficient of secondary consolidation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$W$ (%)</td>
<td>$\gamma/\gamma'$</td>
<td>$\delta'(%)$</td>
<td>$C_U$ (kN/m$^2$)</td>
<td>$E_S$ (MN/m$^2$)</td>
<td>$C_V$ (m$^2$/year)</td>
</tr>
<tr>
<td>Mud</td>
<td>142</td>
<td>13/3</td>
<td>20/0</td>
<td>0.5-5</td>
<td>0.8</td>
<td>0.35</td>
</tr>
<tr>
<td>Young clay</td>
<td>119</td>
<td>14/4</td>
<td>20/0</td>
<td>2-10</td>
<td>0.9</td>
<td>0.35</td>
</tr>
<tr>
<td>Clay</td>
<td>70</td>
<td>15/5</td>
<td>17.5/10</td>
<td>5-20</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Peaty clay</td>
<td>139</td>
<td>14/4</td>
<td>20/5</td>
<td>5-20</td>
<td>0.9</td>
<td>0.4</td>
</tr>
<tr>
<td>Peat</td>
<td>240</td>
<td>11/1</td>
<td>20/0</td>
<td>5-15</td>
<td>0.5</td>
<td>$\geq 0.4$</td>
</tr>
</tbody>
</table>
How to move on the mud!

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Case history – EADS Airbus Plant, Hamburg
Case history – EADS Airbus Plant, Hamburg
PORT OF BRISBANE – PADDock S3B

PROJECT OVERVIEW

- Located at the mouth of the Brisbane river;
- New reclamation area: 234 ha enclosed in the Port Expansion Seawall;
- Part of the new reclaimed area to be ready in 5 years;
- Seawall construction completed in 2005;

Port of Brisbane
Sydney 1000 km
PORT OF BRISBANE – PADDock S3B

- GEOTECHNICAL LONG SECTION

![Geotechnical Long Section Diagram]

- SAND CAPping LAYER
- Dredged MUD
- Upper Holocene CLAY/SAND
- Lower Holocene CLAY
- Soft to firm CLAY
- SUBSTRATUM - IMPERVIOUS OLD ALLUVIAL SOIL

~430.0 m

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## GEOLOGICAL PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Dredged Material</th>
<th>Upper Holocene Sand</th>
<th>Upper Holocene Clay</th>
<th>Lower Holocene Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_c / (1 + e_0)</td>
<td>[-]</td>
<td>0.235</td>
<td>0.01</td>
<td>0.18</td>
<td>0.235</td>
</tr>
<tr>
<td>C_a / (1 + e_0)</td>
<td>[-]</td>
<td>0.0059</td>
<td>0.001</td>
<td>0.008</td>
<td>0.0076</td>
</tr>
<tr>
<td>γ</td>
<td>[kN/m³]</td>
<td>14</td>
<td>19</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>C_v</td>
<td>[m²/y]</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>0.9</td>
</tr>
<tr>
<td>C_h</td>
<td>[m²/y]</td>
<td>1</td>
<td>10</td>
<td>10</td>
<td>1.8</td>
</tr>
<tr>
<td>S_u</td>
<td>[kPa]</td>
<td>4</td>
<td>-</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>S_u / σ'_v</td>
<td>[-]</td>
<td>0.25</td>
<td>0.3</td>
<td>0.3</td>
<td>0.2</td>
</tr>
</tbody>
</table>
PORT OF BRISBANE – PADDOCK S3B

GEOLOGICAL SOIL PROFILE

AREA 2a

P474 location

- Water level during construction: RL+7.1m and RL+8.3m at vacuum start
- Working platform at RL+8.6m (thickness=6.8m) as of 22/12/08

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PORT OF BRISBANE – PADDOCK S3B

DESIGN CRITERIA & ASSUMPTIONS

Service Load:
- Zone 1: 36kPa
- Zone 2: 25kPa
- Zone 3: 15kPa
- Zone 4: 5kPa

Residual Settlement (20y):
- Zone 1 to 3: 150mm
- Zone 4: 300mm

Vacuum pumping operation: 18 months

Vacuum depresssure: 75.0 kPa
Calculation of primary and secondary settlement;
- Secondary settlement to commence after primary settlement;
- Change in vertical stress is constant over the depth of the stratum;
- Buoyancy effect on the fill below the groundwater level due to settlement
- Fill to be removed instantaneous at the end of preloading period;
- Design load immediately applied at end of preloading period;
• Up to 15 surcharge steps;
• Up to 30 soil layers;
• Calculation of shear strength increase during consolidation of cohesive soils;
• Different types of drains available: MCD 34, MD88-3, FD767;
• Effect of smear due to mandrel insertion
• Graphical output Settlement / Fill thickness chart
ANALYSIS METHOD

• **Secondary Settlement**

Program uses a method based on Bjerrum’s concept to calculate instantaneous and delayed consolidation (Bjerrum, 1967).

\[
\Delta e = C_{e} \log \left( \frac{20 \text{ years}}{T_{p}} \right)
\]

\[
\Delta H_{\text{primary}} = \frac{Cc}{1+e_{o}} \log \left( \frac{\sigma'_{o} + \Delta \sigma_{\text{final}}}{\sigma'_{o}} \right)
\]
PORT OF BRISBANE – PADDock s3b

CONSTRUCTION SEQUENCE

- VACUUM UNITS
- SEALING TRENCH BY BENTONITE
- MEMBRANE HDPE 1mm
- PROTECTION FILL
- VERTICAL TRANSMISSION PIPES INSTALLATION
- 2ND SURCHARGE PLACEMENT
- VACUUM UNITS
- PERMEABLE LAYER
- SOIL BENTONITE CUT-OFF WALL
- VERTICAL MEMBRANE
- Impermeable Strata

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TYPICAL SBW CONSTRUCTION – LONG SECTION

Full roll of liner
Inner frame
Wheeled frame

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PORT OF BRISBANE – PADDock S3B

- Backfilling works
- Two membrane rolls - overlapping
- Trench excavation works under bentonite slurry
Stress path for Vacuum Process

Surcharge

\[ p' = \frac{2}{3} \sigma'_1 \]

\[ K_0 = 0.5 \]

\[ \sigma'_1 = 80\text{kPa} \]

\[ \sigma'_2 = 80\text{kPa} \]

\[ \sigma'_3 = 80\text{kPa} \]

Vacuum

\[ \sigma'_1 = 80\text{kPa} \]

\[ \sigma'_2 = 80\text{kPa} \]

\[ \sigma'_3 = 80\text{kPa} \]

Active Zone

\[ \varepsilon_h < 0 \]

Passive Zone

\[ \varepsilon_h > 0 \]

\[ K_o (\varepsilon_h = 0) \]

Isotropic

\[ p' = \sigma'_1; K_o = 1 \]

\[ \sigma'_1 = 80\text{kPa} \]

\[ \sigma'_2 = 80\text{kPa} \]

\[ \sigma'_3 = 80\text{kPa} \]

Vacuum Consolidation

\[ K_f (\text{failure line}) \]

\[ \varepsilon_h < 0 \]

\[ \varepsilon_h > 0 \]
Case history : Kimhae (Korea) - 1998
### Soil Improvement Techniques

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Without added materials</th>
<th>With added materials</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cohesive soil</strong></td>
<td>1 Drainage</td>
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</tr>
<tr>
<td></td>
<td>2 VAcuum</td>
<td>5 Stone columns</td>
</tr>
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<td>6 CMC</td>
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<tr>
<td><strong>Peat, clay ...</strong></td>
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<td></td>
</tr>
<tr>
<td><strong>Sand, fill</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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CONCEPT

PARAMETERS

- Age if fill saturated or not
- \( P_L \)
- Selfbearing level
- \( \emptyset \)
- \( E_P \) or \( E_M \)
- \( Q_C, F_R \)
- \( N \)
- R.D. (???)
- Shear wave velocity
- Seismic parameters
- Grain size

DC : \( h(m) = C \delta \sqrt{E} \)

\( C(\text{menard}) = 0.9-1 \)
\( C(\text{hydraulic}) = 0.55 \)

\( \delta \) = SBC
\( \delta \) = LOAD

\( \delta \) = 0.9-1 (SILICA SAND)
\( \delta \) = 0.4-0.6 (SILICA SAND)

S.B.C. = Self Bearing Coefficient
S.B.C. = \( S(t) \)

\( S(\infty) \)
Case History

Nice airport runway consolidation
Granular soil

Very high energy (250 t, 40 m)

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Concept and application of ground improvement for a 2,600,000 m²
Typical Master Plan

- Desalination Plant
- Wind Turbines
- Golf Course
- Golf Course Neighborhood
- Island Neighborhood
- Commercial Center
- University Campus
- Beach Club
- Research Park
- Waste Water Treatment Plant
- Future Residential

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Discovering the Habitants
Areas to be treated

AREAS TO BE TREATED

• AL KHODARI (1,800,000 m²)
• BIN LADIN (720,000 m²)

SCHEDULE

• 8 month
Dynamic Consolidation


(P) Wave:
- Increases pore water pressure
- Dislocates soil matrix

(S) And rayleigh waves:
- Shear soil grains
- Rearrange structure towards denser state
Specifications

• Isolated footings up to 150 tons

• Bearing capacity 200 kPa

• Maximum footing settlement 25 mm

• Maximum differential settlement 1/500

• Footing location unknown at works stage
Depth of footing = 0.8m
Below G.L.

Engineered fill

Working platform (gravelly sand)

Compressible layer from loose sand to very soft sabkah

0 to 9 meters

Concept

150 TONS

$\sigma_z = 200 \text{ kn/m}^2$

+ 4.0

+ 2.5

+ 1.2
(D) = C δ√WH

where: C is the type of drop. Its value is given in Table.
δ is a correction factor. δ = 0.9 for metastable soils, young fills, or very recent hydraulic fills and δ = 0.4 – 0.6 for sands.

Table  Values of coefficient C in the equation

<table>
<thead>
<tr>
<th>Drop method</th>
<th>Free drop</th>
<th>Rig drop</th>
<th>Mechanical winch</th>
<th>Hydraulic winch</th>
<th>Double hydraulic winch</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.0</td>
<td>0.89</td>
<td>0.75</td>
<td>0.64</td>
<td>0.5</td>
</tr>
</tbody>
</table>

The equation has been revised recently by Varaksin and Racinais (2009) as:

\[ f(z) = \frac{f_2 - f_1}{D^2} (z - NGL)^2 + f_1 \]

Where: \( f(z) \) is the improvement ratio at elevation \( z \); \( z \) is the depth in meters; NGL is the natural ground level; \( D \) is the depth of influence of dynamic consolidation; \( f_1 \) is the maximum improvement ratio observed at ground surface and it is dimensionless. The value may be taken as \( f_1 = 0.008E \) and \( E \) is the energy in tons-meter/m²; and \( f_2 \) is the improvement ratio at the maximum depth of influence that can be achieved.
Selection of technique

DR (Dynamic Replacement)

HDR (High Energy Dynamic Replacement) + surcharge

Preloading

Soil Conditions

Working Platform

FPL
WPL
NGL
GWT
BSL (variable)

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Specifications

TYPICAL SITE CROSS SECTION OF UPPER DEPOSITS

SITE ≈ 1.5 km

LAGOON FILLED BY SABKAH

ELEVATION (meters)

<table>
<thead>
<tr>
<th>LAYER</th>
<th>USC</th>
<th>w %</th>
<th>% fines</th>
<th>N</th>
<th>Qc BARS</th>
<th>Fp %</th>
<th>Pl BARS</th>
<th>Ep BARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - SABKAH</td>
<td>SM + ML</td>
<td>35-48</td>
<td>28-56</td>
<td>0-2</td>
<td>0-2</td>
<td>1.2-4</td>
<td>0.4-1.9</td>
<td>avg-17</td>
</tr>
<tr>
<td>2 - LOOSE SILTY SAND</td>
<td>SM</td>
<td>-</td>
<td>15-28</td>
<td>3-9</td>
<td>12-45</td>
<td>0.5-1.2</td>
<td>2.1-4</td>
<td>18-35</td>
</tr>
<tr>
<td>3 - CORAL</td>
<td>-</td>
<td>26-35</td>
<td>-</td>
<td>6-12</td>
<td>-</td>
<td>-</td>
<td>5.1-7.2</td>
<td>35-60</td>
</tr>
<tr>
<td>4 - LOOSE TO MED DENSE SAND</td>
<td>SM</td>
<td>-</td>
<td>12-37</td>
<td>3-18</td>
<td>15-80</td>
<td>0.5-1.8</td>
<td>4-12</td>
<td>28-85</td>
</tr>
</tbody>
</table>

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Variation in soil profile over 30 meters
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Typical surface conditions
ANALYSIS OF \((P_L - P_o)\) IMPROVEMENT AS FUNCTION OF ENERGY AND FINES

K.A.U.S.T. – Saudi Arabia

### BASIS
- 60 grainsize tests
- 180 PMT tests

### PARAMETERS
- \(P_L - P_o\) = pressuremeter limit pressure
- \(\text{kJ/m}^3\) = Energy per \(\text{m}^3\) (E)
- % = % passing \#200 sieve
- \(I\) = improvement factor
- S.I : energy specific improvement factor \(\frac{P_{LF}}{P_{Li}} \times \frac{100}{E}\)

### LEGEND
- Average pre-treatment values
- Average values between phases
- Average post-treatment values
It can be assumed that those impacts du generate a pore pressure at least equal to the pore pressure generated by the embankment load.

This new consolidation process with the final at a time $t'_f$, where

$$ T_V = 0.848 = \frac{C'_v (t'_f - t_1)}{H^2} + \frac{C_v T_1}{H^2} $$

With

$$ C'_v = C_v \left[ 1 + \frac{du}{\Delta\sigma(1-U_1)} \right] $$

The following equation allows to compare the respective times of consolidation being:

$t'_f$ with impact
$t_f$ without impact

$$ t'_f = \frac{du}{du + \Delta\sigma(1-U_1)} t_1 + \frac{\Delta\sigma(1-U_1)}{du + \Delta\sigma(1-U_1)} t_f $$

For the considered case,

$$ du = U\Delta\sigma $$

and thus

$$ t'_f = U_1 t_1 + (1-U_1) t_f $$

The Table allows to compare the gain in consolidation time, at different degrees of consolidation.

<table>
<thead>
<tr>
<th>$U_1$</th>
<th>10%</th>
<th>20%</th>
<th>30%</th>
<th>40%</th>
<th>50%</th>
<th>60%</th>
<th>70%</th>
<th>80%</th>
<th>90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t/t_f$</td>
<td>0.009</td>
<td>0.037</td>
<td>0.083</td>
<td>0.148</td>
<td>0.231</td>
<td>0.337</td>
<td>0.474</td>
<td>0.669</td>
<td>1.00</td>
</tr>
<tr>
<td>$t'/t_f$</td>
<td>0.901</td>
<td>0.963</td>
<td>0.725</td>
<td>0.669</td>
<td>0.615</td>
<td>0.602</td>
<td>0.735</td>
<td>0.735</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Supposing primary consolidation completed

$$ U = 0.9 \quad \text{or} \quad T = 0.848 \quad \text{if} \quad du = U_1 \Delta\sigma, $$

then

$$ t'_f = U_1 t_1 + (1-U_1) t_f $$

The optimal effectiveness occurs around $U_1 = 60\%$.

One can thus conclude that, theoretically the consolidation time is reduced by 20% to 50%, what is for practical purpose insufficient.
Dynamic surcharge
VIBROFLOTS

Amplitude
28 – 48mm

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PORT BOTANY EXPANSION PROJECT

GROUND COMPACTION WORKS

EXTENSION PORT

EXISTING PORT

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GROUND COMPACTION WORKS

EARLY WORKS

NEW TERMINAL AREA

TRENCH FOUNDATIONS / COUNTERFORT BACKFILL

600 M

1300 M

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PORT BOTANY EXPANSION PROJECT

GENERAL ARRANGEMENT COUNTERFORTS INCLUDING RECLAMATION
## PORT BOTANY EXPANSION PROJECT

### RESUME / QUANTITIES

<table>
<thead>
<tr>
<th>PHASE</th>
<th>AREA (M²)</th>
<th>VOLUME (M³)</th>
<th>TECHNIQUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>EARLY WORKS</td>
<td>90.000</td>
<td>650.000</td>
<td>DYNAMIC COMPACTION / VIBRO COMPACTION</td>
</tr>
<tr>
<td>TRENCH FOUNDATIONS</td>
<td>64,000</td>
<td>800.000</td>
<td>OFFSHORE VIBROCOMPACTION</td>
</tr>
<tr>
<td>COUNTERFOURT BACKFILL</td>
<td>92.000</td>
<td>1.330.000</td>
<td>ONSHORE TANDEM VIBRO COMPACTION</td>
</tr>
<tr>
<td>NEW TERMINAL AREA</td>
<td>404.000</td>
<td>5.250.000</td>
<td>DYNAMIC COMPACTION</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>650.000</td>
<td>8.000.000</td>
<td>DC / VC</td>
</tr>
</tbody>
</table>
**PORT BOTANY EXPANSION PROJECT**

**DYNAMIC COMPACTION**

POUNDER WEIGHT 25 TON / 23 METERS HIGH DROP

5.0M X 5.0M GRID / 3 PHASES – 10 BLOWS

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PORT BOTANY EXPANSION PROJECT

- LOAD OUT WHARF – VIBRO COMPACTION V48

UPLIFT STEPS 1.0M / 40 SEC EACH

V48 REQUIRES WATER & AIR FOR COMPACTION

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PORT BOTANY EXPANSION PROJECT

VIEW OF LOAD OUT WHARF – DC / VC WORKING

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1. Except for the upper 50cm, the combination of VC and DC satisfied the $q_c = 15$ MPa (upper 0.5m requires surface roller compaction).

2. Enforced settlement:
   - After VC – 47cm
   - After DC – 27cm
   - Total – 74 cm (~ 10% of treatment depth)

Compaction was less effective in this layer!
## Soil Improvement Techniques

<table>
<thead>
<tr>
<th>Cohesive soil</th>
<th>Without added materials</th>
<th>With added materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peat, clay</td>
<td>1 Drainage</td>
<td>4 Dynamic replacement</td>
</tr>
<tr>
<td></td>
<td>2 VAcuum</td>
<td></td>
</tr>
<tr>
<td>Granular soil</td>
<td>3 Dynamic consolidation</td>
<td>5 Stone columns</td>
</tr>
<tr>
<td>Sand, fill</td>
<td>4 Vibroflottation</td>
<td>6 CMC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7 Jet Grouting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Cement Mixing</td>
</tr>
</tbody>
</table>
Dynamic Replacement

**CONCEPT**

- Very soft to stiff soils
- Unsaturated soft clays
- Thickness of less than 6 meters
- Arching layer available

**PARAMETERS**

- \( C, \phi, \mu, E_y \) of soil, column and arching layers, grid
- \( P_L, E_P, \mu \) of soil, column and arching layers, grid
Stone Columns – Bottom Feed

Vibrator penetration  
Material feeding  
Vibration of material during extraction

Principle of the technology - bottom feed with air tank

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Stone Columns – Bottom Feed

Stone Columns
bottom feed to 22 m depth
**CONCEPT**
- Soft to stiff clays
- Thickness up to 25 meters
- Arching layer available

**PARAMETERS**
- $C$, $\varnothing$, $\mu$, $E_y$ of soil, column and arching layers, grid
- or $P_L$, $E_P$, $\mu$ of soil, column and arching layers, grid
CMC – Execution

- Fleet of specialized equipment
  - Displacement auger => quasi no spoil
  - High torque and pull down
- Fully integrated grout flow control
CMC – Typical Testing

- **Load testing on isolated CMC**
  - Checking of individual capacity,
  - Checking of adequate soil parameters taken into account.

- **Compression tests on material**
  - Checking of good grout resistance

- **Data recording system during execution**
  - Recording of drilling parameters => Checking of anchorage,
  - Recording of grouting parameters => No necking
# Rigid Inclusions - Parameters

<table>
<thead>
<tr>
<th>Soil</th>
<th>Inclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C'$, $\varnothing'$, $E_y$, $\mu$, $\gamma$, $\phi$</td>
<td>$E_y$, $\mu$, $\gamma$, $D$ (non porous medium)</td>
</tr>
<tr>
<td>$K_v$, $K_h$ if consolidation is considered</td>
<td></td>
</tr>
</tbody>
</table>
CMC Principle

- Create a **composite material** Soil + Rigid Inclusion (CMC) with:
  - Increased bearing capacity
  - Increased elastic modulus
- Transfer the load from structure to CMC network with a **transition layer**

![Diagram of CMC Principle](image)

**Transition layer**

**Stress concentration**

**Residual stress**

**Arch effect between the columns**
CMC - Basic behavior under uniform load

- Negative skin friction allows to develop a good arching effect

![Diagram showing settlement and stress in the column]
Axisymmetric FEM calculation with one CMC and the soil => eq. Stiffness

Global axisymmetric calculation by modelising the improved ground by material having an improved stiffness

Complex Soil + CMC with improved characteristics
**CMC Design – Specific case of non vertical loading**

- **Calculation principle**

1/ Estimation of the vertical stress in the column (% of the embankment load),
2/ Thus maximum momentum so that $M / N \leq D / 8$ (no traction in the mortar),
3/ Thus maximum shear force taken by the inclusion (similar to a pile to which a displacement is applied),
4/ Modeling of the CMC as nails working in compression + imposed shear force under TALREN software (or equivalent).

<table>
<thead>
<tr>
<th>Embankment</th>
<th>Soil/CVC</th>
<th>Differential displacement soil/CVC</th>
<th>Pressure soil/CVC</th>
<th>Shear force in the CMC</th>
<th>Bending moment in the CMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft soil</td>
<td>$\delta$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substratum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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CMC Design – Benefits for the structure

- Structure shall be designed as if soil was of good quality
  - Specialist contractor provides structural designer with bearing capacity, k, etc...

- No connection between foundation and structure
  - Structure is less complex to be designed,
  - No stiff connection, thus no increase under seismic analysis,
  - Structure very simple to be built: footings and slab on grade, no pile cap, thus benefit in terms of cost and speed of execution
New Development - CMC Compaction - Principle

- **Aim of CMC Compaction**
  Densify granular material to decrease liquefaction potential

- **Method of densification**
  - Injected mortar used to displace and compact the soil around the injection point
  - Successive injection according to a regular grid induce a global compaction of the soil
  - Mesh and diameter designed so as to achieve a given replacement ratio
New Development - CMC Compaction - Design

- **Principle: Execution and testing procedure**
  - Seismic parameters (seism PGA, Magnitude) => qc soil profile to be achieved (Seed and Idriss methodology)
  - Estimation of Replacement ratio to achieve required qc
  - Execution of Works and testing by CPT
  - Additional grouting if necessary

  Execution of Compaction Grouting as per preanalysis (replacement ratio => mesh and diameter)

  Execution of CPT testing

  Results OK

  Results not OK

  Execution of additional Compaction Grouting in the problematic layers

  Until CPT results are satisfactory
New Development - CMC Compaction - Execution

- Same type of equipment as for CMC
  - Soil displacement rig and Pump,

- Key points
  - Quality of grout (grain size distribution, workability, consistancy)
  - Injection speed and successive phases

- Final Testing = CPT
New Development - CMC Compaction – Fos LNG Terminal

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DCM: Deep Cement Mixing

CONCEPT

Site logistics

Binder storage
Carrier; refilled during execution
Installer; computer controlled & cont. monitoring

The MDM process (1)
Future Caisson Stability Analysis

File Name: Future Caisson at operation stage (undrain) SCP+Sandkey10 gsz

Future Caisson (Type-B) Slip Stability Analysis
At Operation Stage (Undrain) (Undrained)

Factor of Safety: 1.498

改良範囲全体のφは、仕様書により32°を用いる。
Sandkeyのφは35°。

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As built conditions

EXHIBITED DESIGN

- compacted sand fill
  \( \varphi = 35^\circ \)

- dredged line

- natural undisturbed clay
  \( (N \geq 50) \)
  \( C_u = 250 \text{ kN/m}^2 \)

AS-BUILT CONDITION

- compacted sand fill
  \( \varphi = 35^\circ \)

- dredged line

- disturbed softened clay layer (1 - 1.5m)
  \( C_u = 50 \text{ kN/m}^2 \)

- natural undisturbed clay
  \( (N \geq 50) \)
  \( C_u = 250 \text{ kN/m}^2 \)
Proposed solution

**EXHIBITED DESIGN**

- compacted sand fill
  \( \varphi = 35^\circ \)

- 1.3m compacted sand fill
  \( \varphi = 35^\circ \ C = 0 \)

- 1.5m undisturbed clay
  \( \varphi = 0^\circ \ C_u = 250 \text{ kN/m}^2 \)

- natural undisturbed clay
  \( N \geq 50 \)
  \( \varphi = 0^\circ \ C_u = 250 \text{ kN/m}^2 \)

**PROPOSED SOLUTION**

- compacted sand fill
  \( \varphi = 35^\circ \)

- 1.3m compacted rock mat
  \( \varphi = 45^\circ \ C = 0 \)

- 15% rock \( \varphi = 45^\circ \) + 85% clay \( C_u = 80 \text{ kPa} \)

- 1.5m natural undisturbed clay
  \( N \geq 50 \)
  \( \varphi = 0^\circ \ C_u = 250 \text{ kN/m}^2 \)
View of pounder construction
View of pounder ready to work
General SFT up
After compaction actual results

Original rock surface before compaction

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Angle (degree)</th>
<th>Shear Strength (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>48</td>
<td>50</td>
</tr>
<tr>
<td>1.3</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>1.3</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>1.3</td>
<td>48</td>
<td>250</td>
</tr>
</tbody>
</table>

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THANK YOU