INTRODUCTION TO SOIL IMPROVEMENT, PARAMETERS, CLASSIFICATION, CASE HISTORY OF KAUST

Presented by
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17TH INTERNATIONAL CONFERENCE ON
SOIL MECHANICS & GEOTECHNICAL ENGINEERING

STATE OF THE ART REPORT

Construction Processes
Procédés de Construction

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5-9 October 2009

NOTA: TC 17 meeting ground improvement – 07/10/2009
Website: www.bbri.be/go/tc17
<table>
<thead>
<tr>
<th>Category</th>
<th>Method</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Ground improvement without admixtures in</td>
<td>A1. Dynamic compaction</td>
<td>Densification of granular soil by dropping a heavy weight from air onto</td>
</tr>
<tr>
<td>non-cohesive soils or fill materials</td>
<td></td>
<td>ground.</td>
</tr>
<tr>
<td>A2. Vibrocompaction</td>
<td></td>
<td>Densification of granular soil using a vibratory probe inserted into</td>
</tr>
<tr>
<td>A3. Explosive compaction</td>
<td></td>
<td>ground. Shock waves and vibrations are generated by blasting to cause</td>
</tr>
<tr>
<td>A4. Electric pulse compaction</td>
<td></td>
<td>granular soil ground to settle through liquefaction or compaction.</td>
</tr>
<tr>
<td>A5. Surface compaction (including rapid</td>
<td></td>
<td>Compaction of fill or ground at the surface or shallow depth using a</td>
</tr>
<tr>
<td>impact compaction)</td>
<td></td>
<td>variety of compaction machines.</td>
</tr>
<tr>
<td>B. Ground improvement without</td>
<td>B1. Replacement/displacement (including load reduction using light</td>
<td>Remove bad soil by excavation or displacement and replace it by good soil</td>
</tr>
<tr>
<td>admixtures in cohesive soils</td>
<td>weight materials)</td>
<td>or rocks. Some light weight materials may be used as backfill to reduce</td>
</tr>
<tr>
<td>B2. Preloading using fill (including the use</td>
<td></td>
<td>the load or earth pressure.</td>
</tr>
<tr>
<td>of vertical drains)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B3. Preloading using vacuum (including</td>
<td></td>
<td>Fill is applied and removed to pre-consolidate compressible soil so that</td>
</tr>
<tr>
<td>combined fill and vacuum)</td>
<td></td>
<td>its compressibility will be much reduced when future loads are applied.</td>
</tr>
<tr>
<td>B4. Dynamic consolidation with enhanced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>drainage (including the use of vacuum)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B5. Electro-osmosis or electro-kinetic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>consolidation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B6. Thermal stabilisation using heating or</td>
<td></td>
<td></td>
</tr>
<tr>
<td>freezing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B7. Hydro-blasting compaction</td>
<td></td>
<td>Collapsible soil (loess) is compacted by a combined wetting and deep</td>
</tr>
<tr>
<td></td>
<td></td>
<td>explosion action along a borehole.</td>
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</tbody>
</table>
### C. Ground improvement with admixtures or inclusions

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Vibro replacement or stone columns</td>
</tr>
<tr>
<td></td>
<td>Hole jetted into soft, fine-grained soil and back filled with densely compacted gravel or sand to form columns.</td>
</tr>
<tr>
<td>C2</td>
<td>Dynamic replacement</td>
</tr>
<tr>
<td></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>
</tr>
<tr>
<td>C3</td>
<td>Sand compaction piles</td>
</tr>
<tr>
<td></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>
</tr>
<tr>
<td>C4</td>
<td>Geotextile confined columns</td>
</tr>
<tr>
<td></td>
<td>Sand is fed into a closed bottom geotextile lined cylindrical hole to form a column.</td>
</tr>
<tr>
<td>C5</td>
<td>Rigid inclusions (or composite foundation, also see Table 5)</td>
</tr>
<tr>
<td></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>
</tr>
<tr>
<td>C6</td>
<td>Geosynthetic reinforced column or pile supported embankment</td>
</tr>
<tr>
<td></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>
</tr>
<tr>
<td>C7</td>
<td>Microbial methods</td>
</tr>
<tr>
<td></td>
<td>Use of microbial materials to modify soil to increase its strength or reduce its permeability.</td>
</tr>
<tr>
<td>C8</td>
<td>Other methods</td>
</tr>
<tr>
<td></td>
<td>Unconventional methods, such as formation of sand piles using blasting and the use of bamboo, timber and other natural products.</td>
</tr>
</tbody>
</table>
Concept and application of ground improvement for a 2,600,000 m²
The Future Site
JEDDAH, A MODERN CITY
Discovering the Habitants
Areas to be treated

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

Schedule

- 8 month
Dates for soil improvement

KAUST
Dates for soil improvement
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
Concept

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

150 TONS

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

2 meters arching layer

$+ 4.0$

$+ 2.5$

$+ 1.2$

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

(S) Rayleigh waves:
- Shear soil grains
- Rearrange structure towards denser state
**Decision process of selection of technique**

1. **Presence of Silt (Sabkha) layer**
   - **No**
     - **Presence of Deep silt (Sabkha) layer**
       - **No**
         - **Transition layer > 2 m**
           - **Case A**
             - DC
         - **Transition layer < 2 m**
           - **Case B1**
             - DR
       - **Yes**
         - **Deep silt (Sabkha) layer, ie bottom elevation lower than 5 m below Working Platform Level**
           - **Case B2**
             - Sabkha Substitution over 1 m + DR
     - **Yes**
       - **Deep silt (Sabkha) layer, ie bottom elevation higher than 5 m below Working Platform Level**
         - **Case B3**
           - HDR + temporary surcharge
Selection of technique

DR (Dynamic Replacement)

HDR (High Energy Dynamic Replacement) + surcharge
PMT loading test applies the *cavity expansion theory* which is similar to granular column bulging under applied vertical load.

Pressure induced to fail the surrounding soil = ultimate bearing capacity of column supported by lateral pressure of the surrounding soil.
Variation in soil profile over 30 meters
Typical soil profile

Limit Pressure

Pressuremeter Modulus

Cone Resistance

Typical soil profile
Human Resources

1. Project management (4)
2. Production team (32)
3. Mecanical team (18)
4. Survey team (16)
5. Administrative team (6)
6. Geotechnical team (8)
7. Safety and Quality (2)
8. Logistic team (4)
Typical surface conditions
Typical test pits (120) and grain size
Equipment Resources

- 13 DC/DR Rigs of 95 to 120 tons
- 15 pounders from 12-23 tons
- 30 vehicles (bus, 4x4, pick-up, berlines)
- 1 truck with crane
- 1 forklift
- 3 CPT rigs
- 1 drill + pressuremeter
- 15 containers
- 1 set of site offices
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Limit Pressure

Elevation (m EL)

P (bar)

0 5 10 15 20 25 30

0 1 2 3

Before DC

Minimum Average

PMT results before DC
PMT results before and after DR

**Before DR**

**Limit Pressure**

- **Before DR**
  - Limit Pressure
  - Elevation (m EL)
  - **P** (bar)

**After DR – Between columns**

**Limit Pressure**

- **After DR**
  - Limit Pressure
  - Elevation (m EL)
  - **P** (bar)

- Between columns
- Inside columns
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
• kJ/m^3 = Energy per m^3 (E)
• % = % passing n°200 sieve
• I = improvement factor \( \frac{P_{LF}}{P_{LU}} \)
• S.I : energy specific improvement factor \( I \times 100 \) / E

LEGEND
- Average pre-treatment values
- Average values between phases
- Average post-treatment values

Analysis of improvement
Stress distribution

Analysis of worst case for various grids
A – Identify depth trend of SABKAH by CPT Tests

B – Closely eyewitness the penetration of pounder to confirm DC or DR treatment

C – Verify by PMT that factor of safety is at least 3 for bearing capacity

D – Verify by stress analysis that limit pressure at any depth exceeds factors of safety of at least 3 in order to safely utilize the settlement analysis (no creep)

E – Vary the grid to obtain at any location the condition D

F – Test the gravelly sand columns and check if specified settlement is achieved

G – Monitor surcharge if HDR is required
Calculation of the Settlement and Bearing Capacity of a foundation
According to D60

Project Name: 
According to PMT #: 
Dated: 
Zone Ref #: X Y Z

DESCRIPTION OF SOIL, TREATMENT AND FOOTING TYPE

Footings Characteristics

<table>
<thead>
<tr>
<th>Load</th>
<th>DR Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 tons</td>
<td></td>
</tr>
</tbody>
</table>

Mean contact stress

- p = 0.20 MPa
- Hence: L/B = 1.0

Length of the footing

- L = 2.74 m
- And: λ₁ = 1.10
- Hence, a = 12.6%

Width of the footing

- B = 2.74 m
- λ₂ = 1.12

Embedment

- D = 0.80 m

Pressuremeter characteristics

According to calibration #

- Eดร 10.0 Mpa
- Pดร 1.5 Mpa
- αดร 1/3

Soil Description

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Description</th>
<th>Soil category</th>
<th>DR</th>
<th>Thickness (m)</th>
<th>Depth from FPL (m)</th>
<th>γ (kN/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engineering fill</td>
<td>III</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>Working platform</td>
<td>III</td>
<td>1.0</td>
<td>2.5</td>
<td>20</td>
<td>17.0</td>
</tr>
<tr>
<td>3</td>
<td>Soft Material</td>
<td>II</td>
<td>1.0</td>
<td>3.5</td>
<td>20</td>
<td>11.1</td>
</tr>
<tr>
<td>4</td>
<td>Soft Material</td>
<td>II</td>
<td>1.0</td>
<td>4.5</td>
<td>20</td>
<td>6.3</td>
</tr>
<tr>
<td>5</td>
<td>Soft Material</td>
<td>II</td>
<td>1.0</td>
<td>5.5</td>
<td>20</td>
<td>16.3</td>
</tr>
<tr>
<td>6</td>
<td>Soft Material</td>
<td>II</td>
<td>1.0</td>
<td>6.5</td>
<td>20</td>
<td>12.2</td>
</tr>
<tr>
<td>7</td>
<td>Soft Material</td>
<td>II</td>
<td>1.0</td>
<td>7.5</td>
<td>20</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Remark:
The depth described is sufficient

\[ P_{eq} = aP_{c1} + (1-a)P_{c2} \]

D60 MODELISATION

Modulus

- E1 18.41 MPa
- E2 11.84 MPa
- E3,5 7.20 MPa
- E6,8 35.00 MPa
- E9,16 35.00 MPa

Limit Pressure

- p1 2.46 MPa
- p1' 1.81 MPa

CALCULATION RESULTS

Bearing Capacity

- qa = 643 kPa

Settlement

- w = \[ \frac{1.33}{3E_0} p_k \left( \frac{R}{R_k} \right)^{\gamma_{w \cdot k} + \frac{a_{\delta}}{4.5E_0} p_k R} w \]

Higher than 200 kPa => Specification reached
Lower than 25 mm => Specification reached
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>$t/\tau$</td>
<td>0.009</td>
<td>0.087</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>$t'/\tau$</td>
<td>0.901</td>
<td>0.807</td>
<td>0.725</td>
<td>0.659</td>
<td>0.615</td>
<td>0.602</td>
<td>0.632</td>
<td>0.735</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Supposing primary consolidation completed $U = 0.9$ or $T = 0.848$ if $du=U_1\Delta\sigma$,

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
Settlement curves from dynamic surcharge
THANK YOU