Lessons learned from Ground Improvement projects Around the World

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Around the world, Geotechnical Engineers face many of the same challenges

Principle 1:
Owners don’t want to pay for a thorough geotechnical investigation incl. Lab testing -> There’s never enough information
Principle 2: Terzaghi is our god

\[ \sigma = \sigma' + u \]
Principle 3:

- The three main issues that may lead to the use of deep foundations or ground improvement are:

- Settlement / Heave
- Bearing Capacity
- Liquefaction
To deal with these three issues, there are basically three ways:

1. **CONsolidate**
   - Vacuum consolidation
   - Vertical drains

2. **DENsify**
   - Radio impact compaction
   - Dynamic compaction
   - Vibratation

3. **STRENGTHen**
   - Deep soil mixing
   - Rigid inclusions
   - Stone columns
   - Bitumenous columns
   - Dynamic replacement
WICK DRAINS

- Band-Shaped plastic strip – Accelerate consolidation of compressible soils
The Art of Wick Cutting

with Jonah

US Wick Drain

Charleston 2016
- Use of atmospheric pressure to simulate surcharge and accelerate consolidation
DYNAMIC COMPACTION

- Free fall of 12-20 tons weights from 50-100 ft for compaction of granular soils
RAPID IMPACT COMPACTION ( RIC )

- High Frequency tamping using a 9-12 tons weight
VIBROFLOTTATION

- High energy vibratory probe using water jets to densify clean sands
CONTROLLED MODULUS COLUMNS (CMC)

- Grouted Rigid Inclusions installed with a displacement tool
STONE COLUMNS / AGGREGATE PIERS

Columns of Vibrated Compacted Crushed Stone – Seismic mitigation
BI-MODULUS COLUMNS

- Combination of a Stone Column Installed Directly Above a Rigid Inclusion
Influence of local conditions: Depth

- Excavate
- RIC / DR
- DC / RAP
- VSC
- Vibro / DSM
- CMC / WD / Vac

Depth:
- 5 ft
- 15 ft
- 30 ft
- 60 ft
- 90 ft
- 150 ft
### Influence of Local Conditions:

#### Soil Type

<table>
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<tr>
<th></th>
<th>Peat / Soft Organic Clays</th>
<th>Stiff Clays / Silts</th>
<th>Silty Sands / Sandy Silts</th>
<th>Sand / Gravel</th>
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<tr>
<td><strong>Vacuum / Wick Drains</strong></td>
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<td><strong>CMC Rigid Inclusions / DSM</strong></td>
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Project: Kimhae & Jangyoo Sewage Treatment Plant
Country: South Korea (Busan)
Summary: New plant in Greenfield with final grade raised several meters and large net new loads

Main Issues to Solve:

- Local condition: deep very soft young deposits (>45M) from NakDong River Valley
- Settlement: predicted long term settlement > 6M over 20 years due to deep soft clays
- Construction period – Fast schedule
- Lack of availability of fill material
Kimhae & Jangyoo Sewage Treatment Plant
GENERAL DATA ON PROJECT:

- 160,000 m² (1.7M ft²)
- 2 Water Sewage Treatment plant to meet the growing demand of boom of population of Kimhae and Jangyoo township, suburbs of Busan, 2nd largest city in South Korea
Silty Sand to Sandy Silt – 5m (17 ft)

Soft Organic clay – 40m (130 ft)

Weathered Rock
Main Characteristics of the Soft Clay Layer:
- normally Consolidated
- Water content average 75%
- $N(SPT) = 0$ to $1$
- $Cc = 1.21$
- $eo = 2.012$
- $Cv = 1.32 \text{ m}^2/\text{y}$

Thickness between 25 and 40m (85ft to 130ft)

Expected max settlement $> 6\text{m}$ (15% of clay thickness)
BEFORE VACUUM APPLICATION:

\[
\sigma_T = \gamma z + \gamma_f h + P_a = \sigma_t + P_a \\
\gamma_T = \gamma_w z + P_a = \gamma_t + P_a \\
\sigma_i' = \sigma_T - \gamma_T \\
= \gamma' z + \gamma_f h
\]

AFTER VACUUM APPLICATION:

\[
\sigma_T = \gamma z + \gamma_f h + P_a = \sigma_t + P_a \\
\gamma_T = \gamma_w z + P_a - P_a \\
\sigma_i' = \sigma_T - \gamma_T \\
= \sigma_i' + P_a \\
\Delta \sigma' = nP_a \quad \text{Where } n \approx 0.7 - 0.8
START OF VACUUM / DEPRESSURE

Days since start of vacuum

Depressur (bars)

- phase 1
- phase 3
- phase 2

Value are average between 7:30 and 13:30 CPV readings
1D consolidation theory

\[ \Delta \sigma'(z) = \gamma H_{\text{fill}} + \sigma_o + \gamma' \Delta H_{\text{primarysettlement}} \]

\[ \Delta H_{\text{primarysettlement}} = \frac{C_c}{1+e_o} \cdot H \cdot \log \left( \frac{\sigma_o + \Delta \sigma'(z)}{\sigma_o} \right) \]

Calibration Coefficient

\[ \beta = \frac{\Delta H_{\text{asaoka}}}{\Delta H_{\text{theory}}} = \frac{\left( \frac{C_c}{1+e_o} \right)_{\text{actual}}}{\left( \frac{C_c}{1+e_o} \right)_{\text{soilinvestigation}}} \]

Asaoka Analysis of monitoring results

Target reached? Yes -> Stop vacuum
Target reached? No -> Continue analysis
Project : Airbus A380 Assembly Plant
Country : Germany ( Hamburg )
Summary : New Assembly plant on Elbe River for Airbus A380 – extension of runway

Main Issues to Solve :
- Local condition : underconsolidated river tidal deposits ( Elbe River
- Settlement : predicted long term settlement > 2M over 20 years due to very compressible deposits ( Muck )
- Bearing capacity / Slope Stability at edge
- Reclaimed Area = 170 ha (about 1.9m ft²)
- Final Assembly of Airbus A380
- Spare parts delivered by barge, plane or road to the Hamburg plant

- Containment dike on GCC
- Hydraulic sand reclamation
- Wick drains + Vacuum
ORIGINAL DESIGN OF DIKE

VALUE ENGINEERING DIKE
Dyke

Flooding of site NN+3m

Sand spray

Hydraulic fill

Vertical drain

Horizontal drain

Dewatering

Fill to final elevation + estimated settlement or vacuum + fill

Very soft clay

Clay / peat

Sand
Stability problem

$\eta << 1.3$

$\nabla + 2.5 \text{ mNN}$

$\nabla + 6.5 \text{ mNN}$

**Solution:**
Installing a "corset"
• Vacuum 70 kN/m² (0.7 bar)

• $V + 2.5$ mNN
Project: King Abdullah University of Science and Technology (KAUST)
Country: Saudi Arabia (Jeddah)
Summary: New University (3M m²) built from scratch in record time in the desert

Main Issues to Solve:
- Local condition: relatively heterogeneous deposits of Sabkah (loose silt deposited by wind)
- Fast track project and project not well defined at time of ground improvement
- High water table
• KAUST = King Abdullah University for Science and Technology
• New university campus of 36 million m² (i.e. 6 km x 6 km) to be completed in 26 months
• Located in the desert near Jeddah
• Includes desalination plant, wind turbines, golf course, residences, services, campus, infrastructures
• **Initial Conditions and Challenges:**
  
  • Sabkah: saturated loose fine silty sand – wind blown. On this project, up to 5m thick at surface
  
  • Fast-track project: project was launched before 100% drawings – Menard needed to propose a ground improvement system without having final structural drawings and loads
VARIATION IN SOIL PROFILE OVER 30 METERS
DESIGN CONCEPT WHEN LOCATION OF FOOTINGS UNKNOWN

Total settlement < 1 inch (25mm) – max diff 1/500 on footings

150 tons max

Engineered Fill

Working Platform (gravelly sand)

Loose sand (DC)

Soft Sabkah (DR)

Arching layers
Minimum 2m

200 kN/m² max

EL +4.0

EL +2.5

0.8 m

Contour of Subarea
DC treatment area
DR treatment area
HDR treatment area
Green area
DESIGN DECISION TREE

Based on Observational Method

Selection of G.I. method is dependent on site observation during compaction and borings
12 Cranes ( LRB 855 & 885 ) x 2 shifts

12 to 25 tons weight depending on areas

Over 2,500,000 m² ( 25,000,000 ft² ) of DC/DR

Team of 100 persons on site
Project: FedEx Ground Sorting Facility  
Country: USA (Jersey City)

Summary: New plant in Greenfield with final grade raised several meters and large net new loads.

Main Issues to Solve:
- Local condition: thick deposits of varved soft clay below a layer of thick organics
- Settlement: predicted long term settlement >2ft over 20 years due to deep soft clays
- Construction period – Fast schedule
- Limited budget
Soil profile:
Fill (with some MSW) over Organics (meadow mat) over varved silt and clays

Main Challenge was thickness of compressible soil extending beyond the capacity of classical CMC rigid inclusions elements.
Second challenge was to limit total settlements to under 2 inches long term and differential settlement of \( \frac{3}{4} \) inch between two column footings.

Differential settlement between loaded bay and unloaded bay is also to be studied.

Differential between footings and slab is another focus.
Develop two custom made lead mast systems attached to crawler cranes with high torque / high pull down capacity.
Settlement challenge solve

Combination of Global support (with one added CMC at concentrated loads) and thick LTP to spread load
Fedex NJ

- Jersey City, NJ
- warehouse
- 350,000 sf
- 600 psf floor load
- 135 ft max
- 4,150 CMC
LESSONS LEARNED:
- Each site is unique and has its own challenges that lead to unique design-build solutions
- Innovate to find the right solution
- Being entrepreneurial and a risk-taker often pays off

THANKS!