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

Presented by
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5-9 October 2009

NOTA : TC 17 meeting ground improvement – 07/10/2009
Website : www.bbri.be/go/tc17

PERTH - AUSTRALIA - JUNE 2010
<table>
<thead>
<tr>
<th>Category</th>
<th>Method</th>
<th>Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Ground improvement without</td>
<td>A1. Dynamic compaction</td>
<td>Densification of granular soil by dropping a heavy weight from air onto</td>
</tr>
<tr>
<td>admixtures in non-cohesive</td>
<td>A2. Vibrocompaction</td>
<td>ground.</td>
</tr>
<tr>
<td>soils or fill materials</td>
<td>A3. Explosive compaction</td>
<td>Densification of granular soil using a vibratory probe inserted into</td>
</tr>
<tr>
<td></td>
<td>A4. Electric pulse compaction</td>
<td>ground.</td>
</tr>
<tr>
<td></td>
<td>A5. Surface compaction</td>
<td>Densification of granular soil using the shock waves and energy generated</td>
</tr>
<tr>
<td></td>
<td></td>
<td>by electric pulse under ultra-high voltage.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compaction of fill or ground at the surface or shallow depth using a</td>
</tr>
<tr>
<td></td>
<td></td>
<td>variety of compaction machines.</td>
</tr>
<tr>
<td>B. Ground improvement without</td>
<td>B1. Replacement/displacement (including</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>load reduction using light weight materials)</td>
<td>or rocks. Some light weight materials may be used as backfill to reduce</td>
</tr>
<tr>
<td></td>
<td>B2. Preloading using fill (including the use</td>
<td>the load or earth pressure.</td>
</tr>
<tr>
<td></td>
<td>of vertical drains)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B3. Preloading using vacuum (including</td>
<td>Fill is applied and removed to pre-consolidate compressible soil so that</td>
</tr>
<tr>
<td></td>
<td>combined fill and vacuum</td>
<td>its compressibility will be much reduced when future loads are applied.</td>
</tr>
<tr>
<td></td>
<td>B4. Dynamic consolidation with enhanced</td>
<td>Similar to dynamic compaction except vertical or horizontal drains (or</td>
</tr>
<tr>
<td></td>
<td>drainage (including the use of vacuum)</td>
<td>together with vacuum) are used to dissipate pore pressures generated in</td>
</tr>
<tr>
<td></td>
<td>B5. Electro-osmosis or electro-kinetic</td>
<td>soil during compaction.</td>
</tr>
<tr>
<td></td>
<td>consolidation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>B6. Thermal stabilisation using heating or</td>
<td>DC current causes water in soil or solutions to flow from anodes to</td>
</tr>
<tr>
<td></td>
<td>freezing</td>
<td>cathodes which are installed in soil.</td>
</tr>
<tr>
<td></td>
<td>B7. Hydro-blasting compaction</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>
</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>
</tbody>
</table>
### D. Ground improvement with grouting type admixtures

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>D2. Chemical grouting</strong></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><strong>D3. Mixing methods (including premixing or deep mixing)</strong></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>
</tr>
<tr>
<td><strong>D4. Jet grouting</strong></td>
<td>High speed jets at depth erode the soil and inject grout to form columns or panels.</td>
</tr>
<tr>
<td><strong>D5. Compaction grouting</strong></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>
</tr>
<tr>
<td><strong>D6. Compensation grouting</strong></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>
</tr>
</tbody>
</table>

### E. Earth reinforcement

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E1. Geosynthetics or mechanically stabilised earth (MSE)</strong></td>
<td>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.</td>
</tr>
<tr>
<td><strong>E2. Ground anchors or soil nails</strong></td>
<td>Use of the tensile strength of embedded nails or anchors to enhance the stability of slopes or retaining walls.</td>
</tr>
</tbody>
</table>
# Unified Soil Classification System

## TABLE 1 Soil Classification Chart

<table>
<thead>
<tr>
<th>Criteria for Assigning Group Symbols and Group Names Using Laboratory Tests</th>
<th>Soil Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COARSE-GRAINED SOILS</strong></td>
<td></td>
</tr>
<tr>
<td>Gravels (More than 50% of coarse fraction retained on No. 4 sieve)</td>
<td></td>
</tr>
<tr>
<td>Clean Gravels (Less than 5% fines)</td>
<td></td>
</tr>
<tr>
<td>Cu ≥ 4 and 1 ≤ Cc ≤ 3</td>
<td>GW</td>
</tr>
<tr>
<td>Cu &lt; 4 and/or [Cc &lt; 1 or Cc &gt; 3]</td>
<td>GP</td>
</tr>
<tr>
<td>Gravels with Fines (More than 12% fines)</td>
<td></td>
</tr>
<tr>
<td>Fines classify as ML or MH</td>
<td>GM</td>
</tr>
<tr>
<td>Fines classify as CL or CH</td>
<td>GC</td>
</tr>
<tr>
<td><strong>Sands (50% or more of coarse fraction passes No. 4 sieve)</strong></td>
<td></td>
</tr>
<tr>
<td>Clean Sands (Less than 5% fines)</td>
<td></td>
</tr>
<tr>
<td>Cu ≥ 6 and 1 ≤ Cc ≤ 3</td>
<td>SW</td>
</tr>
<tr>
<td>Cu &lt; 6 and/or [Cc &lt; 1 or Cc &gt; 3]</td>
<td>SP</td>
</tr>
<tr>
<td>Sands with Fines (More than 12% fines)</td>
<td></td>
</tr>
<tr>
<td>Fines classify as ML or MH</td>
<td>SM</td>
</tr>
<tr>
<td>Fines classify as CL or CH</td>
<td>SC</td>
</tr>
<tr>
<td><strong>FINE-GRAINED SOILS</strong></td>
<td></td>
</tr>
<tr>
<td>Silts and Clays (IL less than 50)</td>
<td></td>
</tr>
<tr>
<td>Inorganic</td>
<td></td>
</tr>
<tr>
<td>PI &gt; 7 and plots on or above &quot;A&quot; line</td>
<td>CL</td>
</tr>
<tr>
<td>PI ≤ 4 or plots below &quot;A&quot; line</td>
<td>MI</td>
</tr>
<tr>
<td>50% or more passes the No. 200 sieve</td>
<td></td>
</tr>
<tr>
<td>Silts and Clays (Liquid limit 50 or more)</td>
<td></td>
</tr>
<tr>
<td>Inorganic</td>
<td></td>
</tr>
<tr>
<td>PI plots on or above &quot;A&quot; line</td>
<td>CH</td>
</tr>
<tr>
<td>PI plots below &quot;A&quot; line</td>
<td>MH</td>
</tr>
<tr>
<td>Organic</td>
<td></td>
</tr>
<tr>
<td>Liquid limit – oven dried</td>
<td></td>
</tr>
<tr>
<td>Liquid limit – not dried &lt; 0.75</td>
<td>OL</td>
</tr>
<tr>
<td>Organic silt</td>
<td></td>
</tr>
<tr>
<td>Liquid limit – oven dried</td>
<td></td>
</tr>
<tr>
<td>Liquid limit – not dried &lt; 0.75</td>
<td>OH</td>
</tr>
<tr>
<td>Organic clay</td>
<td></td>
</tr>
<tr>
<td>Organic silt</td>
<td></td>
</tr>
<tr>
<td>Highly Organic Soils</td>
<td></td>
</tr>
<tr>
<td>Primarily organic matter, dark in color, and organic odor</td>
<td>PT</td>
</tr>
</tbody>
</table>

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Unified Soil Classification

OTHER MATERIAL SYMBOLS

- Poorly Graded Sand with Clay
- Clayey Sand
- Sandy Silt
- Low to High Plasticity Clay
- Poorly Graded Gravely Sand
- Gravely Silt
- Well Graded Gravely Sand
- Silt
- Sand
- Aschfait
- Boulders and Cobble

SAMPLE TYPES

- Split Sample
- Shelby Tube
- Rock Core
- Grab Sample

ADDITIONAL TESTS

- CA - CHEMICAL ANALYSIS (CORROSIVITY) (20%) - % WITH % PASSING NO. 200 SIEVE
- CD - CONSOLIDATED DRAINED TRIAXIAL (20%) - SWELL TEST
- CH - CONSOLIDATION (SWELL TEST) (20%) - CYCLIC TRIAXIAL
- QT - CONSOLIDATED UNDRAINED TRAAXIAL (20%) - TORSION SHEAR
- POCKET PENETROMETER (TSF) (20%) - UNCONSOLIDATED UNDRAINED TRAAXIAL
- PIP - PENETROMETER (TSF) (20%) - UNCONSOLIDATED COMPRESSION
- Ks - PENETROMETER (TSF) (20%) - WITH SHEAR STRENGTH IN KSF
- R - R-VALUE (20%) - WITH SHEAR STRENGTH IN KSF
- V - VANE TEST (20%) - % WITH % PASSING NO. 200 SIEVE
- N - WATER LEVEL (WITH DATE) (20%) - MEASUREMENT
- WA - VANE TEST (20%) - UNCONSOLIDATED UNDRAINED TRAAXIAL

PENETRATION RESISTANCE

<table>
<thead>
<tr>
<th>SAND &amp; GRAVEL</th>
<th>Silt &amp; Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td>RELATIVE DENSITY</td>
<td>CONSISTENCY</td>
</tr>
<tr>
<td>VERY LOOSE</td>
<td>2 - 6</td>
</tr>
<tr>
<td>LOOSE</td>
<td>7 - 10</td>
</tr>
<tr>
<td>MEDIUM DENSE</td>
<td>10 - 30</td>
</tr>
<tr>
<td>DENSE</td>
<td>30 - 50</td>
</tr>
<tr>
<td>VERY DENSE</td>
<td>OVER 50</td>
</tr>
</tbody>
</table>

* NUMBER OF BLOWS OF 146-LB HAMMER FALLING 30 INCHES TO DRIVE 2 INCH D.O. (1.0 INCH SPLIT BARREL SAMPLER THE LAST 12 INCHES OF AN 18 INCH DRIVE) (ASTM D697 STANDARD PENETRATION TEST)
2.1 – UD: 2” or 3’ Shelby Tube
Suitable for cohesive soils

2.2 – Piston sampler Osterberg
Suitable for cohesive and fine granular soils

2.3 – SPT: suitable for cohesive and granular Soil

2.4 – Core barrel
Suitable for rock type of soils

2.5 – Block sample
Define terms important for Unified Soil Classification System

Percent Fines
Mechanical Analysis
Liquid Limit
Plastic Limit, Plasticity Index
Water Content
Organic
Laboratory Engineering Properties
Direct shear test

\( \phi \) (imposed failure plane)
Laboratory Engineering Properties

Triaxial on cohesionless soil $\phi$, Mohr Coulomb curve
Laboratory Engineering Properties

\[ W, C_0, C_e, C_v, P_c, k, A_v, C_\alpha \]

Consolidation test

Frame with consolidation units
Proctor Test

$w, w_{cpt}, \gamma_{\text{max}}, \text{Proctor curve}$
Different types of In Situ tests

Vane test (VT)
Static Cone Penetration Test (CPT)
Standard Penetration Test (SPT)
Pressuremeter (PMT)

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Why Soil Improvement?

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

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

| **Soil with friction**  | **Without added**    |
| Sand, fill              | **With added**       |
|                         | 3 Dynamic consolidation|
|                         | 4 Vibroflotation      |

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Parameters For Concept

• Soil characteristics
  - Cohesive or non cohesive
  - Blocks?

• Site environment
  - Close to existing structures
  - Height constraints

• Water content, water table position

• Available construction time

• Organic materials

• Soil thickness

• Structure to support
  - Isolated or uniform load
  - Deformability
**CONCEPT**

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

**PARAMETERS**

\[ DC : h(m) = C \delta \sqrt{E} \]
\[ C(\text{menard}) = 0.9-1 \]
\[ C(\text{hydraulic}) = 0.55 \]
\[ \delta \rightarrow \text{SBC} \rightarrow = 0.9-1 \text{ (SILICA SAND)} \]
\[ \delta \rightarrow \text{LOAD} \rightarrow = 0.4-0.6 \text{ (SILICA SAND)} \]

S.B.C. = Self Bearing Coefficient
S.B.C. = \( S(t) \)
\[
\frac{S(\infty)}{S(t)}
\]
Nice International Airport Runway consolidation
Granular soil

Very high energy (170 t, 23 m)
Concept and Application of 2,600,000 m² of ground improvement for
King Abdulla University of Science & Technology (KAUST)
JEDDAH, A MODERN CITY

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Discovering the Habitants

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Areas to be treated

- Al Khodari (1,800,000 m²)
- Saudi Bin Ladin 720,000 m²

Schedule

- 8 months
Dates for soil improvement

KAUST
Dates for soil improvement

LEGEND
- 01/10/2007
- 05/10/2007
- 15/10/2007
- 01/11/2007
- 15/11/2007
- 15/12/2007
Dynamic Consolidation

Wave Type  Percent of Total Energy
Rayleigh    67
Shear       26
Compression 7

After R.D. Woods (1968)

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

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

150 TONS

+ 4.0

\( \sigma_z = 200 \text{ kN/m}^2 \)

+ 2.5

2 meters arching layer

Working platform (gravelly sand)

+ 1.2

Compressible layer from loose sand to very soft sabkha

0 to 9 meters

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**Decision process of selection of technique**

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

Cone Resistance

Pressuremeter Modulus

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1. Project management (4)
2. Production team (32)
3. Mechanical 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
Equipment Resources

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PMT results before DC

Before DC

Limit Pressure

![Graph showing pressure limits before DC](image)

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PMT results before and after DR

Before DR

Limit Pressure

After DR – Between columns

Limit Pressure

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ANALYSIS OF \((P_L - P_o)\) IMPROVEMENT AS FUNCTION OF ENERGY AND FINES

KAUST – Saudi Arabia

BASIS
- 60 grainsize tests
- 180 PMT tests

PARAMETERS
- \(P_L - P_o\) = pressuremeter limit pressure
- \(kJ/m^3\) = Energy per m³ (E)
- \% = % passing n°200 sieve
- \(I\) = improvement factor
- \(S.I\) : energy specific improvement factor \(\frac{P_{L_E}}{P_{L_o}} \times \frac{I}{E}\)

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

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Analysis of Worst Case Scenario for Various Grids
Site procedure

A – Identify depth trend of SABKAH by CPT Tests

B – Closely eye witness 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
It can be assumed that those impacts do 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 \( t' \), where

\[
T_v = 0,848 = \frac{C_v'}{H^2} \left( t'_1 - t_1 \right) + \frac{C_v T_1}{H^2}
\]

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:
- \( t' \) 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_f/t )</td>
<td>0.009</td>
<td>0.037</td>
<td>0.08</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'_f/t )</td>
<td>0.001</td>
<td>0.087</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

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

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.
Settlement curves from dynamic surcharge

PERTH - AUSTRALIA - JUNE 2010
Thank You