VACUUM CONSOLIDATION IN PEAT

Eric R Farrell AGL Consulting and Trinity College

Brendan O’Kelly, Trinity College, Dublin
and

Juan Pablo Osorio-Salas Universidad de Antioquia, Colombia, formerly Trinity College
Structure of Presentation

- Background
- Principles of vacuum consolidation
- Current practical applications
- TCD/NRA test site
  - Geotechnical/geology/hydrogeology of test site
  - Construction of test area
  - Instrumentation
  - Benchmark ground movement readings.
- Results from vacuum consolidation test
  - Vacuum achieved
  - Settlement versus time
  - Practical difficulties
- Numerical modelling
  - Laboratory parameters
  - Soil model
  - Comparison of field performance with predictions
- Conclusions
PRINCIPLES OF VACUUM CONSOLIDATION

• Vacuum consolidation is a construction method used to accelerate ground settlement by reducing the air pressure at the ground surface.

• Normally atmospheric pressure ($p_{atm}$) is taken as the base line when computing $\sigma' = \sigma - u$.

• $p_{atm}$ is about 100kPa, and the pwp can be reduced below atmospheric using vacuum pumps. This increases the effective stress without generally increasing the shear stresses.

• Vacuum consolidation was originally proposed by Kjellman in Sweden in the 1950s.
Background - Rampart roads

• The construction of roads over peat bogs in the 18th & 19th centuries opened up the bog for harvesting

• The easiest place to harvest was adjacent to the roads, roads ended up elevated above the adjacent ground. These are called Rampart Roads. Heights of 9m have been recorded.

• Many of these roads are used today, resulting in narrow and very dangerous roads.

• Vacuum consolidation may assist in overcoming some of the challenges in widening these roads.
VACUUM CONSOLIDATION

Atmospheric pressure = 100kPa

Pump creates a suction of up to 80kPa

Δu up to -80kPa (20kPa absolute)
VACUUM CONSOLIDATION

Depth, z

Initial pressure

Reduced pressure

Vacuum pressure

Pore pressure reduction

Pa

Zo

PVD
Current applications

Menard vacuum

Baudrain – Cofra bv

Figure 1. Typical setup of vacuum consolidation method

Hayashi et al, 2003
TCD/NRA TEST SITE
Raised Bog under milled peat production, therefore some peat has been removed. Site is at edge of bog.

Top 1m - very clayey sandy Gravel f% ≈ 30%
Below – slightly clayey sandy Gravel f% ≈ 4-11%
K = 1.96x10⁻⁶ to 1.15x10⁻⁵ m/s
In-situ vanes (55mm x 110mm)
Drain within 8m of edge of test area.
## TCD/NRA VACUUM CONSOLIDATION FIELD TRIAL

### Table 1 – Simplified soil profile

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (m)</th>
<th>Description</th>
<th>Observations and properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 – 0.7</td>
<td>Man-made fill</td>
<td>Black peat; occasional plastic bags, gravel, pieces of geotextile, machine parts.</td>
</tr>
</tbody>
</table>
| 2     | 0.7 – 4.0 | Pseudo-fibrous peat | $w = 561 – 1340\%$  
LOI = 87 – 99%  
$e_o = 6.78 – 14.83$  
$pH = 4.5 – 6.2$  
$C_c = 2.2 – 6.4$  
$G_s = 1.38 – 1.59$  
$\gamma_h = 9.57 – 10.56\text{kN/m}^3$  
$S_r = 94 – 100\%$  
Von Post = $H_4 – H_7$ |
| 3     | 4.0 – 7.0 | Glacial till        | The clay fraction reduces with depth, about 30% fines in top metre, reducing to 4-11%.        |
TCD/NRA VACUUM CONSOLIDATION FIELD TRIAL

- 0.85m sq. spacing
- 1.2m sq. spacing

- G.W.T. = 0.25 - 0.90 m
- Peat
- Boulder clay

- Prefabricated vertical drains
- Horizontal drains $\phi = 76.2mm$
- Peat seals

- Air tight sheet
Instrumentation

- 10 No. Vibrating wire (VW) piezometers (also calibrated for suction)
- 6 No. push-in VW settlement cells 0.9m, 1.5m & 2.65m
- Settlement plates
- Standpipes
- Barometric pressure/temp.
- Rain gauge
- Water meter
- Air pressure gauges

Acknowledge assistance of NVM Ireland Ltd.
TCD/NRA VACUUM CONSOLIDATION
FIELD TRIAL
Pumping system: 30\textsuperscript{th} Nov 2009 – 23\textsuperscript{rd} Jun 2010

- 1.5kW Centrifugal pump
- 38mm diameter jet pump
Pumping system: 29th Jul 2010 – 29th Oct 2010

- 2.2kW Liquid ring pump
- 1.5kW Centrifugal pump
- 38mm diameter jet pump
MONITORING BEFORE PUMPING

• Prior to starting the TCD/NRA vacuum consolidation field trial, four months of baseline monitoring were conducted.

• The vacuum consolidation trial was run from 30th November 2009 and was terminated on 29th October 2010
PORE WATER PRESSURE vs TIME - SPACING=0.85m (Before pumping)

Granular bed 0.44m thick and load = 8.8kPa

Depth=0.90m
Depth=2.65m - Edge of test area
Depth=1.90m
Depth=4.05m
Depth=2.60m - Outside test area

Time (Days)
Flooding in August 2009
MONITORING DURING PUMPING

• The TCD/NRA vacuum preloading field trial commenced on the 30th November 2009.

• The results for the eleven months of pumping presented here.

• Rain, water table, vacuum, settlement and pore water pressure are presented.
Sett = 1.11m for 0.85m spacing
Sett = 1.09m for 1.20m spacing

Settlement cell reservoir empty
Volume of water extracted

TOTAL WATER

Volume (m³)

Time (days)

Volume of water
One-dimensional volumetric compression
Pipe leak/burst

Leak at membrane

Flooded surface to check for leaks

Electric failure

Stopped flooding surface.

found and fixed big tear at membrane at bottom of side ditch.

Water frozen in pipes

Time (days)

Vacuum (kPa)

Jetpump

- Jet and 1.5kW LR pumps

- 0.75kW LR pump

- Jet and 2.2kW LR up to 12 Aug 2010

- Jet and 2.2 kW LR from 26 Aug 2010

Reinstalled Jetpump
\[ \Delta u_{\text{max}} = 38.9 - 53.2 \text{kPa} \text{ for depths 0.90 to 2.65m.} \]

\[ \Delta u_{\text{max}} = 13.9 \text{kPa} \text{ for 4.05m depth.} \]
MAXIMUM SURFACE SETTLEMENT 1.23m (Strain of 33%)
Visual 1\textsuperscript{st} June 2010
CRACKS AT EDGE

Chai et al. (2005)
SETTLEMENT OF PEAT

Rate of settlement

$c_v$, $c_{vh}$, $c_{hh}$

$k$, $k_v$, $k_h$
\[ \Delta e = C_k \Delta \log t \]

\[ C_k \approx 0.25e_0 \]
Soil models investigated

- Simple EOP $C_s$ & $C_c$ ($C_R = \frac{C_c}{(1+e_o)}$ & $R_R$) and $\sigma_{vc}'$

- Soft Soil model (SS) Plaxis ($\lambda^* = \frac{C_c}{2.3(1+e_o)}$, $\kappa^*$)

- Soft Soil Creep model Plaxis ($\lambda^* = \frac{C_c}{2.3(1+e_o)}$, $\kappa^*$, $\mu^*$)
\[ E' = 100 \text{kPa} \]
Modelling vacuum consolidation
VALUES USED ON BACK ANALYSIS WITH SSC MODEL

<table>
<thead>
<tr>
<th></th>
<th>Upper peat</th>
<th>Middle peat</th>
<th>Lower peat</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP</td>
<td>10</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>l*</td>
<td>0.125</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>k*</td>
<td>0.05</td>
<td>0.055</td>
<td>0.04</td>
</tr>
<tr>
<td>m*</td>
<td>0.0065</td>
<td>0.0078</td>
<td>0.009</td>
</tr>
<tr>
<td>g</td>
<td>10.45</td>
<td>10.1</td>
<td>10.06</td>
</tr>
<tr>
<td>e₀</td>
<td>7.42</td>
<td>13.81</td>
<td>12.05</td>
</tr>
<tr>
<td>(k_v=k_H) (m/day)</td>
<td>0.3</td>
<td>0.2</td>
<td>0.01</td>
</tr>
<tr>
<td>(c_k)</td>
<td>1.8</td>
<td>3.44</td>
<td>3.44</td>
</tr>
</tbody>
</table>

PARAMETERS INTERPRETED FROM LABORATORY OEDOMETER TESTS

<table>
<thead>
<tr>
<th></th>
<th>Upper peat</th>
<th>Middle peat</th>
<th>Lower peat</th>
</tr>
</thead>
<tbody>
<tr>
<td>POP</td>
<td>10</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>l*</td>
<td>0.11 to 0.125</td>
<td>0.14 to 0.16</td>
<td>0.16 to 0.2</td>
</tr>
<tr>
<td>k*</td>
<td>0.022 to 0.05</td>
<td>0.03 to 0.055</td>
<td>0.033 to 0.04</td>
</tr>
<tr>
<td>m*</td>
<td>0.0065 to 0.008</td>
<td>0.0078 to 0.01</td>
<td>0.0065 to 0.009</td>
</tr>
<tr>
<td>g</td>
<td>10.45</td>
<td>10.1</td>
<td>10.06</td>
</tr>
<tr>
<td>e₀</td>
<td>6.78 – 8.69</td>
<td>13.43 – 14.5</td>
<td>11.5 – 12.5</td>
</tr>
<tr>
<td>(k_v=k_H) (m/day)</td>
<td>0.011 to 0.128</td>
<td>0.0053 to 0.011</td>
<td>0.0015 to 0.0029</td>
</tr>
<tr>
<td>(c_k)</td>
<td>1.8</td>
<td>3.44</td>
<td>3.44</td>
</tr>
</tbody>
</table>
- Swell using simple soil model = 0.161m
- Swell measured = 0.13m
- Equivalent $E' \approx 100$ kPa at this very low effective stress.
CONCLUSIONS

• The TCD/NRA vacuum preloading field trial was implemented and showed that this technique can be successfully used in peat soils.

• The drainage system comprising PVDs, horizontal drains and a granular bed, was effective in distributing the applied vacuum pressure and collecting the drained water.
Practical difficulties/Observations

• Summer conditions general water table was lower than side barrier.

• Higher suctions achieved with vacuum pump but more stable values with liquid ring pump

• Pore pressure reduction at edges was slightly lower (2kPa to 8.5kPa) than at centre.

• $\Delta$PWP roughly uniform with depth

• Vacuum pressure adequately transmitted in 0.85m and 1.2m spacings.
• Calcification of pumps a significant issue

• Freezing, tears, bursts electrical cuts affected the performance.

• Airtight cover could be improved, use of water seal should be considered.

• Vacuum consolidation had little effect on the water table outside the test area.

• Behaviour can be simulated using standard soil models.
ACKNOWLEDGEMENTS

• National Road Authority.
• Trinity College Dublin.
• Geotechnical Trust Fund Award (Engineers Ireland).
• Universidad de Antioquia
• Bord na Móna