Diaphragm wall at location of the 5th Fluxys LNG Tank in Zeebrugge
Valérie Whenham

Journée d'étude Franco-Belge – Dimensionnement sismique des fondations – 15 Mars 2018
Fifth Storage Tank – Zeebrugge LNG Terminal (FLUXYS)

Tank diameter: 95 m
Useful capacity of the tank: 180,000 m³

Length of diaphragm wall panels: 36 m
Construction of the diaphragm wall dated November 2016

Preliminary design: dated 2014
Plan of the presentation

• Ground Motion Parameters
• Stratigraphy and Key Soil Parameters
• Assessment of Liquefaction Potential
• Seismic Design
• Results and Conclusions
Ground Motion at the location of the project (Zeebrugge)

- Seismotectonic study by the Royal Observatory of Belgium
  - Operating Basis Earthquake (OBE): Return period = 475y
  - Safe Shutdown Earthquake (SSE): Return period = 10,000y (EN 1473-1997)

Elastic response spectra (32m BGL)

Magnitude & Peak Ground Accelerations (32m BGL)
Definition of time histories (accelerograms)

- Target response spectra
- Selection of natural 3-components accelerograms
- Spectral matching
Stratigraphy & Soil conditions

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Sandfill (I)

Water table at ~4m depth (2 different aquifers)

Sandy clay + peat (II)

Locally slightly clayey dense to very dense sand (III->VI)

-32m BGL – Definition of Elastic Response Spectra

Soft-firm & sandy tertiary clay (VII&VIII)
### Key Soil parameters (preliminary design)

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Lithology</th>
<th>Unit weight</th>
<th>$\gamma_{\text{sat}}$ [kN/m$^3$]</th>
<th>Friction Angle $\phi'$ [°]</th>
<th>Cohesion $c'$ [kPa]</th>
<th>Undrained shear strength $S_u$ [kPa]</th>
<th>At rest Coefficient $K_0$ [-]</th>
<th>Poisson Ratio $\nu$ [-]</th>
<th>Max. (dyn) shear modulus $G_0$ [MPa]</th>
<th>Fines Content (&lt;60µm) [%]</th>
<th>Clay Content (&lt;2µm) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>SANDFILL</td>
<td>20.0</td>
<td></td>
<td>35</td>
<td>0</td>
<td>-</td>
<td>0.43</td>
<td>0.3</td>
<td>95</td>
<td>1-3</td>
<td>-</td>
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<tr>
<td>II</td>
<td>SANDY CLAY+PEAT</td>
<td>19.0</td>
<td></td>
<td>15</td>
<td>15</td>
<td>-</td>
<td>0.74</td>
<td>0.1</td>
<td>130</td>
<td>4-27</td>
<td>0-7</td>
</tr>
<tr>
<td>III -&gt; VI</td>
<td>SAND</td>
<td>19–21</td>
<td></td>
<td>25-37</td>
<td>0-10</td>
<td>-</td>
<td>0.40-0.58</td>
<td>0.3</td>
<td>155-240</td>
<td>0-8</td>
<td>-</td>
</tr>
<tr>
<td>VII -&gt;VIII</td>
<td>TERTIARY CLAY</td>
<td>20-21</td>
<td></td>
<td>15-25</td>
<td>24-33</td>
<td>150</td>
<td>0.58-1.00</td>
<td>0.45-0.49</td>
<td>175-180</td>
<td>34-100</td>
<td>3-50</td>
</tr>
<tr>
<td>IX</td>
<td>SANDSTONE</td>
<td>22.0</td>
<td></td>
<td>25</td>
<td>24</td>
<td>-</td>
<td>0.58</td>
<td>0.3</td>
<td>250</td>
<td>12-76</td>
<td>2-8.5</td>
</tr>
</tbody>
</table>

**Static analyses**

**Dynamic analyses**

**Liquefaction assessment**

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**Site Investigation data includes:**

- Field tests: CPT, BH, PMT
- Laboratory tests: identification, triaxial tests (incl. bender elements), oedometer tests
- Geophysical testing: Horizontal Cross-hole seismic survey
- Ground water monitoring
Assessment of Liquefaction Potential

- For granular soils (fines content < 35%, clay content < 20%)

- CRR = Cyclic Resistance Ratio: derived from CPT
- CSR = Cyclic Stress Ratio: derived from seismic loading specifications

\[
CSR = \frac{(\tau_h)_{av}}{\sigma'_{v_0}} = 0.65 \frac{a_{\max}}{g} \frac{\sigma_{v_0}}{\sigma'_{v_0}} r_d
\]

\[
CRR = 0.833 \left( \frac{q_{c1N}}{1000} \right) + 0.05 \quad \text{if} \quad (q_{c1N})_{cs} < 50
\]

\[
CRR = 93 \left( \frac{q_{c1N}}{1000} \right)^3 + 0.08 \quad \text{if} \quad 50 \leq (q_{c1N})_{cs} < 160
\]

\[
MSF = \frac{CRR_M}{CRR_{M=7.5}} = 10^{2.24} / M_w^{2.56}
\]

\[(\tau_h)_{av} = \text{average induced cyclic shear stress}\]
\[\sigma_{v_0} = \text{total in-situ vertical stress relative to ground surface}\]
\[\sigma'_{v_0} = \text{effective in-situ vertical stress}\]
\[a_{\max} = \text{peak horizontal ground acceleration}\]
\[g = \text{acceleration due to gravity}\]
\[r_d = \text{stress reduction coefficient to allow for deformability of the soil column}\]
\[(q_{c1N})_{cs} = \text{the Clean Sand Equivalent Normalised Cone Resistance}\]

\[\text{Safety Factor against liquefaction } FS_{\text{liq}} = \frac{\text{CRR}}{\text{CSR}}\]

[Youd et al.2001]
Assessment of Liquefaction Potential

Safety factors close to 1.0 for SSE at 15m depth (« sandy clay ») in preliminary design
Assessment of Liquefaction Potential & Residual Shear Strength

Thickness of soil layers considered close or below the SF against liquefaction

Idriss & Boulanger 2007
Seismic Design Approach

- **Safety Approach:**
  - OBE seismic design: Ultimate Limit State (ULS)
    - Approach DA2 of Eurocode 7
    - Calculations performed with characteristic values
    - The variable loads are multiplied by $\gamma_Q/\gamma_G = 1.5/1.35 = 1.11$
    - Calculation results (M,V,N) are multiplied by $\gamma_G = 1.35$ (Bauduin et al. 2003)

  - SSE seismic design: Accidental Limit State (ALS)
    - A load factor = 1 is applied to both the permanent and transient loads

- **Calculation methods:**
  - Pseudo-static loading approach
  - Frequency approach
  - Full dynamic (time history) loading approach
Seismic Design – Simplified pseudo-static approaches

Dynamic wall pressures & permanent wall deflections:
- Influenced by the dynamic response of the wall and backfill
- Can increase significantly near the natural frequency of the wall-backfill system

![Dynamic Forces Diagram]

**Mononobe-Okabe analysis**

**Forces acting on active wedge**

\[ P_{AE} = 0.5 \gamma H^2 (1-k_V) K_{AE} \]

**Forces acting on passive wedge**

! Assumption: retained soil mass behaves as a rigid body
Seismic Design – Finite Element Modeling

- Methodology:
  - Step 1: Selection of Soil Models
  - Step 2: Static Design
  - Step 3: 2D vs 3D models
  - Step 4: Seismic Pseudo-Static Calculations
  - Step 5: Seismic Time Domain Calculations
FEM - Selection of Soil Models

- Use of Simplified Linear Elastic Soil Model (eg. Mohr-Coulomb in PLAXIS)

Soil parameters need to be chosen taking into account the actual range of deformations.
FEM - Selection of Soil Models

- Use of more “advanced” Soil Model (eg. Hardening Soil Small Strain in PLAXIS)

Soil parameters adjusted based on degradation curves
FEM – Static Design & 2D/3D equivalence

2D Axisymmetric Model

2D Plane Strain Model

- Bending Moment profiles
- Shear Forces
- Hoop Forces
- Convergence displacements

Ground loads taken by hoop forces

Earth pressures applied as external (stabilising) loads
No specific requirements regarding the:
- meshing
- time integration
- Boundary conditions
FEM – Time Domain analyses

Max. displacement < 0.5m

Use of « Advanced » Soil Models (eg. HS Small Strain)
Use of numerical (Rayleigh) damping parameters
Use of Tied degrees of freedom or viscous boundary lateral conditions
Mesh and Time integration condition: \[ \Delta L_{\text{mesh}} < \lambda_{\text{min}}/10 = V_{s,\text{min}}/(10 \times f_{\text{max}}) \]
\[ \Delta t < \Delta L_{\text{mesh}} / V_{s,\text{min}} \]

Seismic input (after deconvolution) + Compliant base motion
FEM – Example of Comparative Results

Bending Moments [kN.m]

Shear Force [kN]

- Time Domain Analysis (no liquefaction)
- Time Domain Analysis (1m liquefied soil)
- Pseudo-Static analysis (no liquefaction)
Conclusions

• Importance of the depth / definition of the target response spectra
• Importance of considering potential liquefaction assessment early in the design process (soil investigation !)
• Simplifying the problem to 2D equivalent analyses allows saving valuable time, especially for preliminary design
• Pseudo-static analyses may be very overconservative as compared to time-domain analyses

Aknowledgements:
F. Meskens (STRABAG)
K. Stassen and M. Ramos da Silva (FUGRO)
Prof. A. Holeyman (UCL)
Thank you