Earthquake Design of Retaining Structures
Master thesis

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Carsten Lyse, Cowi
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Introduction - Problem Statement

Problem Statement

Water  Wall  Backfill + Water

Static forces  Dynamic forces
Motivation of the Study

- **Pseudostatic**

  One parameter to give the inertia force

- **Full-Dynamic**

  When taking a decision:
  - resources: seismic hazard analysis, time, software, personnel
Literature - Earthquake analyses

Earthquake Analyses

- Mononobe-Okabe Theory

- Full-Dynamic Analysis

- Richard-Elms Theory

\[ d_{perm} = 0.087 \frac{v_{max}^2 a_{max}^3}{a_y^4} \]

- performed with use of Finite Element Software

\[ v_{max} \text{ is the peak ground velocity} \]

\[ a_{max} \text{ is the peak ground acceleration.} \]

\[ a_y \text{ is the yield acceleration.} \]
Literature - Westergaard solution

Westergaard Solution (1931)
-Water Pressures on Dams during Earthquake-

- Two causes for added stresses during earthquake:
  - accelerations of the mass of the dam
  - changes of water pressures

- Rigid vertical wall
- Horizontal acceleration
- No shear stresses

\[
p_{wd} = \frac{7 k_h}{8 g} \gamma_w \sqrt{z_w H}
\]
**Eurocode EN 1998-5**

\[ k_h = \alpha \frac{S}{r} \]

Horizontal seismic coefficient

- \( \alpha \) Ratio of the design ground acceleration on type A ground, \( a_g \), to the acceleration of gravity \( g \)
- \( S \) Soil factor

**Type of retaining structure**

<table>
<thead>
<tr>
<th>Type of retaining structure</th>
<th>( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free gravity walls that can accept a displacement up to ( d_e = 300 \alpha S ) (mm)</td>
<td>2</td>
</tr>
<tr>
<td>Free gravity walls that can accept a displacement up to ( d_e = 200 \alpha S ) (mm)</td>
<td>1.5</td>
</tr>
<tr>
<td>Flexural reinforced concrete walls, anchored or braced walls, reinforced concrete walls</td>
<td>1</td>
</tr>
<tr>
<td>founded on vertical piles, restrained basement walls and bridge abutments</td>
<td></td>
</tr>
</tbody>
</table>

- **Hydrodynamic pressure on the outer face of the wall (Westergaard)**

\[ q(z) = \pm \frac{7}{8} \, k_h \gamma_w \sqrt{h \cdot z} \]

- \( k_h \) is the horizontal seismic coefficient with \( r = 1 \)
- \( h \) is the free water height;
- \( z \) is the vertical downward coordinate with the origin at the surface of water.

- **Hydrodynamic pressure: water on both faces of the wall**

\[ 2 \times q(z) = \pm \frac{7}{8} \, k_h \gamma_w \sqrt{h \cdot z} \]
Numerical Modelling

• **Westergaard Solution**
  - Numerical investigation in Abaqus of Westergaard solution using two different approaches: water as an acoustic medium; water as a continuum.

• **L-Shaped Retaining Wall**
  - Check of the failure surface using pseudostatic analysis in Plaxis
Numerical Modelling - Westergaard solution

Westergaard Solution

- Type of elements
- Resonance
Westergaard Solution

- Results
L-Shaped Retaining Wall

- Soil: M-C material
- Concrete: L-E material
- PGA = 0.25g

Total horizontal displacements
Numerical Modelling- L-Shaped Retaining Wall

L-Shaped Retaining Wall


(b) Niels Krebs Ovesen, *Lærebog i Geoteknik*, 2007

Total deviatoric strains
Port of Beirut - New Quay Wall

Quay wall cross section (courtesy of Rambøll)
Geometry of the Model and Geotechnical Conditions
Case Study - Pseudostatic Analysis

Pseudostatic Analysis

- PGA = 0.25g

- Boundary conditions: standard fixities

- M-C Model for soil

- Static Young’s Modulus (average from the given range)
Case Study - Pseudostatic Analysis

Pseudostatic Analysis

• Results

|                      | Max horizontal displacement $|u_x|$ [mm] | Max vertical displacement $|u_y|$ [mm] |
|----------------------|---------------------------------|---------------------------------|
| Point A - top of the capping beam | 60                              | 16                              |
| Point B - bottom of the quay wall    | 16                              | 16                              |

Horizontal displacement

D-deviatoric strain
Dynamic Analysis

- Boundary conditions: free field; viscous
- Hardening soil model with small strain stiffness for fill material;
- Linear- Elastic soil model for bedrock
- Dynamic Young’s Modulus (3-4 times the static one)
Case Study - Dynamic Analysis

Dynamic Analysis

- **Hardening Soil model with small strain stiffness**

\[
E_{50} = E_{50}^{\text{ref}} \left( \frac{c \cos \varphi - \sigma_3' \sin \varphi}{c \cos \varphi + p^{\text{ref}} \sin \varphi} \right)^m
\]

\[
E_{ur} = E_{ur}^{\text{ref}} \left( \frac{c \cos \varphi - \sigma_3' \sin \varphi}{c \cos \varphi + p^{\text{ref}} \sin \varphi} \right)^m
\]

\[
E_{oed} = E_{oed}^{\text{ref}} \left( \frac{c \cos \varphi - \frac{\sigma_3'}{K_0^{\text{nc}}} \sin \varphi}{c \cos \varphi + p^{\text{ref}} \sin \varphi} \right)^m
\]

- **Strain dependent stiffness**

\[
G_0 = \rho \cdot V_s^2
\]

\[
\gamma_{0.7} \approx \frac{1}{9G_0} \left[ 2c' \left( 1 + \cos(2\varphi') \right) - \sigma_1' \left( 1 + K_0 \right) \sin(2\varphi') \right]
\]
Dynamic Analysis

Elastic response spectra for ground type A

- EC8
- T-H1
- T-H2
- T-H3
Case Study - Dynamic Analysis

Dynamic Analysis

- Results - Horizontal Displacements

<table>
<thead>
<tr>
<th></th>
<th>TH1</th>
<th>TH2</th>
<th>TH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>horizontal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[mm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>20</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>4.5</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
Case Study - Dynamic Analysis

Dynamic Analysis

- Results - T-H along the wall

Peak ground acceleration [g]

<table>
<thead>
<tr>
<th></th>
<th>TH1</th>
<th>TH2</th>
<th>TH3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.9</td>
<td>0.73</td>
<td>1.1</td>
</tr>
<tr>
<td>B</td>
<td>2.5</td>
<td>0.9</td>
<td>0.61</td>
</tr>
</tbody>
</table>

TH 1

TH 2

TH 3
Case Study - Dynamic Analysis

Conclusion and Further Research

• **Conclusions**
• **Pseudostatic vs. Dynamic**

<table>
<thead>
<tr>
<th>Maximum horizontal displacement [mm]</th>
<th>Analysis time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC8</td>
<td>Pseudostatic</td>
</tr>
<tr>
<td>90</td>
<td>60</td>
</tr>
<tr>
<td>Pseudostatic</td>
<td>Dynamic</td>
</tr>
<tr>
<td>1</td>
<td>8-43</td>
</tr>
</tbody>
</table>

• **Further research**
• **Analysis of the quay wall**

- interface between the concrete blocks – relative movements
- parametric study performed
- displacement-based methods
Thank you for your attention!