Seismic Analysis and Design of Retaining Structures and Basement Walls: Lessons from Observed Performance and Recent Research

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My Motivation – “Living” with a fault...
Objectives

- A brief discussion of performance of mechanically stabilized embankments
- Discuss in detail the issues related to the analysis and design of retaining structures and basements
  - Observed performance
  - Current Design Methods
  - Experimental Results
  - Numerical Analyses/Challenges
  - Recommendations
Seismic Performance of Mechanically Stabilized Walls and Embankments
Block Facing Walls

Nisqually 2001, Tacoma, WA

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Mechanically stabilized viaduct approach on improved ground - Seattle, 2001
Chile - 2010 - excellent performance
Our Approach: Physical and Numerical Modeling

Use Physical Modeling to Verify Failure Mechanisms

• Why centrifuge?
  - Good scaling relationships
  - Repeatability
  - Reproducibility
  - Cost effectiveness

• UC Davis centrifuge:
  - 9.1m radius, 4,500Kg maximum payload, area of bucket 4m²
How does the centrifuge work?

The centrifugal force increases the "weight" of the model to simulate weight of a full scale structure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model Dimension/Prototype Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length, L</td>
<td>1/N</td>
</tr>
<tr>
<td>Area, A</td>
<td>1/NP</td>
</tr>
<tr>
<td>Volume, V</td>
<td>1/NP</td>
</tr>
<tr>
<td>Mass, m</td>
<td>1/NP</td>
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<tr>
<td>Density, ρ</td>
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</tr>
<tr>
<td>Force, F</td>
<td>1/NP</td>
</tr>
<tr>
<td>Moment, M</td>
<td>1/NS</td>
</tr>
<tr>
<td>Stress, σ</td>
<td>1</td>
</tr>
<tr>
<td>Strain, ε</td>
<td>1</td>
</tr>
<tr>
<td>Shear Rate</td>
<td>N</td>
</tr>
<tr>
<td>Acceleration, Gravity</td>
<td>N</td>
</tr>
<tr>
<td>Acceleration, Dynamic</td>
<td>N</td>
</tr>
<tr>
<td>Time, Dynamic</td>
<td>1/N</td>
</tr>
<tr>
<td>Frequency</td>
<td>N</td>
</tr>
</tbody>
</table>
Static Centrifuge Experiments


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Seismic Centrifuge Experiments

*Height:* 15.2 cm (model: 19.2g), 7.3 m (proto)
*Relative Density:* 75%
*Reinforcement:* Tru-Grid (70%H-right, 90%H-left)
Summary

• Mechanically stabilized embankments perform very well, especially those using geosynthetic grids or fabric

• Conventional design appears quite adequate for most applications and seismic design guidelines are extremely conservative

• An important element is close spacing (18-24 in.) of the reinforcement layers to achieve good compaction, i.e. 3ft - 90 cm between reinforcements is too much for good compaction.

Conventional Retaining Structures and Basements

• Discuss in detail the issues related to the analysis and design of retaining structures and basements
  - Observed performance
  - Current Design Methods
  - Experimental Results
  - Numerical Analyses/Challenges
  - Recommendations
Types of Retaining Structures

Flexible/Yielding

- Level ground

- Sloping ground
- “nonyielding” - walls that do not satisfy the movement condition
Present Design Guidance (such as it is...)

• Confusion regarding the type of analysis to use, especially the yielding and non-yielding designation

• ?... recommendations: e.g FEMA 750
  - “In the past, it was common practice for geotechnical engineers to reduce the instantaneous peak by a factor from 0.5 to 0.7 to represent an average seismic coefficient for determining the seismic earth pressure on a wall. ...
    ...This approach can result in confusion on the magnitude of the seismic active earth pressure and, therefore, is not recommended. Any further reduction to represent average rather than instantaneous peak loads is a structural decision and must be an informed decision made by the structural designer.”
Past Performance

Delphi: polygonal wall and temple of Apollo 548 B.C., temple destroyed by quake 373 B.C., other major quakes 551, and 1870 A.D.
Taiwan, 1999

A lot of problems with old walls on sloping ground and with sloping backfill. No problems with basements and flat ground ....

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Wenchuan - 2008 - Traditional retaining structures
Favorable performance under seismic load
Crest Acceleration at Zipingpu Dam during Wenchuan Earthquake
Crest Settlement
~ 73 cm at center
Crack repair in progress, expansion seals in process of being replaced
Great Tohoku Earthquake - 2011

• No reported failures of underground structures/basements

• Segmented geosynthetically reinforced structures performed well

• Minor damage to conventional retaining walls on sloping ground

Source: J. Wartman, UW

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Iquique - 2014 - cantilever walls without footings

G. Candia - RCINDIM - National Research Center for Integrated Natural Disaster Management
CONICYT/FONDAP/15110017
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Railway Overpass, SR 1 at Kekerengu, Kaikoura Earthquake
Railway Overpass, SR 1 south of Kekerengu, Kaikoura Earthquake
U-Wall Damage During 1971 San Fernando Earthquake, Clough & Fragaszy (1977)

![Diagram of U-Wall damage with annotations and soil properties]

**Figure 1.4 Wilson Canyon Channel.** Cracking in soil as a result of wall displacements. Fine cracking was detected a distance of 15 ft behind wall.

![Graph showing the range of possible accelerations and the estimated peak accelerations for U-Wall damage]

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Typical Methods of Analysis

Mononobe and Okabe (M-O)

Mononobe and Matsuo, 1929

- Assumes a fully developed Coulomb wedge
- Force applied at 1/3H

\[ P_{AE} = \frac{1}{2} \cdot \gamma \cdot H^2 \cdot (1 - k_v) \cdot K_{AE} \]
Seed and Whitman, 1970

- Solution is asymptotic to M-O for PGA < 0.4g
- Seismic earth pressure increment at 0.6H

\[ \Delta P_{AE} = \frac{1}{2} \left( \frac{3}{4} k_h \right) \gamma H^2 \]
Wood (1973) – Non-Yielding (Rigid) Walls

\[ \Delta P_{AE} = F_p \cdot k_h \cdot \gamma \cdot H^2, \quad F_p = [0.9 \ 1.1] \]

- Homogeneous linear elastic soil and connected to a rigid base
- Seismic earth pressure increment at 0.6H
# Point of Load Application

<table>
<thead>
<tr>
<th>Author</th>
<th>Point of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mononobe-Okabe (1926-1929)</td>
<td>0.33H</td>
</tr>
<tr>
<td>Seed and Whitman (1970)</td>
<td>0.6H</td>
</tr>
<tr>
<td>Nandakumaran and Joshi (1973)</td>
<td>&lt;0.65H</td>
</tr>
<tr>
<td>Krishna et al. (1974)</td>
<td>~0.5H</td>
</tr>
<tr>
<td>Sherif et al. (1982)</td>
<td>~0.42H</td>
</tr>
<tr>
<td>Prakash and Brasavanna (1969)</td>
<td>varies with acceleration</td>
</tr>
<tr>
<td>Ichihara and Matsuzawa (1973)</td>
<td>varies with acceleration</td>
</tr>
<tr>
<td>Ortiz et al. (1983)</td>
<td>varies, but higher than H/3</td>
</tr>
<tr>
<td>Woodward and Griffiths (1992)</td>
<td>varies with acceleration</td>
</tr>
<tr>
<td>Steedman and Zeng (1990)</td>
<td>varies, but higher than H/3</td>
</tr>
<tr>
<td>Mylonakis et al. (2007)</td>
<td>0.33H</td>
</tr>
</tbody>
</table>
Younan and Veletsos (2000) – Elastic Solution $f(\text{stiffness & rotation})$

- **a)** Pressure Distribution
- **b)** Point of Application of Dynamic Increment

\[ \frac{\sigma_{st}(\eta)}{\rho \chi_g H^3} \]
Centrifuge Experiment
Geometry & Instrumentation Layout
Centrifuge Modeling – Spinning and Shaking
Results

Earth Pressure Time History
Seismic Pressure Increment
Fixed Base Cantilever Walls in Sand

Kocaeli YPT060 - PGA = 0.34g

Loma Prieta sc - PGA = 0.52g

Kobe Tak090 - PGA = 0.6g

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Typical Design Considerations (cont.)

✓ Displacing Cantilever Wall

![Graphs showing displacement ratios for different incipient conditions](image-url)

- **Free Field PGA**
- **M-O** Seed & Whitman, 1970
- **Mylonakis et al., 2007**
- **Al Atik & Sitar**
- **Free Base Cantilever in Sand**

**Typical Design Considerations (cont.)**

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Typical Design Considerations

✓ Stiff-Embedded Structure

Free Field PGA

\[ \frac{\Delta \rho_{se}}{Y^2} \]

Seed & Whitman, 1970
Wood, 1973
Mylonakis et al., 2007

Braced Walls in Sand

Stiff-Embedded Structure

FS=1.5
FS=2.0
FS=2.0
FS=1.5

Free Field PGA

\[ \frac{\Delta M_{se}}{Y^2} \]

Seed & Whitman, 1970
Wood, 1973
Mylonakis et al., 2007

Braced Walls in Sand

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Stiff Walls - Basements

Centrifuge Experiments

Numerical Models - FLAC

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Observed and Modeled Dynamic Earth Pressure

**Centrifuge Model**

**FLAC Simulation**

![Dynamic Earth Pressure Distributions](image)

**Dynamic Earth Pressure Distributions Observed on North Wall**
KobeTAK090 - 3, PGA base input = 0.702g

**Normalized Earth Pressure, \( \Delta \sigma / \gamma H \)**

**Normalized Depth, \( z/H \)**

Static At-Rest Earth Pressure, \( \phi = 32.5^\circ \)

Maximum Dynamic Earth Pressure

Minimum Dynamic Earth Pressure

Observed Dynamic Earth Pressure

![Dynamic Earth Pressure Distributions Calculated in FLAC](image)

**Dynamic Earth Pressure Distributions Calculated in FLAC**
KobeTAK090 - 3, PGA base input = 0.702g

**Normalized Earth Pressure, \( \Delta \sigma / \gamma H \)**

**Normalized Depth, \( z/H \)**

Static At-Rest Earth Pressure, \( \phi = 32.5^\circ \)

Maximum Dynamic Earth Pressure

Minimum Dynamic Earth Pressure

M-O Predicted Dynamic Earth Pressure

Observed Dynamic Earth Pressure
Effective Seismic Coefficient

Makdisi & Seed (1978)
[from Anderson et al. (2008)]

Seed & Idriss (1971)
[from Cetin et al. (2004)]

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Effective Seismic Coefficient
NCHRP Report 611 (Anderson et al., 2008)

Wall Height (ft) vs. Scaling Factor ($\alpha$)
Dynamic Earth Pressure Coefficient
Numerical and Centrifuge Model Results

\[ \Delta K_{ae} = \frac{\Delta P_{ae}}{0.5\gamma H^2} \]

- Okabe (1924), \( \phi = 32.5^\circ \)
- Seed & Whitman (1970), 100% PGA
- Wood (1973)
- Mikola & Sitar (2013), Nevada Sand D_\text{r} \sim 75% 
- Candia & Sitar (2013), Yolo Loam RC \sim 90%
- Current Study (NW01), Nevada Sand D_\text{r} \sim 90%

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Site Effects

\[ \Delta K_{se} = \frac{\Delta P_{ae}}{0.5 \gamma H^2} \]

Okabe (1924), \( \phi = 32.5^\circ \)
Seed & Whitman (1970)
Wood (1973)
- H = 3m Basement
- H = 6m Basement
- H = 9m Basement
- H = 12m Basement

Seismic Coefficient, \( k_{MHEA} \) (g)

Site Class D

Okabe (1924), \( \phi = 40.0^\circ \)
Seed & Whitman (1970)
Wood (1973)
- H = 3m Basement
- H = 6m Basement
- H = 9m Basement
- H = 12m Basement

Seismic Coefficient, \( k_{MHEA} \) (g)

Site Class C
Conclusions

• Earth pressure during seismic loading increases with depth similar to static and the “inverse triangle” does not represent this condition.

• Mononobe - Okabe solution is overly conservative at high PGA> 0.4 - 0.5 g and fails to converge for high acceleration > 0.7 g with cohesionless soil.

• Our results show that for cantilever and stiff basement walls lateral earth pressure increment is insignificant for a large range of ground motions. However, inertial forces on the walls have to be properly accounted for.

• The height of the wall or depth of embedment should be considered for structures >6.5m
  - More important for deeper structures
  - Already used in other geotechnical earthquake engineering applications (e.g., seismic slope deformation, liquefaction)
Recommendations for Design

1. Obtain PGA and use Seed & Whitman (1970)

2. Obtain PGA, reduce using NCHRP guidelines, and use Mononobe-Okabe method

3. Perform 1-D site response analysis, compute depth-averaged acceleration, and use Mononobe-Okabe method

4. Perform calibrated 2-D or 3-D dynamic analysis and compute demands on the structure
References:

