Seismic Earth Pressures under Restricted Condition

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Chief Engineer
C.H.J., Incorporated
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- **Pseudostatic Seismic Coefficient, $k_h$**
- **Static Design vs. Seismic Design**
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Introduction

- Seismic Earth Pressure (SEP) – a classic but unresolved problem
  - Studies since 1920’ (Okabe, 1926, Mononobe & Matsuo, 1929)
  - Seismic earth pressure for non-yielding wall (Wood, 1973)
  - Seismically Induced Earth Pressures for LRFD Seismic Design of Retaining Structures - Transportation Research Board’s 4 years & $850k project since 2010
Research Needs Statements

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Seismically Induced Earth Pressures for LRFD Seismic Design of Retaining Structures

RESEARCH PROBLEM STATEMENT

In development of the AASHTO LRFD Bridge Design Specifications as well as the AASHTO Guide Specifications for LRFD Seismic Bridge Design (SGS), several unresolved issues associated with the design of earth retaining structures have been identified. The most critical of these unresolved issues are the distribution and magnitude of the seismic earth pressure behind walls that are restrained in their ability to move laterally. There also remains uncertainty regarding seismic earth pressure behind free standing walls that have ability to move laterally during seismic loading. The resolution of these issues is essential to safe and economical seismic design. However, these issues cannot be resolved with the existing knowledge base. Therefore, research is needed to provide a sound basis for these aspects of the seismic design of Earth Retaining Structures (ERS). The results of this work will be useful to design engineers for all types of bridge abutment walls and free standing earth retaining structures in AASHTO Seismic Design Categories C and D, the two highest seismic design categories. It will also provide information on static earth pressures behind restrained wall systems that will be useful to bridge designers in all parts of the country.

ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding: $850,000

Research Period: 4 years

Sponsoring Committee: AFF50, Seismic Design and Performance of Bridges
Source Info: Edward Kavazanjian, Jr., Associate Professor of Civil Engineering, Arizona State University, Tempe, AZ, 85287-5306; Tel: 480-727-8566; Email: edkav@asu.edu
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Index Terms: Earth pressure, Base isolation, Earthquake resistant design, Seismicity, Bridge design, AASHTO LRFD Bridge Design Specifications, Load factor, Bridge abutments, Retaining walls, Geotechnical engineering.
Introduction

Introduction

- Main unresolved problems
  - Existing SEP formula may be too conservative
  - SEP distributions – normal triangular, inverted triangular, parabolic
  - Seismic vs. pseudostatic – confusion in pseudostatic seismic coefficient, $k_h$
REVIEW OF PREVIOUS STUDIES
Review of Previous Studies

- Cantilever Wall (Flexible / Yielding)
  - Okabe (1924), Mononobe & Matsuo (1929)
  - Seed & Whitman (1970)
  - ...

- Restrained Wall (Stiff / Non-yielding)
  - Wood (1973)

- Most recent
  - Maleki & Mahjoubi (2010)
Mononobe-Okabe (M-O) Method

- Okabe (1926), Mononobe & Matsuo (1929)

\[ P_{AE} = p_{AE} \cdot \frac{H^2}{2} \]

\[ p_{AE} = K_{AE} \gamma (1 - k_v) \cos \delta \]

\[ \phi - \beta \geq \psi \]

\[ \psi = \tan^{-1} \left( \frac{k_h}{1 - k_v} \right) \]

\[ K_{AE} = \frac{\cos^2 (\phi - \theta - \psi)}{\cos \psi \cos^2 \theta \cos (\delta + \theta + \psi) \left[ 1 + \frac{\sin (\delta + \phi) \sin (\phi - \beta - \psi)}{\cos (\delta + \theta + \psi) \cos (\beta - \theta)} \right]^2} \]
Seed & Whitman (1970)

\[
\Delta K_{AE} = \frac{3}{4} k_h \quad \text{or} \quad \frac{\Delta P_{AE}}{\gamma H^2} = \frac{3}{8} k_h
\]

---

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<th>k_h</th>
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<td>0.365</td>
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<td>0.42</td>
<td>0.495</td>
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Seed & Whitman (1970)

by Fred Yi, 2/16/2011
Wood (1973)

\[ \Delta P_{eq} = \gamma H^2 \frac{a_h}{g} F_p \]

Figure 1. Typical SASSI Model of the Foundation

\[ p(y) = -0.0015 + 5.05y - 15.84y^2 + 28.25y^3 - 24.59y^4 + 8.14y^5 \]  \hspace{1cm} (3)

Figure 4. Comparison of Normalized Pressure Profiles
Fig. 6.17 Back-calculated dynamic earth pressure coefficients at time of maximum dynamic wall moments and maximum dynamic earth pressures on stiff and flexible walls as function of peak ground acceleration measured at top of soil in free field.
Figure 3. Soil-wall finite element model.

Figure 4. Pseudo acceleration (PSA) spectra for selected ground motions.

Figure 7. Seismic soil pressure for 8 m height wall. (a) Bridge abutment; (b) flexible wall; (c) rigid wall.
Purpose of This Study

• This study intends to solve
  – Effects of soil strength parameters
  – Effects of base conditions
  – Relationship between $k_H$ and PGA
  – A simple equation for engineers
PSEUDOSTATIC NUMERICAL SIMULATION
Pseudostatic Simulation by FEM

• Soil property
  – Elastoplastic
  – Mohr-Coulomb failure criteria (c=0, Φ)

• Boundary conditions
  – Rigid base model
    • Wall movement = 0 & deflection = 0
  – Non-rigid base model
    • Wall movement & deflection = 0
    • Wall movement ≠ 0, deflection = 0
FEM model

- Rigid base, Restrained Rigid Wall

Fixed in X

5H

H

Gravity

k_H

Fixed in XY

Changed to Fixed in Y

Fixed in X
FEM model

- Non-Rigid base, Restrained Rigid Wall

- Fixed in X
- Fixed in X
- Fixed in XY
- Gravity
- Changed to Fixed in Y
- 5H
- Fixed in X
- Fixed in X

 ICTPA 24th Annual Conference & NACGEA International Symposium on Geo-Trans
May 27-29, 2011 Los Angeles, CA U.S.A.
FEM model

- Non-Rigid base, Rigid Wall

- Fixed in X

- No rotation

- 5H

- Fixed in X

- Gravity

- Changed to Fixed in Y

- Fixed in XY

- \( k_H \)
FEM Results

- **Rigid base, Restrained Rigid Wall**

![Lateral Stress (psf)](image)

**Passive EP**

**At-rest EP**

**Lateral Stress (psf)**
FEM Results

- Non-Rigid base, Restrained Rigid Wall

Lateral Stress (psf)
FEM Results

- Non-Rigid base, Rigid Wall
FEM Results

- Non-Rigid base, Rigid Wall
Seismic Earth Pressure

- Rigid base, Restrained Rigid Wall

\[
\frac{\Delta P_{0E}}{\gamma H^2} = 1.02 k_H
\]
Seismic Earth Pressure

- Non-Rigid base, Restrained Rigid Wall

\[
\frac{\Delta P_{0E}}{\gamma H^2} = 1.17 k_H
\]
Seismic Earth Pressure

- Non-Rigid base, Rigid Wall

\[
\frac{\Delta P_{0E}}{\gamma H^2} = 1.15k_H
\]
Seismic Earth Pressure

\[ \frac{\Delta P_{0E}}{\gamma H^2} = 1.17k_H \]

- Rigid base, Restrained rigid wall
- Non-Rigid base, Restrained rigid wall
- Non-Rigid base, Rigid wall

Wood (1973)

\[ \frac{\Delta P_{0E}}{\gamma H^2} = 1.15k_H \]

\[ \frac{\Delta P_{0E}}{\gamma H^2} = 1.02k_H \]
Seismic Earth Pressures of Rigid Walls

- Rigid base, Restrained Rigid Wall
  \[ \frac{\Delta P_{0E}}{\gamma H^2} = 1.02k_H \]

- Non-Rigid base, Restrained Rigid Wall
  \[ \frac{\Delta P_{0E}}{\gamma H^2} = 1.17k_H \]

- Non-Rigid base, Rigid Wall
  \[ \frac{\Delta P_{0E}}{\gamma H^2} = 1.15k_H \]
Distribution of Seismic Earth Pressure

- Rigid base, Restrained rigid wall
- Non-Rigid base, Restrained rigid wall
- Non-Rigid base, Rigid wall

\[
\frac{\Delta P_{0E}}{P_0} = \frac{1}{k_h} \cdot \text{for different } k_h = 0.1, 0.2, 0.3, 0.4, 0.5
\]

\[
\frac{\Delta P_{0E}}{P_0} = \frac{1}{1.02k_H} \cdot \text{for different } k_h = 0.1, 0.2, 0.3, 0.4, 0.5
\]

\[
\frac{\Delta P_{0E}}{P_0} = \frac{1}{1.15k_H} \cdot \text{for different } k_h = 0.1, 0.2, 0.3, 0.4, 0.5
\]
Thrust Point of Seismic Earth Pressure

- Rigid base, Restrained rigid wall
- Non-Rigid base, Restrained rigid wall
- Non-Rigid base, Rigid wall

Thrust Point, z/H vs. Pseudostatic Seismic Coefficient, k_H

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PSEUDOSTATIC SEISMIC COEFFICIENT, $k_h$
Seismic Coefficient ($k_H$)

• Confusion:
  – $k_H$ = PGA
    • Seed & Whitman (1970)
    • FEMA 450 ($k_H = S_{DS}/2.5$)
    • HCHRP Report 611
    • FHWA-NHI-10-024
  – $k_H$ = PGA/2
    • ASSHTO LRFD Bridge Design Specification, 2010
    • Kramer (1996), $k_H = (1/3 \sim 1/2)$ PGA

• What should it be?
What should $k_h$ be?

- The magic number of 0.65

Consequently, Seed and Idriss (1971) chose to represent earthquake-induced cyclic stresses by using a representative value (or equivalent uniform value) equal to 65% of the peak cyclic stress. The corresponding earthquake-induced CSR is therefore computed as

$$CSR = 0.65 \frac{\tau_{max}}{\sigma_{vc}} = 0.65 \frac{\sigma_{vc} a_{max}}{\sigma_{vc} r_d}$$

(25)

The choice of 0.65 to represent a reference stress level is somewhat arbitrary, but it was selected in the beginning of the development of liquefaction evaluation procedures in 1966 and has been in use ever since. More importantly, the overall liquefaction evaluation procedure would be essentially unaffected by the choice of a different reference stress ratio, provided that the adjustment factors for the duration of shaking and the empirically derived liquefaction correlations were all derived for that reference stress (see Section 3.5).

Idriss & Boulanger (2008), Soil Liquefaction During Earthquakes, EERI MNO-12
Data by Atik & Sitar (2008)

\[ k_h = 0.46 \text{PGA} - 0.113 \]

\[ k_h = 0.47 \text{PGA} - 0.1675 \]

<table>
<thead>
<tr>
<th>PGA</th>
<th>( \Delta K_{ae} )</th>
<th>( k_h )</th>
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<tr>
<td>0.4</td>
<td>0.05</td>
<td>0.02</td>
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<tr>
<td>0.5</td>
<td>0.16</td>
<td>0.07</td>
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<td>0.6</td>
<td>0.26</td>
<td>0.11</td>
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<td>0.7</td>
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<td>0.8</td>
<td>0.48</td>
<td>0.21</td>
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</table>

Atik & Sitar (2008), Experimental and Analytical Study of the Seismic Performance of Retaining Structures, University of California, Berkeley
Examination of an earthquake record

- Acceleration records

- Velocity time history

- Displacement time history
Earthquake record, cyclic and pseudostatic

- **Irregular time history of earthquake records**

![El Centro Earthquake Record (N-S)](image)

- **Cyclic loading in laboratory testing**

- **Pseudostatic seismic coefficient**
Considering Energy Conservation: $t=0\sim5$ s

- **Original acceleration record**
  
  ![Original acceleration record graph]
  
  PGA = 3.42 m/s$^2$

- **Equivalent Harmonic cyclic wave**
  
  ![Equivalent Harmonic cyclic wave graph]
  
  Amp = 1.27 m/s$^2$, $T = 0.556$ sec

- **Equivalent Pseudostatic load**
  
  ![Equivalent Pseudostatic load graph]
  
  $k_H = 0.81$ m/s$^2$
Equivalent cyclic wave Amp & Pseudostatic $k_H$

El Centro Earthquake Record (N-S)
Examination of an earthquake record

- Acceleration records

- Velocity time history

- Displacement time history
Equivalent cyclic wave Amp & Pseudostatic $k_H$

Kobe Earthquake (1995), Type111
Suggested $k_H – PGA$ relationship

- **Essential Structures**
  \[ k_H = \frac{1}{2} \, PGA \]

- **Other Structures**
  \[ k_H = \frac{1}{3} \, PGA \]
STATIC DESIGN VS. SEISMIC DESIGN
Static Design vs. Seismic Design

- Factor of safety for static design
  \[ FS_{\text{static}} = \frac{S}{F_{\text{static}}} = 1.5 \]

- Factor of safety for seismic design
  \[ FS_{\text{seismic}} = \frac{S}{F_{\text{seismic}}} = 1.1 \]

- Therefore, a statically designed structure can withstand a seismic load of
  \[ F_{\text{seismic}} = \frac{1.5}{1.1} F_{\text{static}} = 1.36 F_{\text{static}} \]
Upper Bound of PGA covered by static design

- Essential Structures (Rigid Base)
- Others (Rigid Base)
- Essential Structures (Rigid Base)
- Others (Non-Rigid Base, restrained)
- Essential Structures (Rigid Base)
- Others (Non-Rigid Base, rigid wall)
CONCLUSIONS AND RECOMMENDATIONS
Conclusions

- The increment of SEP of rigid walls is independent of internal frictional angle of the backfill soils.
- The ratio of the increment of SEP of rigid walls to $\gamma H^2$ depends only on $k_h$ and base conditions.
- The increment can be expressed as:
  $$\Delta P_{OE} = \alpha_k \cdot k_h \cdot \gamma H^2$$
  $$\alpha_k = 1.02 \text{ for rigid base} \& \alpha_k = 1.17 \text{ for non-rigid base}$$
- Thrust point is lower than the middle point of the wall and can be conservatively taken as $0.45H$.
- $k_h$ is significantly lower than PGA and can be conservatively taken as:
  $$k_h = \beta \cdot (PGA)$$
  $$\beta = \frac{1}{2} \text{ for essential structures}$$
  $$\beta = \frac{1}{3} \text{ for other structures}$$
Recommendations

- Seismic Earth Pressures under Restrained Condition

\[ \Delta P_{0E} = \alpha \cdot (PGA) \cdot \gamma H^2 \]

<table>
<thead>
<tr>
<th>Type of Structures</th>
<th>Rigid Base</th>
<th>Non-Rigid Base</th>
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<td>Essential Structures</td>
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</tr>
<tr>
<td>Other Structures</td>
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- Thrust point = 0.45H