Seismic Earth Pressures on Retaining Walls

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You can observe a lot by just watching.  
Geotechnical Interpretation: Observational method

If you don't know where you are going, you might wind up someplace else. 
Never forget the fundamentals.

I usually take a two hour nap from one to four. 
We’re geotechnical errors, 50% error isn’t so bad

...when I die, just bury me where you want. Surprise me. 
We’ll miss you.
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Seismic Earth Pressures on Retaining Walls

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ATC-83 Project

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Outline

• Mechanisms for wall-soil interaction
• Current practice & recent research
• Wall-soil interaction springs
• Kinematic wall-soil interaction
• Summary
Interaction Mechanisms

Kinematic soil-structure interaction (SSI)

• Foundation input motion (FIM)
• No external inertial forces
• Pressure from differential wall-soil movements
Physical Basis for *Kinematic SSI Effects*

Low frequency

Long wavelength

\[ \lambda = \frac{V_s}{f} \]

\[ u_{FIM} \approx u_{g0} \]

\[ \theta_{FIM} \approx 0 \]

Negligible wall pressures
Physical Basis for *Kinematic SSI Effects*

High frequency

Short wavelength
\[ \lambda = \frac{V_s}{f} \]

\[ u_{FIM} < u_{g0} \]
\[ \theta_{FIM} > 0 \]

Large wall pressures
Interaction Mechanisms

Inertial SSI
- Inertia in structure produces base shear and moment (V & M)
- V & M resisted by soil reactions (incl. walls)
- Key issue: connectivity of structural lateral force resisting system to walls
Interaction Mechanisms

Important Points:

Both kinematic and inertial effects give rise to seismic earth pressures

Both produce pressures as a result of relative movements between wall and soil.
Outline

• Mechanisms for wall-soil interaction
• **Current practice & recent research**
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Current Practice & Recent Research

• Mononobe-Okabe procedure
  – Basis for current standards of practice, with various modifications over time
  – Current guideline using M-O: NCHRP (2008)\(^{(1)}\)

• Results of recent research
  – Centrifuge tests
  – Dynamic SSI analysis

M-O Approach\textsuperscript{(1)}

- Begin with static earth pressure (e.g., $K_a$ or $K_0$). Resultant $P_A$.
- Limit equilibrium analysis with seismic coefficient $k_h (\propto PGA)$ in Coulomb-type wedge. Produces $P_E$.
- Problem: Seismic earth pressure correlated to acceleration

\textsuperscript{(1)} Okabe (1924) and Mononobe and Matsuo (1929)
Consider case of vertically propagating, horizontally coherent, SH wave

Acceleration: $\mathbf{a}_g(z) = -\omega^2 u_0 \cos \left( \frac{\omega z}{V_S} \right) e^{i\omega t}$

Inertia generated by wave resisted by mobilized shear stresses, $\tau_{hv}(z)$

Wave produces no change in normal stresses on vertical or horizontal planes (absent $\Delta u$)

∴. Horizontal stresses have no fundamental association with PGA
CCW

$\sigma'_{vo}$

$\tilde{J}_e$

$\sigma'_{ho}$

$\tilde{J}_e$

$\sigma'_{vo}$

$\sigma'_{vo} = k_0 \sigma'_{vo}$

— before eqk

— eqk stress $\tilde{J}_e$

applied.
Centrifuge Tests

- Al Atik and Sitar (2009, 2010)
- U-shaped walls, rigid & flexible. $H = 6.5$ m and $B = 5.3$ m (prototype)
- $D = 19$ m
- 3 time series

Al Atik and Sitar, 2010: *JGGE*
Centrifuge Tests

Total earth pressures. Below M-O predictions.

Al Atik and Sitar, 2010: *JGGE*
Centrifuge Tests

Recommendation: No seismic earth pressure for PGA < 0.4g. M-O over-predicts.

Al Atik and Sitar, 2010: JGGE
Dynamic SSI Analysis

• Ostadan, 2005
• No wall-soil movement at base
• $H = 9.14 \text{m}$. Broadband input
• Strong site response due to rigid base and input energy at $f_1 = V_s/(4H)$

Similar results by Wood, 1973; Veletsos and Younan, 1994;
Dynamic SSI Analysis

- Ostadan, 2005
- No wall-soil movement at base
- $H = 9.14$ m. Broadband input
- Strong site response due to rigid base and input energy at $f_1 = V_S / (4H)$
- Substantially larger pressures than M-O

Ostadan, 2005
Summary of Recent Studies: Free-Standing Walls

• Centrifuge tests tend to support pressures lower than M-O
• Analyses involving a strongly resonant site condition support higher pressures than M-O

No surprise that there is considerable confusion in practice surrounding this issue
Outline

• Mechanisms for wall-soil interaction
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Interaction Springs

- Our objective: wall-soil pressures
- Evaluate from relative displacements and foundation-soil interaction springs
Interaction Springs

We have solutions for:

- Stiffness of surface foundation: $K_y, K_{xx}$
Interaction Springs

We have solutions for:

- Stiffness of surface foundation: $K_y$, $K_{xx}$
- Stiffness of embedded foundation: $K_{y,emb}$, $K_{xx,emb}$
Interaction Springs

We have solutions for:

- Stiffness of surface foundation: $K_y, K_{xx}$
- Stiffness of embedded foundation: $K_{y,emb}, K_{xx,emb}$

Partition into:

- Stiffness of base slab
Interaction Springs

We have solutions for:

- Stiffness of surface foundation: $K_y, K_{xx}$
- Stiffness of embedded foundation: $K_{y,emb}, K_{xx,emb}$

Partition into:

- Stiffness of base slab
- Wall contributions (our objective)

Partitioning of stiffness values derived in present work
Interaction Springs

Wall reactions computed using stiffness intensities:

• Defined as stiffness/area on wall.

• Notation: $k_y^i$ and $k_z^i$

Units of Force/Length$^3$
Interaction Springs

Wall reactions computed using stiffness intensities:

- Defined as stiffness/area on wall.
- Notation: $k_y^i$ and $k_z^i$
- Units of Force/Length$^3$
Interaction Springs

**Approach:**

- Develop expressions for $k_y^i$ and $k_z^i$
- Take as known: $K_y$, $K_{xx}$, $K_{y,emb}$, $K_{xx,emb}$ (literature)
- Use equilibrium to relate $(K_y, K_{xx})$ and $(k_y^i, k_z^i)$ to $(K_{y,emb}, K_{xx,emb})$
- Thereby derive coupling terms ($\chi_y$, $\chi_{xx}$)
Interaction Springs

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• Develop expressions for $k_y^i$ and $k_z^i$
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Interaction Springs

*Stiffness intensity expressions:*

- Rigid vertical wall over rigid base at depth $H$ (Kloukinas et al, 2012: JGGE)
- Rigid vertical wall over finite soil layer, including interaction effects (this study)
Interaction Springs

**Stiffness intensity expressions:**

\[
k^i_y = \chi_y \frac{\pi}{\sqrt{(1-v)(2-v)}} \frac{G}{H} \sqrt{1- \left( \frac{2\omega H}{\pi V_s} \right)^2}
\]

\[
k^i_z = \chi_{xx} \frac{\pi}{2 \sqrt{1-v}} \frac{G}{H} \sqrt{1- \left( \frac{2\omega H}{\pi V_s} \right)^2}
\]

Dynamic stiffness modifiers:
Unity when \( \lambda/H \to \infty \)
(common condition)
Interaction Springs

**Stiffness intensity expressions:**

\[
k_y^i = \chi_y \frac{\pi}{\sqrt{(1 - \nu)(2 - \nu)}} \frac{G}{H} \sqrt{1 - \left(\frac{2\omega H}{\pi V_s}\right)^2}
\]

\[
k_z^i = \chi_{xx} \frac{\pi}{2} \frac{G}{(1 - \nu) H} \left(1 - \left(\frac{2\omega H}{\pi V_s}\right)^2\right)
\]

- Modulus taken from \(V_s\) of soil materials adjacent to walls (not below foundation).
- Adjustments for nonhomogeneity and nonlinearity.
Interaction Springs

Stiffness intensity expressions:

\[
k^i_y = \chi_y \frac{\pi}{\sqrt{(1-\nu)(2-\nu)}} \frac{G}{H} \sqrt{1 - \left( \frac{2\omega H}{\pi V_s} \right)^2}
\]

\[
k^i_z = \chi_{xx} \frac{\pi}{2} \sqrt{\frac{2-\nu}{1-\nu}} \frac{G}{H} \sqrt{1 - \left( \frac{2\omega H}{\pi V_s} \right)^2}
\]

Coupling factors
**Interaction Springs**

*Coupling terms: why necessary?*

Wall-soil reactions affect multiple stiffness terms for embedded foundation. Examples:

- $k_y^i$ affects $K_{y,emb}$ and $K_{xx,emb}$
**Interaction Springs**

**Coupling terms: why necessary?**

Wall-soil reactions affect multiple stiffness terms for embedded foundation. Examples:

- \( k_i \) affects \( K_{y,emb} \) and \( K_{xx,emb} \)
- \( k_i \) affects \( K_{z,emb} \) and \( K_{xx,emb} \)

Unfactored base slab stiffnesses and wall stiffness intensities combine to overestimate \( K_{y,emb} \) & \( K_{xx,emb} \)
Interaction Springs

*Equilibrium equations:*

**Horizontal:**  \[ K_{y,\text{emb}} = 2k_i^y H + \chi_y K_y \]

**Rotation:**  \[ K_{xx,\text{emb}} = k_i^y H^2 + \chi_{xx} K_{xx} + 2k_i^z H B^2 \]

Where \( K_j \) and \( K_{jj} \) stiffness terms are from the literature
Outline

• Mechanisms for wall-soil interaction
• Current practice & recent research
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• **Kinematic wall-soil interaction**
• Summary
Kinematic Interaction Problem

- Formulation of solution
- Kinematic model results
- Synthesis of method
- Comparison to centrifuge tests and SASSI results
Formulation of Solution

• Formulate $P_E$ from integration over depth of $k_y^i \times$ relative wall displacement

\[ P_E = \int_0^H k_y^i (u_{g0} \cos kz - u_w(z)) \, dz \]

• Similar expression for $M_E$

• Equations apply for uniform $V_s$ and rigid wall
Formulation of Solution

• Wall displacement affected by translation and rotation

\[ u_w(z) = u_{FIM} + \theta_{FIM} (H - z) \]

• Wall force balanced by base shear

\[
P_E = \int_0^H k_y^i \left[ u_g^0 \cos kz - u_{FIM} - \theta_{FIM} (H - z) \right] dz
\]

\[
P_E = \frac{K_y}{2} \left[ u_{FIM} - u_g^0 \cos kH \right]
\]
Formulation of Solution

• Wall displacement affected by translation and rotation
  \[ u_w(z) = u_{FIM} + \theta_{FIM} (H - z) \]

• Wall force balanced by base shear

• Similar eqns for \( M_E \)

• System of eqns solved for \( u_{FIM} \) and \( \theta_{FIM} \)

• \( P_E \) and \( M_E \) computed
Base Slab Motions

- Ordinate: FIM / \( u_{g0} \) ratios
- Abscissa: \( \lambda / H \)
- Translation decreases for small \( \lambda / H < \sim 10 \)
- Rotation increases for same conditions
- Kausel et al. (1978) model ok for translation, low for rotation
Kinematic Model Results

- Ordinate: $P_E/(u_0k_yiH)$
- Abscissa: $\lambda/H$
- Peaks at $\lambda/H = 2.3$
- Small for $\lambda/H > \sim 10$
Kinematic Model Results

- Ordinate: $P_E/(u_g k_i H)$
- Abscissa: $\lambda/H$
- Peaks at $\lambda/H = 2.3$
- Small for $\lambda/H > \sim 10$
- Modest effects of relative foundation-wall stiffness

Critical finding: interaction force depends strongly on $\lambda/H$
Kinematic Model Results

• Can relax uniform soil assumption

Peak shifts to right. Amplitudes decrease.

Figure: Scott Brandenberg
Mode shape for soil displacement behind wall. As \( n \) increases, displaced shape becomes nearly vertical.
Kinematic Model Results

- Can relax rigid wall assumption

Figure: Scott Brandenberg
Synthesis

1. Compute FFT of free-field motion, $\hat{u}_{g0}(\omega)$
2. Compute foundation stiffnesses, $k_y^i$, $k_z^i$, $K_y$, $K_{xx}$, $K_{y\_emb}$, $K_{xx\_emb}$
3. Solve for FIM in frequency-domain: $\hat{u}_{FIM}(\omega) \hat{\theta}_{FIM}(\omega)$
4. Solve for $P_E$ in frequency-domain: $\hat{P}_E(\omega)$
5. Inverse Fourier transform to $P_E(t)$
Synthesis: Simplified Approach

1. Estimate mean period, $T_m$, from GMPE
2. Compute $\lambda/H = V_s T_m/H$
3. Use graphical result for $P_E/(u_{g0}k_yiH)$ vs. $\lambda/H$ to find normalized force
4. Compute $k_y^i$
5. Estimate $u_{g0}$ as $PGV/\omega$, where $\omega=2\pi/T_m$
6. Solve for maximum value of $P_E$
Comparison to Prior Results

*In theory there is no difference between theory and practice. In practice there is.*

– Yogi Berra

\[ \frac{P_E}{u_0k_yH} \]

\[ K_{xx}/(k_yH^2/3) = 100 \]

- **SASSI**: \( \lambda/H = 4 \)
- **Centrifuge**: \( \lambda/H = 12 \)
Comparison to Prior Results

(a) Analysis of Simulations by Ostadan (2005)

- **Good match**

(b) Analysis of Centrifuge Tests by Al Atik and Sitar (2009)

- **Right resultant.**
- **Wrong shape.**
Considering profile inhomogeneity...

Rigid Wall, Constant $V_s$ Profile
$P_E = 150$ kN/m

Flexible Wall, Parabolic $V_s$ profile
$P_E = 86$ kN/m

Mononobe-Okabe $P_E = 180$ kN/m

Measured $P_E = 90$ kN/m

Figure: Scott Brandenberg
Pending Comparisons to Experimental Results

UCB-UCD-NEESR centrifuge test data (Mikola et al., 2014)

U. Colorado Boulder centrifuge test data (Hushmand et al., 2015)

U. Bristol-U. Naples-U. Sannio shake table testing (Kloukinas et al., 2014)

UCSD-NEESR shake table testing (Wilson and Elgamal, 2015)
Summary

• Seismic earth pressures on walls result from relative wall/free-field displacements.
• These relative displacements can arise from distinct inertial and kinematic mechanisms.
• M-O procedures capture neither mechanism.
• The seismic earth pressure increment has no fundamental relationship to PGA.
Summary

• Kinematic wall pressures governed by $u_{g0}$ and $\lambda/H$. Often small for practical conditions.
• Proposed procedures resolves conflicting findings in literature
• No specialty software required
• Inertial interaction computed using dynamic analysis of structure with foundation springs. Wall pressures depend on load path.
Details in:


Java Applet at:

http://uclageo.com/
References


When is Inertial Interaction Important?

\[
\tilde{T} = \sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_{yy}}}
\]

Most critical factor for is \( h/(V_s T) \).

The flexibility (period) and damping of the system are affected.
Period Lengthening Trends

Inertial SSI significant if $h/(V_sT) > 0.1$
Foundation Damping Trends:

![Diagram showing the relationship between h/(V_sT) and β_f for different values of h/B: h/B = 1 (solid line), h/B = 2 (dashed line), h/B = 4 (dotted line). The plot shows an increasing trend in β_f as h/(V_sT) increases for all values of h/B.](image-url)
Effects of Period Lengthening & Damping on Base Shear

\[ S_a(g) \propto \text{Base Shear} \]

\[ \tilde{T}, \beta_0 = \text{Flexible-base period, damping ratio} \]
\[ T, \beta_i = \text{Fixed-base period, damping ratio} \]
\[ T_p = \text{Predominant period of ground motion} \]

(i.e., period of largest spectral peak)

Increased base shear

Decreased base shear
Response History Recommendations

- Apply bathtub model (no multi-support excitation req’d)
- Wall springs can be evaluated from $k_y^i$
- Computed wall spring forces applied in combination with kinematic loads

Source: NIST (2012)

Large wall demands from inertial SSI require rigid foundation or lateral load transfer above base level
Java Applet Demonstration