Soil-Structure Interaction Issues

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Motivation

• Soil-structure interaction (SSI) is coupling of structural and soil responses

• SSI can be modeled using techniques ranging from simple (e.g., “springs” attached to the base of structural elements) to complex (e.g., 3D nonlinear effective stress analysis combining soil and structural elements).

• However, it is very often ignored. Why?
Motivation

• SSI requires effective communication between structural and geotechnical engineers.
Two recent SSI research projects on topics for which geotechnical engineers generally ignore SSI, but including it is important:

1. Seismic earth pressures acting on flexible vertical retaining walls
2. Influence of shallow foundations on earthquake-induced ground failure potential
Collaborators

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Shannon & Wilson

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Seismic Earth Pressures
• Mononobe-Okabe (M-O) method is most common method utilized today.

• Begin with static earth pressure (e.g., $K_a$ or $K_o$). Resultant $P_A$.

• Limit equilibrium analysis with seismic coefficient $k_h$ ($\propto$ PGA) in Coulomb-type wedge. Produces $P_E$.

• Predicts very high earth pressures when shaking is strong.

• Empirical evidence is that retaining walls perform well during earthquakes, even if they were not seismically designed.

• Questions:
  - Does horizontal acceleration necessarily give rise to seismic earth pressure?
  - Is seismic earth pressure influenced by factors not considered in M-O method?

Okabe (1924) and Mononobe and Matsuo (1929).
Consider case of vertically propagating, horizontally coherent, SH wave

Acceleration: $\ddot{u}_y(z) = -\omega^2 u_0 \cos \left( \frac{\omega z}{V_s} \right) e^{i\omega t}$

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 soil plasticity)

If we were to make an excavation and replace the excavated soil with a structural system with the exact same mass and stiffness as the excavated soil, seismic earth pressures would be zero

∴ Horizontal stresses have no fundamental association with acceleration. Rather, it is relative displacement between the soil and wall that creates earth pressure.
Figure 2. Schematic illustration of free-standing retaining wall subjected to seismic waves with different wavelengths (a) wall, (b) $u_g$ (long $\lambda$), and (c) $u_g$ (short $\lambda$).

Durante et al. (2022), BSSC (2020).
\[ EI \frac{\partial^4 u_w}{\partial z^4} + k_y^l \left[ u_{g0} \cos(kz) - u_w \right] = 0 \]

\[ \beta = \sqrt{\frac{k_y^l}{4EI}} \]

\[ u_{g0} = f_u PGV/\omega_m \]

\[ f_u = \begin{cases} 
0.65 & \text{if } \lambda/H < 2.5 \\
0.95 & \text{if } \lambda/H > 20 \\
0.607 + 0.017\lambda/H & \text{otherwise}
\end{cases} \]

\[ \frac{P_E}{P_{E,\text{rigid}}} = \xi = \begin{cases} 
1 - \exp\left(1 - \frac{2.9}{\beta H}\right) & \beta H < 1 \\
\sin\left(-0.45 + \frac{1.43}{\beta H}\right) + \cos\left(1.22 + \frac{0.34}{\beta H}\right) & \beta H \geq 1
\end{cases} \]

\[ \frac{h}{H} = \begin{cases} 
0.6 - \exp\left(-0.12 - \frac{2.8}{\beta H}\right) & \beta H < 1 \\
\sin\left(1.68 + \frac{1.5}{\beta H}\right) + \cos\left(2.87 - \frac{1.92}{\beta H}\right) & \beta H \geq 1
\end{cases} \]

**Figure 3.** Variation with normalized wavelength \( \lambda/H \) of (a) normalized amplitude of \( P_E \) and (b) its point of application above the wall base for various values of \( \beta H \). Dotted lines at low \( \lambda/H \) are approximations of exact solution.

Durante et al. (2022), BSSC (2020).
**Figure 4.** Variation of median values of mean period ($T_m$) with magnitude, distance, and site condition (Rathje et al., 2004).

Durante et al. (2022), BSSC (2020)
Figure 5. Ground motion amplitude adjustment factor for use with simplified method for evaluation of amplitude of seismic earth pressure resultant force, $P_E$.

Durante et al. (2022), BSSC (2020)
### NEES-2010-0943: Seismic Earth Pressures on Retaining Structures

**PIs:** Nicholas Sitar  
**Organizations:** University of California, Berkeley CA, United States  
**NEES ID:** NEES-2010-0943  
**Sponsor:** NSF-0936376  
**Project Type:** NEES  
**Start Date:** 2009-08-01T00:00:00

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Figure 6. Measured and predicted earth pressure coefficients, $K_E$, versus PGA. The “predicted” values are from the single-frequency simplified procedure presented in this article. (a) Hushmand et al. (2016), Test 1A; (b) Hushmand et al. (2016), Test 2; (c) Hushmand et al. (2016), Test 3A; (d) Hushmand et al. (2016), Test 4A; (e) Ostadian (2005) SASSI analyses; (f) Al Atik and Sitar (2009), Test LAA02; (g) Wagner and Sitar (2016), test NW01; and (h) Candia et al. (2016), test GC01.

Durante et al. (2022).
Figure 7. Dimensionless earth pressure, $P_E/(k_y u_{go} H)$, versus wavelength-to-height ratio, $\lambda/H$ (a) Hushmand et al. (2016), Test 1A; (b) Hushmand et al. (2016), Test 2; (c) Hushmand et al. (2016), Test 3A; (d) Hushmand et al. (2016), Test 4A; (e) Ostadan (2005), SASSI analyses; (f) Al Atik and Sitar (2009), LAA02; (g) Wagner and Sitar (2016), Test NW01; and (h) Candia et al. (2016), Test GC01.

Durante et al. (2022).
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Ground Failure
Free-Field Level Ground

Cyclic Stress Ratio

\[ CSR = r_c \cdot \frac{a_{\text{max}}}{g} \cdot \frac{\sigma_{vo}}{\sigma_{vo}}, r_d = 0.65 \cdot \tau_{\text{max}} \]

Cauchy Stress Tensor

\[
\begin{bmatrix}
\sigma_y & 0 & 0 \\
0 & \sigma_H & 0 \\
0 & 0 & \sigma_H
\end{bmatrix}
+ \begin{bmatrix}
0 & \tau & 0 \\
\tau & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
= \begin{bmatrix}
\sigma_y & \tau & 0 \\
\tau & \sigma_H & 0 \\
0 & 0 & \sigma_H
\end{bmatrix}
\]
SSI Effects on Ground Failure

Brandenberg et al. (2022)

Free-field

\[ u_g \]

\[ P \]

\[ M \]

\[ V \]

\[ 2B \]

Foundation Stresses

\[ \frac{P}{2B} \]

\[ \frac{V}{2B} \]

\[ 3M/2B^2 \]

Cauchy Stress Tensor

\[
\begin{bmatrix}
\sigma_{xx,o} & \sigma_{xy,o} & \sigma_{xz,o} \\
\sigma_{yx,o} & \sigma_{yy,o} & \sigma_{yz,o} \\
\sigma_{zx,o} & \sigma_{zy,o} & \sigma_{zz,o}
\end{bmatrix}

\Delta \sigma

\begin{bmatrix}
\Delta \sigma_{xx} & \Delta \sigma_{xy} & \Delta \sigma_{xz} \\
\Delta \sigma_{yx} & \Delta \sigma_{yy} & \Delta \sigma_{yz} \\
\Delta \sigma_{zx} & \Delta \sigma_{zy} & \Delta \sigma_{zz}
\end{bmatrix}

\begin{bmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{bmatrix}

\]

Cyclic Stress Ratio

\[ CSR = ??? \]

Overturning of building B1 as seen from the North-West after the Kocaeli event. (Photo by Jonathan D. Bray)

PEER (2000). Documenting Incidents of Ground Failure Resulting from the August 17, 1999 Kocaeli, Turkey Earthquake.

https://apps.peer.berkeley.edu/publications/turkey/adapazari/index.html
SSI Effects on Ground Failure

Free-field Stresses

\[ \sigma_{zz,FF} = \rho_g z \]
\[ \sigma_{xx,FF} = \sigma_{yy,FF} = (\rho_g z - u) K_0 + u \]
\[ \Delta \sigma_{xz,FF} = \bar{u}_g \rho_z r_d \]

Assumptions

1. Flexible strip footing
2. Soil is isotropic elastic halfspace
3. Loading frequency is low enough that static solutions are reasonably accurate

Brandenberg et al. (2022)
\[
\begin{align*}
\begin{pmatrix}
\sigma_1 \\
\sigma_2 \\
\sigma_3
\end{pmatrix} &= \text{eigenvals} \begin{pmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{pmatrix}
\end{align*}
\]

Principal stresses

\[
q = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2 \right]}
\]

Deviatoric stress invariant

\[
p_o' = \frac{\sigma_1' + \sigma_2' + \sigma_3'}{3} = \frac{1}{3} \text{tr}(\sigma')
\]

Mean effective stress

\[
CSR = r_c \frac{\sigma_{vo}}{\sigma_{vo}} \cdot \frac{a_{\text{max}}}{g} \cdot r_d = r_c \frac{\tau}{\sigma_{vo}}
\]

Classical definition of cyclic stress ratio

Brandenberg et al. (2022)
SSI Effects on Ground Failure

Free-Field Level Ground

\[CSR = r_e \frac{\sigma_{vo}, a_{max}}{\sigma_{vo}} r_d = r_e \frac{\tau}{\sigma_{vo}},\]

\[
\begin{bmatrix}
\sigma_v & 0 & 0 \\
0 & \sigma_H & 0 \\
0 & 0 & \sigma_H
\end{bmatrix} +
\begin{bmatrix}
0 & \tau & 0 \\
\tau & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} =
\begin{bmatrix}
\sigma_v & \tau & 0 \\
\tau & \sigma_H & 0 \\
0 & 0 & \sigma_H
\end{bmatrix}
\]

Invariants

\[
p_o' = \sigma_{vo} \cdot \frac{1 + 2K_o}{3}
\]

\[
q_o = \sigma_{vo} - \sigma_{ho}'
\]

\[
q = \sqrt{q_o^2 + 3\tau^2}
\]

Invariant-based definition of cyclic stress ratio

Brandenberg et al. (2022)
SSI Effects on Ground Failure

(a) JZB01: Hinged Plate Container

(b) JZB02: Flexible Shear Beam Container

Brandenberg et al. (2022)
SSI Effects on Ground Failure

Brandenberg et al. (2022)
Brandenberg et al. (2022)
SSI Effects on Ground Failure

Brandenberg et al. (2022)
• Soil-structure interaction problems are inherently complex because they combine structural and geotechnical disciplines.

• Physical modeling studies provide key insights into fundamental mechanics that allow us to distill the problem into digestible units, and ultimately make design recommendations that are simple and straightforward to implement.

• Publishing experimental data is extremely important to facilitate these insights.
Conclusions

• I presented centrifuge modeling studies today.
• Structural models are necessarily simplified due to centrifuge scaling laws.
• There is tremendous need to validate SSI models using full-scale experiments, like those made possible by the UCSD shake table facility, because we are able to realistically model structural components
• **Seismic Earth Pressures:** Partial support for the first author was provided by Caltrans under contract number 65A0413. The first author has recently received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement number 101029903 – ReStructure 2.0 – H2020 – MSCA – IF – 2020.

• **Ground Failure Potential:** This material is based on work supported by the National Science Foundation under award 1563638. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. Construction of each centrifuge model required extensive help and support provided by the CGM staff and others at UC-Davis. We gratefully acknowledged their assistance. Special thanks to Mandro Eslami for invaluable contributions during the construction and testing of model JZB01 and continued support during model JZB02.


