Evaluating Liquefaction-Induced Building Settlement

Jonathan Bray and Jorge Macedo

Univ. of California, Berkeley

Contributions from: R. Luque, S. Dashti, M. Cubrinovski, C. Markham, J. Zupan, R. Sancio, C. Hayden, C. Beyzaei, M. Riemer, etc.

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Liquefaction-Induced Building Movement

1999 M7.5 Kocaeli, Turkey EQ

- Bearing Capacity Failure of Buildings
- Sediment Ejecta-Induced Settlement of Buildings

2011 M6.3 Christchurch, NZ EQ

- Tilting and Sliding of Buildings
- Building Settlement
- Tilt of Tall Buildings

- 15 cm
- 1.8°
DISPLACEMENT MECHANISMS

1. Ground Loss due to Ejecta

2. Shear-Induced Deformations
   - Bearing Capacity ($\varepsilon_{q-BC}$)
   - SSI Ratcheting ($\varepsilon_{q-SSI}$)

3. Volumetric Deformations
   - Partial Drainage ($\varepsilon_{p-DR}$)
   - Sedimentation ($\varepsilon_{p-SED}$)
   - Consolidation ($\varepsilon_{p-CON}$)

\[ \delta = \sum (\varepsilon_v)(\Delta z) \]

Estimates 1D settlements due to post-liquefaction volumetric reconsolidation

No shear-induced displacements

Does not estimate building movement

\[ D_r = 60\% \quad FS_r = 0.6 \]
\[ D_r = 40\% \quad FS_r = 0.4 \]
\[ D_r = 90\% \quad FS_r = 2.5 \]

Ishihara & Yoshimine 1992
Nonlinear Dynamic SSI Effective Stress Analysis

Over 1,300 analyses with 36 EQ ground motions

Baseline Model

Parameters Considered in Sensitivity Study (105 models)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HC$</td>
<td>non-liquefiable layer thickness</td>
<td>1, 2, 4, 6 m</td>
</tr>
<tr>
<td>$HL$</td>
<td>liquefiable layer thickness</td>
<td>1, 2, 3, 6, 12, 18 m</td>
</tr>
<tr>
<td>$HB$</td>
<td>thickness below liquefiable layer</td>
<td>20-HL-HC m</td>
</tr>
<tr>
<td>$D_r$</td>
<td>liquefiable layer relative density</td>
<td>35, 50, 60, 75, 90 %</td>
</tr>
<tr>
<td>$B$</td>
<td>building width</td>
<td>6, 12, 24 m</td>
</tr>
<tr>
<td>$H$</td>
<td>building height</td>
<td>6, 12, 24 m</td>
</tr>
<tr>
<td>$Q$</td>
<td>foundation contact pressure</td>
<td>20, 40, 80, 160, 240 kPa</td>
</tr>
</tbody>
</table>
Shear-Induced Deformations

Shear Strain Distribution after Strong Shaking (baseline case with GM 4)

Liquefiable Soil Layer

Shear and Volumetric Strain Profiles under Building Edge during and at End of Strong Shaking (baseline case with GM 1)

Liquefiable Soil Layer
Influence of Ground Motion

Amplitude-Scaled (2.2x) Herceg Novi/000 Motion: $R = 26$ km from M7.1 Montenegro EQ

Excess pore water pressure response

Building settlement vs. time follows $CAV_{dp}$ vs. time curve

Standardized Cumulative Absolute Velocity
Campbell and Bozorgnia (2011):

$$CAV_{dp} = \sum_{i=1}^{N} \left( H(PGA_i - 0.025) \int_{i-1}^{i} |a(t)| \, dt \right)$$
Influence of Building – Building Contact Pressure ($Q$)

Building Settlement $\uparrow$ as $Q$ $\uparrow$ to a point

($HL = 3m$, $D_r = 50\%$, $HC = 2m$, $B = 12m$, $H = 12m$ for GMs 1-12)
Influence of Site – Relative Density ($D_r$)

Building Settlement ↓ as $D_r$ ↑

($HL = 6$ m, $HC = 2$ m, $B = 12$ m, $H = 12$ m, & $Q = 80$ kPa for GMs 1-12)
Liquefaction Building Settlement (LBS) Index

\[ LBS = \sum_{i=1}^{n} W_i \times \frac{\varepsilon_{\text{shear}_i}}{z_i} \, dz_i \]

where \( W = 0 \) for \( z < D_r \) & \( W = 1 \) for \( z \geq D_r \)

\( D_r \) from CPTu

\( FS_l \) from liquefaction triggering procedure

Soil layer defined by: \( D_r, FS_l, z, dz \)

\( q_t \) (MPa)

\( FS_l \)

\( D_r, FS_l \)

\( FS_l = 0.8 \)

\( D_r = 40\% \)

\( D_r = 60\% \)

\( D_r = 70\% \)

\( D_r = 80\% \)

\( D_r = 90\% \)

\( \varepsilon_{\text{shear}} = 10\% \)

\( z_{\text{max}} \)
Shear-Induced Liquefaction Building Settlement Estimate ($Ds$)  
Bray & Macedo (2017)

$$Ln(Ds) = c1 + c2 \times LBS + 0.58 \times Ln\left(Tanh\left(\frac{HL}{6}\right)\right)$$

$$+ 4.59 \times Ln(Q) - 0.42 \times Ln(Q)^2 - 0.02 \times B$$

$$+ 0.84 \times Ln(CAV_{dp}) + 0.41 \times Ln(Sa1) + \varepsilon$$

(Implemented in $CLiq$)

$Ds$ (mm), $Q$ (kPa), $B$ (m), $LBS$ (integer), $HL$ (m), $CAV_{dp}$ (g-s), $Sa1$ (g)

$c1=-7.48$ and $c2=0.014$ for $LBS > 16$ & $c1=-8.35$ & $c2=0.072$ for $LBS \leq 16$

$\varepsilon$ is a normal random variable with $\mu = 0.0$ and $\sigma = 0.50$ in $Ln$ units
COMPARISONS

Comparison with FE analyses by Karimi & Dashti 2016 (OpenSees with PDMY02)


$Ds < 5\text{ mm}$
## Validation with 19 Field Case Histories
(Brady & Macedo 2017)

<table>
<thead>
<tr>
<th>Case</th>
<th>Building</th>
<th>EQ¹</th>
<th>Observed Ds (mm)</th>
<th>Estimated Ds from CPT (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FTG7</td>
<td>C</td>
<td>150</td>
<td>D16 - D84</td>
</tr>
<tr>
<td>4</td>
<td>FTG4</td>
<td>C</td>
<td>110-150</td>
<td>60 - 160</td>
</tr>
<tr>
<td>5</td>
<td>CTUC</td>
<td>C</td>
<td>100-200</td>
<td>110 - 290</td>
</tr>
<tr>
<td>8</td>
<td>CTH</td>
<td>C</td>
<td>50-210</td>
<td>70 - 180</td>
</tr>
<tr>
<td>9</td>
<td>CTH</td>
<td>D</td>
<td>0-20</td>
<td>30 - 70</td>
</tr>
<tr>
<td>10</td>
<td>CTH</td>
<td>J</td>
<td>10-30</td>
<td>20 - 60</td>
</tr>
<tr>
<td>17</td>
<td>C2</td>
<td>K</td>
<td>175</td>
<td>90 - 250</td>
</tr>
<tr>
<td>19</td>
<td>F1</td>
<td>K</td>
<td>450</td>
<td>220 - 600</td>
</tr>
</tbody>
</table>

### Notes:
1. C: Christchurch, D: Darfield, J: June, K: Kocaeli
2. D16: 16% estimate, and D84: 84% estimate
Ejecta-Induced Settlement

Residential Properties & Light Buildings – Christchurch

THICK CLEAN SAND SITE

- LSN < 10  Ejecta Not Likely
- LSN > 10  Ejecta Likely

STRATIFIED SILTY SITE

- LSN < 25  Ejecta Not Likely
- LSN > 25  Minor Ejecta Only

Bray & Hutabarat
FTG7 Building – CHC EQ Observations

<table>
<thead>
<tr>
<th>Type of Settlement</th>
<th>Measured (mm)</th>
<th>Estimated (mm)</th>
<th>Measured (mm)</th>
<th>Estimated (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total: CES</td>
<td>400 – 450</td>
<td>550 – 600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total: CHC EQ</td>
<td>250 – 470</td>
<td>380 – 600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ejecta-Induced</td>
<td>40 – 80</td>
<td>40 – 80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shear-Induced</td>
<td>90 – 130</td>
<td>170 – 210</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volumetric-Induced</td>
<td>120 – 260</td>
<td>170 – 310</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1. Liquefaction triggering evaluation: $FS_l < 1$

   W: $HL = 12 \text{ m}$ & E: $HL = 13 \text{ m}$

2. Post-liquefaction bearing capacity: $FS_{BC} = 1.1$

   Crust: $c_u = 35 \text{ kPa}$ & Liquefied Layer: $S_r = 12 \text{ kPa}$

   (using Meyerhof & Hanna 1978, and Idriss & Boulanger 2008)

3. Ejecta-induced settlement: W: $De = 40 - 80 \text{ mm}$ & E: $De = 40 - 80 \text{ mm}$

   W: $LSN = 41$ & E: $LSN = 45$
CTUC Liquefaction-Induced Building Settlement Estimate

   \[ W: \ D_v = 120 - 260 \text{ mm} \quad \& \quad E: \ D_v = 170 - 310 \text{ mm} \]

5. Shear-induced settlement using Bray & Macedo (2017):
   \[ W: \ D_s = 100 - 270 \text{ mm} \quad \& \quad E: \ D_s = 120 - 310 \text{ mm} \]
   \[ \text{with: } S_{a1} = 0.90 \text{ g, } \text{CAV}_{dp} = 1.0 \text{ g-s, } LBS = 71 \text{ (W) or 82 (E),} \]
   \[ HL = 12 \text{ m (W) or 13 m (E), } Q = 100 \text{ kPa, } \& \ B = 29 \text{ m} \]

6. Total liquefaction-induced settlement using \( D_t = D_e + D_v + D_s \):
   \[ W: \text{median } D_t = 60 \text{ mm} + 220 \text{ mm} + 160 \text{ mm} = 440 \text{ mm}; \quad D_t = 260 - 610 \text{ mm} \]
   \[ E: \text{median } D_t = 60 \text{ mm} + 240 \text{ mm} + 190 \text{ mm} = 490 \text{ mm}; \quad D_t = 330 - 700 \text{ mm} \]
   \[ \text{observed} = 380 - 600 \text{ mm} \]

7. Estimated median differential settlement = 50 mm
   \[ \text{observed} = 30 \text{ mm} \]
CONCLUSIONS

• Liquefaction-induced building settlement is caused by ejecta, shear, and volumetric mechanisms

• Shear-induced mechanism often governs during EQ shaking

• Bray & Macedo (2017) procedure can estimate shear-induced liquefaction building settlement and its uncertainty

• Procedure provides results consistent with 19 field case histories, 102 centrifuge test results, and thousands of dynamic SSI analyses