Geotechnics of Tsunami Flood Losses
Tsunami Scour & Geo-Risk Reduction

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Chair, ASCE Committee on Critical Infrastructure
1. Historical perspectives
2. Tohoku observations
3. **ASCE 7 tsunami loads & effects**
4. ASCE 24 flood scour provisions
5. Needed validations & measurements
6. **DRR through geo-risk reduction**
Geo-disasters vs Hydro-disasters

- **Frequency:** 10% vs 90%
- **$ Losses:** 30% vs 70%
- **Fatalities:** 65% vs 35%

**TABLE 6** Total number of people reported killed, by type of phenomenon and year (2003–2012)

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droughts/food insecurity</td>
<td>38</td>
<td>80</td>
<td>88</td>
<td>208</td>
<td>n.a.</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>n.a.</td>
<td>n.a.</td>
<td>424</td>
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<tr>
<td>Earthquakes/tsunamis</td>
<td>29,617</td>
<td>227,290</td>
<td>76,241</td>
<td>6,692</td>
<td>780</td>
<td>87,918</td>
<td>1,888</td>
<td>226,735</td>
<td>20,946</td>
<td>711</td>
<td>678,818</td>
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<tr>
<td>Extreme temperatures</td>
<td>74,748</td>
<td>556</td>
<td>814</td>
<td>5,104</td>
<td>1,044</td>
<td>2,120</td>
<td>57,064</td>
<td>806</td>
<td>1,758</td>
<td>144,714</td>
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<tr>
<td>Floods</td>
<td>3,770</td>
<td>7,102</td>
<td>5,754</td>
<td>5,845</td>
<td>8,565</td>
<td>4,029</td>
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<td>8,571</td>
<td>6,142</td>
<td>3,574</td>
<td>56,986</td>
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<tr>
<td>Forest/scrub fires</td>
<td>47</td>
<td>14</td>
<td>47</td>
<td>16</td>
<td>150</td>
<td>86</td>
<td>190</td>
<td>135</td>
<td>10</td>
<td>22</td>
<td>717</td>
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<td>Insect infestation</td>
<td>n.d.r.</td>
<td>n.a.</td>
<td>n.d.r.</td>
<td>n.a.</td>
<td>n.d.r.</td>
<td>n.d.r.</td>
<td>n.d.r.</td>
<td>n.d.r.</td>
<td>n.d.r.</td>
<td>n.d.r.</td>
<td>n.a.</td>
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<tr>
<td>Mass movement: dry</td>
<td>n.d.r.</td>
<td>44</td>
<td>n.d.r.</td>
<td>11</td>
<td>n.d.r.</td>
<td>120</td>
<td>36</td>
<td>n.d.r.</td>
<td>16</td>
<td>227</td>
<td></td>
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<tr>
<td>Mass movement: wet</td>
<td>707</td>
<td>313</td>
<td>646</td>
<td>1,638</td>
<td>271</td>
<td>504</td>
<td>657</td>
<td>3,402</td>
<td>314</td>
<td>504</td>
<td>8,956</td>
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<td>Volcanic eruptions</td>
<td>n.a.</td>
<td>2</td>
<td>3</td>
<td>5</td>
<td>11</td>
<td>10</td>
<td>n.a.</td>
<td>323</td>
<td>3</td>
<td>n.a.</td>
<td>363</td>
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<td>Windstorms</td>
<td>1,030</td>
<td>6,609</td>
<td>5,294</td>
<td>4,329</td>
<td>6,035</td>
<td>140,985</td>
<td>3,287</td>
<td>1,498</td>
<td>3,103</td>
<td>3,071</td>
<td>175,241</td>
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<td>Subtotal climato-, hydro- and meteorological disasters</td>
<td>80,340</td>
<td>14,674</td>
<td>12,643</td>
<td>17,140</td>
<td>16,065</td>
<td>147,218</td>
<td>8,882</td>
<td>70,672</td>
<td>10,375</td>
<td>8,929</td>
<td>386,933</td>
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<td>Subtotal geophysical disasters</td>
<td>29,617</td>
<td>227,290</td>
<td>76,244</td>
<td>6,708</td>
<td>791</td>
<td>88,054</td>
<td>1,924</td>
<td>227,058</td>
<td>20,949</td>
<td>727</td>
<td>679,401</td>
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<tr>
<td>Total natural disasters</td>
<td>109,957</td>
<td>242,010</td>
<td>88,887</td>
<td>23,848</td>
<td>16,865</td>
<td>236,272</td>
<td>16,806</td>
<td>297,730</td>
<td>31,324</td>
<td>9,656</td>
<td>1,066,346</td>
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<td>Industrial accidents</td>
<td>1,444</td>
<td>1,797</td>
<td>2,281</td>
<td>1,857</td>
<td>1,607</td>
<td>770</td>
<td>933</td>
<td>1,001</td>
<td>684</td>
<td>787</td>
<td>13,287</td>
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<tr>
<td>Miscellaneous accidents</td>
<td>1,438</td>
<td>2,115</td>
<td>2,669</td>
<td>1,126</td>
<td>909</td>
<td>895</td>
<td>911</td>
<td>1,507</td>
<td>755</td>
<td>1,112</td>
<td>13,437</td>
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<td>Transport accidents</td>
<td>7,868</td>
<td>6,417</td>
<td>6,702</td>
<td>7,021</td>
<td>5,075</td>
<td>5,275</td>
<td>5,021</td>
<td>4,176</td>
<td>5,144</td>
<td>4,151</td>
<td>56,850</td>
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<td>Total technological disasters</td>
<td>10,750</td>
<td>10,329</td>
<td>11,652</td>
<td>10,004</td>
<td>7,681</td>
<td>6,946</td>
<td>6,865</td>
<td>6,744</td>
<td>6,583</td>
<td>6,050</td>
<td>83,574</td>
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<tr>
<td>Total</td>
<td>120,707</td>
<td>252,339</td>
<td>100,539</td>
<td>33,852</td>
<td>24,507</td>
<td>242,218</td>
<td>17,671</td>
<td>304,474</td>
<td>37,907</td>
<td>15,706</td>
<td>1,149,920</td>
</tr>
</tbody>
</table>

Source: EM-DAT, CRED, University of Louvain, Belgium
1. Historic Perspectives on Geo-Scour

Local Scour vs General Erosion

- 1930s - Terzaghi vs. Fillunger theories
- 1950s - River/Bridge fieldwork - Einstein
- 1960s - DOT scour programs emerge
- 1970s - HEC process development
- 1980s - FEMA tsunami scour criteria
- 1990s - Theorize tsunami liquefaction
- Post 2004 - Tsunami scour liquefaction data; FEMA P55 & P646 update
- Post 2011 - ASCE 7: refine tsunami scour limits with flow, soil, site effects.

About 60% of US bridge failures are due to scour. Only 1 DOT in the USA manages scour in the structures geotechnical dept. All others manage scour in the hydraulics dept.

– Ref. Prof. Jean Louis-Briaud, Texas A&M
Observations:
Tohoku scour took many forms, from myriad combinations of water, soils & topography.

Conclusions: Needed ASCE 7 Mitigation Alternatives

- Elevate - structure, site
- Harden Foundations
- Countermeasures – barriers, MSE walls, paving, soil-cement
## Perspective by Comparison

<table>
<thead>
<tr>
<th></th>
<th>2004 Sumatra Tsunami</th>
<th>2011 Tohoku Tsunami</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnitude</strong></td>
<td>M9.3</td>
<td>M9.1</td>
</tr>
<tr>
<td><strong>Rupture area:</strong></td>
<td>800 x 100 mi</td>
<td>300 x 100 mi</td>
</tr>
<tr>
<td><strong>Rupture subsidence:</strong></td>
<td>~25 ft</td>
<td>~25 ft</td>
</tr>
<tr>
<td><strong>Maximum runup:</strong></td>
<td>80 ft</td>
<td>150 ft</td>
</tr>
<tr>
<td><strong>Infrastructure damage:</strong></td>
<td>~35B</td>
<td>~350B</td>
</tr>
<tr>
<td><strong>Population Affected:</strong></td>
<td>~3M</td>
<td>~3M</td>
</tr>
<tr>
<td><strong>Displaced:</strong></td>
<td>~500k</td>
<td>~250k</td>
</tr>
<tr>
<td><strong>Casualties</strong></td>
<td>~250,000</td>
<td>~25,000</td>
</tr>
</tbody>
</table>
Onagawa Hospital

Evacuation Building
8m tsunami wall intact parallel to flow
Large scour holes in concrete pavement.
6m Sendai Seawall
Iwaki
Onahama:
Combined seismic liquefaction & tsunami scour
Scour modes identified for ASCE 7

Ref. Tonkin, Francis & Bricker, 2013

Figure 1. Local scour, Koh Khao, Thailand. Case SS-4.

Figure 2. Overtopping scour, Taito Port, Japan. Case TO-1.

Figure 3. Channelized scour. Great Nicobar Case RS-3.

Figure 4. General scour. Yamamoto-cho, Japan. Case TN-12.
Fig. 5. Google Earth image taken 4/5/2011 showing the survey transect line, remnant artificial dune pedestals and associated shore-parallel scour depressions, probable partially-infilled return-flow channels on the beach face and average flow direction as determined from bent pine trees.
• Tsunami deposits - infilled scour
• Modeling energy distributions

Ref, Richmond et al, 2012.
Figure 4. SRICOS scour data comparison, critical shear stress vs. soil particle size (TRB, 2003).

Figure 8. Liquefaction caused by wave (DeGroot, ASCE 2006).

Figure 28. Gary Chock measures the depth of scour below a building corner (photo: Robertson/ASCE).

Figure 19. Liquefaction sand boils from the great tsunami, northwest coast of Sumatra (EERI, 2006, photo by W. Sengara).

Ref Tonkin, Francis & Bricker, 2013

**Scour observations**

IOT & Tohoku Events

<table>
<thead>
<tr>
<th>Case</th>
<th>Location</th>
<th>Flow Depth</th>
<th>Scour Depth</th>
<th>Scour Mechanism</th>
<th>Scour Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS-1</td>
<td>Aceh Harbor</td>
<td>2.4</td>
<td>2.5</td>
<td>General</td>
<td>Road / bridge washout</td>
</tr>
<tr>
<td>RS-2</td>
<td>Gile Bruk, Sumatra</td>
<td>2.4</td>
<td>2.5</td>
<td>Local</td>
<td>Abutment washout</td>
</tr>
<tr>
<td>RS-3</td>
<td>Great Nicobar</td>
<td>2.2</td>
<td>4.0</td>
<td>Channelized</td>
<td>Drawdown along road</td>
</tr>
<tr>
<td>RS-4</td>
<td>Pt. Blair, Andaman</td>
<td>2.2</td>
<td>1.0</td>
<td>Local</td>
<td>Seawall road slide</td>
</tr>
<tr>
<td>RS-5</td>
<td>Bang Tao, Phuket</td>
<td>2.15</td>
<td>2.0</td>
<td>General</td>
<td>Scour</td>
</tr>
<tr>
<td>RS-6</td>
<td>Fishery Pier, Phangaa</td>
<td>2.15</td>
<td>1.5</td>
<td>Local</td>
<td>Abutment sinkhole</td>
</tr>
<tr>
<td>RS-7</td>
<td>Kuraburi, Phangaa</td>
<td>1.8</td>
<td>1.0</td>
<td>General</td>
<td>Road scour</td>
</tr>
<tr>
<td>RS-8</td>
<td>Ranong</td>
<td>1.8</td>
<td>1.0</td>
<td>General</td>
<td>Road boil</td>
</tr>
<tr>
<td>RS-9</td>
<td>Chennai</td>
<td>2.6</td>
<td>1.0</td>
<td>General</td>
<td>Road scour</td>
</tr>
<tr>
<td>RS-10</td>
<td>Kottapattam</td>
<td>2.6</td>
<td>0.5</td>
<td>General</td>
<td>Road scour</td>
</tr>
<tr>
<td>SS-1</td>
<td>Lock Nga, Aceh</td>
<td>2.4</td>
<td>2.0</td>
<td>General</td>
<td>Flow though structure</td>
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<td>SS-2</td>
<td>Samala, Phuket</td>
<td>2.15</td>
<td>2.0</td>
<td>Local</td>
<td>Footing scour</td>
</tr>
<tr>
<td>SS-3</td>
<td>Khao Lak</td>
<td>2.15</td>
<td>2.0</td>
<td>Local</td>
<td>Footing scour</td>
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<tr>
<td>SS-4</td>
<td>Koh Khao</td>
<td>1.8</td>
<td>2.0</td>
<td>Local</td>
<td>Footing and utilities</td>
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<tr>
<td>SS-5</td>
<td>Kalapakkom</td>
<td>2.6</td>
<td>1.5</td>
<td>Local</td>
<td>Footing scour</td>
</tr>
<tr>
<td>SS-6</td>
<td>Cuddalore</td>
<td>2.6</td>
<td>0.5</td>
<td>Local</td>
<td>Footing scour</td>
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<tr>
<td>SS-7</td>
<td>Allapad, Kerala</td>
<td>1.2</td>
<td>1.0</td>
<td>Local</td>
<td>Footing scour</td>
</tr>
<tr>
<td>SS-8</td>
<td>Xaafuun Peninsula</td>
<td>2.65</td>
<td>0.5</td>
<td>Local</td>
<td>Footing scour</td>
</tr>
</tbody>
</table>

Tohoku Tsunami: Tohoku North (TN) and Tohoku South (TS). Source: Chock et al. (2012).

<table>
<thead>
<tr>
<th>Case</th>
<th>Location</th>
<th>Flow Depth</th>
<th>Scour Depth</th>
<th>Scour Mechanism</th>
<th>Scour Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>TN-1</td>
<td>Hachinohe Kancheha</td>
<td>10.5</td>
<td>1.0</td>
<td>General</td>
<td>Stream bank, culvert</td>
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<tr>
<td>TN-2</td>
<td>Hirochono Taneichi</td>
<td>6.0</td>
<td>2.0</td>
<td>Local</td>
<td>Footing scour</td>
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<tr>
<td>TN-3</td>
<td>Noda Beach</td>
<td>14.0</td>
<td>3.0</td>
<td>Local</td>
<td>Drain outlet</td>
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<tr>
<td>TN-4</td>
<td>Miyako City</td>
<td>6.0</td>
<td>4.0</td>
<td>Local</td>
<td>Bridge approach</td>
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<td>TN-5</td>
<td>Miyako City</td>
<td>6.0</td>
<td>2.0</td>
<td>Local</td>
<td>Viaduct pier</td>
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<td>Otsuchi Harbor</td>
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<td>Plunging</td>
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<td>Wall and barrier gate</td>
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<td>3.0</td>
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<td>Building foundation</td>
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<td>Narrow valley</td>
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<td>TN-10</td>
<td>Onagawa Harbor</td>
<td>17.0</td>
<td>3.0</td>
<td>General</td>
<td>Paved waterfront</td>
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<td>TN-11</td>
<td>Sendai Airport</td>
<td>8.0</td>
<td>4.0</td>
<td>Overtopping</td>
<td>Seawall</td>
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<td>TN-12</td>
<td>Nakahama School</td>
<td>9.0</td>
<td>2.0</td>
<td>General</td>
<td>Open plain</td>
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<td>TS-13</td>
<td>Kashima Port</td>
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<td>2.0</td>
<td>Local</td>
<td>Footings</td>
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<td>Nikawahama</td>
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<td>&lt;1</td>
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<td>Sump tank</td>
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<td>Iioha Inlet</td>
<td>5.0</td>
<td>3.0</td>
<td>General</td>
<td>Roadway by channel</td>
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</table>

Tohoku Overtopping Examples (TO). Source: Bricker et al. (2012).
Scour patterns

Combined IOT & Tohoku event data

Figure 5. Correlation between observed scour depth and estimated flow depth.

Figure 6. Observed local scour depth and estimated flow depth for different sediment types, with bounding plausible design envelopes shown.

Ref. Tonkin, Francis & Bricker, 2013
Enhanced scour due to liquefaction induced by rapid drawdown

Tonkin & Yeh (2003) applying Terzaghi (1925):

- Soil supported by both excess pore pressure gradient and intergranular shear
- The fraction of the submerged weight of a soil particle supported by the pore pressure gradient is \( \Lambda = \frac{d\rho_e/dz}{\gamma_b} \)
- Experiments show that above a critical value (\( \Lambda_T \)) when \( \Lambda > 0.5 \), \( \tau_{\text{effective}} \) is reduced enough to result in less frictional resistance to scour
- Drawdown-induced liquefaction enhances scour

\[ \nu_b = (\rho - \rho_{\text{water}})g \]

\[ \frac{d\rho_e}{dz} \]

\[ \frac{\tau_{\text{effective}}}{dz} \]
Figure 12. Measured scour depth and estimated Shields parameter for a cylinder initially at the shoreline during long period wave modeling. Water depth=2.45m, offshore incident solitary-wave height H=33cm. H/h=0.09 (Yeh et al. 2003).
Limits on enhanced scour depth due to rapid-drawdown-induced liquefaction

- Diffusion of excess pore pressure within a saturated soil per Terzaghi (1956)

\[ \frac{\partial p_e}{\partial t} = c_v \frac{\partial^2 p_e}{\partial z^2} \]

- Diffusion time scale is \( d_s^2 / c_v \), so drawdown time \( \Delta T \) must be shorter than this: \( \Delta T < d_s^2 / c_v \)

- Change in head \( \Delta P \) must be at least as large as the change in excess pore pressure over the scour depth: \( \Delta P > \Lambda_T \gamma_b d_s \)

- Combine for limits on enhanced scour depth due to pore pressure softening

\[ \sqrt{c_v \Delta T} < d_s < \frac{\Delta P}{\Lambda_T \gamma_b} \]
Upper limit on enhanced scour depth due to rapid-drawdown-induced liquefaction

\[ \sqrt{c_v \Delta T} < d_s < \frac{\Delta P}{\Lambda_T \gamma_b} \]

- Measured scour depths did not show a dependence on soil type, so the right-hand inequality appears dominant.
- Estimate \( \Delta P = H_{\text{flow}} \) (flood depth), \( \gamma_b = 1.65 \) (typical submerged soil specific weight), and \( \Lambda_T = 0.5 \) (from experiments).
- Results in \( d_s < 1.2H_{\text{flow}} \).
- Same as measured value for local scour, so enhanced local scour due to pore pressure softening appears an important process during large tsunami events!
Indian Ocean Tsunami sites, hypothesized liquefaction for Lambda > 0.5

1.2-2.6m tide gauge wave heights, 5-50min periods

Ref Francis, 2007 EERI Fellowship Report
Can be predicted using Fahlbusch (1994) with limit

\[
\begin{align*}
  d_{\text{scour}} &= 2.8 \sqrt{q U \sin \theta / g} \\
  \max d_{\text{scour}} &= 4m
\end{align*}
\]
Conclusions on Tsunami Scour Analysis

- Upper limit to local scour
  \[ d_{scour} = 1.2 H_{flow} \]
  \[ \text{max} \quad d_{scour} = 3m \]
  
  - Pore pressure softening important

- Upper limit to overtopping scour
  \[ d_{scour} = 2.8 \sqrt{q U \sin \theta / g} \]
  \[ \text{max} \quad d_{scour} = 4m \]

- No clear dependence on soil type
  - Data quantity not sufficient?
  - High energy means macro-scale (clast) sediment transport, entrapped air pluviation, non individual grain suspension? (Ref Harry Yeh, 2013)
3. ASCE 7 Tsunami Loads & Effects

Ref. ASCE 7-16 provisional draft TOC
The basic Tonkin equation (2003 Tonkin & Yeh):

\[
\Lambda(d_s) = \frac{\Delta P}{\gamma_b d_s} \left(1 - 4i^2 \text{erfc} \left[ \frac{d_s}{2\sqrt{c_v \Delta T}} \right] \right)
\]

Note: The maximum scour \(d_s\) limits at 1.2H as \(\Delta T\) goes to zero

As the flow height gets larger, the time scale gets longer, and scour depth moves further below the 1.2H theoretical limit, supporting observations of depth limitations.

Ref. Susan Tonkin, Moffat Nichol

Ref. ASCE 7-16
provisional draft
• Conceptual comparison: Seismic vs Tsunami Liquefaction

Ref. ASCE 7-16 provisional draft

Figure C6.12-2. Schematic diagram showing differences between seismic liquefaction and tsunami-induced pore pressure softening.
• Foundations & barriers must consider soil & site changes from design event at end of shaking impacts
• Use design load combinations
• FS 1.3- uplift/seepage force (USACE EM1110-2-2100)
• Strength loss for scour D=1.2H
• General erosion- must include amplification/channelizing, except rock or non-erodable at v>9m/s
Table 6.12-1 Design Local Scour Depth due to Sustained Flow and Pore Pressure Softening

<table>
<thead>
<tr>
<th>Flow Depth $h$</th>
<th>Scour Depth $D^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 10 ft (3.05 m)</td>
<td>1.2$h$</td>
</tr>
<tr>
<td>≥10 ft (3.05 m)</td>
<td>12 ft (3.66 m)</td>
</tr>
</tbody>
</table>

* Not applicable to scour of sites with intact rock strata

Figure 6.12-1 Local Scour Depth due to Sustained Flow and Pore Pressure Softening

- Adjust downward linearly for Froude No. Fr < 0.5

Ref. ASCE 7-16 provisional draft
Dynamic modeling is permitted to supersede simplified procedure.
1. **FS**: 1.3 for bearing capacity, lateral/overturning, internal stability, slope stability

2. **Displacement**: $D_v, D_h$ (footing & slopes) w traditional EP calculations to satisfy structural criteria.

3. **Fill**: follow ASCE 24- must be stable during inundation & resist loads. Add erosion/scour protection if needed
   (also ref. FEMA 55, section 10.3)

Ref. ASCE 7-16 provisional draft
4. **Deep foundations**: resist $F_v$, $F_h$ incl. general erosion & local scour w exposed grade beam

![Diagram of scour around a group of foundation piles](image)

Figure 8-16. Scour around a group of foundation piles

SOURCE: ADAPTED FROM SUMER ET AL. 2001

Ref. ASCE 7-16 provisional draft

(ref. FEMA 55, section 10.5)
1. **Pavements** (for roads & building perimeters)

1. Shear forces from sustained flow at maximum tsunami flow velocity, $u_{max}$, over the pavement.
2. Uplift pressures from flow acceleration at upstream and downstream pavement edges for both inflow and return flow.
3. Seepage flow gradients under the pavement if the potential exists for soil saturation during successive tsunami waves.
4. Pressure fluctuations over pavement sections and at joints.
5. Pore pressure increases from liquefaction and from the passage of several tsunami waves.
6. Erosion of substrate at upstream, downstream and flow parallel pavement edges as well as between pavement sections.

Ref. ASCE 7-16 provisional draft

Ref Catherine Petroff, Univ of Washington

Figure C6.12-3. Schematic of tsunami –induced loading on pavement.
2. Geotextiles & Reinforced Earth

same FS 1.3 criteria as foundations – bearing capacity, lateral/overturning, internal stability, slope stability

1. Geotechnical Engineering Circular No. 11 - Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes 2010 FHWA-NHI-10-024


The following reinforced earth systems are permitted to be used and are presented in order of increasing strength and robustness.

1. Geotextile tubes constructed of high strength fabrics capable of achieving full tensile strength without constricting deformations when subject to the design tsunami loads and effects.

2. Geogrid earth and slope reinforcement systems including adequate erosion protection and a maximum lift thickness of 1 ft (0.3m) and facing protection.

3. Geocell earth and slope reinforcement erosion protection system designs including an analysis to determine anticipated erosion performance if no facing is used.

Ref. ASCE 7-16 provisional draft
3. Facing systems

Facing systems shall be sufficiently strong and anchored to resist uplift and displacement during design load inundation. The following are facing methods for reinforced earth systems that shall be permitted to be used:

1. Vegetative facing for erosion resistance where tsunami flow velocities are less than 12.5 ft/s (3.8 m/s). Design shall be in accordance with methods and requirements in the recognized literature.

2. Geotextile filter layers including primary filter protection of countermeasures using a composite grid assuming high contact stresses and high energy wave action design criteria in AASHTO M288-06, including Soil Retention, Permeability, Clogging Resistance and Survivability.

3. Mattresses including adequate flexibility include energy dissipation characteristics, and edges shall be embedded to maintain edge stability under design inundation flows.

4. Concrete facing provided in accordance with pavement countermeasures in Section 6.12.7.1 and containing adequate anchorage to the reinforced earth system under design inundation flows.

5. Stone armor and riprap provided to withstand tsunami shall be designed as follows:

a) Stone diameter per HEC 23 Design Guideline 4

b) For Fr>0.5 consider high velocity turbulence

c) Peer reviewed numerical model permitted alternate.
4. **Ground improvement**

Soil cement mixing for non-erodible surface-100psi avg UCS.

5. **Risk Category IV Structures**

Encouraged soil-structure-fluid interaction analysis to verify performance consistent with structural design load combinations.

**Key references:**


Ref. ASCE 7-16 provisional draft
4. ASCE 24 flooding scour provisions
- Non prescriptive analysis not routinely applied
- Flood zone vs. elevation and foundation types

Hurricane Sandy moved sand off the beach and ocean water undermined beachfront properties.

Source: Liz Roll/FEMA

Wave, storm surge and erosion damage to oceanfront house in Belle Harbor, Rockaway, NY.

Source: Figure 3-1/Hurricane Sandy MAT Report
5. Needed validations & Measurements

1. More scalable scour photos
2. Soil samples from events
3. Instrumentation of pore pressures during events
4. Catalog foundation type, embedment, siting and failure loss vs scour depth
5. Load energy & orientation
6. Discrete element modeling
7. Work with insurers, ie. FEMA COASTAL Equation, **fragilities**.
8. Debris flows/mud flows in flood
Examples: (google keywords for details)

1. PPD-8/21 NDRF – functional resilience & recovery goals
2. New ASCE resilience division (www.ciasce.asce.org)
3. NYC: SIRR, PlaNYC & open industrial siting
4. Coastal vs building protections—hard vs soft; green infrastructure & climate adaptation
5. Oregon Resilience Plan
6. FEMA MAT & Hazus modeling
7. ATC-1: Geo-disaster focus

6. DRR through geo-risk reduction
- Quantify geo-loss drivers (elevate, harden, protect)
- SROI for prioritization

April 9, 2014
EERI Liquefaction Short Course, Salt Lake City, UT
Guidance on Construction in floodplains

Mitigation Assessment Team (MAT) Report - Hurricane Sandy in NY & NJ

Published November 2013

Federal Emergency Management Agency
(FEMA P-942)

http://www.fema.gov/hurricane-sandy-building-science-activities-resources

Ref: john.ingargiola@fema.dhs.gov

Building Science Branch
Foundation Requirements and Recommendations for Elevated Homes

Purpose: To provide information for reconstructing and building new elevated flood-resistant homes

Many homes in New York and New Jersey damaged during Hurricane Sandy experienced flood levels that exceeded the base flood elevation (BFE). The Federal Emergency Management Agency’s (FEMA) Mitigation Assessment Teams (MATs) observed several construction and foundation types in the disaster area. The assessment teams also observed narrow building lots and lots with constrained access that will pose construction challenges if those homes are required to be elevated or if owners elect to elevate them to reduce exposure to future flooding (Figure 1).

This fact sheet is intended to assist architects, builders, code officials, planners, and engineers with reconstruction and new construction to create elevated flood-resistant homes. The concepts in this fact sheet will help qualified, experienced professionals (licensed engineers or architects) determine proper site-specific foundation design recommendations when working on narrow lots and lots with constrained access. This fact sheet assumes the reader is familiar with the National Flood Insurance Program (NFIP) Special Flood Hazard Area (SFHA) zone designations, including Coastal A Zones. For more information about the coastal SFHA zone designations, visit http://www.fEMA.gov/coastal-mapping-guidance.
Key Issues

Elevating a building sited on small, confined lot can be difficult

1. Eliminates possibility of moving building while timber piles are driven for new foundation
2. If elevating in place, overhead clearance is usually insufficient to drive traditional timber piles

Source: FEMA
Key Recommendations

3. Understand Substantial Improvement (SI) / Substantial Damage (SD) as they relate to NFIP requirements – with regards to flood zone

Examples of NFIP-compliant homes in Zone V

Source: FEMA
4. Consider possible foundations
   a) Pier
   b) Pile
   c) Use of micropiles

Source: FEMA
### Table 1: Design Considerations for Elevating Buildings on Open Foundations in Zone V (and Coastal A Zones)

<table>
<thead>
<tr>
<th>Overall Category</th>
<th>Data Needed</th>
<th>Consider</th>
</tr>
</thead>
<tbody>
<tr>
<td>State and local requirements</td>
<td>State and local building code requirements</td>
<td>Open foundations are required in Zone V</td>
</tr>
<tr>
<td>Local flood ordinance requirements</td>
<td></td>
<td>For new homes and homes that have sustained Substantial Damage or will be Substantially Improved, open foundations including piers, columns, and piles, and micropiles may be used</td>
</tr>
<tr>
<td>Zoning ordinance requirements BFE or ABFE, if applicable</td>
<td></td>
<td>Elevating to (or above) the BFE/ABFE will help protect the home in future storms and reduce flood insurance costs</td>
</tr>
<tr>
<td>Natural resources conservation regulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structural condition of home</td>
<td>Structural strength of load paths. Determine whether the home is structurally strong enough to be lifted</td>
<td>How connections can be improved to strengthen the home</td>
</tr>
<tr>
<td>Structural strength of the existing footings. Determine whether the footings are adequate for the proposed modification</td>
<td></td>
<td>How the footings can be strengthened or replaced</td>
</tr>
<tr>
<td>Geotechnical condition of site</td>
<td>Determine whether a shallow foundation is feasible</td>
<td>Piers/Columns are appropriate for shallow foundations</td>
</tr>
<tr>
<td></td>
<td>Determine whether a deep foundation is required</td>
<td>Piles, piers/columns and micropiles are appropriate for deep foundations</td>
</tr>
<tr>
<td></td>
<td>Predicted flood conditions, including the effects of scour and long term erosion</td>
<td>Piling and Pier/Column foundations with footings and grade beams can be designed to withstand 3-foot wave loads, but may fail if erosion and scour undermine the foundation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Micropile foundations may not be able to withstand lateral loads when exposed by scour and erosion</td>
</tr>
<tr>
<td></td>
<td>Elevation of the water table</td>
<td>Grade beams can be elevated above the water table, but the pile or pier/column must be designed to resist cantilever action, moments, and deflection at the top. Deeper embedment may be necessary</td>
</tr>
</tbody>
</table>
### Table 2: Comparison of Relative Costs and Considerations Associated with Elevating Homes on Alternative Open Foundations in Tight, Narrow Lots

<table>
<thead>
<tr>
<th>Consideration</th>
<th>Column/Pier Foundation</th>
<th>Traditional Pile Foundation</th>
<th>Micropile Foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requires moving home off footprint</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Elevate-in-place</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Impacts to neighboring properties</td>
<td>Medium to High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundation</td>
<td>$</td>
<td>$$$</td>
<td>$$</td>
</tr>
<tr>
<td>Foundation connection</td>
<td>$$</td>
<td>$</td>
<td>$$</td>
</tr>
<tr>
<td>Elevation</td>
<td>$$</td>
<td>$$$</td>
<td>$$</td>
</tr>
<tr>
<td>Ease of installation</td>
<td>Yes</td>
<td>Maybe</td>
<td>Yes</td>
</tr>
<tr>
<td>Design basis</td>
<td>IBC¹/ASCE 24/FEMA P-55²</td>
<td>IBC¹/ASCE 24/FEMA P-55²</td>
<td>IBC¹/ASCE 24/FEMA P-55²/FHWA NHI-05-039³</td>
</tr>
</tbody>
</table>

1 IBC, International Building Code
2 Coastal Construction Manual (2011)
MAT Support – Code Changes

2015 IRC Code Change Proposals: FEMA Proponent

- IRC, requirements for tanks
- IRC, freeboard in all zones
- IRC, Flood-resistant foundation wall requirements
- IRC, treat CAZ, if delineated, as CHHA (Zone V), except permit filled stemwalls
- IFC, fire safety and evacuation plans must consider flood hazard

The FEMA MAT has been providing additional code support to NYC

Source: FEMA
Example of Tsunami Resilience

Oregon Resilience Plan

Cascadia Subduction Earthquake

Source: kentyu@seftconsulting.com
Cascadia Subduction Earthquake

- Strong Ground Shaking (M9 w/ 2 - 4 min shaking)
- Tsunami within 15 to 25 minutes

Source: kentyu@seftconsulting.com
**Definition of Resilience**

- Resilience: Save lives, Reduce Losses, Speed Recovery, & Rebuild Better
- Sustainability without **Resilience** is NOT sustainable!

Source: kentyu@seftconsulting.com
Oregon Resilience Planning Steps

- Assess **performance** of existing critical facilities and lifeline systems, and estimate timeframes required to restore functions at present conditions;
- Develop resilience goals based on business and community needs for each zone;
- Define acceptable target timeframes to restore functions to meet resilience goals; and
- Prepare **recommendations** for statewide policies and actions to achieve the desired performance targets.

Source: kentyu@seftconsulting.com
Oregon businesses can only tolerate two to four weeks of disruption of essential services.

<table>
<thead>
<tr>
<th>Critical Service</th>
<th>Zone</th>
<th>Estimated Time to Restore Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Valley</td>
<td>1 to 3 months</td>
</tr>
<tr>
<td>Electricity</td>
<td>Coast</td>
<td>3 to 6 months</td>
</tr>
<tr>
<td>Police and fire stations</td>
<td>Valley</td>
<td>2 to 4 months</td>
</tr>
<tr>
<td>Drinking water and sewer</td>
<td>Valley</td>
<td>1 month to 1 year</td>
</tr>
<tr>
<td>Drinking water and sewer</td>
<td>Coast</td>
<td>1 to 3 years</td>
</tr>
<tr>
<td>Top-priority highways (partial restoration)</td>
<td>Valley</td>
<td>6 to 12 months</td>
</tr>
<tr>
<td>Healthcare facilities</td>
<td>Valley</td>
<td>18 months</td>
</tr>
<tr>
<td>Healthcare facilities</td>
<td>Coast</td>
<td>3 years</td>
</tr>
</tbody>
</table>
Asian Technical Committee 1 (ATC-1)

• “Mitigation and Adaptation to Climate Change-Induced Geodisasters” – Inaugural meeting VNU, Hanoi Nov 2013
• Prof Yasuhara, Co-chair from Ibaraki Univ. to lead special pub.
• 2014 event in Fukuoka

• Extreme events related to geotechnical engineering may be caused by climate change, particularly in Asia-Pacific Regions.
• However, IPCC has paid less attention to Geo-disaster aspects.
• Generally, most of natural disasters are thought to be water-related disasters, though “Geo-Engineering” provides the mitigations.

Ref. Dennes Bergado, AIT
Vulnerable Coastal Deltas

Figure TS.8. Relative vulnerability of coastal deltas as indicated by estimates of the population potentially displaced by current sea-level trends to 2050 (extreme >1 million; high 1 million to 50,000; medium 50,000 to 5,000) [B6.3]. Climate change would exacerbate these impacts.

(After IPCC AR 4, 2007)

Ref. Dennes Bergado, AIT
Compound Disasters

Ref. Dennes Bergado, AIT
“Compound Disasters”

Ref. Dennes Bergado, AIT
## Comparative results from different approaches

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Methodology</th>
<th>Results</th>
</tr>
</thead>
</table>
| **Hydraulic approach** | Kawagoe & Kazama (2009)  
  • Evaluation of probability of slope failure occurrence using climate change-induced precipitation and geographical information | • Indicate locations where climate change-induced slope failure increases  
  • Specify areas where countermeasures are urgent |
| **Geotechnical approach** | Chen & Mitani (2012)  
  • Quantitative estimation of slope risk and its economical loss by considering torrential rainfall-induced occurrences | • Specify areas where global warming-triggered risk and economic loss by slope failure increases |

Ref. Dennes Bergado, AIT
### Examples of geotechnical responsive measures

<table>
<thead>
<tr>
<th>Response</th>
<th>Responsive measure</th>
<th>Geotechnical responsive measure</th>
</tr>
</thead>
</table>
| **Mitigation** | • Emission control of GHG  
• Utilization of emissions trading  
• Development of renewable energy | • Underground containment of GHG  
• Development of geo-materials to absorb GHG\(^2\)  
• GHG absorption, fixation using thinned woods |
| **Protection** | • Control of external force triggering the impacts of climate change | • Multiple protection using soil improvement and earth reinforcing techniques |
| **Accommodation** | • Moderate response to climate change by accepting the impacts to some degree | • Construction of highly robust structures  
• Easily replaceable wall structures if damaged |
| **Retreat** | • Retreat from regions undergoing impacts of climate change | • Early warning system utilizing ICT  
• Construction of robust shelters and refuges using geosynthetics |
| **Synergy of mitigation and adaptation** | • Early warning system based on future climate prediction \(^1\)  
• Development of innovative geo-materials | • Monitoring system using ICT  
• Early warning system using ICT  
• Application of geo-materials to absorb GHG for geo-hazard reduction |


Ref. Dennes Bergado, AIT
Integrated ICT: 4S-Technology

Collection of information

- Sensor
- GPS
- Sensor
- IC-Tag
- Remote Sensing
- GPS

GIS

Visualization of analytical results

4S-ICT can contribute to the development of monitoring technologies

Mobile

(supported by Dr. Yuji Kuwahara and Dr. Osamu Saitoh)
Collaboration & cooperation between two sciences & engineering

Mutual understanding of different scientific communities

Ref. Dennes Bergado, AIT
Projected impacts of climate change

<table>
<thead>
<tr>
<th>Global temperature change (relative to pre-industrial)</th>
<th>0°C</th>
<th>1°C</th>
<th>2°C</th>
<th>3°C</th>
<th>4°C</th>
<th>5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Food</strong></td>
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<tr>
<td>Falling crop yields in many areas, particularly</td>
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<tr>
<td>developing regions</td>
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<tr>
<td>Possible rising yields in some high latitude regions</td>
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<tr>
<td>Falling yields in many developed regions</td>
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<tr>
<td><strong>Water</strong></td>
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<tr>
<td>Small mountain glaciers disappear – water supplies</td>
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<tr>
<td>threatened in several areas</td>
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<td>Significant decreases in water availability in many</td>
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<td>areas, including Mediterranean and Southern Africa</td>
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<td>Sea level rise threatens major cities</td>
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<tr>
<td><strong>Ecosystems</strong></td>
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<tr>
<td>Extensive Damage to Coral Reefs</td>
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<tr>
<td>Rising number of species face extinction</td>
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<tr>
<td><strong>Extreme Weather Events</strong></td>
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<tr>
<td>Rising intensity of storms, forest fires, droughts,</td>
<td></td>
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<tr>
<td>flooding and heat waves</td>
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<tr>
<td><strong>Risk of Abrupt and Major Irreversible Changes</strong></td>
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<tr>
<td>Increasing risk of dangerous feedbacks and abrupt,</td>
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<tr>
<td>large-scale shifts in the climate system</td>
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</tbody>
</table>

Ref. Dennes Bergado, AIT
NGOs and Advocacy Groups devoted to public interests have multiplied exponentially. Thus, human well-being can be improved while protecting the environment such as:

1) Investments in ecosystem conservation
2) Management system to promote recovery of marine life
3) Watershed restoration schemes
4) **Prevention of riverbank and coastal erosion**
5) **Risk assessments of lateral spreads, debris flows and landslides**
6) Forecasts of flooding and flood protection schemes
7) Promote waste containment systems
8) Construct water supply reservoirs

Ref. Dennes Bergado, AIT
Goals of ATC-1 (FY2013 – FY2015)

- Collection of case studies
- Database construction
- Publication of book(s)
- International Symposium
  ⇒ The roles of geotechnical engineering in DRR should be clarified and serve as a strategy for performance goals
- Detailed activities will be led by Prof. Bergado

Ref. Dennes Bergado, AIT
Conclusion

- Historical empirical approaches for scour are diverse.
- Tohoku data increased reliability of predictive liquefaction scour.
- New ASCE 7 tsunami chapter provides best practice procedure.
- Tsunami scour and erosion need more validation measurements.
- ASCE 24 flooding scour provisions need a general erosion procedure.
- DRR of hydraulics hazards can be advanced through geo-risk reduction: elevated foundations, ground treatment & tsunami/coastal barriers.
- FEMA is modeling financial benefits of code compliant foundations for DRR.

Hydraulics & Geotechnical collaboration for tsunami and floods provides a lens for assessing loss drivers and innovating balanced soft/hard mitigations.

Thank you.

mathew.francis@urs.com