Comparison between Japanese and North American method for liquefaction assessment

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Introduction

- What method do you use for liquefaction evaluation to average engineer?
  - Japan: e.g. Design specification of Highway bridge
  - U.S.: e.g. Technical paper by Seed 1971
  - North American engineer studies more than Japanese engineer
  - NSF Workshop in 1996 and 1998

Technical report NCEER-97-0022,
Youd, T. L. etc., Journal of GT, Vol. 127, No. 10

Basic standpoint

- North America
  - United Engineers
    - NSF Workshop
  - Study and think
    - Unsuggested (not recommended) issues

- Japan
  - Going my way
    - Many design specifications
  - Do not think or consider
    - Everything is written
      - Do as written following the specification
    - Poor engineer education system

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<td>1. Design standards for port and harbour facilities</td>
<td>The Japan Port and Harbour Association</td>
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<td>2. Technical standards for port and harbour facilities in Japan</td>
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<td>3. System design manual for highway bridges</td>
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<td>Japan Society for Civil Engineers</td>
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<td>6. Design standard for national railway structures (foundation and retaining wall)</td>
<td>Architectural Institute of Japan</td>
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<td>7. Design criteria of building foundation structures and components</td>
<td>Ministry of Home Affairs, Fire Defense Agency</td>
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<td>8. Recommendations for design of building foundations</td>
<td>The Japan Gas Association</td>
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<td>9. Notification specifying particulars of technical standards concerning control of hazardous materials</td>
<td>Japan Water Works Association</td>
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<td>10. Recommended practice for LNG in-ground storage</td>
<td>Japan Mining Industry Association, Ministry of International Trade and Industry</td>
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<td>11. Guidelines for remedial measures of water works facilities against earthquakes</td>
<td>Japan Sewage Works Association</td>
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<td>Japan Road Association</td>
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<td>13. Evaluation for remedial measures or sewage works facilities against earthquakes</td>
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<td>14. Design manual for common utility ducts</td>
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</tbody>
</table>

Highway bridge, Building foundation, Port facilities, Railway structures
Japanese academic system

- Architectural Institute of Japan
  - Architect
  - Building engineer
- Japan Society of Civil Engineers
  - Road
  - Airport and port
  - Railway
  - Dam
- Governmental office
  - Responsible only what they handles
    - Do not like to follow outside organization

Why many specifications

- When damage occurs, who is responsible?
  - Japan
    - Engineer: I calculated following the design specification, therefore I am not responsible
    - Governmental office: I made it under the assistance of academic expert, therefore it is unexpected.
    - Therefore, everything is to be written in the design specification.
    - Otherwise somebody judged it resulting in responsibility
  - North America
    - Sued by a customer?
      - Moss Landing Marine Research Institute
        - Damaged during 1989 eq.

Compared specifications

- NSF workshop recommendation
- Highway bridge and Building foundation
  - Hwy. and Bulg.

Job or volunteer

- If job, revised on a periodic basis
  - Highway bridge by Public Work Research Institute
- If volunteer, may not revised without something happen
  - Building foundation
    - 1995 Kobe earthquake (Large ground shaking)
    - 2011 Tohoku earthquake (Long duration)

Standard Penetration test

- Turkey, Philippines
  - Half of Japan
- Recent auto or semi-auto machine
  - Cone pulley: 63~73%
    - With special care: 80~90%
  - Semi automatic: 84% (average)
  - Full automatic: 81% (Average)
- ISO22476-3
  - Energy correction with measurement method
- JIS A 1219 (2013)
  - No description, therefore no measurement method
**External load**

- **Bldg.:** Equivalent cyclic stress ratio
  \[ L = \frac{\tau_{av}}{\sigma'_{v0}} = \frac{r_{\nu}}{\sigma'_{v0}} \]
  \[ \tau_{av} = \frac{\alpha_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} \]

- **Hwy.:** Stress ratio during an earthquake
  \[ L = \frac{\tau_{av}}{\sigma'_{v0}} = r_{\nu} \frac{\alpha_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} \]

**CSR**
- **Cyclic stress ratio**
  \[ CSR = \frac{\tau_{av}}{\sigma'_{v0}} = \frac{0.65}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} \]

**Evaluation of effective number of cycles**

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>( N_e ) at 0.65( \tau_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>8.5</td>
</tr>
<tr>
<td>6.5</td>
<td>7.5</td>
</tr>
<tr>
<td>7.0</td>
<td>6.75</td>
</tr>
<tr>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>8.0</td>
<td>5.25</td>
</tr>
</tbody>
</table>

\( N_e \): Number of cycles
\( k \): Conversion coeff.
\( N_e \times k \): Equivalent number of cycles

**Line with gradient 0.2**
- \( r_n = 0.65 (N_e / 15)^{0.2} \)
  - can be approximated by
  \[ r_n = 0.1 (M - 1) \]
  - **Applicability for** \( M > 8.5 \)
    - **Arai, 2011**
  - **Data scatters**
    - **Has it meaning?**

**Other research shows** 1/0.9~1/0.8
Hwy
- Shock and vibration type
  - Number of cycles 2 and 3
  - Number of waves larger than \( \tau_{\text{max}} \) before \( \tau_{\text{max}} \) appears
  - Side same as \( \tau_{\text{max}} \)
- \( r_n \) equivalent value 0.55~0.70

MSF: Magnitude scaling factor (N.A.)

\[
F_I = MSF \frac{CRR_{c5}}{CSR} = \frac{CRR_{c5}}{CSR / MSF}
\]

<table>
<thead>
<tr>
<th>( M )</th>
<th>Seed &amp; Idriss</th>
<th>Idriss*1</th>
<th>Ambrogio</th>
<th>Arango</th>
<th>Andrus &amp; Stokoe</th>
<th>Youd &amp; Noble</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>1.43</td>
<td>2.20</td>
<td>2.86</td>
<td>3.00</td>
<td>2.20</td>
<td>2.8</td>
</tr>
<tr>
<td>6.0</td>
<td>1.32</td>
<td>1.76</td>
<td>2.20</td>
<td>2.00</td>
<td>1.65</td>
<td>2.1</td>
</tr>
<tr>
<td>6.5</td>
<td>1.19</td>
<td>1.44</td>
<td>1.69</td>
<td>1.60</td>
<td>1.40</td>
<td>1.6</td>
</tr>
<tr>
<td>7.0</td>
<td>1.08</td>
<td>1.10</td>
<td>1.30</td>
<td>1.25</td>
<td>1.10</td>
<td>1.25</td>
</tr>
<tr>
<td>7.5</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>8.0</td>
<td>0.94</td>
<td>0.84</td>
<td>0.67</td>
<td>0.75</td>
<td>0.85</td>
<td>0.87</td>
</tr>
<tr>
<td>8.5</td>
<td>0.89</td>
<td>0.72</td>
<td>0.44</td>
<td>-</td>
<td>-</td>
<td>0.65?</td>
</tr>
</tbody>
</table>

*1 Lecture at 1995 Seed Memorial Lecture, no paper
*2 Distance to liquefied site
*3 Use energy from equivalent cycles by Seed
Too conservative
Recommended (No recommendation for \( M < 7.5 \))

Stress reduction coefficient, \( r_d \)
- Apply until GL-20m
  \[
  r_d = 1 - 0.015z
  \]
- Applicable until GL-15m
  \[
  \begin{align*}
  r_d &= 1 - 0.00765 z_{0.5} \quad (z_{0.5} < 0.15m) \\
  r_d &= 1.174 - 0.0267 z_{0.5} \quad (0.15m < z < 0.3m)
  \end{align*}
  \]
  Excel use
  \[
  r_d = \frac{1 - 0.4133 z_{0.5} + 0.0405 z_{0.5} + 0.00173 z_{0.5}}{1 - 0.4177 z_{0.5} + 0.0572 z_{0.5} + 0.00121 z_{0.5}}
  \]

Liquefaction strength

- Bldg.

- Cyclic resistance ratio

Test vs Back Analysis
Read data point from figure

Degree of liq. | Comment | \( CRR_{c5} \)
|---|---|---|
Severe liq. | Sand boil and ground subsidence more than 2% or settlement of heavy structure more than 20cm | \( 1 \times 10^{-5} \) | 0.5 |
Medium liq. | Sand boil and ground subsidence less than 2% or settlement of heavy structure less than 20cm | \( 10^{-5} \) | 0.3 |
Border line | Site to distinguish liq. and no liq. | \( 10^{-6} \) | 0.1 |
No liq. | No sand boil nor subsidence | \( 10^{-6} \) | 0.1 |

\[
CRR_{c5} = \frac{1}{34} \left( N_{c5} \right) + \frac{1}{135} \left( N_{c5} \right) + \frac{1}{45} \left( N_{c5} \right) + \frac{1}{200} \left( N_{c5} \right)
\]
**Basic concepts**
- Relative density vs. strength
  \[ \frac{D_r}{100} = a \left( \frac{D_c}{C} \right)^n \]
  \( a = 0.45, \; n = 14 \)
- Value of C
  \[ C = 97 - 19 \log DA \]
  \( D_r = 21 \left( \frac{100N}{\sigma'_v + 70} \right) \)
  \( D_r = 16 \left( \sqrt{N_1 + \Delta N_f} \right) \)

**Triaxial test**
- Simple shear
- Meyerhof
  \( \gamma = 5\% \)

**Confining stress dep.**
- \( N_1 = C_N N = \frac{170}{\sigma'_v + 70} N \)
- \( N_1 = \sqrt{98/\sigma'_v} \cdot N \)

**Hwy.**
- After 1995 Kobe eq. liquefaction strength significantly changed based on frozen samples

**Alluvial/Diluvial vs. Holocene/Pleistocene**
- In Japan, Alluvial and Diluvial are used instead of Geologic age (Holocene and Pleistocene)
- In this presentation Holocene=Alluvial, Pleistocene= Diluvial

**Spec. for highway bridges (1990 version)**
- Specification for highway bridges (1996 version) (Cw=1)
- Design criteria of building foundation structures and commentaries
- Design standard for railway structures
- Technical guidelines for aseismic design of nuclear power plants
- Technical standards for port and harbor facilities in Japan

**Mammalian evolution**
- Cenozoic
  - Quaternary
    - Holocene
    - Pleistocene
  - Tertiary
    - Cretaceous
    - Jurassic
    - Triassic
  - Mesozoic
  - Paleozoic
    - Cambrian
    - Ordovician
    - Silurian
    - Devonian
    - Carboniferous
    - Permian

**Sea level change**
- Change in 2010 by Goecological Society of Japan

**Geologic age**
- millenary
  - Holocene
  - Pleistocene
- sea level (m)
  - 0
  - 100
- 1,650
- 2,580
- Change in 2010 by Goecological Society of Japan
Findings on frozen sampling

Frozen sample has been believed to be an undisturbed sample

Liquefaction strength

Bldg.
Highway Bridge

North America

\( N_a = \alpha + \beta (N_i)_{60} \)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( F_c \leq 5% )</th>
<th>( 5% &lt; F_c \leq 35% )</th>
<th>( 35% &lt; F_c )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \alpha )</td>
<td>0</td>
<td>1.76–190/( F_c^2 )</td>
<td>5</td>
</tr>
<tr>
<td>( \beta )</td>
<td>1</td>
<td>0.99 + ( F_c^{1.5} )/1000</td>
<td>12</td>
</tr>
</tbody>
</table>

Various factors (N.A.)

\( (N_i)_{60} = c_x c_y c_z c_k c_i N \)

<table>
<thead>
<tr>
<th>Factor</th>
<th>Variable</th>
<th>( N_t )</th>
<th>Correction</th>
</tr>
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<tbody>
<tr>
<td>Overburden stress</td>
<td>–</td>
<td>( c_N )</td>
<td>( (P_o/\sigma'_0)^{0.5} )</td>
</tr>
<tr>
<td>Overburden stress</td>
<td>–</td>
<td>( c_N )</td>
<td>( c_N \leq 1.7 )</td>
</tr>
<tr>
<td>Energy ratio</td>
<td>Donut</td>
<td>( c_E )</td>
<td>0.5~1.0</td>
</tr>
<tr>
<td>Energy ratio</td>
<td>Safety</td>
<td>( c_E )</td>
<td>0.7~1.2</td>
</tr>
<tr>
<td>Energy ratio</td>
<td>Automatic fall donuts</td>
<td>( c_E )</td>
<td>0.8~1.3</td>
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<tr>
<td>Diameter of borehole</td>
<td>65~115mm</td>
<td>( c_B )</td>
<td>1.0</td>
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<tr>
<td>Diameter of borehole</td>
<td>150mm</td>
<td>( c_B )</td>
<td>1.05</td>
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<tr>
<td>Diameter of borehole</td>
<td>200mm</td>
<td>( c_B )</td>
<td>1.15</td>
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<tr>
<td>Rod length</td>
<td>&lt;3m</td>
<td>( c_R )</td>
<td>0.75</td>
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<tr>
<td>Rod length</td>
<td>3~4m</td>
<td>( c_R )</td>
<td>0.8</td>
</tr>
<tr>
<td>Rod length</td>
<td>4~6m</td>
<td>( c_R )</td>
<td>0.85</td>
</tr>
<tr>
<td>Rod length</td>
<td>6~10m</td>
<td>( c_R )</td>
<td>0.95</td>
</tr>
<tr>
<td>Rod length</td>
<td>10~30m</td>
<td>( c_R )</td>
<td>1.0</td>
</tr>
<tr>
<td>Sampling method</td>
<td>Standard</td>
<td>( c_s )</td>
<td>1.0</td>
</tr>
<tr>
<td>Sampling method</td>
<td>No liner</td>
<td>( c_s )</td>
<td>1.1~1.3</td>
</tr>
</tbody>
</table>

Other (N.A.)

Seed (Original)

\( F_l = MSF \frac{CRR_{1.5}}{CSR} K_{\sigma} K_{\sigma} \)

- \( K_{\sigma} \): Confining stress correction

Recommended among various research

\( K_{\sigma} = (\sigma'_0/\sigma)^{1.5} \)

Japan

\( c_N = \frac{98}{\sigma'_v} \)

\( c_N = \frac{170}{\sigma'_v + 70} \)

Other (N.A.)

\( D_{<40\%}(f=0.8) \)

\( D_{>80\%}(f=0.6) \)

Effective overburden stress ratio \( \sigma_0/P_o \)
Correction by slope
- Defined ad
  \[ \alpha = \frac{\tau_{xy}}{\sigma'_{v_0}} \]
- Determine by triaxial test, but large scatter
  - Average engineer do not use

Aging effect
- Seed: 25% increase in 100 days
- Youd: Young ground is more liquefiable
- Not recommended because of short data
- Old sediment (older than several thousands)
  - Limited engineer uses aging, not Ks

Design ground shaking
- N.A.
  - Consider only Magnitude and other factor such as area, duration, fault mechanism is difficult. Conservative side
    - Not a big issue in the liquefied site
  - Use Moment magnitude, \( M_w \)
  - PGA when liquefaction does not occur
    - Empirical equation considering earthquake magnitude, focal distance, site condition, etc.
    - If empirical eq. is not available, seismic response analysis such as SHAKE and DESRA
    - Use amplification factor to be multiplied to PGA at the engineering seismic base layer
      - Require highly engineering judgement

- 2 directional components
  - geometric mean, but larger value is conservative
  - High frequency component (Period<0.1 s)
    - Spiky wave does not cause displacement because of short active time, therefore neglect
    - High frequency component is attenuated in SHAKE and DESRA
    - When using amplification factor, choice of frequency range is important

Japan
- Bldg. (1985)
  - Affected by various factors
    - Some of them is not clear
    - Affected by local ground condition
      - If liquefied, earthquake motion does not propagate to the ground surface
    - Target is horizontally layered deposit, but important is the case with structure exists
    - Proposed method gives rough indication
  - THEN, PGA recorded during past earthquakes is relevant
    - 200 cm/s²
      - Kawagishi-cho apartment house in Niigata eq. = 158
PGA is a result of response of ground, and is affected by
the ground conditions.
- Damage limit: 150~200 cm/s²
- Ultimate limit: 350 cm/s²
- PGA at Port Island during the 1995 Kobe eq.

PGA in liquefied site

- Change of acceleration by liquefaction is not considered
  in $\alpha_{max}$
- Considering liquefaction requires effective stress
  seismic response analysis, but it is impossible
- FL method is a simplified method
- FL method is safety factor method
  - External load becomes large under larger ground shaking

<table>
<thead>
<tr>
<th>Ground type</th>
<th>1995</th>
<th>1996</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1  (Ocean trench)</td>
<td>0.3</td>
<td>0.35</td>
</tr>
<tr>
<td>Type 2  (Near field eq.)</td>
<td>0.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Comparison of Japanese specifications

Comparison between Bldg. and Hwy

- 1996 version
2017 version

Definition of $F_L$

- **Bldg.**
  \[ L = \frac{\sigma_{\text{max}} - \sigma_0}{\sigma_0} r_d \]
  \[ r_d = 0.1(M - 1) \]

- **Hwy vs. Budg**
  \[ F_L = \frac{c_1c_2c_3c_4R_L}{L} = \frac{c_1c_2R_L}{c_2L/r_d} = \frac{C}{r_d} \]
  \[ C_v = 0.9 \left( 1 + \frac{2K_0}{3} \right) = 0.57 \]

Relative density, Dr

<table>
<thead>
<tr>
<th>SPT N</th>
<th>$D_r$ (%)</th>
<th>$\phi$ (deg.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Peck</td>
<td>Meyerhof</td>
</tr>
<tr>
<td>0~4</td>
<td>very loose</td>
<td>0~20</td>
</tr>
<tr>
<td>4~10</td>
<td>loose</td>
<td>28.5~30</td>
</tr>
<tr>
<td>10~30</td>
<td>medium</td>
<td>30~35</td>
</tr>
<tr>
<td>30~50</td>
<td>dense</td>
<td>35~40</td>
</tr>
<tr>
<td>50以上</td>
<td>very dense</td>
<td>40~45</td>
</tr>
</tbody>
</table>

Meyerhof
\[ D_r = 21 \left( \frac{100N}{\sigma' + 70} \right) \]

Relative density in sites

- **Miyagi Pref.**
- **Seed**
- **Mikami**

$R_L$ vs. $D_r$
Accuracy (2011, PWRI)

<table>
<thead>
<tr>
<th>Liq.</th>
<th>No Lq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL$\leq$1</td>
<td>53</td>
</tr>
<tr>
<td>FL$&gt;$1</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Tokyo Bay area**: Old fill / natural deposit
  - Many no liq. site although FL$\leq$1
  - Fill after 1945 liquefy
  - There is no clear difference between borehole data between liq. and no liq. sites
- **Tone River area**
  - FL is relatively large in the liquefied sites
  - Thin thickness in case FL$\leq$1

Accuracy (2007)

- Proposed correction, $c_2=0.5$ is too conservative!
  - Large scatter under ocean trench type eq.

$r_d$ is good evaluation
Concluding remarks

- Same framework, but different definition
- Liquefaction strength
  - Average or boundary
    - If average, half of them is in critical side!
  - Result was conservative, Why?

- Parameters
  - SPT N-value, overburden stress, fines contents
    - Is those sufficient? No!
      - What are other parameters?
        - Aging, $K_a$, ....