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

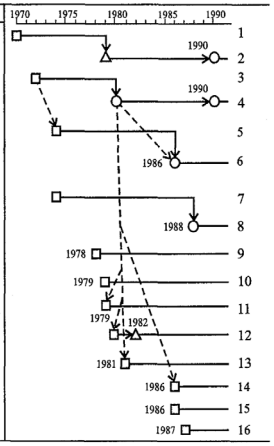
Technical report NCEER-97-0022,
Youd, T. L. etc., Journal of GT, Vol. 127, No. 10

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

Design codes and standards

Title	Organization
1. Design standards for port andharbour facilities	The Japan Port and Harbour Association
2. Technical standards for port andharbour facilities in Japan	ditto
3. Seismic design manual for highway bridges	Japan Road Association
4. Specifications for highway bridges, part 5 seismic design	ditto
5. Design standard for railway structures, foundation and retaining wall	Japan National Railway
6. Design standard for national railway structures (foundation and retaining wall)	Japan Society for Civil Engineers
7. Design criteria of building foundation structures and commentaries	Architectural Institute of Japan
8. Recommendations for design of building foundations	ditto
9. Notification specifying particulars of technical standards concerning control of hazardous materials	Ministry of Home Affairs, Fire Defense Agency
10. Recommended practice for LNG in-ground storage	The Japan Gas Association
11. Guidelines for remedial measures of water works facilities against earthquakes	Japan Water Works Association
12. Specifications of construction of tailings dams and commentary	Japan Mining Industry Association, Ministry of International Trade and Indusry
13. Guidelines for remedial measures of sewage works facilities against earthquakes	Japan Sewage Works Association
14. Design manual for common utility ducts	Japan Road Association
15. Highway earthwork series, manual for soft ground remediation	ditto
16. Technical guidelines for aseismic design of nuclear power plants	Japan Electric Association



□Liquefaction assessment was introduced in standards.
△Standard was revised, but liquefaction assessment was not corrected.
○Standard was revised (corrected).

- 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

Japan	Hammer	Falling	Energy ratio
Japan	Donut	Free fall	78
	Donut	Cone pulley	67
U.S.A	Safety	Cone pulley	60
	Donut	Cone pulley	45

- 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

$$L = \frac{\tau_{av}}{\sigma'_{v0}} = r_n r_d \frac{\alpha_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}}$$

- CSR
  - Cyclic stress ratio

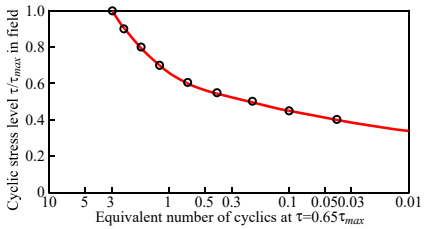
$$CSR = \frac{\tau_{av}}{\sigma'_{v0}} = 0.65 r_d \frac{\alpha_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}}$$

- Hwy.: Stress ratio during an earthquake

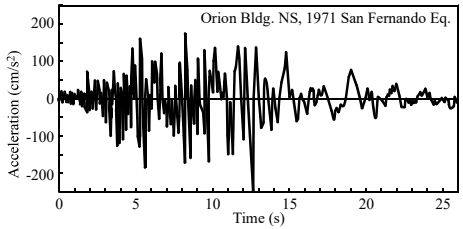
$$L = \frac{\tau_{av}}{\sigma'_{v0}} = r_d \frac{\alpha_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}}$$

r_n

- r_n=0.1(M-1) Bldg.
  =0.65/MSF
  - MSF: Moment scaling factor
    - ▸Number of effective cycles at τ_{av}=0.65τ_{max}



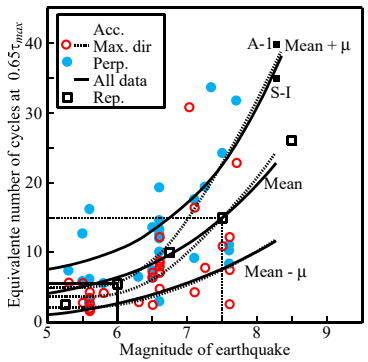
Reference liquefaction strength curve



Orion Bridge record during the 1971 San Fernando Eq.

- Evaluation of effective number of cycles

	Positive			Negative		
Amp.	N	k	N_e	N	k	N_e
τ_{max}					3.00	3.00
0.70τ_{max}	2	1.20	2.40	2	1.20	2.40
0.65τ_{max}	1	1.00	1.00	2	1.00	2.00
0.60τ_{max}	-	-	-	2	0.70	1.40
0.55τ_{max}	6	0.40	2.40	-	-	-
0.50τ_{max}	1	0.20	0.20	3	0.20	0.60
0.45τ_{max}	1	0.10	0.10	2	0.10	0.20
0.40τ_{max}	2	0.04	0.08	3	0.04	0.12
0.35τ_{max}	1	0.02	0.02	6	0.02	0.12
0.30τ_{max}	-	-	-	-	-	-
Sum			6.20			9.84



Magnitude	N_e at 0.65τ_{max}
8.5	26
7.5	15
6.75	10
6	5~6
5.25	2~3

N: Number of cycles
k: Conversion coef.
N_e :Equivalent number of cycles
$=N\times k$

Bldg.

Magnitude	N_e	r_n
5.5	3	0.47
6.5	6	0.54
7	10	0.60
7.5	15	0.65
8.3	25	0.72

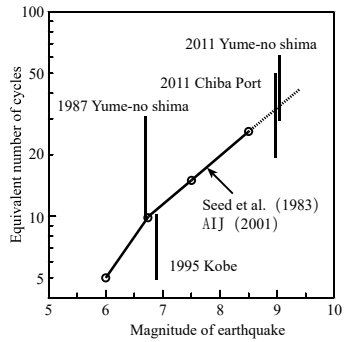
- Line with gradient 0.2

$$r_n = 0.65(N_c/15)^{0.2}$$

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

Moment magnitude

- Hwy
  - Shock and vibration type
    - ▶Number of cycles 2 and 3
      - Number of waves larger than τ_{max} before τ_{max} appears
      - Side same as τ_{max}
  - r_n equivalent value 0.55~0.70

- MSF: Magnitude scaling factor (N.A.)

$$F_L = MSF\frac{CRR_{7.5}}{CSR} = \frac{CRR_{7.5}}{CSR/MSF}$$

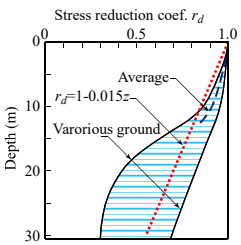
M	Seed & Idriss	Idriss*1	Ambraseys	Arango		Andrus & Stokoe	Youd & Noble		
				Distance *2	Energy*3		P_L<20%	P_L<32%	P_L<50%
5.5	1.43	2.20	2.86	3.00	2.20	2.8	2.86	3.42	4.44
6.0	1.32	1.76	2.20	2.00	1.65	2.1	1.93	2.35	2.92
6.5	1.19	1.44	1.69	1.60	1.40	1.6	1.34	1.66	1.99
7.0	1.08	1.10	1.30	1.25	1.10	1.25	1.00	1.20	1.39
7.5	1.00	1.00	1.00	1.00	1.00	1.00	-		1.00
8.0	0.94	0.84	0.67	0.75	0.85	0.87	-		0.73?
8.5	0.89	0.72	0.44	-	-	0.65?	-		0.56?

*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

$$r_d = 1 - 0.015z$$

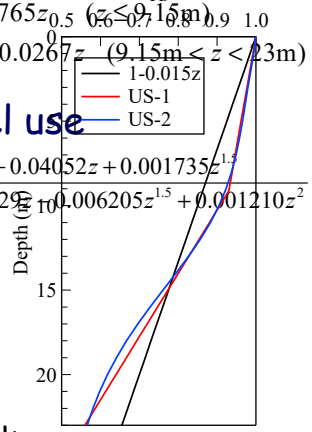


- Applicable until GL-15m

$$r_d = 1 - 0.00765z \quad (z \le 9.15\text{m})$$
$$r_d = 1.174 - 0.0267z \quad (9.15\text{m} < z < 23\text{m})$$

Excel use

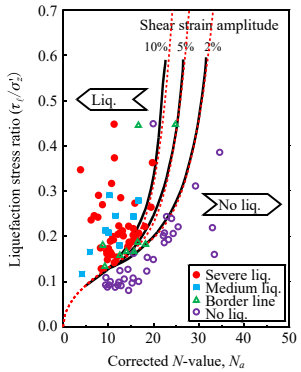
$$r_d = \frac{1 - 0.4133z^{0.5} + 0.04052z + 0.001735z^{1.5}}{1 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2}$$



Predominant vibration mode
Depth of engineering seismic bedrock

Liquefaction strength

- Bldg.



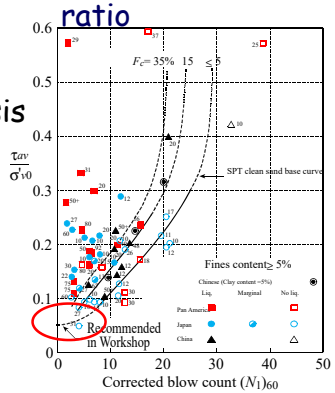
Test vs Back Analysis

Read data point from figure

$$R = aC_r\left[\frac{16\sqrt{N_a}}{100} + \left(\frac{16\sqrt{N_a}}{C_s}\right)^n\right]$$

Degree of liq.	Comment	
Severe liq.	Sand boil and ground subsidence more than 2% or settlement of heavy structure more than 20cm	●
Medium liq.	Sand boil and ground subsidence less than 2% or settlement of heavy structure less than 20cm	■
Border line	Site to distinguish liq. and no liq.	△
No liq.	No sand boil nor subsidence	○

- CRR
  - Cyclic resistance ratio



$$CRR_{7.5} = \frac{1}{34-(N_1)_{60}} + \frac{(N_1)_{60}}{135} + \frac{50}{\{10\cdot(N_1)_{60}+45\}^2} - \frac{1}{200}$$

- Basic concepts
  - Relative density vs. strength

$$\frac{\sigma_d}{2\sigma_o'} = a\left\{\frac{D_r}{100} + \left(\frac{D_r}{C}\right)^n\right\}$$

a=0.45, n=14

  - Value of C

$C_a = 97 - 19\log DA$ Triaxial test

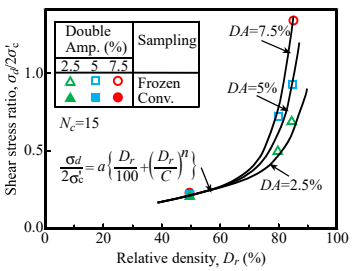
$C_s = 94 - 19\log\gamma$ Simple shear

γ=5%

  - Meyerhof

$$D_r^* = 21\sqrt{\frac{100N}{\sigma_v' + 70}}$$

$$\rightarrow \quad D_r = 16\sqrt{N_1 + \Delta N_f}$$

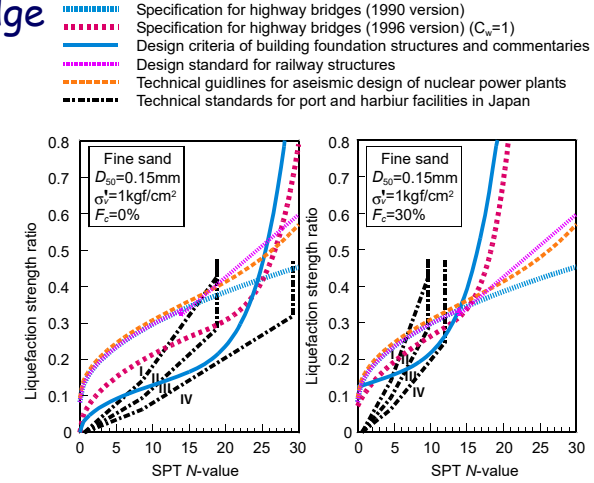


Confining stress dep.

$$N_1 = C_N N = \frac{170}{\sigma_v' + 70} N$$

$$N_1 = \sqrt{98/\sigma_{v0}'} \cdot N$$

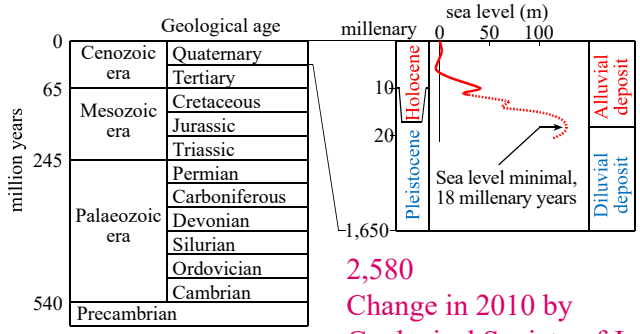
- Highway Bridge



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

Alluvial/Diluvial vs. Holocene/Pleistocene

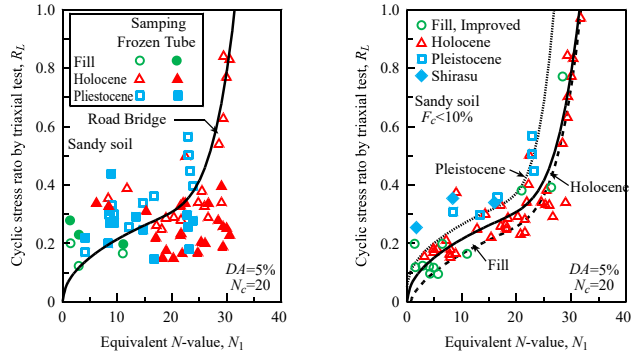
- In Japan, Alluvial and Diluvial are used instead of Geologic age (Holocene and Pleistocene)
- In this presentation Holocene=Alluvial, Pleistocene= Diluvial

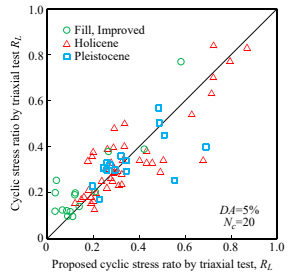


2,580

Change in 2010 by Goelocical Society of Japan

- Hwy.
- 1996





$$R_L = \begin{cases} 0.0882\sqrt{N_1/1.7} & (N_1 \le 14) \\ 0.0882\sqrt{N_1/1.7} + 1.57\cdot 10^{-6}\cdot(N_1 - 14)^{4.5} & (N_1 > 14) \end{cases}$$

$$N_a = C_1 N_1 + C_2$$

$$N_1 = 170N/(\sigma_v' + 70)$$

$$C_1 = \begin{cases} 1 & (0\% \le F_c < 10\%) \\ (F_c + 40)/50 & (10\% \le F_c < 60\%) \\ F_c/20 - 1 & (60\% \le F_c) \end{cases}$$

$$C_2 = \begin{cases} 0 & (0\% \le F_c < 10\%) \\ (F_c - 10)/18 & (10\% \le F_c) \end{cases}$$

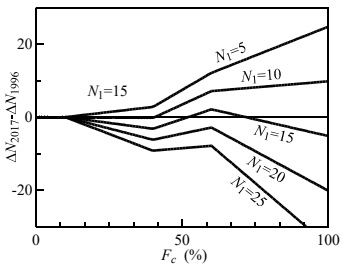
- Hwy.
- 2017

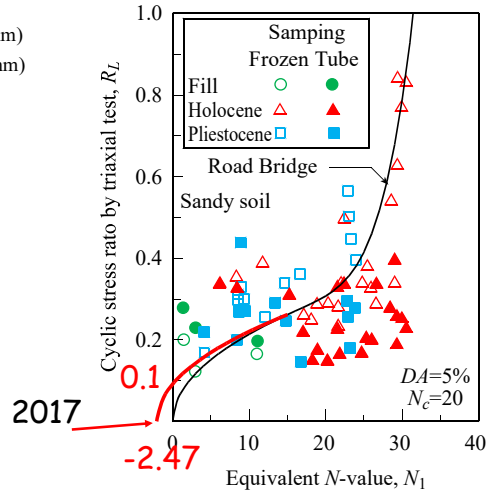
$$R_L = \begin{cases} 0.0882\sqrt{(0.85N_a + 2.1)/1.7} & (N_a < 14) \\ 0.0882\sqrt{N_a/1.7} + 1.6\times10^{-6}\cdot(N_a - 14)^{4.5} & (N_a \geq 14) \end{cases}$$

$$N_a = \begin{cases} C_{FC}(N_1 + 2.47) - 2.47 & (D_{50} < 2\text{mm}) \\ \{1 - 0.36\log_{10}(D_{50}/2)\}\cdot N_1 & (D_{50} \geq 2\text{mm}) \end{cases}$$

$$N_1 = 170N/(\sigma'_v + 70)$$

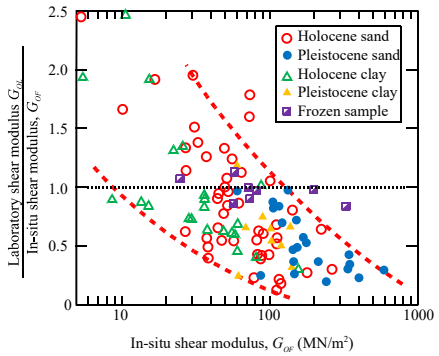
$$c_{FC} = \begin{cases} 1 & (0\% \leq F_c < 10\%) \\ (F_c + 20)/30 & (10\% \leq F_c < 40\%) \\ (F_c - 16)/12 & (40\% \leq F_c) \end{cases}$$



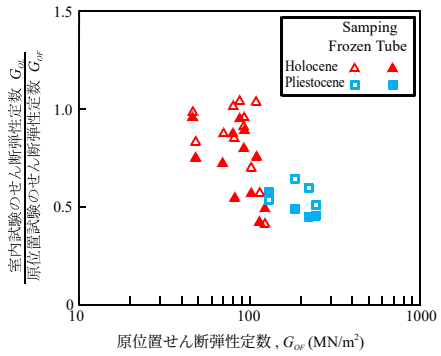


Findings on frozen sampling

- Frozen sample has been believed to be an undisturbed sample

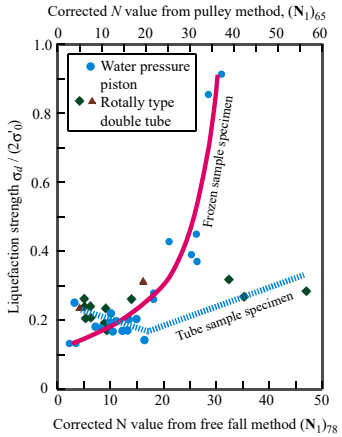


Past researches

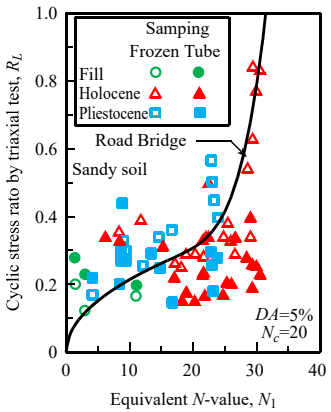


New tests, PWRI

- Liquefaction strength



Past researches



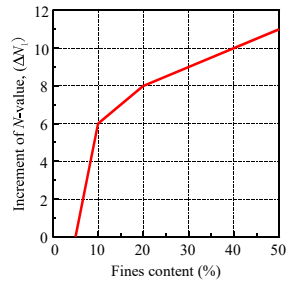
New tests, PWRI

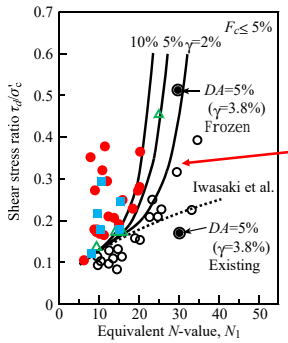
Fines contents

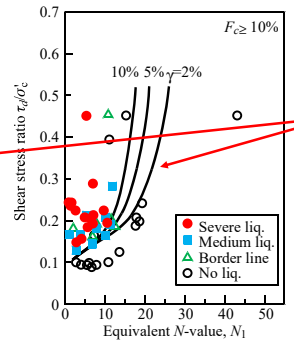
- Bldg.

F_c (%)	ΔN_f
0~5	0
5~10	Interpolation
10~	$0.1F_c$

←Original
Revised based on recent research

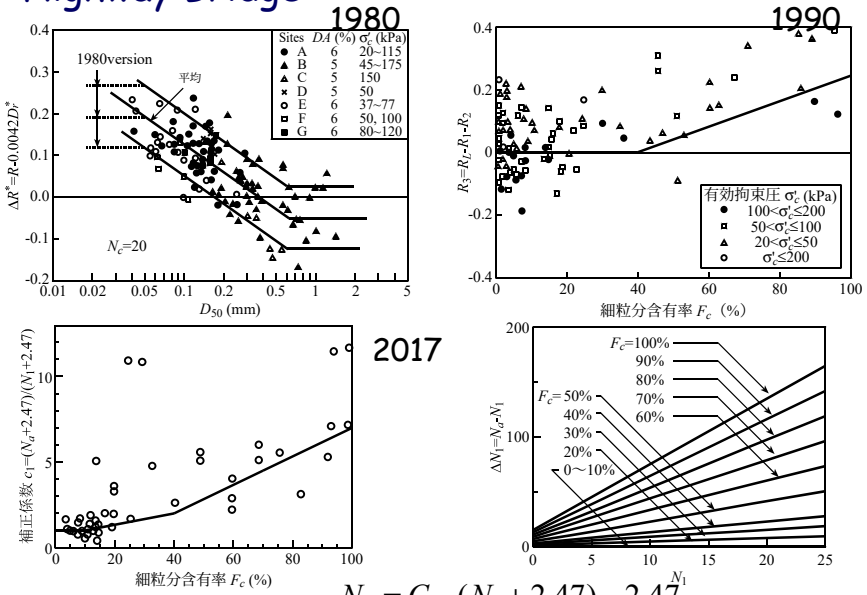






Parallel

■ Highway Bridge



$$N_a = C_{FC}(N_1 + 2.47) - 2.47$$

■ North America

$$N_a = \alpha + \beta (N_1)_{60}$$

Parameter	$F_c \le 5\%$	$5\% < F_c < 35\%$	$35\% \le F_c$
α	0	$e^{1.76-190/F_c^2}$	5
β	1	$0.99+F_c^{1.5}/1000$	1.2

Various factors (N.A.)

$$(N_1)_{60} = c_N c_E c_B c_R c_s N$$

Factor	Variable	Nt.	Correction
Overburden stress	–	c_N	$(P_a/\sigma'_{v0})^{0.5}$
Overburden stress	–	c_N	$C_N \le 1.7$
Energy ratio	Donut	c_E	0.5～1.0
Energy ratio	Safety	c_E	0.7～1.2
Energy ratio	Automatic fall donuts	c_E	0.8～1.3
Diameter of borehole	65～115mm	c_B	1.0
Diameter of borehole	150mm	c_B	1.05
Diameter of borehole	200mm	c_B	1.15
Rod length	<3m	c_R	0.75
Rod length	3～4m	c_R	0.8
Rod length	4～6m	c_R	0.85
Rod length	6～10m	c_R	0.95
Rod length	10～30m	c_R	1.0
Sampling method	Standard	c_s	1.0
Sampling method	No liner	c_s	1.1～1.3

P_a=101 kPa

C_N: 2→1.7

Better eq.

$$c_N = \frac{2.2}{1.2 + \sigma'_{v0}/P_a}$$

Japan

$$c_N = \sqrt{\frac{98}{\sigma'_v}}$$

$$C_N = \frac{170}{\sigma'_v + 70}$$

Other (N.A.)

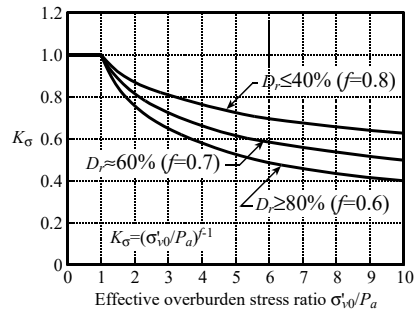
■ Seed (Original)

$$F_L = MSF \frac{CRR_{7.5}}{CSR} K_\sigma K_\alpha$$

- Kσ: Confining stress correction

■ Recommended among various research

$$K_\sigma = (\sigma'_{v0}/P_a)^{f-1}$$



- Correction by slope
  - Defined ad

    $$\alpha = \tau_{st} / \sigma'_{v0}$$

  - 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 Kσ

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

- Bldg. (2001)
  - ▶PGA is a result of response of ground, and is affected by the ground conditions.
  - ▶Damage limit: 150~200 cm/s^2
  - ▶Ultimate limit: 350cm/s^2
    - ◆PGA at Port Island during the 1995 Kobe eq.

PGA in liquefied site

- Hwy 1996
  - ▶Change of acceleration by liquefaction is not considered in α_{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

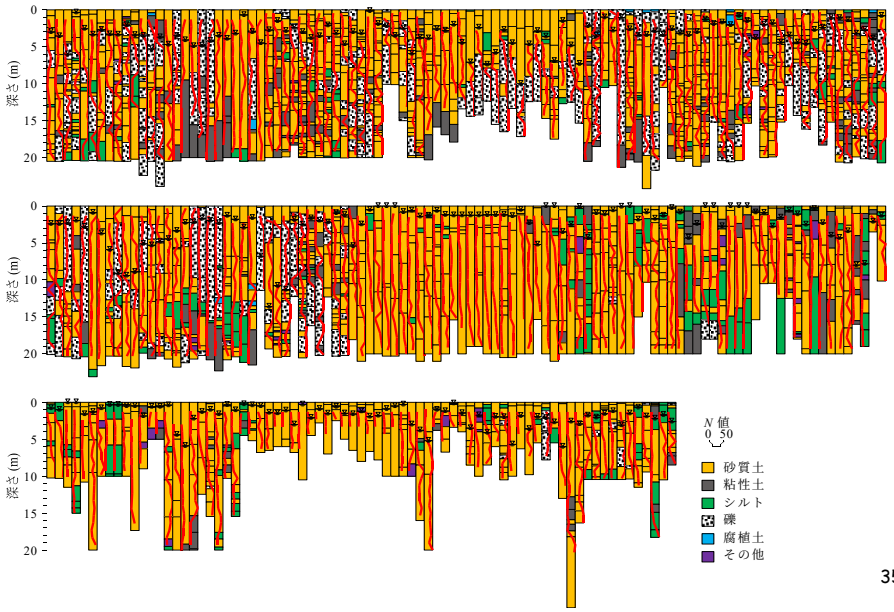
PGA in non liquefied case

Only level 2 eq.

~1995	1996~			
	Ground type	1	2	3
0.15	Type 1 (Ocean trench)	0.3	0.35	0.4
	Type 2 (Near field eq.)	0.8	0.7	0.6

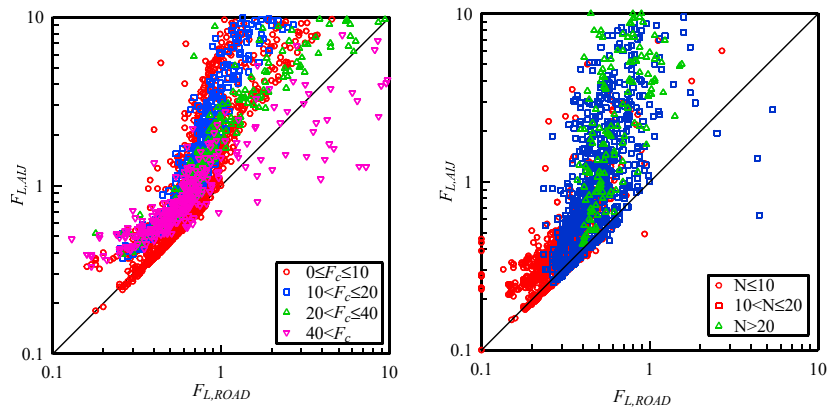
Seismic coefficient

Comparison of Japanese specifications

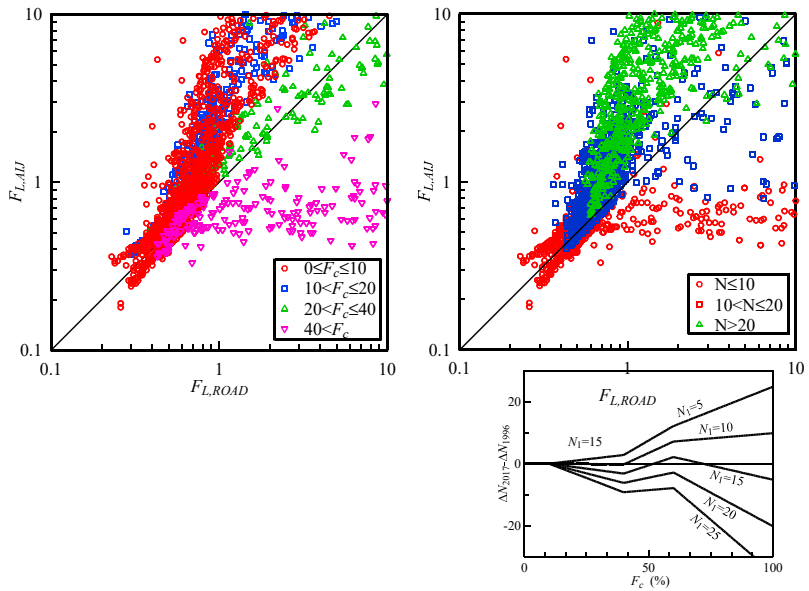


Comparison between Bldg. and Hwy

■ 1996 version



■ 2017 version



Definition of F_L

■ Bldg.

$$L = r_n \frac{\alpha_{max}}{g} \frac{\sigma_{v0}}{\sigma'_{v0}} r_d$$

$$r_n = 0.1(M - 1)$$

■ Hwy vs. Budg

$$F_L = \frac{c_1 c_2 c_3 c_4 c_5 R_L}{L} = \frac{c_1 c_2 c_5 R_L}{L} = \frac{c_1 c_5 R_L}{L / c_2} = \frac{C_r R}{r_n L}$$

$$C_r = 0.9 \frac{1 + 2K_0}{3} = 0.57$$

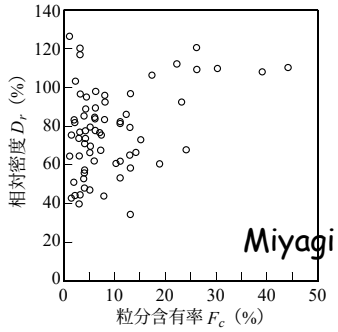
Relative density, Dr

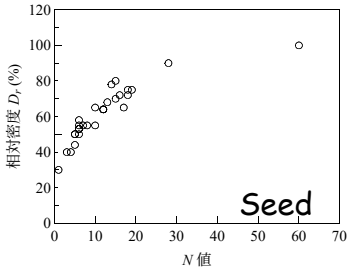
SPT N	D_r (%)		ϕ (deg.)	
			Peck	Meyerhof
0~4	very loose	0~20	<28.5	<30
4~10	loose	20~40	28.5~30	30~35
10~30	medium	40~60	30~36	35~40
30~50	dense	60~80	36~41	40~45
50以上	very dense	80~100	>41	>45

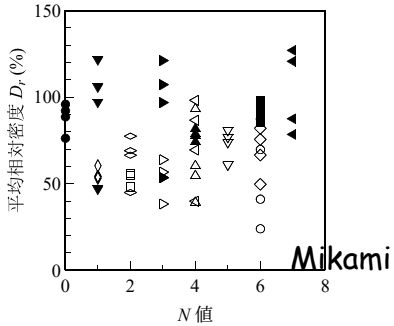
Meyerhof

$$D_r = 21\sqrt{\frac{100N}{\sigma'_v + 70}}$$

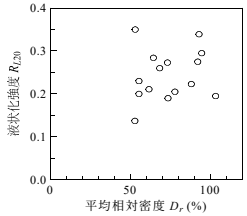
■ Relative density in sites







R_L vs. D_r

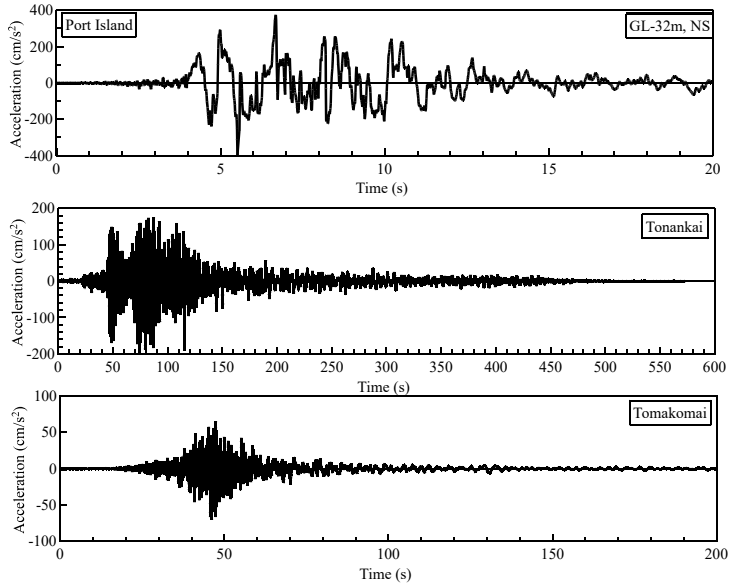


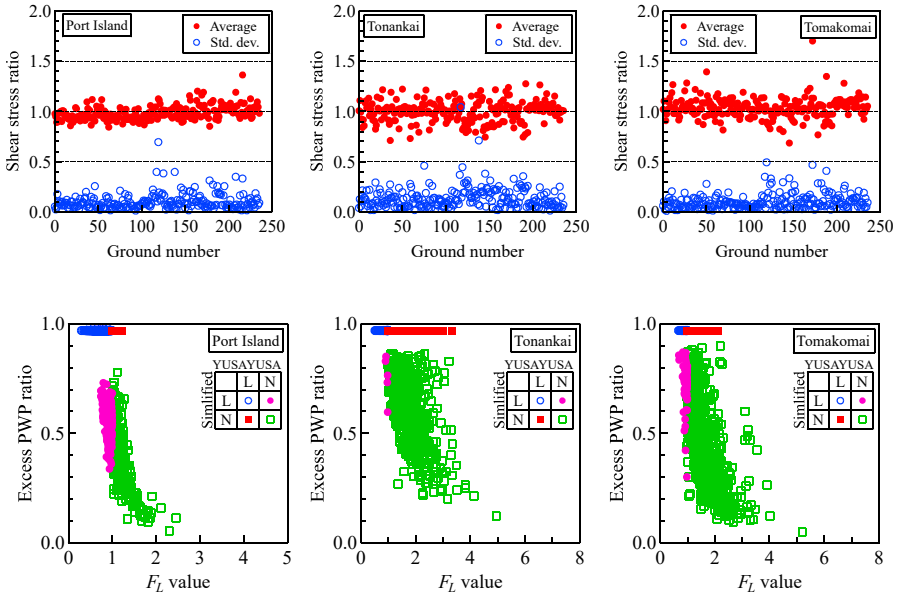
Accuracy (2011, PWRI)

	Liq.	No Lq.
$F_L \leq 1$	53	35
$F_L > 1$	0	24

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

Accuracy (2007)

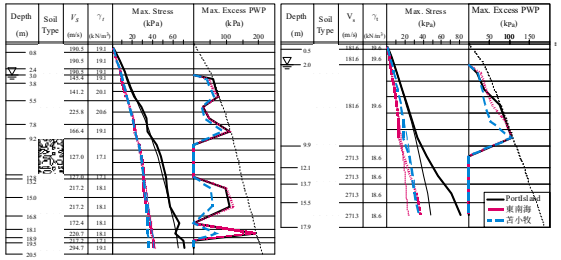




	PI	Tonankai	Tomakomai
Liq. both	64.7	6.9	4.2
Conservative	15.0	0.4	4.9
hazard ratio	1.4	46.8	11.6
no liq. both	18.9	45.9	79.3
Accuracy rate	83.6	52.8	83.5

TNK	TMK
51.7	15.8
34.1	73.8
2.1	0.1
12.2	10.3
63.9	26.1

- Proposed correction, c2=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, $K\alpha$, ...