ROCSCIENCE

Settle3

Liquefaction

Theory Manual

Table of Contents

1. Introduction

Settle3D offers different methods of calculating the factor of safety associated with liquefaction resistance, probability of liquefaction, and the input parameters required for those calculations. This manual also describes the calculating of lateral spreading displacement as well as the vertical settlement due to liquefaction.

2. Theory

The use of in situ “index” testing is the dominant approach for assessment of the likelihood of “triggering” or initiation of liquefaction. The methods available in *Settle3D* are:

- Standard Penetration Test (SPT)
- Cone Penetration Test (CPT)
- Shear Wave Velocity (VST)

The potential for liquefaction can be evaluated by comparing the earthquake loading (CSR) with the liquefaction resistance (CRR), expressed as a factor of safety against liquefaction:

$$FS = \frac{CRR_{7.5} MSF}{CSR} K_{\alpha} K_{\sigma} \quad (1)$$

where

$CRR_{7.5}$ = cyclic resistance ratio for an earthquake with magnitude 7.5

CSR = cyclic stress ratio

MSF = magnitude scaling factor

K_{σ} = overburden stress correction factor

K_{α} = ground slope correction factor

3. Cyclic Stress Ratio (CSR)

The cyclic stress ratio, CSR, as proposed by Seed and Idriss (1971), is defined as the average cyclic shear stress, τ_{av}, developed on the horizontal surface of soil layers due to vertically propagating shear waves normalized by the initial vertical effective stress, σ_v', to incorporate the increase in shear strength due to increase in effective stress. By appropriately weighting the individual stress cycles based on laboratory test data, it has been found that a reasonable amplitude to use for the “average” or equivalent uniform stress, τ_{av}, is about 65% of the maximum shear stress.

$$CSR = \frac{\tau_{av}}{\sigma_v'} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_v}{\sigma_v'}\right)r_d \tag{2}$$

where

a_{max} = maximum horizontal ground surface acceleration (g)

g = gravitational acceleration

σ_v = total overburden pressure at depth z

σ_v' = effective overburden pressure at depth z

r_d = stress reduction factor

This equation is used to calculate CSR for all three analysis types.

4. Stress Reduction Factor, r_d

The stress reduction factor, r_d, is used to determine the maximum shear stress at different depths in the soil. Values generally range 1 at the ground surface to lower values at larger depths.

The SPT, CPT, and VST methods use the same r_d formulations. The following are provided in *Settle3D*:

- NCEER (1997)
- Idriss (1999)
- Kayen (1992)
- Cetin et al. (2004)
- Liao and Whitman (1986b)

4.1. NCEER (1997)

$$r_d = 1.0 - 0.00765z \quad for\ z \leq 9.15m \tag{3}$$

4.2. Idriss (1999)

$$\ln(r_d) = \alpha(z) + \beta(z)M_w \tag{4}$$

$$\alpha(z) = -1.012 - 1.126\sin\left(\frac{z}{11.73} + 5.133\right)$$

$$\beta(z) = 0.106 + 0.118\sin\left(\frac{z}{11.28} + 5.142\right)$$

where

z = depth in meters $\leq 34m$

M_w = earthquake magnitude

For depths greater than 34m, r_d = 0.5.

4.3. Kayen (1992)

$$r_d = 1 - 0.012z \qquad \textbf{5}$$

where

z = depth in meters

4.4. Cetin et al. (2004)

$$r_d\left(z, M_w, a_{max}, V^*_{s,12m}\right) = \frac{\left[1 + \frac{-23.013 - 2.949a_{max} + 0.999M_w + 0.0525V^*_{s,12m}}{16.258 + 0.201e^{0.341\left(-d+0.0785V^*_{s,12m}+7.586\right)}}\right]}{\left[1 + \frac{-23.013 - 2.949a_{max} + 0.999M_w + 0.0525V^*_{s,12m}}{16.258 + 0.201e^{0.341\left(0.0785V^*_{s,12m}+7.586\right)}}\right]} \pm \sigma_{\epsilon_{r_d}}$$

for z<20 m (65ft)

$$r_d\left(z, M_w, a_{max}, V^*_{s,12m}\right) = \frac{\left[1 + \frac{-23.013 - 2.949a_{max} + 0.999M_w + 0.0525V^*_{s,12m}}{16.258 + 0.201e^{0.341\left(-20+0.0785V^*_{s,12m}+7.586\right)}}\right]}{\left[1 + \frac{-23.013 - 2.949a_{max} + 0.999M_w + 0.0525V^*_{s,12m}}{16.258 + 0.201e^{0.341\left(0.0785V^*_{s,12m}+7.586\right)}}\right]} - 0.0046(z - 20) \pm \sigma_{\epsilon_{r_d}}$$

for z≥20m (65ft)

$\sigma_{\epsilon_{r_d}}(z) = z^{0.8500} \times 0.0198$ for z<12m (40ft)

$\sigma_{\epsilon_{r_d}}(z) = 12^{0.8500} \times 0.0198$ for z≥12m (40ft) **6**

where

$\sigma_{\epsilon_{r_d}}$ = standard deviation (assumed to be zero)

z = depth in meters

a_{max} = gravitational acceleration

$V^*_{s,12m}$ = site shear wave velocity over the top 12m

Notes:

- If the site stiffness estimation is difficult, take $V_{s,12m}^{*}\ as$ 150-200m/s.
- For very soft sites with $V_{s,12m}^{*}$less than 120m/s, use a limiting stiffness of 120m/s in calculations.
- For very stiff sites, $V_{s,12m}^{*}$with stiffness greater than 250m/s, use 250m/s as the limiting value in calculations.

4.5. Liao and Whitman (1986b)

$r_d = 1.0 - 0.00765z$ for z≤9.15m **7**

$r_d = 1.174 - 0.0267z$ for 9.15 m<z≤ 23 m

where

z = depth below ground surface in meters

5. Magnitude Scaling Factor, MSF

If the magnitude of the earthquake is not 7.5, then the CRR values need to be corrected for earthquake magnitude. The following corrections are available:

- Tokimatsu and Seed (1987)
- Idriss (1999)
- Idriss and Boulanger (2014) – SPT and CPT only
- Andrus and Stokoe (1997)
- Youd and Noble (1997) – SPT only
- Cetin (2004)
- Idriss (NCEER)

5.1. Tokimatsu and Seed (1987)

$$MSF = 2.5 - 0.2M \qquad \textbf{8}$$

Idriss (1999)

$$MSF = 6.9 \exp\left(-\frac{M}{4}\right) - 0.058 \leq 1.8 \qquad \textbf{9}$$

This method can also be found in Idriss and Boulanger 2004 and 2008.

Idriss and Boulanger (2014)

$$MSF = 1 + (MSF_{max} - 1)\left(8.64 \exp\left(-\frac{M}{4}\right) - 1.325\right) \qquad \textbf{10}$$

$$MSF_{max} = 1.09 + \left(\frac{q_{C1Ncs}}{180}\right)^3 \leq 2.2$$

$$MSF_{max} = 1.09 + \left(\frac{(N_1)_{60cs}}{31.5}\right)^2 \leq 2.2$$

5.2. Andrus and Stokoe (1997)

$$MSF = \left(\frac{M_w}{7.5}\right)^{-3.3}$$

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5.3. Youd and Noble (1997)

The summary of the 1996/1998 NCEER Workshop proceedings by Youd and Idriss (2001) outlines various methods for calculating the MSF and provide recommendations for engineering practice.

The following MSF values are for calculated probabilities of liquefaction, the equation for which is also shown.

$$Logit(P_L) = \ln\left(\frac{P_L}{1 - P_L}\right) = -7.0351 + 2.1738M_w - 0.2678(N_1)_{60cs} + 3.0265\ln(CRR)$$

$$for\ P_L < 20\%\ \ MSF = \frac{10^{3.81}}{M^{4.53}}\ \ for\ M_w < 7$$

$$for\ P_L < 32\%\ \ MSF = \frac{10^{3.74}}{M^{4.33}}\ for\ M_w < 7$$

$$for\ P_L < 50\%\ \ MSF = \frac{10^{4.21}}{M^{4.81}}\ for\ M_w < 7.75$$

$$for\ M_w \geq 7.5\ \ MSF = \frac{10^{2.24}}{M_w^{2.56}}$$

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5.4. Cetin (2004)

$$MSF = \left(\frac{7.5}{M_w}\right)^{2.217}$$

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5.5. Idriss (from NCEER report)

$$MSF = \frac{10^{2.24}}{M^{2.56}} \tag{14}$$

6. Standard Penetration Test (SPT) Based Calculations

This section summarizes the methods available for calculating liquefaction resistance based on SPT data. The following are presented:

- SPT N-Value Correction Factors
- Cyclic Resistance Ratio (CRR)
- Relative Density (D_R)
- Fines Content Correction
- Overburden Correction Factor
- Shear Stress Reduction Factor

SPT-based calculations can be carried out two ways in Settle3D:

1. Pre-defined Triggering Methods – Users choose one of four pre-defined methods for calculating liquefaction. When one of the pre-defined options are chosen, the correction factors and triggering method are automatically selected according to the method and cannot be modified.
2. Customized Triggering Methods – Users can select any combination of correction factors and triggering methods.

6.1. Pre-Defined Triggering Methods

The following pre-defined triggering methods are available in Settle3D:

1. Youd et al. (2001)
2. Idriss and Boulanger (2008)
3. Cetin et al. – Deterministic (2004)
4. Cetin et al. – Probabilistic (2004)

The table below outlines the options that are automatically selected when each pre-defined triggering method is used.

	Triggering Methods			
	Youd et al. (2001)	Idriss and Boulanger (2008)	Cetin et al. (2004) – Deterministic	Cetin et al. (2004) – Probabilistic
Triggering Method	NCEER (1997)	Idriss and Boulanger (2004)	Cetin et al. (2004) Deterministic	Cetin et al. (2004) Probabilistic

Depth Correction	Depth Correction	Liao & Whitman (1986)	Idriss and Boulanger (2004)	Liao & Whitman (1986)	Liao & Whitman (1986)
	Sampling Method	Standard	Standard	Standard	Standard
Advanced Settings	MSF	Idriss (1999)	Idriss and Boulanger (2008)	None	None
	Stress Reduction Factor	Idriss (1999)	Idriss (1999)	Cetin et al. (2004)	Cetin et al. (2004)
	Relative Density	Skempton (1986)	Idriss and Boulanger (2003)	Skempton (1986)	Skempton (1986)
	Fines Content Correction	Youd et al. (2001)	Idriss and Boulanger (2008)	Cetin et al. (2004)	Cetin et al. (2004)
	K sigma	Hynes and Olsen (1999)	Idriss and Boulanger (2008)	Cetin et al. (2004)	Cetin et al. (2004)
	K alpha	None	None	None	None

6.2. SPT-N Value Correction Factors

Before the CRR can be calculated, the N values obtained from the SPT must be corrected for the following factors: overburden, rod length, non-standard sampler, borehole diameter, and hammer energy efficiency, resulting in a $(N_1)_{60}$ value. The equation below illustrates the correction.

$$N_{60} = N C_R C_S C_B C_E \tag{15}$$

$$(N_1)_{60} = N_{60} C_N \tag{16}$$

Table 1: Summary of Correction Factors for Field SPT-N Values

Factor	Equipment Variable	Term	Correction
Overburden Pressure		C_N	Section 6.2.1
Energy Ratio	Donut hammer	C_E	0.5-1.0
	Safety hammer		0.7-1.2
	Automatic hammer		0.8-1.3
Borehole Diameter	65 mm -115 mm	C_B	1.0
	150 mm		1.05
	200 mm		1.12
Rod Length	<3 m	C_R	0.75
	3 m – 4 m		0.80
	4 m - 6 m		0.85
	6 m -10 m		0.95
	10 m – 30 m		1.00
Sampling Method	Standard Sampler	C_S	1.0
	Sampler without Liner		1.0-1.3

6.2.1. Overburden Correction Factor, C_N

The overburden correction factor adjusts N values to the N_1 value that would be measured at the same depth if the effective overburden stress was 1 atm.

The following formulations are available:

- Liao and Whitman (1986a)
- Bazaraa (1967)
- Idriss and Boulanger (2004)
- Peck (1974)
- Kayen et al. (1992)

Liao and Whitman (1986a)

$$C_N = \left(\frac{P_a}{\sigma'_{v0}}\right)^{0.5} \tag{17}$$

Bazaraa (1967)

$$C_N = \frac{4}{1 + 2\sigma'_{v0}} \qquad for\ \sigma'_{v0} \leq 1.5$$

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$$C_N = \frac{4}{3.25 + 0.5\sigma'_{v0}} \quad for\ \sigma'_{v0}{}' > 1.5$$

$\sigma'_v\ is\ in\ ksf$

$C_N \leq 2.0$

Idriss and Boulanger (2004)

$$C_N = \left(\frac{P_a}{\sigma'_{vo}}\right)^{0.784-0.0768\sqrt{(N_1)_{60}}} \leq 1.7 \tag{19}$$

$(N_1)_{60} \leq 46$

Peck, Hansen and Thorburn (1974)

$$C_N = 0.77 \log\left(\frac{2000}{\sigma'_{v0}}\right) \tag{20}$$

$\sigma'_{v0}\ is\ in\ kPa\ \leq 282\ kpa$

Kayen et al. (1992)

$$C_N = \frac{2.2}{1.2 + \frac{\sigma'_{vo}}{P_a}} \leq 1.7$$

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6.2.2. Hammer Energy Efficiency Correction Factor, C_E

The energy efficiency correction factor is calculated using the measured energy ratio as follows.

$$C_E = \frac{ER_m}{60}$$

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It varies from 0.5-1.3. The ranges are taken from Skempton (1986).

Hammer Type	C_E
Donut hammer	0.5-1.0
Safety hammer	0.7-1.2
Automatic hammer	0.8-1.3

More specifically,

Hammer Type	C_E
Automatic Trip	0.9-1.6
Europe Donut Free fall	1.0
China Donut Free Fall	1.0
China Donut Rope& Pulley	0.83
Japan Donut Free Fall	1.3
Japan Donut Rope& Pulley	1.12

United States Safety Rope& pulley	0.89
United States Donut Rope& pulley	0.72
United States Automatic Trip Rope& pulley	1.25

6.2.3. Borehole Diameter Correction Factor, C_B

The following table, from Skempton (1986) summarizes the borehole diameter correction factors for various borehole diameters.

Borehole Diameter (mm)	C_B
65-115	1.0
150	1.05
200	1.15

6.2.4. Rod Length Correction Factor, C_R

The rod length correction factor accounts for how energy transferred to the sampling rods is affected by the rod length.

Youd et al. (2001)

The following table from Youd et al (2001) summarizes the rod correction factor for various rod lengths. The rod length above the ground is added to the depth to obtain the total rod length before choosing the appropriate correction factor.

Rod Length (m)	C_R
<3	0.75
3-4	0.80
4-6	0.85
6-10	0.95
10-30	1.00

Cetin et al. (2004)

The figure below illustrates the recommended C_R values (rod length from point of hammer impact to tip of sampler). Note that Cetin assumes a length of 1.2m for rod protrusion, and this is added to the depth before the correction factor is calculated.

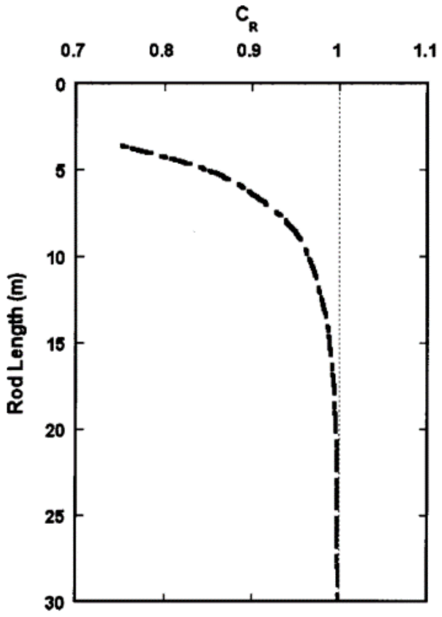

Figure 1: Recommended Cr Values

6.2.5. Sampler Correction Factor, C_S

The sampler correction factor is applied in cases when the split spoon sampler has room for liner rings, but those rings were not used.

For the standard sampler, with a liner, the correction is 1.0.

For samplers without liners, the correction factor *Cs* ranges from 1.0-1.3 (NCEER, 1997). The following C_S values are implemented.

C_S	Condition	Reference
$C_S = 1.1$	$N_{1,60} \leq 10$	(Cetin et al, 2004)
$C_S = 1 + \frac{N_{1,60}}{100}$	$10 \leq N_{1,60} \leq 30$	(Cetin et al, 2004)
$C_S = 1.3$	$N_{1,60} \geq 30$	(Cetin et al, 2004)

6.3. Cyclic Resistance Ratio (CRR)

The cyclic resistance ratio is the other term required to calculate the factor of safety against liquefaction. The cyclic resistance ratio represents the maximum CSR at which a given soil can resist liquefaction.

The equation for CRR, corrected for magnitude, is

$$CRR = CRR_{7.5}MSF \tag{23}$$

The following methods of calculating CRR are available:

- Seed et al. (1984)
- NCEER (1997)
- Idriss and Boulanger (2004)
- Cetin et al. (2004) Deterministic
- Japanese Bridge Code (JRA 1990)
- Cetin et al. (2004) Probabilistic
- Liao et al. (1988) Probabilistic
- Youd and Noble (2001) Probabilistic

6.3.1. Seed et al. (1984)

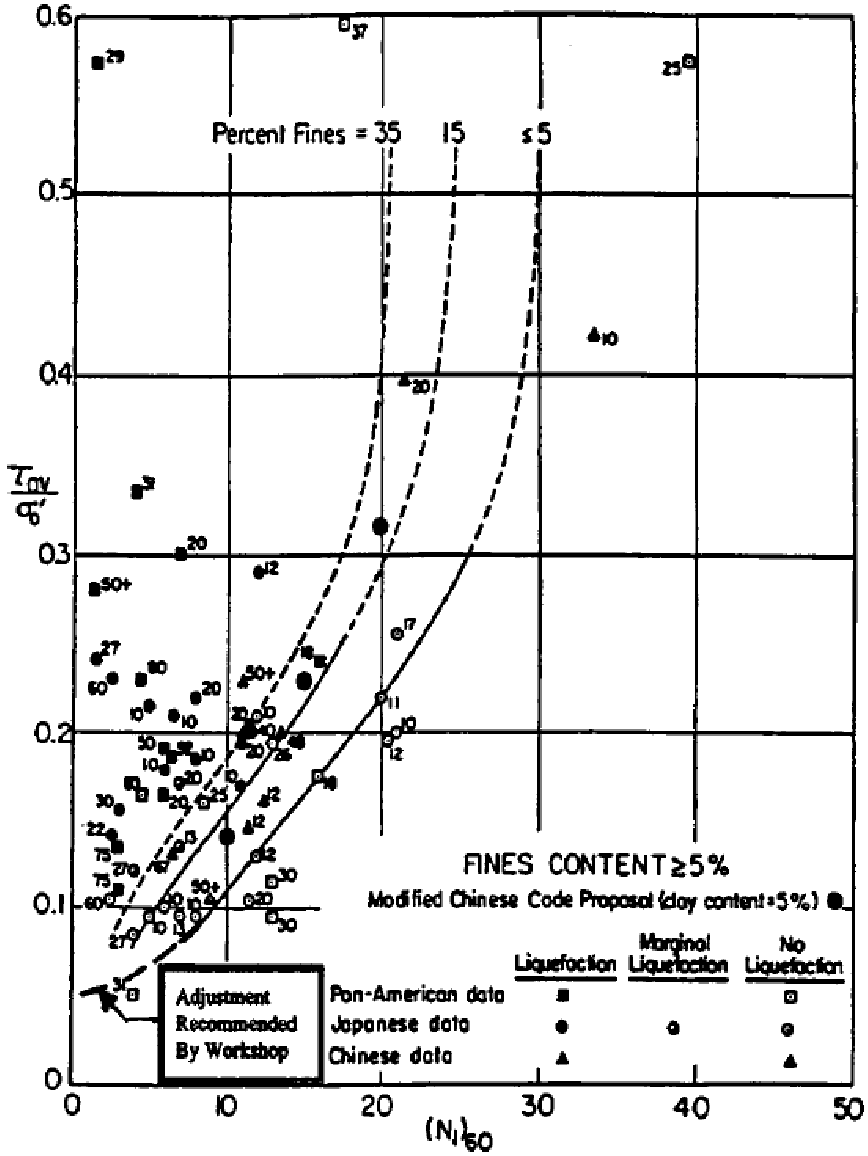

Figure 2: Liquefaction boundary curves -
Correlation of (N1)60 values and CRR (M=7.5) (Seed et al. (1984)

6.3.2. NCEER (1997)

The curves recommended by Youd and Idriss (2001) / NCEER (1997) are based on the Seed et al. (1984) curves.

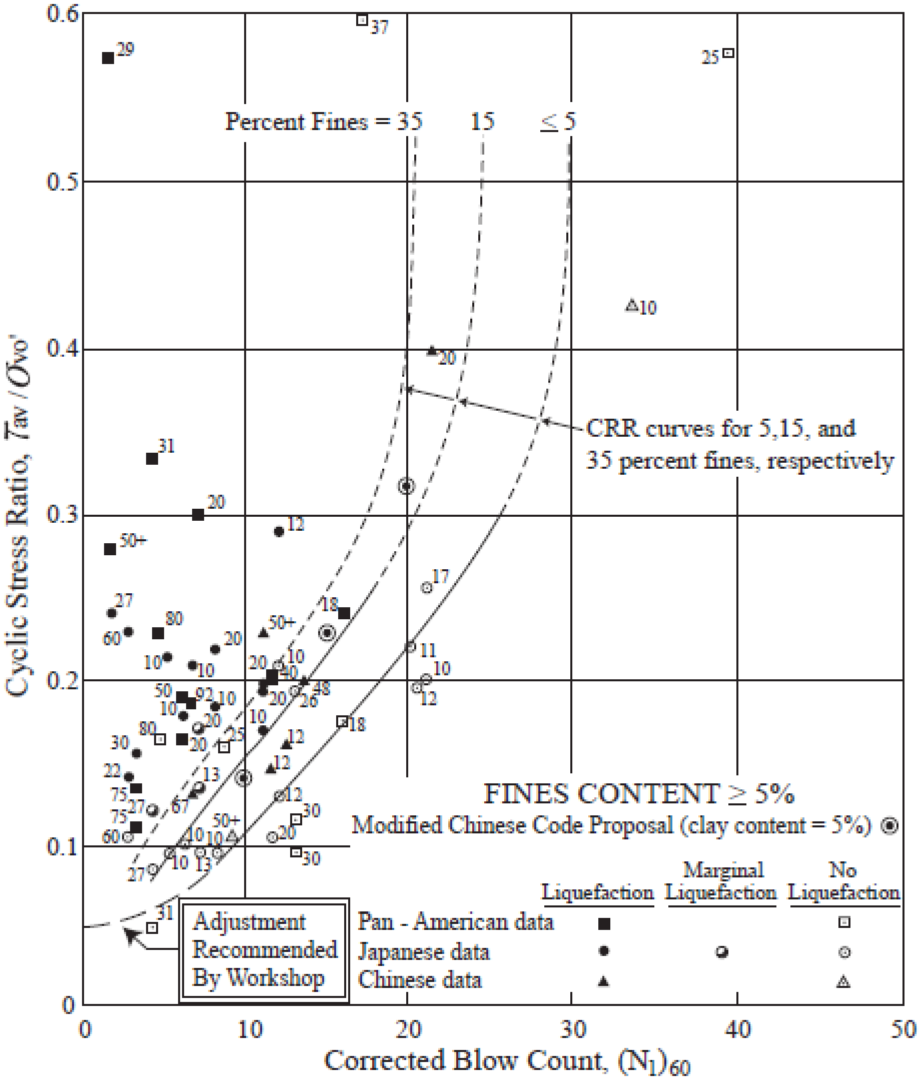

Figure 3: Simplified Base Curve Recommended for Calculation of CRR from SPT data, with Empirical Liquefaction Data (modified from Seed et al., (1985)

The equation implemented in *Settle3D* is:

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

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6.3.3. Idriss and Boulanger (2004)

Idriss and Boulanger (2004) recommend the following equation:

$$CRR_{M=7.5,\sigma=1} = \exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right)$$

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6.3.4. Cetin et al. (2004) – Deterministic

The following equation is used to calculate CRR for a given probability of liquefaction. The correction for fines content is built into the equation.

$$CRR((N_1)_{60}, M_w, \sigma_v', FC, P_L) = \exp\left[\frac{(N_1)_{60}(1 + 0.004FC) - 29.53\, ln(M_w) - 3.70\, ln\left(\frac{\sigma_v'}{P_a}\right) + 0.05FC + 16.85 + 2.70\Phi^{-1}(P_L)}{13.32}\right]$$

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6.3.5. Japanese Bridge Code (JRA 1990)

This method is based on both the equivalent clean sand N value as well as the particle size distribution.

Note that in the equation below σ_v' is in kg/cm^2.

$$CRR_{M=7.5,\sigma=1} = 0.0882\sqrt{\frac{(N_1)_{60cs}}{\sigma_v' + 0.7}} + 0.255\log\left(\frac{0.35}{D_{50}}\right) + R_3 \quad for\ 0.05mm \le D_{50} < 0.6mm$$

$$CRR_{M=7.5,\sigma=1} = 0.0882\sqrt{\frac{(N_1)_{60cs}}{\sigma_v' + 0.7}} - 0.05 \quad for\ 0.6mm \le D_{50} < 2mm$$

$$R_3 = 0 \quad for\ FC < 40\%$$

$$R_3 = 0.004FC - 0.16 \quad for\ FC \ge 40\%$$

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6.3.6. Cetin et al. (2004) – Probabilistic

Similar to the deterministic method, the Cetin et al. (2004) Probabilistic method has the fines content correction built into the P_L formulation.

$$P_L\left((N_1)_{60}, CSR_{eq}, M_w, \sigma_v', FC\right) = \Phi\left(-\frac{(N_1)_{60}(1+0.004FC) - 13.32\ln\left(CSR_{eq}\right) - 29.53\ln(M_w) - 3.70\ln\left(\frac{\sigma_v'}{P_a}\right) + 0.05FC + 16.85}{2.70}\right) \tag{28}$$

6.3.7. Liao et al. (1988) – Probabilistic

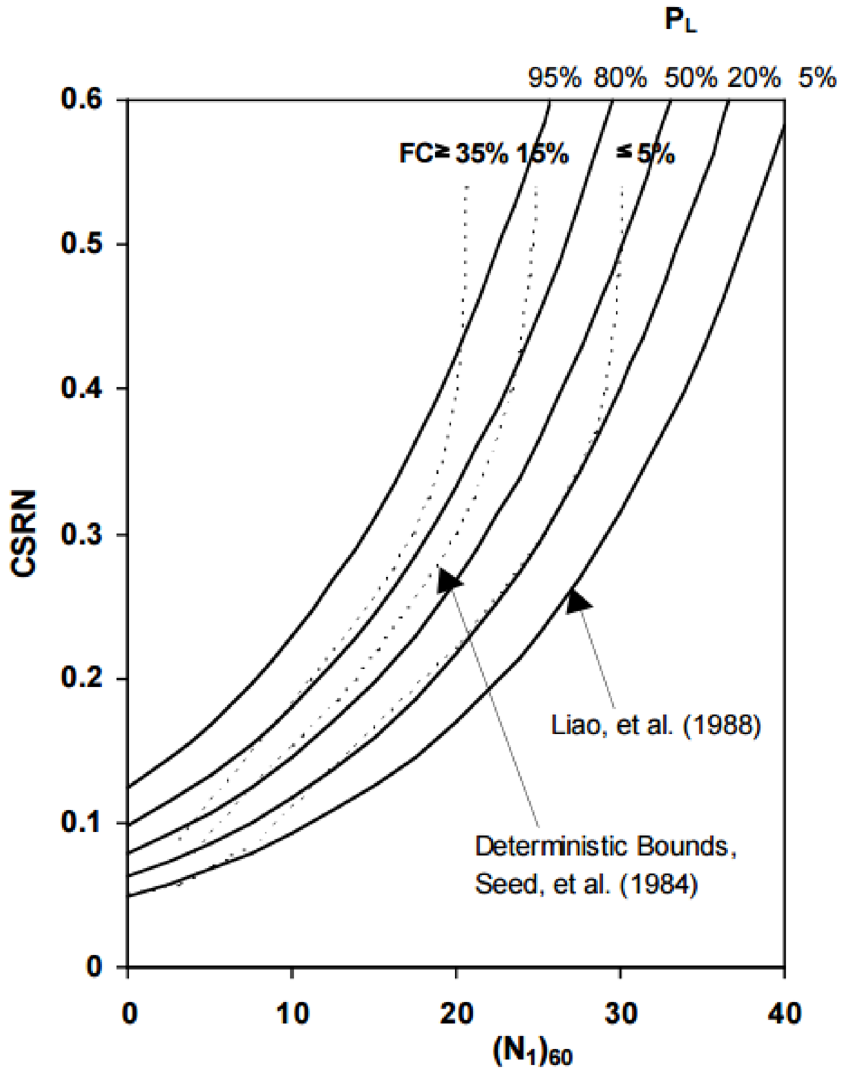

Figure 4: Probabilistic SPT-based liquefaction triggering (Liao et al. 1988)

6.3.8. Youd and Noble (2001) – Probabilistic

The Youd and Noble (2001) formulation is outlined below.

$$Logit(P_L) = \ln\left(\frac{P_L}{1-P_L}\right) = -7.0351 + 2.1738M_w - 0.2678(N_1)_{60cs} + 3.0265\ln(CRR) \tag{29}$$

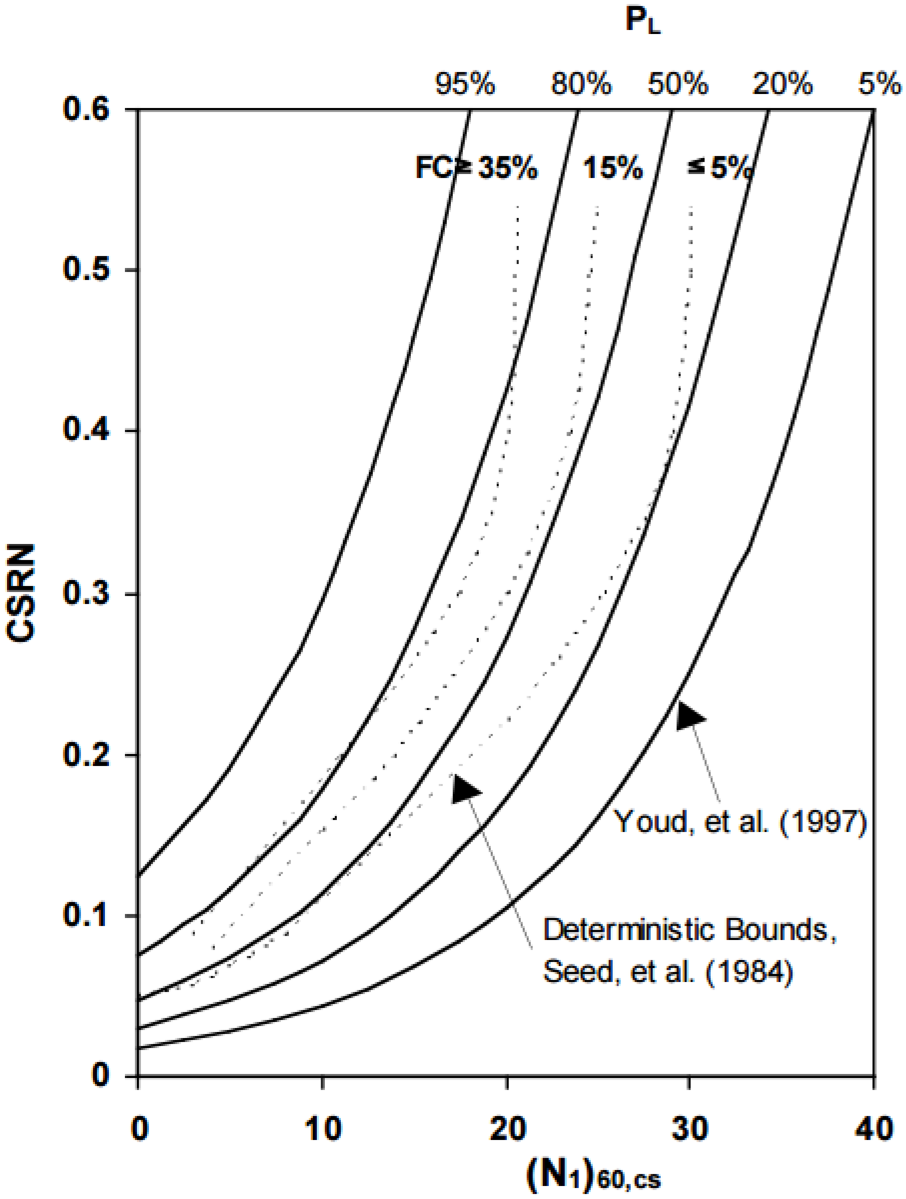

Figure 5: Probabilistic SPT-based liquefaction triggering (Youd and Noble, 1997)

6.4. Relative Density, D_R

The relative density, D_R, of a soil is used in the calculation of the overburden correction factor, C_N. The following methods are available:

- Skempton (1986)
- Ishihara (1979)
- Tatsuoka et al. (1980)
- Idriss and Boulanger (2003)
- Ishihara, Yasuda, and Yokota (1981)

6.4.1. Skempton (1986)

$$N_{1,60} = 41 * {D_R}^2 \tag{30}$$

6.4.2. Ishihara (1979)

$$D_R = 0.9 * \left(N_{1,60} + 14 + 6.51 \log_{10} FC\right) \tag{31}$$

6.4.3. Tatsuoka et al. (1980)

$$D_R = 0.9 * \left(N_{1,60} + 14 + 6.51 \log_{10} FC\right) \tag{32}$$

6.4.4. Idriss and Boulanger (2003)

$$D_R = \sqrt{\frac{N_{1,60}}{46}} \tag{33}$$

6.4.5. Ishihara, Yasuda, and Yokota (1981)

$$D_R = 0.0676\sqrt{N_{1,60}} + 0.085\ log_{10}\left(\frac{0.5}{D_{50}}\right) \tag{34}$$

6.5. Fines Content Correction

The following fines content correction methods are available:

- Idriss and Boulanger (2008)
- Youd et al. (2001)
- Cetin et al. (2004)

6.5.1. Idriss and Boulanger (2008)

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60}$$

$$\Delta(N_1)_{60} = \exp\left(1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right)$$

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6.5.2. Youd et al. (2001)

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

$$\alpha = 0 \quad for\ FC \leq 5\%$$

$$\alpha = \exp\left[1.76 - \left(\frac{190}{FC^2}\right)\right] \quad for\ 5\% < FC < 35\%$$

$$\alpha = 5.0 \quad for\ FC \geq 35\%$$

$$\beta = 1.0 \quad for\ FC \leq 5\%$$

$$\beta = \left[0.99 + \left(\frac{FC^{1.5}}{1000}\right)\right] \quad for\ 5\% < FC < 35\%$$

$$\beta = 1.2 \quad for\ FC \geq 35\%$$

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6.5.3. Cetin et al. (2004)

$$(N_1)_{60cs} = (N_1)_{60} C_{FINES}$$

$$C_{FINES} = (1 + 0.004FC) + 0.05\left(\frac{FC}{N_{1,60}}\right) \quad for\ 5\% \le FC \le 35\%$$

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6.6. Overburden Correction Factor, Kσ

In addition to magnitude, the CRR can be corrected for overburden. The CRR of sand depends on the effective overburden stress; liquefaction resistance increases with increasing confining stress.

There are three options available for SPT:

- Hynes and Olsen (1999) (NCEER)
- Idriss and Boulanger (2008)
- Cetin et al. (2004)

6.6.1. Hynes and Olsen (1999)

$$K_\sigma = \left(\frac{\sigma'_{vo}}{P_a}\right)^{(f-1)}$$

$$f = 0.7 - 0.8 \quad for\ 40\% < relative\ density < 60\%$$
$$f = 0.6 - 0.7 \quad for\ 60\% < relative\ density < 80\%$$

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The parameter *f* is a function of site conditions, and the estimates below are recommended conservative values for clean and silty sands and gravels.

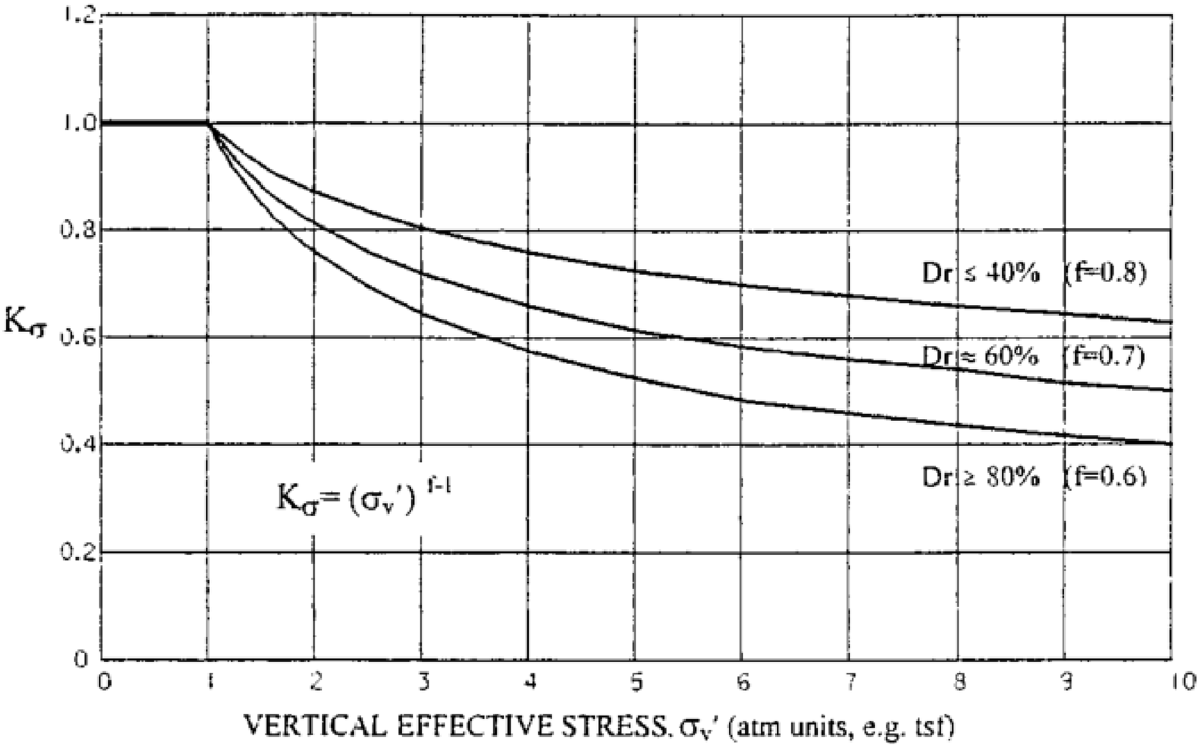

Figure 6: Recommended curves for estimating K_σ for engineering practice (from NCEER 1996 workshop)

6.6.2. Idriss and Boulanger (2008)

This method is essentially the same as the one found in Idriss and Boulanger (2004), except that the limit for K is higher.

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma'_{vo}}{P_a}\right) \leq 1.1$$

$$C_\sigma = \frac{1}{(18.9 - 17.3D_R)} \leq 0.3$$

The D_R can be estimated from the SPT blow count as,

$$D_R = \sqrt{\frac{(N_1)_{60cs}}{C_d}}$$

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Where the D_R cannot exceed 100%.

6.6.3. Cetin et al. (2004)

The following figure illustrates the recommended values.

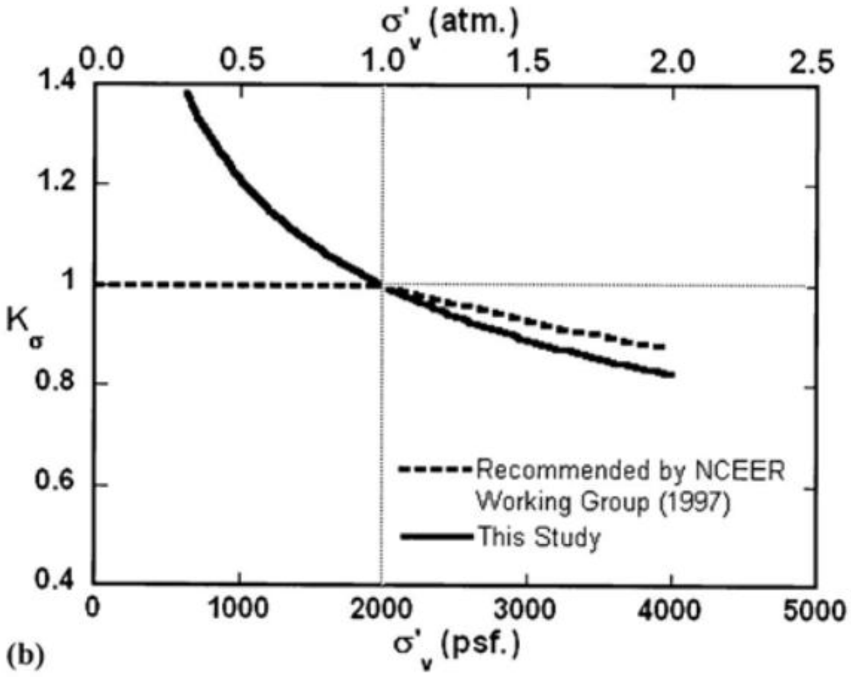

Figure 7: K_σ values, shown with NCEER recommendations (for n=0.7 and DR<60%) for comparison

6.7. Shear Stress Correction Factor, Kα

K_α is the static shear stress correction factor, used to correct CRR values for the effects of static shear stresses. The only option available in Settle3D for this factor is from Idriss and Boulanger (2003).

$$K_\alpha = a + b\exp\left(\frac{\xi_R}{c}\right)$$

$$a = 1267 + 636\alpha^2 - 634\exp(\alpha) - 632\exp(-\alpha)$$

$$b = \exp[-1.11 + 12.3\alpha^2 + 1.31\ln(\alpha + 0.0001)]$$

$$c = 0.138 + 0.126\alpha + 2.52\alpha^3$$

$$\xi_R = \frac{1}{Q - \ln\left(\frac{100p'}{P_a}\right)} - D_R$$

$$\alpha \leq 0.35$$

$$-0.6 \leq \xi_R \leq 0 \tag{40}$$

where

D_R = relative density

p' = mean effective normal stress

Q = empirical constant which determines the value of p' at which dilatancy is suppressed and depends on the grain type (Q~10 for quarz and feldspar, 8 for limestone, 7 for anthracite, and 5.5 for chalk; Settle3D uses 8)

P_a = atmospheric pressure

α = tan of slope angle.

7. Cone Penetration Test (CPT) Based Calculations

The following methods are available in *Settle3D* for determining triggering of liquefaction:

- Robertson and Wride (1997)
- Modified Robertson and Wride (1998)
- Boulanger and Idriss (2004)
- Boulanger and Idriss (2014)
- Moss et al. (2006) – Deterministic
- Moss et al. (2006) – Probabilistic

As mentioned in previous section, the magnitude scaling factor (MSF) and stress reduction factor (r_d) equations are the same as for SPT. These equations can be found in sections 4 and 5.

7.1. Robertson and Wride (1997)

The following methods are employed in the Robertson and Wride (1997) triggering method:

1. Calculate I_c using the procedure outlined in the NCEER summary report.
2. Calculate q_{c1N} using the n value from the I_c calculation.
3. Calculate q_{c1Ncs}, with K_c calculated based on the NCEER recommendation. Depths with $q_{c1Ncs} \geq 160$ are considered not liquefiable.

$$K_c = 1.0 \quad for\ I_c \leq 1.64$$

$$K_c = -0.403 I_c^4 + 5.581 I_c^3 - 21.63 I_c^2 + 33.75 I_c - 17.88 \quad for\ I_c > 1.64 \tag{41}$$

$$q_{c1Ncs} = K_c q_{c1N} \tag{42}$$

4. Calculate CRR based on Robertson and Wride (1997).

$$CRR_{7.5} = 0.833 \left[\frac{q_{c1Ncs}}{1000}\right] + 0.05 \quad if\ q_{c1Ncs} < 50$$

$$CRR_{7.5} = 93 \left[\frac{q_{c1Ncs}}{1000}\right]^3 + 0.08 \quad if\ 50 \leq q_{c1Ncs} < 160 \tag{43}$$

7.1.1. Calculating Ic

The soil behavior type index, I_c, is calculated using the following equation:

$$I_c = \left[(3.47 - \log(Q))^2 + (1.22 + \log(F))^2\right]^{0.5} \tag{44}$$

where

$$F = \left[\frac{f_s}{q_c - \sigma_{vo}}\right] * 100\% \tag{45}$$

$$Q = \left[\frac{q_c - \sigma_{vo}}{P_a}\right]\left[\left(\frac{P_a}{\sigma'_{vo}}\right)^n\right] \tag{46}$$

The recommended procedure for calculating the soil behavior type index is iterative, as outlined in the NCEER summary report (Robertson and Wride, 1997).

1. Assume n=1.0 and calculate Q using the following equation.

   $$Q = \left[\frac{q_c - \sigma_{vo}}{P_a}\right)\left[\left(\frac{P_a}{\sigma'_{vo}}\right)^{1.0}\right] = \left[\frac{q_c - \sigma_{vo}}{\sigma'_{vo}}\right] \tag{47}$$

   Calculate I_c using the equation in the previous section.

2. If $I_c > 2.6$ (or the user-defined $I_{c,max}$), the soil is clayey and not susceptible to liquefaction.
3. If $I_c < 2.6$ (or the user-defined $I_{c,max}$), recalculate Q using n = 0.5, and recalculate I_c.
4. If $I_c < 2.6$ (or the user-defined $I_{c,max}$), the soil is non-plastic and granular. No further calculation is required.
5. If $I_c > 2.6$ (or the user-defined $I_{c,max}$), the soil is probably silty. Calculate q_{c1N} using the equations below, with n = 0.7 in the equation for C_Q.

   $$q_{c1N} = C_Q\left(\frac{q_c}{P_a}\right) \leq 254 \tag{48}$$

   $$C_Q = \left(\frac{P_a}{\sigma'_{v0}}\right)^n \leq 1.7 \tag{49}$$

6. Calculate I_c using the q_{c1N} value calculated in (5).

7.2. Modified Robertson and Wride (1998)

The following methods are employed in Modified Robertson and Wride (1998):

1. Calculate I_c using the procedure outlined in Robertson and Wride (1998).
2. Calculate q_{c1N} using the n value from the I_c calculation.
3. Calculate q_{c1Ncs}, with K_c calculated based on Robertson and Wride (1998). Depths with $q_{c1Ncs} \geq 160$ are considered not liquefiable.

$$K_c = 0 \quad for\ FC \leq 5\%$$

$$K_c = 0.0267(FC - 5) \quad for\ 5 < FC < 35\%$$

$$K_c = 0.8 \quad for\ FC \geq 35\%$$

50

$$\Delta q_{c1N} = \frac{K_c}{1 - K_c} q_{c1N}$$

51

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N}$$

52

4. Calculate CRR based on Robertson and Wride (1997).

$$CRR_{7.5} = 0.833 \left[\frac{q_{c1Ncs}}{1000}\right] + 0.05 \quad if\ q_{c1Ncs} < 50$$

53

$$CRR_{7.5} = 93 \left[\frac{q_{c1Ncs}}{1000}\right]^3 + 0.08 \quad if\ 50 \leq q_{c1Ncs} < 160$$

54

7.2.1. Calculating Ic

The recommended procedure for calculating the soil behavior type index is iterative, as outlined in Robertson and Wride (1998).

1. Assume n=1.0 and calculate Q and I_c as outlined in Section 7.1.1. If $I_c > 2.6$ then the point is considered not liquefiable.

2. If $I_c \leq 2.6$, calculate q_{c1N} using n=0.5, and recalculate I_c using q_{c1N}.

3. If the recalculated $I_c \leq 2.6$, the value of I_c calculated with n=0.5 is used. If I_c iterates around 2.6 depending on n, then use n=0.75 to calculate q_{c1N} and I_c.

7.3. Idriss and Boulanger (2004)

The following methods are employed in the Idriss and Boulanger (2004) triggering method:

1. Calculate q_{c1N} according to Idriss and Boulanger (2004) iterative procedure.
2. Calculate K_c, based on Idriss and Boulanger (2004).

$$C_\sigma = \frac{1}{37.3 - 8.27(q_{c1N})^{0.264}} \leq 0.3; \quad q_{c1N} \leq 211$$

55

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma'_{vo}}{P_a}\right) \leq 1.0$$

56

3. Calculate q_{c1Ncs}, based on Idriss and Boulanger (2004).

$$\Delta q_{c1N} = \left(5.4 + \frac{q_{c1N}}{16}\right) \exp\left(1.63 + \frac{9.7}{FC + 0.01} - \left(\frac{15.7}{FC + 0.01}\right)^2\right)$$

57

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N}$$ **58**

4. Calculate CRR based on Idriss and Boulanger (2004).

$$CRR_{M=7.5,\sigma'_{vc}=1} = \exp\left(\frac{q_{c1Ncs}}{540} + \left(\frac{q_{c1Ncs}}{67}\right)^2 - \left(\frac{q_{c1Ncs}}{80}\right)^3 + \left(\frac{q_{c1Ncs}}{114}\right)^4 - 3\right)$$

59

7.3.1. Calculating q_{c1N}

The following iterative procedure is used to calculate q_{c1N}:

1. Calculate q_{c1N} using n=1.0.
2. Recalculate q_{c1N} using the following equation for n:

$$n = 1.338 - 0.249(q_{c1N})^{0.264}$$ **60**

A total of 100 iterations are performed, after which the last calculated value of q_{c1N} is used.

7.4. Idriss and Boulanger (2014)

The following methods are employed in the Idriss and Boulanger (2014) triggering method:

1. Calculate $q_{cN} = q_t/P_a$.

$$q_t = q_c + u_2(1 - a)$$ **61**

where *a* is the cone area ratio.

$$q_{cN} = \frac{q_t}{P_a}$$

62

2. Calculate q_{c1Ncs} according to Idriss and Boulanger (2008). This is an iterative procedure, as outlined below.

$$C_N = \left(\frac{P_a}{\sigma'_v}\right)^m \leq 1.7$$

$$m = 1.338 - 0.249(q_{c1Ncs})^{0.264} \tag{63}$$

$$q_{c1N} = C_N q_{cN} \tag{64}$$

$$\Delta q_{c1N} = \left(11.9 + \frac{q_{c1N}}{14.6}\right) \exp\left(1.63 - \frac{9.7}{FC + 2} - \left(\frac{15.7}{FC + 2}\right)^2\right) \tag{65}$$

$$q_{c1Ncs} = q_{c1N} + \Delta q_{c1N} \tag{66}$$

3. Calculate K_σ according to Idriss and Boulanger (2014).

$$C_\sigma = \frac{1}{37.3 - 8.27(q_{c1Ncs})^{0.264}} \leq 0.3 \tag{67}$$

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma_v'}{P_a}\right) \leq 1.1 \tag{68}$$

4. Calculate CRR based on Idriss and Boulanger (2014).

$$CRR_{M=7.5,\sigma_v'=1atm} = \exp\left(\frac{q_{c1Ncs}}{113} + \left(\frac{q_{c1Ncs}}{1000}\right)^2 - \left(\frac{q_{c1Ncs}}{140}\right)^3 + \left(\frac{q_{c1Ncs}}{137}\right)^4 - 2.80\right) \tag{69}$$

7.5. Moss et al. (2006) – Deterministic

The following methods are employed in the deterministic Moss et al. (2006) triggering method:

1. Calculate q_{c1}, with c calculated according to the method outlined in Moss et al. (2006).

$$c = f_1 \left(\frac{R_f}{f_3}\right)^{f_2} \tag{70}$$

$$R_f = \left(\frac{f_s}{q_c - \sigma_v}\right) \cdot 100$$

$$f_1 = x_1 \cdot q_c^{x_2}$$

$$f_2 = -\left(y_1 \cdot q_c^{y_2} + y_3\right)$$

$$f_3 = abs(\log(10 + q_c))^{z_1}$$

where

$$x_1 = 0.78; x_2 = -0.33; y_1 = -0.32; y_2 = -0.35; y_3 = 0.49; z_1 = 1.21$$

$$q_{c1} = C_q \cdot q_c$$

$$C_q = \left(\frac{P_a}{\sigma'_v}\right)^c \leq 1.7$$

2. Calculate CRR according to Moss et al. (2006), based on a 50% probability of liquefaction.

$$\begin{aligned} CRR = \exp\{\big[q_{c,1}^{1.045} + q_{c,1}\big(0.110 \cdot R_f\big) + \big(0.001 \cdot R_f\big) + c\big(1 + 0.850 \cdot R_f\big) - 0.848 \cdot \ln(M_w) - 0.002 \\ \cdot \ln(\sigma'_v) - 20.923 + 1.632 \cdot \Phi^{-1}(P_L)\big]/7.177\} \end{aligned} \tag{71}$$

7.6. Moss et al. (2006) – Probabilistic

The following methods are employed in the probabilistic Moss et al. (2006) triggering method:

1. Calculate q_{c1}, with c calculated according to the method outlined in Moss et al. (2006). The calculations are outlined in the section above.
2. Calculate P_L according to Moss et al. (2006), based on the user-defined Factor of Safety, or calculate CRR based on the user-defined probability of liquefaction. The CRR calculation method is outlined above.

$$P_L = \Phi\{-\left(\frac{\begin{gathered} q_{c,1}^{1.045} + q_{c,1}\big(0.110 \cdot R_f\big) + \big(0.001 \cdot R_f\big) + c\big(1 + 0.850 \cdot R_f\big) - 7.177 \cdot \ln(CSR) \\ -0.848 \cdot \ln(M_w) - 0.002 \cdot \ln(\sigma'_v) - 20.923 \end{gathered}}{1.632}\right) \tag{72}$$

8. Shear Wave Velocity (V_S) Based Calculations

The magnitude scaling factor (MSF) and stress reduction factor (r_d) equations are the same as for CPT and SPT. These equations can be found in sections 4 and 5.

The following methods are available in *Settle3D* for determining triggering of liquefaction based on shear wave input:

- Andrus (2004)
- NCEER (1997)
- Juang et al. (2001) Probabilistic

Before triggering, the input v_s value is normalized to v_{s1} as follows:

$$V_{s1} = V_s \left(\frac{P_a}{\sigma_v'}\right)^{0.25}$$

73

8.1. Andrus (2004)

The following methods are employed in the Andrus (2004) triggering method:

1. Calculate V_{s1cs} using the formulation for K_{fc} from Juang et al.
2. Calculate CRR according to Andrus (2004).

$$CRR_{7.5} = 0.022\left[\frac{V_{s1cs}}{100}\right]^2 + 2.8\left[\frac{1}{215 - V_{s1cs}} - \frac{1}{215}\right]$$

74

You can also account for an overburden correction factor. The Idriss and Boulanger (2004) equation is as follows:

$$K_\sigma = 1 - C_\sigma \ln\left(\frac{\sigma_v'}{P_a}\right) \le 1.1$$

$$C_\sigma = \frac{1}{18.9 - 3.1(V_{s1cs}/100)^{1.976}} \le 0.3$$

75

8.2. NCEER (1997)

The following methods are employed in the NCEER method:

1. Calculate CRR according to NCEER recommendations.

$$CRR = a\left(\frac{V_{s1}}{100}\right)^2 + \frac{b}{V_{s1c} - V_{s1}} - \frac{b}{V_{s1c}} \qquad 76$$

   where $a = 0.03$ and $b = 0.9$, and

   V_{s1cs} = 220 for FC < 5%
   V_{s1cs} = 210 for FC < 35%
   V_{s1cs} = 200 for all other FC values

2. Calculate V_{s1cs} according to Juang et al, and calculate K_σ if desired.

8.3. Juang et al. (2001) Probabilistic

The Juang et al. (2001) method is outlined below:

1. Calculate V_{s1cs}.

$$V_{s1cs} = K_{fc}V_{s1} \qquad 77$$

   where

   $K_{fc} = 1$, for $FC \leq 5\%$
   $K_{fc} = 1 + T(FC - 5)$ for $5 < FC < 35\%$
   $K_{fc} = 1 + 30T$ for $FC \geq 35\%$

$$T = 0.009 - 0.0109\left(\frac{V_{s1}}{100}\right) + 0.0038\left(\frac{V_{s1}}{100}\right)^2$$

2. Calculate P_L based on the user-defined Factor of Safety, or calculate CRR based on the user-defined probability of liquefaction.

$$\ln\left[\frac{P_L}{1 - P_L}\right] = 14.8967 - 0.0611V_{s1cs} + 2.6418\ln(CSR) \qquad 78$$

If the P_L is calculated, no further calculations are performed. If FS is being calculated based on the CRR, then K_σ can be calculated.

9. Post-Liquefaction Lateral Displacement

The post-liquefaction lateral spreading is calculated by integrating the maximum shear strain values over depth.

$$LDI = \int_0^{z_{max}} \gamma_{max} \cdot dz \quad \textbf{79}$$

9.1. Ground Profile

Zhang et al. (2004) proposed a method for estimating liquefaction-induced lateral displacements based on the ground slope and/or free face height and distance to a free face.

For a gently sloping ground without a free face:

$$LD = (S + 0.2) \cdot LDI$$
$$for\ 0.2\% < S < 3.5\% \quad \textbf{80}$$

$$LD = 6 \cdot \left(\frac{L}{H}\right)^{-0.8} \cdot LDI$$
$$for\ 4 < L/H < 40 \quad \textbf{81}$$

9.2. SPT γ_{max} Methods

The following methods are available for calculating the maximum shear strain, when SPT data is used:

- Zhang, Robertson, and Brachman (2004)
- Tokimatsu and Yoshimi (1983)
- Shamato et al. (1998)
- Wu et al. (1993)
- Cetin et al. (2009)

9.2.1. Zhang, Robertson, and Brachman (2004)

In this method, the relative density (D_r) is first calculated based on the method selected by the user.

The curves shown in the figure below are interpolated to determine the correct maximum shear strain.

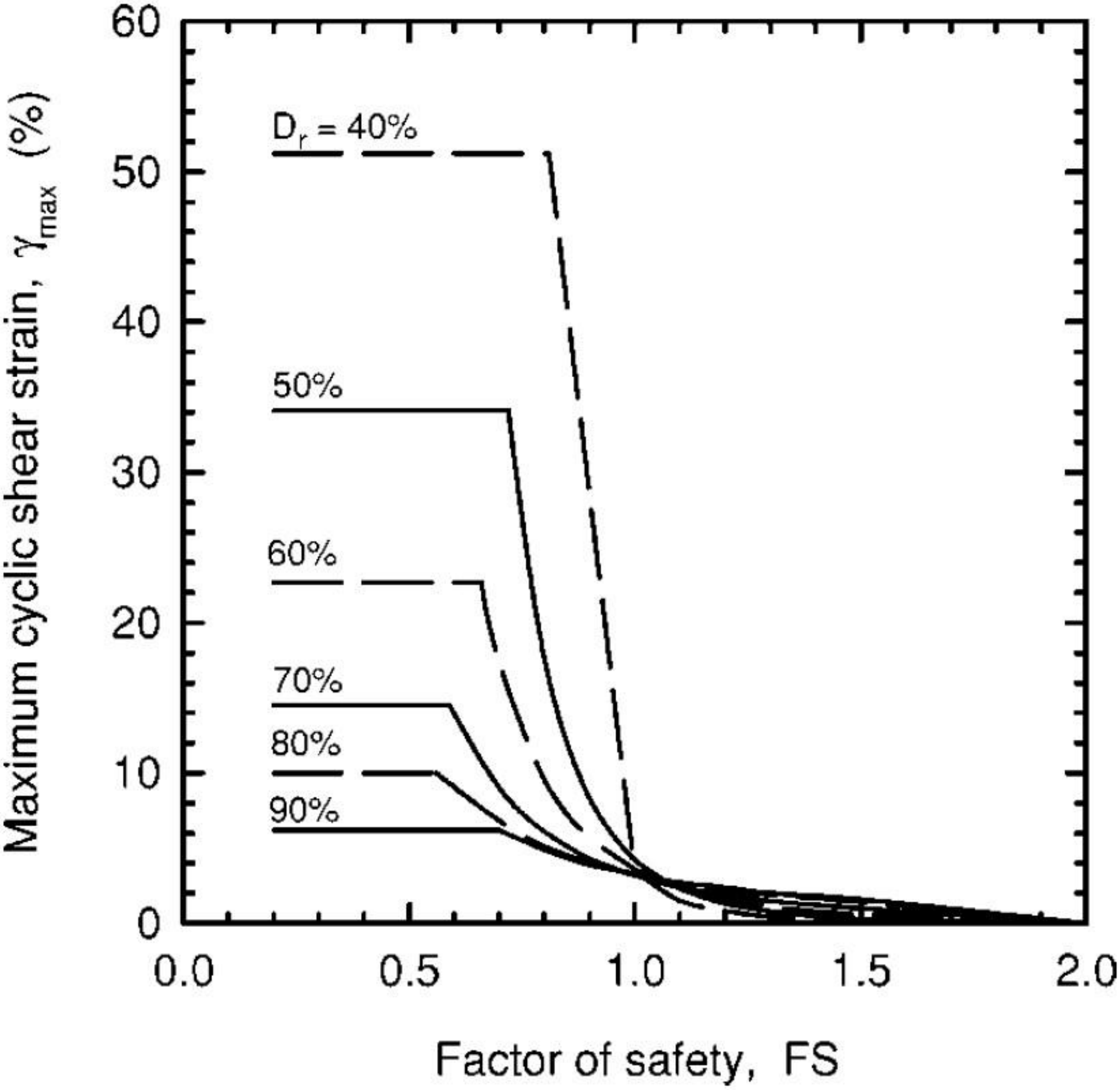

Figure 8: Relationship between maximum cyclic shear strain and factor of safety for different relative densities

9.2.2. Tokimatsu and Yoshimi (1983)

The curves shown below are interpolated to determine the correct maximum shear strain.

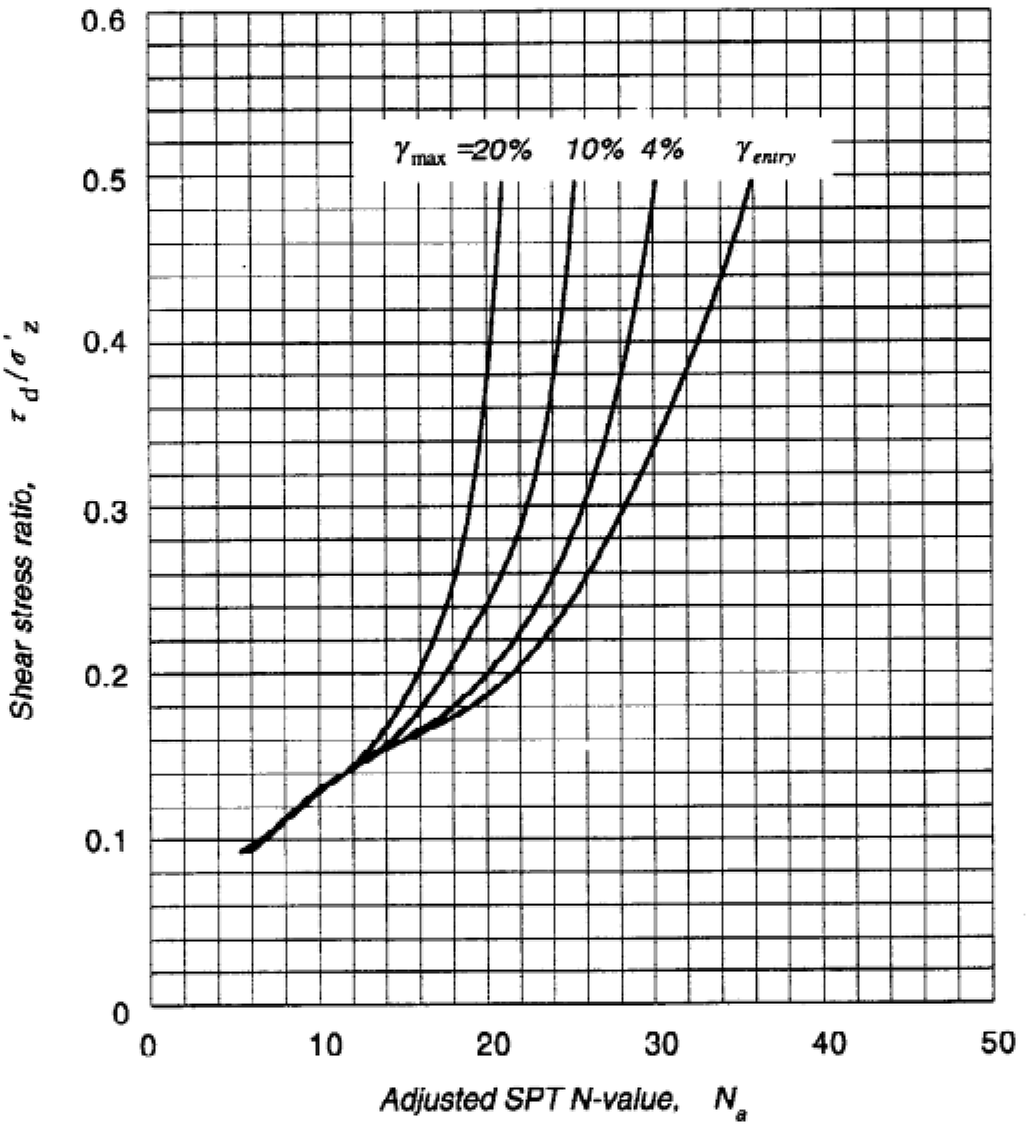

Figure 9: Shear strain induced by earthquake shaking

9.2.3. Shamoto et al. (1998)

For this method, one of three graphs is used to interpolate the maximum shear strain.

For FC < 10%, the graph below is used.

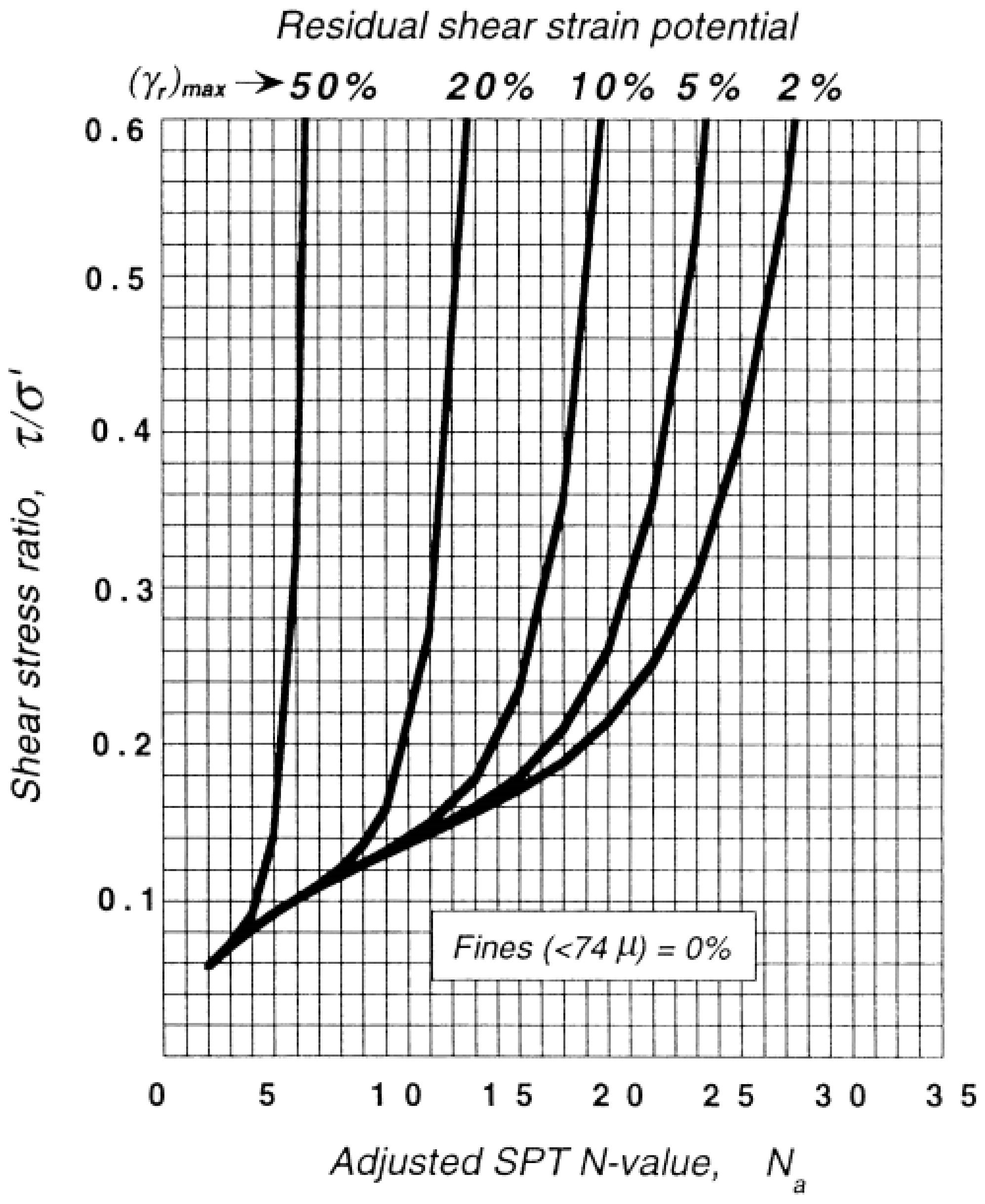

Figure 10: Relationship between normalized SPT-N value and shear strain potential for clean sands

For FC < 20%, the graph below is used.

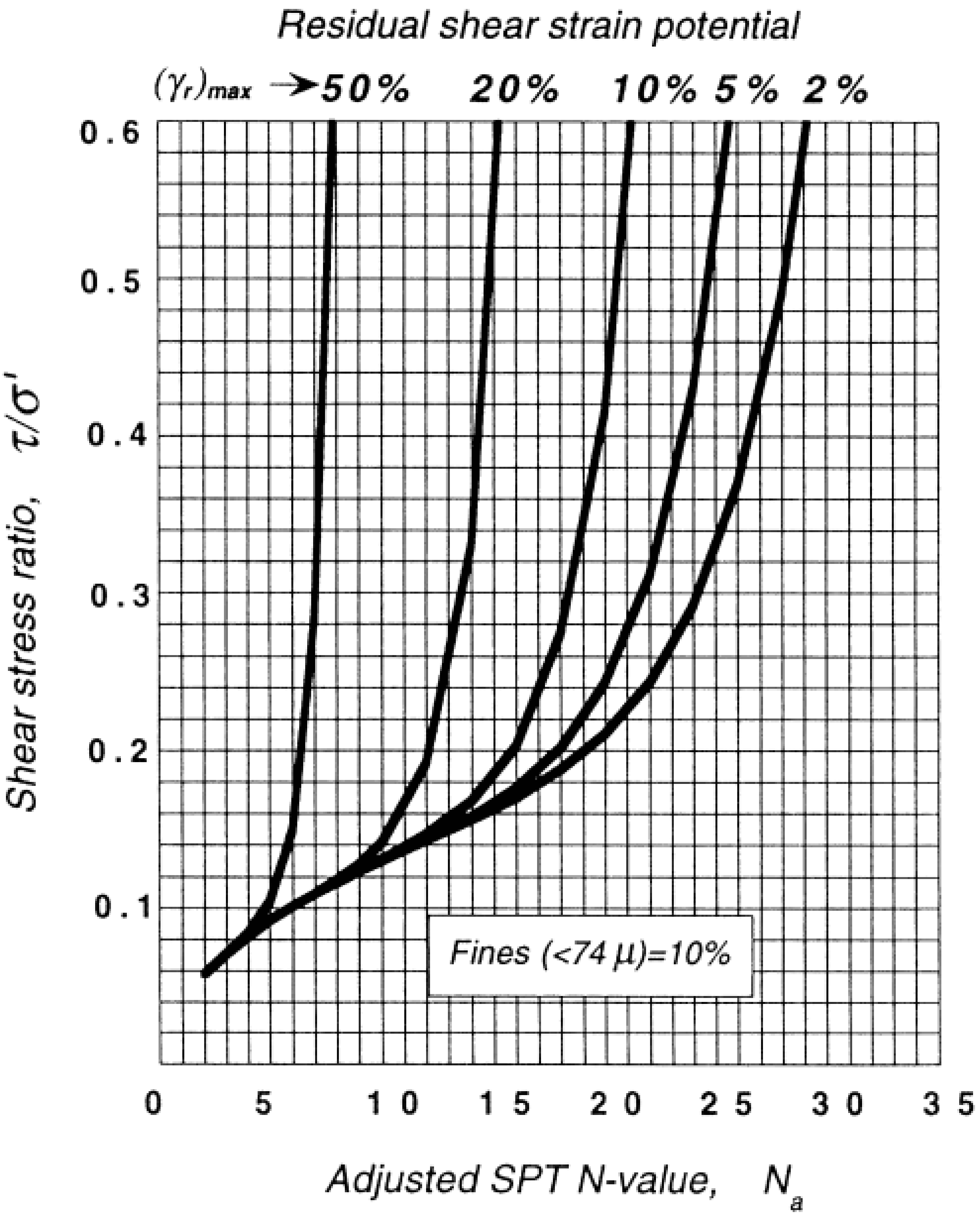

Figure 11: Relationship between normalized SPT-N value and shear strain potential for the case of FC=10%

For FC > 20%, the graph below is used.

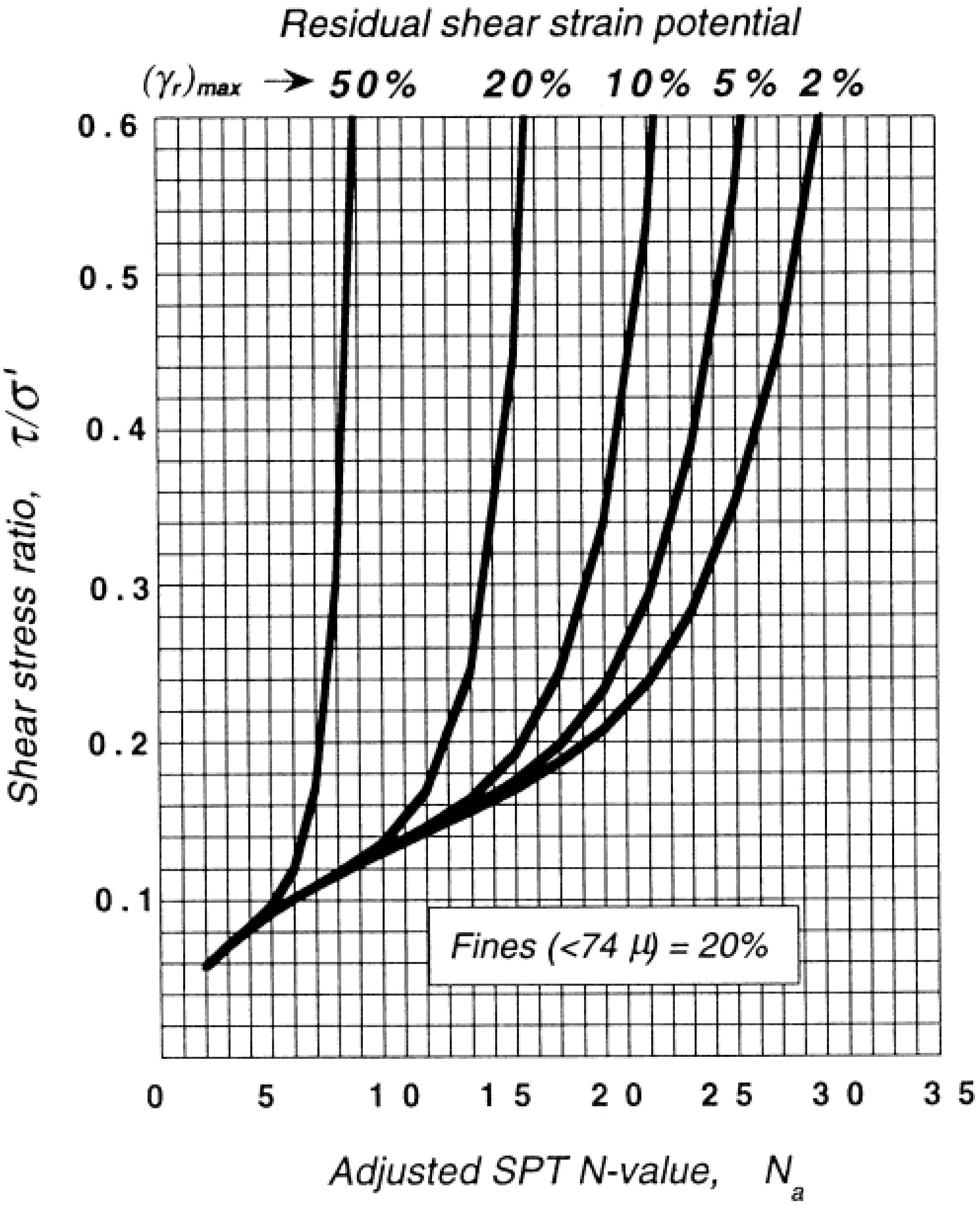

Figure 12: Relationship between normalized SPT-N value and shear strain potential for the case of FC=20%

9.2.4. Wu et al. (2003)

The graphs below are interpolated to find the maximum shear strain.

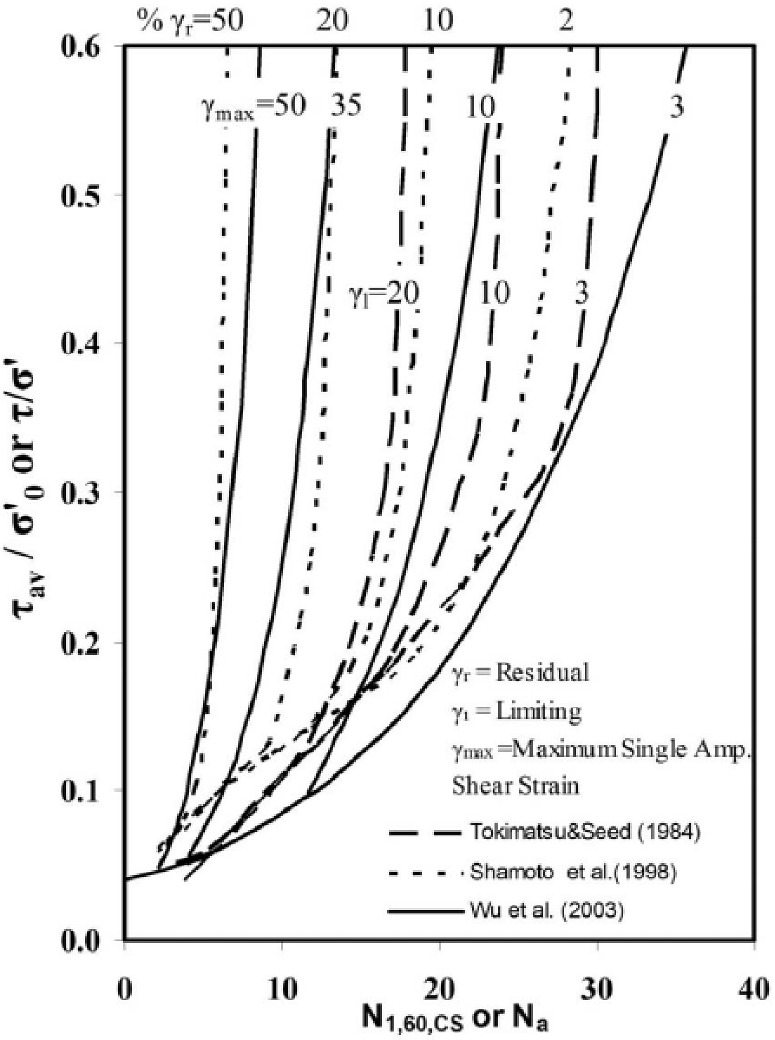

Figure 13: Estimation of cyclically induced deviatoric strains

9.2.5. Cetin et al. (2009)

The steps for calculating the maximum shear strain according to Cetin et al. (2009) are outlined below.

1. Calculate K_σ according to Hynes and Olsen (1999). The formula can be found in Section 6.6.
2. Calculate the relative density, D_r, according to the method selected by the user.
3. Calculate K_{mc}.

$$K_{mc} = -3 \times 10^{-5} \cdot D_R^2 + 0.0048 D_R + 0.7222 \tag{82}$$

4. Calculate $CSR_{ss201D1}$.

$$CSR_{ss,20,1,D,1} = CSR \cdot K_{\sigma} \cdot K_{mc} \tag{83}$$

5. Calculate γ_{max}.

$$\gamma_{max} = \frac{-0.025N_{160cs} + \ln\left(CSR_{ss,20,1,D,1}\right) + 2.613}{0.004N_{160cs} + 0.001} \tag{84}$$

where

$5 \leq N_{160cs} \leq 40; \text{and } 0.05 \leq CSR_{ss,20,1,D,1} \leq 0.6$

9.3. CPT γ_{max} Methods

The following methods are available for calculating the maximum shear strain, when CPT data is used:

- Zhang, Robertson, and Brachman (2004)
- Yoshimine (2006)

9.3.1. Zhang, Robertson, and Brachman (2004)

The relative density is first calculated according to Tatsuoka et al. (1990).

$$D_r = -85 + 76\log(q_{c1N}) \tag{85}$$

where $q_{c1N} \leq 200$.

The graph below is then used to determine γ_{max}.

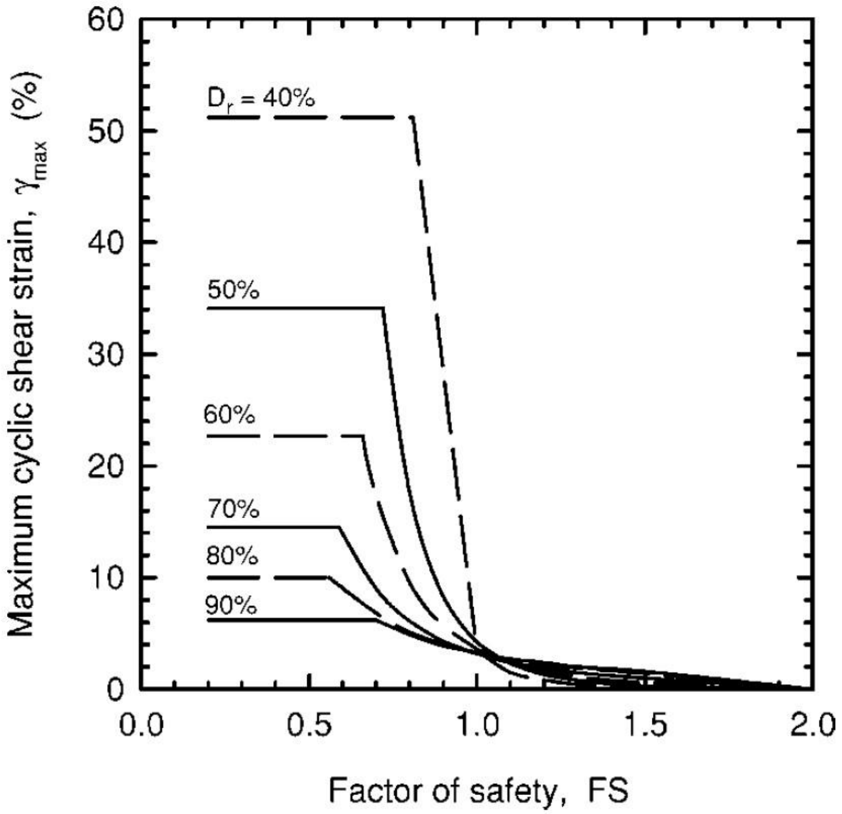

Figure 14: Relationship between maximum cyclic shear strain and factor of safety for different relative densities

9.3.2. Yoshimine et al. (2006)

The Yoshimine et al. (2006) method is based on F_α and a limiting shear strain.

$$F_\alpha = -11.74 + 8.34(q_{c1Ncs})^{0.264} - 1.371(q_{c1Ncs})^{0.528}$$ **86**

where $q_{C1nCS} \geq 69$.

$$\gamma_{lim} = 1.859(2.163 - 0.478(q_{c1Ncs})^{0.264})^3 \geq 0$$ **87**

The maximum shear strain is calculated as follows.

$$\gamma_{max} = \gamma_{lim} \;\; if \; FS < F_\alpha$$

$$\gamma_{max} = \min\left(\gamma_{lim}, 0.035(2 - FS)\left(\frac{1 - F_\alpha}{FS - F_\alpha}\right)\right)$$

88

9.4. VST γ_{max} Methods

The F_α and γ_{lim} expressions from Yoshimine et al. (2006) and Idriss and Boulanger (2008) were adapted for shear wave velocity by Yi (2010).

$$F_\alpha = 0.032 + 0.836\left(\frac{V_{s1cs}}{100}\right)^{1.976} - 0.190\left(\frac{V_{s1cs}}{100}\right)^{3.952}$$

89

where $V_{s1cs} \geq 150$ m/s.

$$\gamma_{lim} = \min\left[0.5, 7.05\left(\frac{V_{s1cs}}{100}\right)^{-5.53}\right] \geq 0$$

90

γ_{max} is calculated as follows:

$$\gamma_{max} = \gamma_{lim} \;\; if\; FS < F_\alpha$$

$$\gamma_{max} = \min\left(\gamma_{lim}, 0.035(2 - FS)\left(\frac{1 - F_\alpha}{FS - F_\alpha}\right)\right)$$

91

10. Post-Liquefaction Reconsolidation Settlement

The post-liquefaction settlement is calculated by integrating the volumetric strain values over depth.

$$S = \int_0^{z_{max}} \epsilon_v \cdot dz \tag{92}$$

10.1. SPT ϵ_v Methods

The following methods are available for calculating ϵ_v when SPT data is used:

- Ishihara and Yoshimine (1992)
- Tokimatsu and Seed (1984)
- Shamato (1984)
- Wu et al. (2003)
- Cetin et al. (2009)

10.1.1. Ishihara and Yoshimine (1992)

The following formulation is used to calculate the volumetric strain:

$$\epsilon_v = 1.5 \cdot \exp(-2.5D_R) \cdot \min(0.08, \gamma_{max}) \tag{93}$$

where D_R is calculated according to the method specified by the user, and γ_{max} is calculated according to Zhang, Robertson, and Brachman (2004).

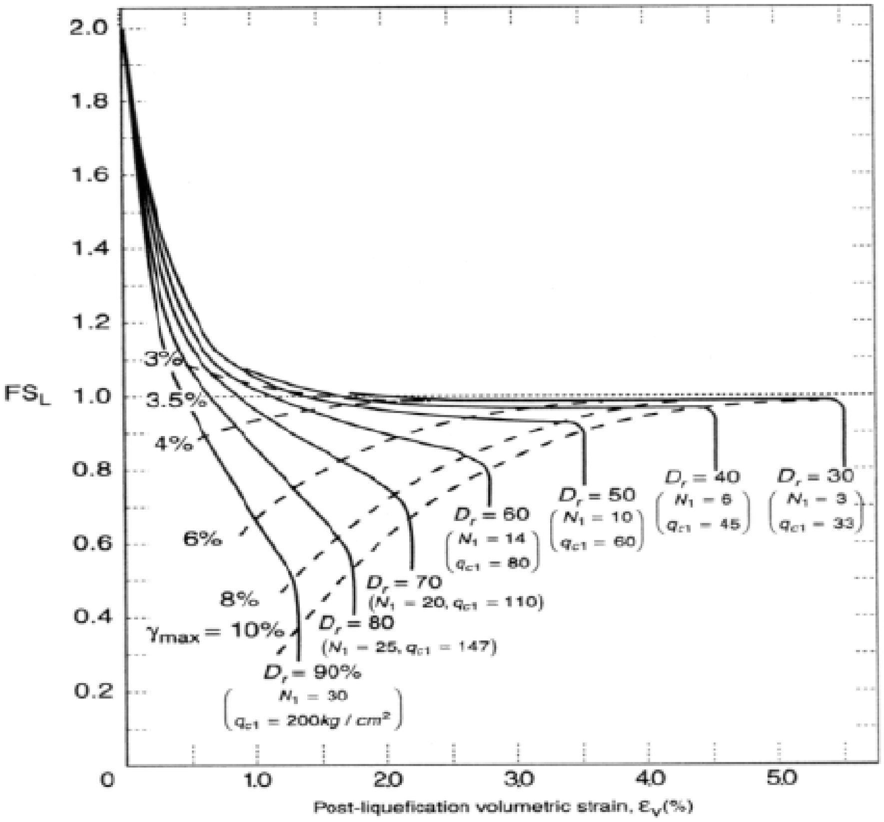

Figure 15: Ishihara and Yoshimine (1992) method for predicting volumetric and shear strain

10.1.2. Tokimatsu and Seed (1984)

The figure below is used to interpolate a value of ϵ_v.

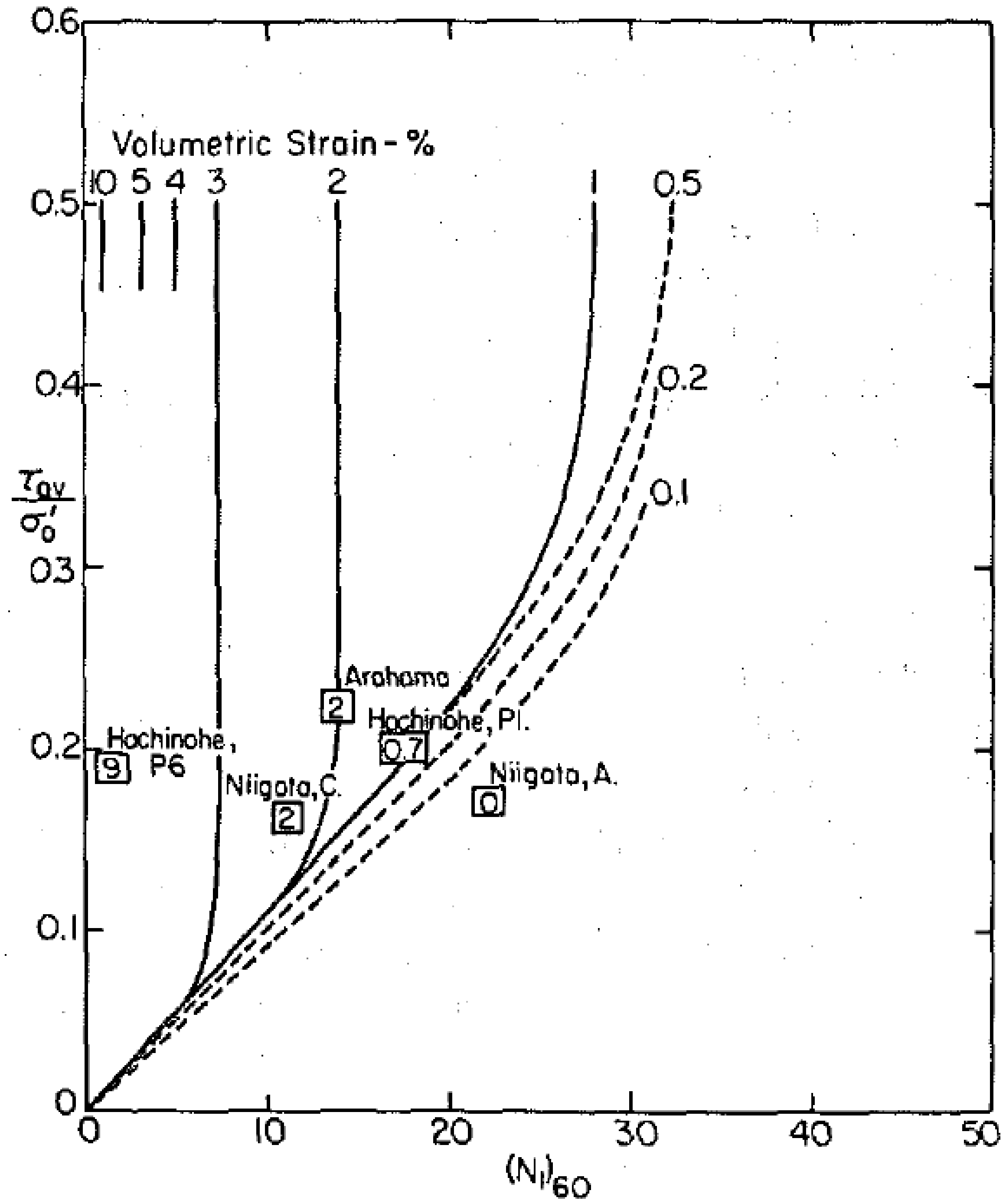

Figure 16: Relationship between CSR, N160, and volumetric strain

10.1.3. Shamoto (1984)

One of three graphs is used to find ϵ_v.

For FC<10%:

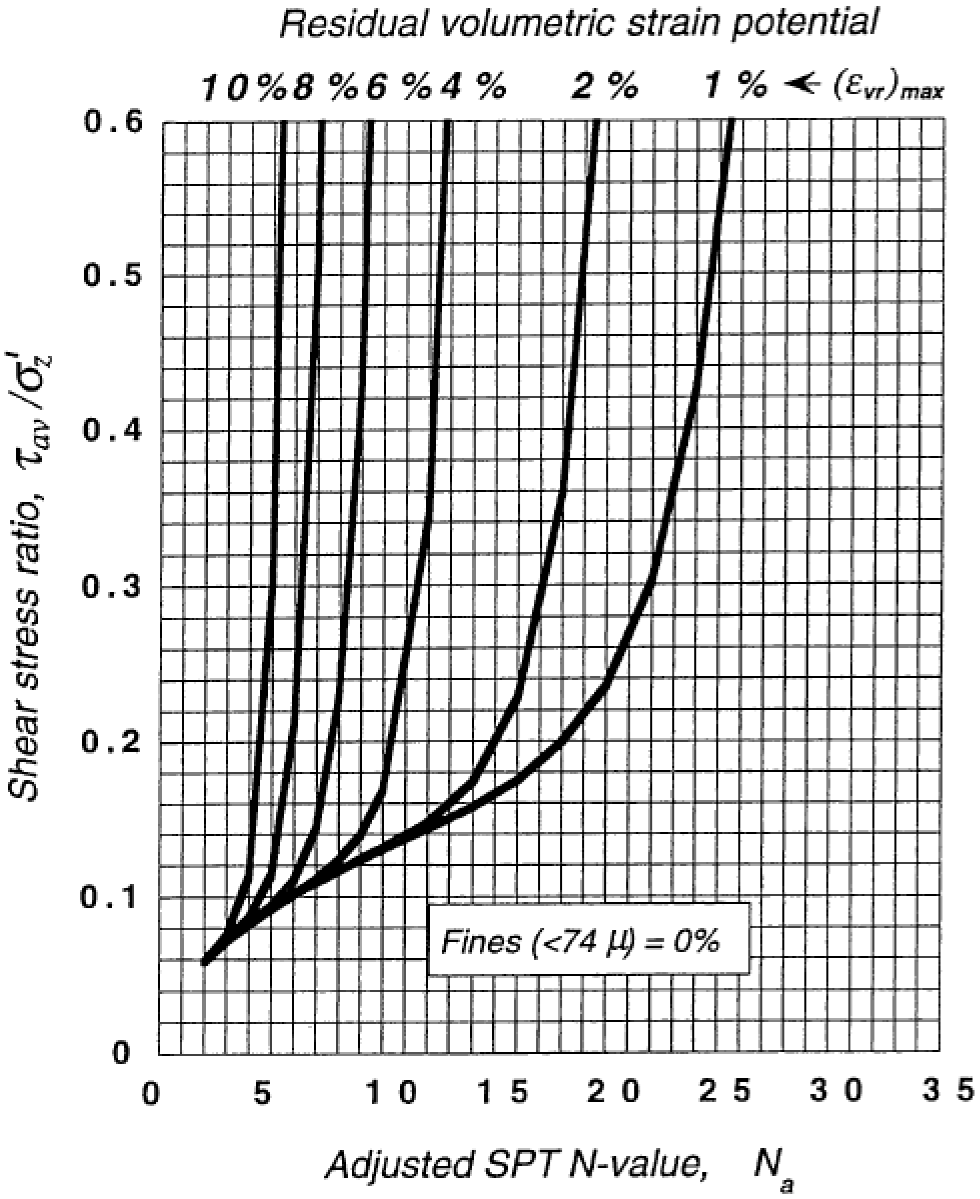

Figure 17: Relationship between normalized SPT-N, dynamic shear stress ratio, and volumetric strain for clean sands

For FC<20%:

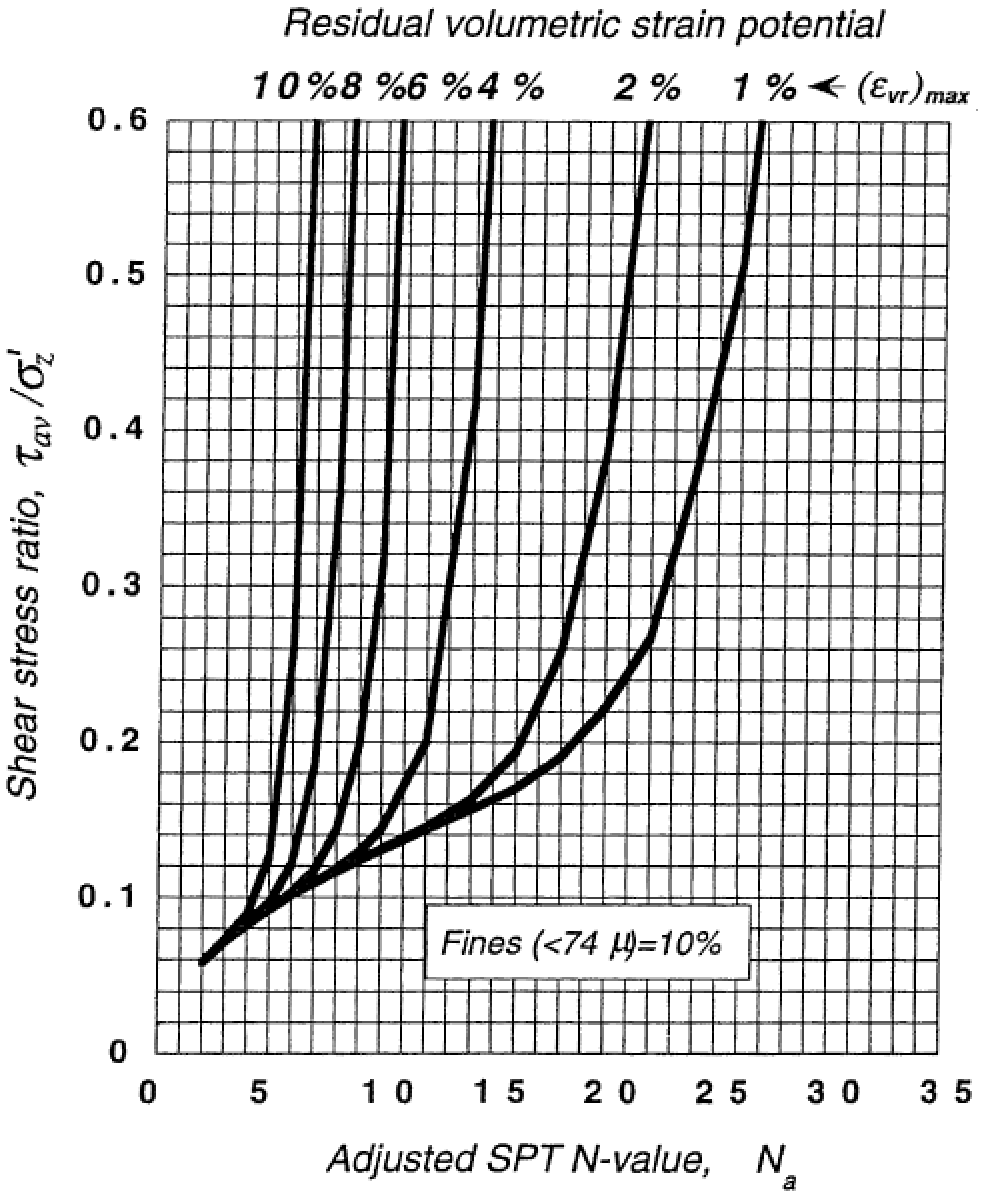

Figure 18: Relationship between normalized SPT-N, dynamic shear stress ratio, and volumetric strain for FC=10%

For other fine content values:

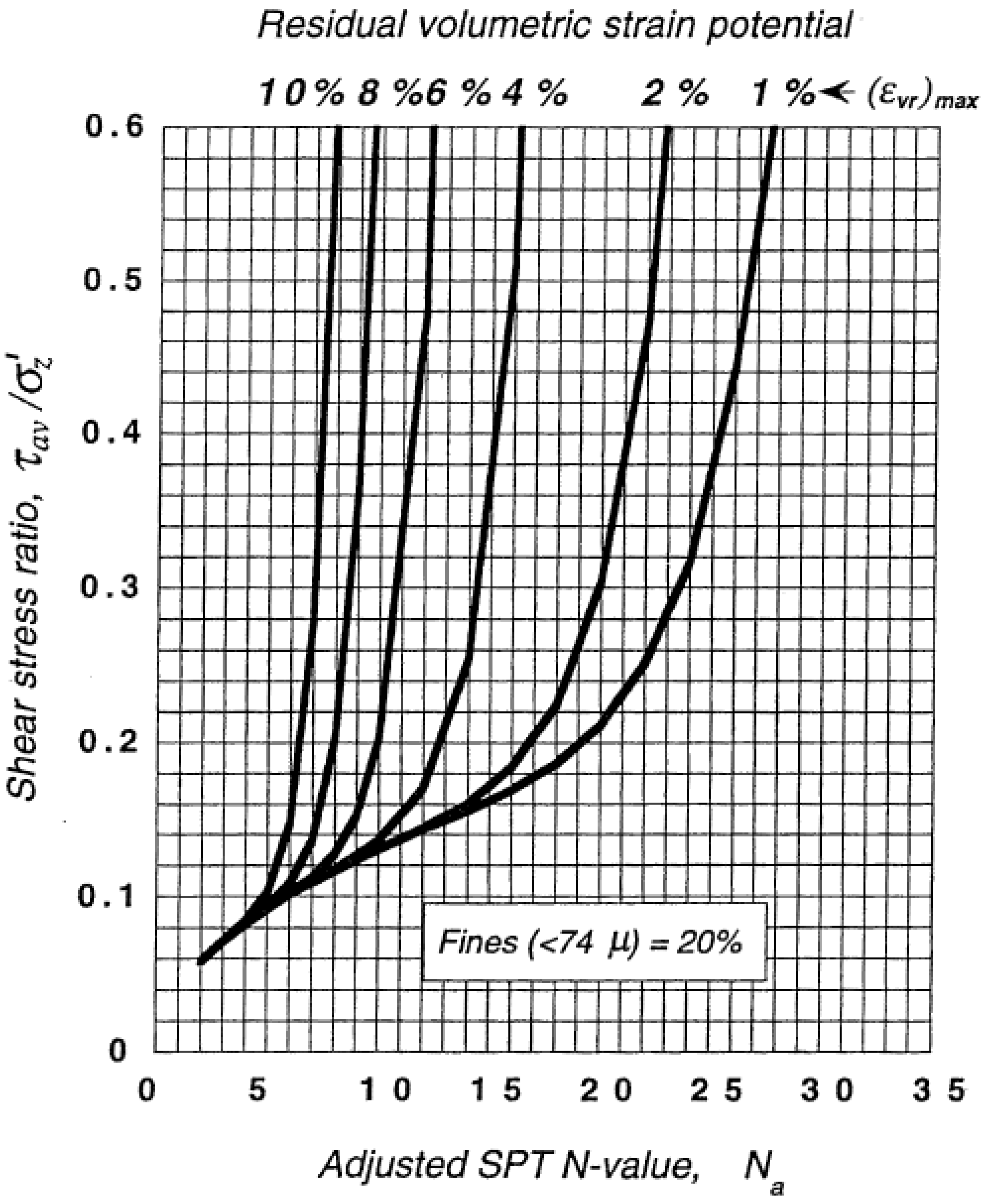

Figure 19: Relationship between normalized SPT-N, dynamic shear stress ratio, and volumetric strain for FC=20%

10.1.4. Wu et al. (2003)

The following graph is used to find ϵ_v.

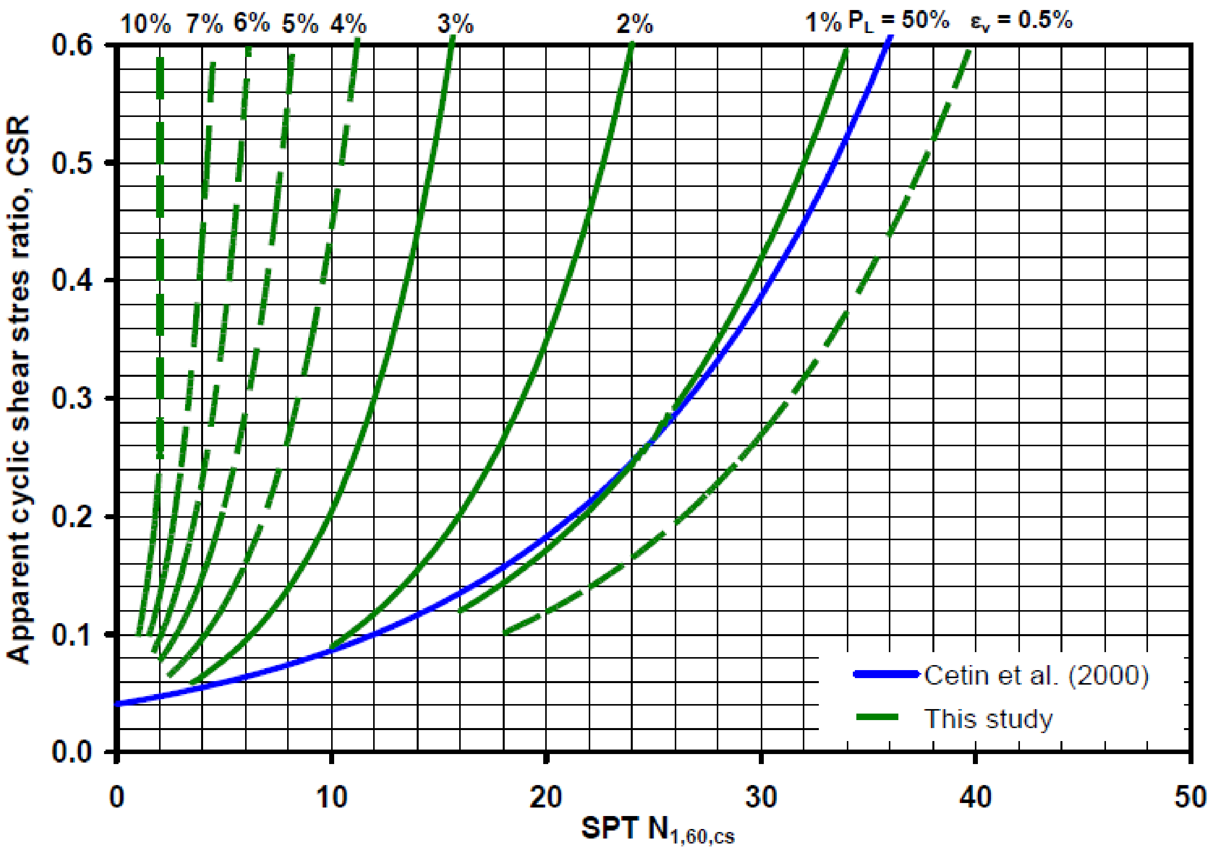

Figure 20: Correlations between CSR, N160cs, and reconsolidation volumetric strain (Wu et al., 2003)

10.1.5. Cetin et al. (2009)

The Cetin et al. (2009) method incorporates a depth factor. With the depth factor, the contribution of layers to settlement at the surface decreases as the depth of the layer increases, and beyond a certain depth (z_{cr}) the settlement of an individual layer cannot be traced at the ground level. It was determined that the threshold depth is 18m.

The steps for calculating the maximum shear strain according to Cetin et al. (2009) are outlined below:

1. Calculate K_σ according to Hynes and Olsen (1999).
2. Calculate relative density, D_r, according to the method selected by the user.
3. Calculate K_{mc}, and $CSR_{ss,20,1,D,1}$.

$$K_{mc} = -3 \times 10^{-5} \cdot D_R^2 + 0.0048 D_R + 0.7222$$

$$CSR_{ss,20,1,D,1} = CSR \cdot K_\sigma \cdot K_{mc}$$

94

4. Calculate the critical depth factor, DF.

$$DF = 1 - \frac{z}{z_{critical}}$$

95

where $z_{critical} = 18\,m$.

5. Calculate ϵ_v, corrected for depth.

$$\epsilon_{v0} = 1.879 \ln\left(\frac{780.416 \ln\left(CSR_{ss,20,1,D,1}\right) - N_{160cs} + 2442.465}{636.613 N_{160cs} + 306.732}\right) + 5.583$$

96

$$\epsilon_v = DF \cdot \epsilon_{v0}$$

97

where the following limits apply:

$5 \leq N_{160cs} \leq 40; 0.05 \leq CSR_{ss,20,1,D,1} \leq 0.60; 0\% \leq \epsilon_v \leq 5\%$

Note that it is left to the user to determine the normalized settlement.

10.1.6. Dry Sand settlement, Pradel (1998)

Procedure to evaluating earthquake induced settlement in dry sandy soils (Pradel, 1998) in Settle3 is explained by the following steps.

1. Determination of cyclic shear stress

Cyclic strains are induced in the ground during an earthquake. The following expression proposed by Seed and Idriss (1971) shows average cyclic shear stress which is a good approximation of dry sand deposits.

$$\tau_{av} = 0.65 * \frac{a_{max}}{g} * \rho * z * \frac{1}{1 + \left(\frac{z}{z_0}\right)^2}$$

98

Where ρ is the unit weight of the material, z is the depth of soil layer, and z_0 is a constant which equals to 30.5m (100 ft).

2. Maximum shear modulus

The maximum shear modulus is obtained by field and laboratory tests. Gmax can be approximated by the standard penetration test using examples provided by Seed and Idriss (1970)

$$G_{max} = 447 * p_0 * (N_1)^{\frac{1}{3}} * \sqrt{\frac{p}{p_0}}$$

99

Where p is the average stress,

p_0 is a reference stress = 1 tsf (95.76 kPa),

N_1 is the SPT N value normalized to effective overburden of 1 tsf (95.76 kPa), effective of 60% of free-fall energy.

For a dry sand with friction angle of 30^0, the lateral stress coefficient of at-rest pressures, K_0 is approximately 0.5. The average stress p then can be approximated by:

$$p = \left(\frac{1 + 2 * K_0}{3}\right) * p * z = 0.67 * p * z$$

3. Cyclic shear strain

The cyclic shear strain induced in the soil can be determined by:

$$\gamma = \frac{\tau_{av}}{G_{max} * \left(\frac{G}{G_{max}}\right)}$$

100

Where G_{max} can be obtained from Seed and Idriss (1970):

$$G_{max} = 447 * p_0 * (N_1)^{\frac{1}{3}} * \sqrt{\frac{p}{p_0}}$$

101

However, this cyclic shear strain requires iteration process in obtaining equivalent shear modulus until shear modulus curve reaches previously assumed strain. Thus, estimate of shear strain obtained from experimental study by Iwasaki et al (1978) is used:

$$\gamma = \frac{\left(1 + a * e^{b} * \frac{\tau_{av}}{G_{max}}\right)}{1 + a}$$

102

Where $a = 0.0389 * \left(\frac{p}{p_0}\right) + 0.124$

$b = 6400 * \left(\frac{p}{p_0}\right)^{-0.6}$

Note the use of different G/G$_{max}$ versus γ curve may result in significantly different settlement prediction.

4. Volumetric strain

ε_{15} is the 15 equivalent uniform strain cycle (N=15) which corresponds to 7.5 magnitude earthquake given in percentage,

$$\varepsilon_{15} = \gamma * \left(\frac{N_1}{20}\right)^{-1.2}$$

103

This leads to estimated volumetric strain ratio where:

$$\varepsilon_{NC} = \varepsilon_{15} * \left(\frac{N_c}{15}\right)^{0.45}$$

104

N_c is the equivalent number of cycles expressed by the following expression:

$$N_c = (M - 4)^{2.17}$$

105

Where Settle3 takes earthquake magnitude from the liquefaction option dialog and calculates Nc. Then, factor of 2 is multiplied to the volumetric strain for taking account of multidirectional nature of earthquake shaking (Pradel 1998, equation (11)).

10.2. CPT ϵ_v Methods

When CPT input data is used, the strain is calculated according to Yoshimine et al. (2006).

$$\epsilon_v = 1.5 \cdot \exp(2.551 - 1.147(q_{c1Ncs})^{0.264}) \cdot \min(0.08, \gamma_{max}) \tag{106}$$

where γ_{max} is calculated using the Yoshimine et al. (2006) formulation.

10.3. VST ϵ_v Methods

Yi (2010) adapted Ishihara and Yoshimine (1992) for V_s data, and the following formulation for reconsolidation strain is used.

$$\epsilon_v = 1.5 \cdot \exp\left(-0.449\left(\frac{V_{s1cs}}{100}\right)^{1.976}\right) \cdot \min(0.08, \gamma_{max})$$

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