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Evaluating Liquefaction Resistance Using Shear Wave Velocity Measurements and Simplified Procedures

by

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BASIS OF THE WORK

(Data Set)

- Field V_S Measurements at Liquefaction Sites

  70 sites and 26 EQs (M_w = 5.3 to 8.3)

  U.S., Japan, Taiwan and China

- Sites Composed of Gravelly, Sandy and Silty Soils

  All Uncemented and Holocene Age (<10,000 years)

- All Sites Exhibited Surface Manifestations of Liquefaction
- All Critical Liquefiable Layers Have Been Shallow (95 % of cases <10 m)

Shear Wave Velocity, V_s

1. **Important Factors**
   (Stokoe et al, 1995)

$$V_s = A \sigma_v'^{\,m} \sigma_h'^{\,m} \qquad (1)$$

where

A = parameter that depends on the soil structure,

σ_v' = initial effective vertical stress,

σ_h' = initial effective horizontal stress, and

m = stress exponent (about 0.125).

2. **Stress-Corrected V_s, V_{s1}**
   (Robertson et al, 1992)

$$V_{s1} = V_s \left(\frac{P_a}{\sigma_v'} \right)^{0.25} \qquad (2)$$

where

P_a = a reference stress, 100 kPa

σ_v' = vertical effective stress in kPa.

Cyclic Stress Ratio, CSR

(Seed and Idriss, 1971)

$$CSR = \frac{\tau_{av}}{\sigma_v'} = 0.65 \left(\frac{a_{max}}{g} \right) \left(\frac{\sigma_v}{\sigma_v'} \right) r_d \qquad (3)$$

where

τ_{av} = average equivalent uniform shear stress (0.65 of the maximum induced stress),

a_{max} = peak horizontal ground surface acceleration,

σ_v' = initial effective vertical (overburden) stress

σ_v = total overburden stress,

g = acceleration of gravity, and

r_d = a shear stress reduction coefficient to adjust for flexibility of the soil profile.

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Cyclic Resistance Ratio (CRR)

1. **Definition:**

   CRR = CSR separating liquefaction and non-liquefaction occurrences.

2. **Equation of the Boundary:**

$$CRR = \left\{ a\left(\frac{V_{s1}}{100}\right)^2 + b\left(\frac{1}{V^*_{s1} - V_{s1}} - \frac{1}{V^*_{s1}}\right)\right\} MSF \qquad (4)$$

where

τ_1 = minimum value of τ_{av} at which liquefaction will occur.

V^*_{s1} = limiting value of V_{s1} for liquefaction occurrence, and

a and b = curve fitting parameters (a = 0.022 and b =2 .8).

Cyclic Resistance Ratio (CRR) continued

3. **Values for V^*_{s1}**

$$\left.\begin{array}{l} V^*_{s1} = 215 \text{ m/s} \\ \quad \text{for sands and gravels with } FC \le 5\% \\ V^*_{s1} = 215 - 0.5(FC\text{-}5) \text{ m/s} \\ \quad \text{for sands and gravels with } 5\% < FC < 35\% \\ V^*_{s1} = 200 \text{ m/s} \\ \quad \text{for sands and silts with } FC \ge 35\% \end{array}\right\} (5)$$

where

FC = the average fines content in percent by mass.

4. **Magnitude Scaling Factor, MSF**

$$MSF = \left(\frac{M_w}{7.5}\right)^n \qquad (6)$$

where

M_w = moment magnitude, and

n = an exponent (suggest n = -2.56).

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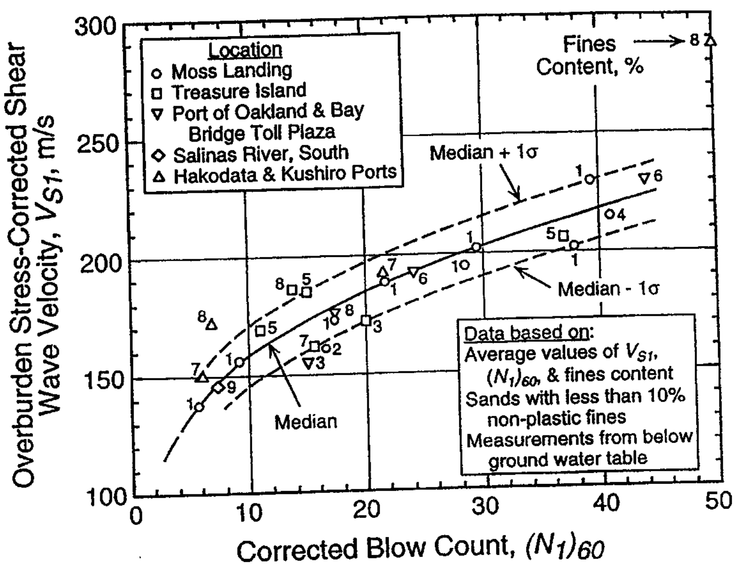
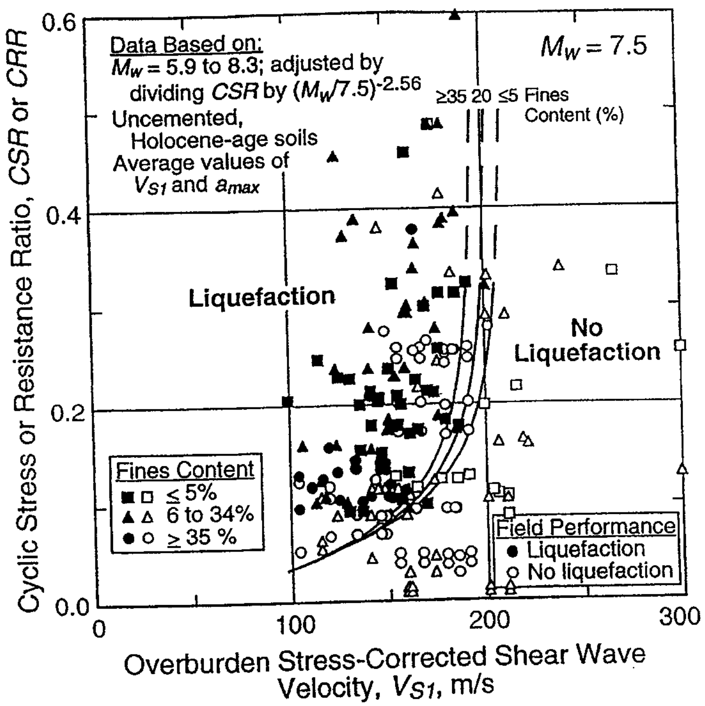


Variations in V_{S1} with $(N_1)_{60}$ for Uncemented, Holocene-age Sands with Less than 10% Non-plastic Fines.



Curves Recommended for Calculation of *CRR* from Shear Wave Velocity Measurements Along with Case History Data Based on Lower Bound Values of *MSF* for the Range Recommended by the 1996 NCEER Workshop (Youd et al., 1997) and r_d Developed by Seed and Idriss (1971).

Recommended Curves for Boundaries:

CRR use Eq. 4 (a = 0.022 and b = 2.8)

V_{s1}^* use Eq. 5

MSF use Eq. 6 (n = −2.56)

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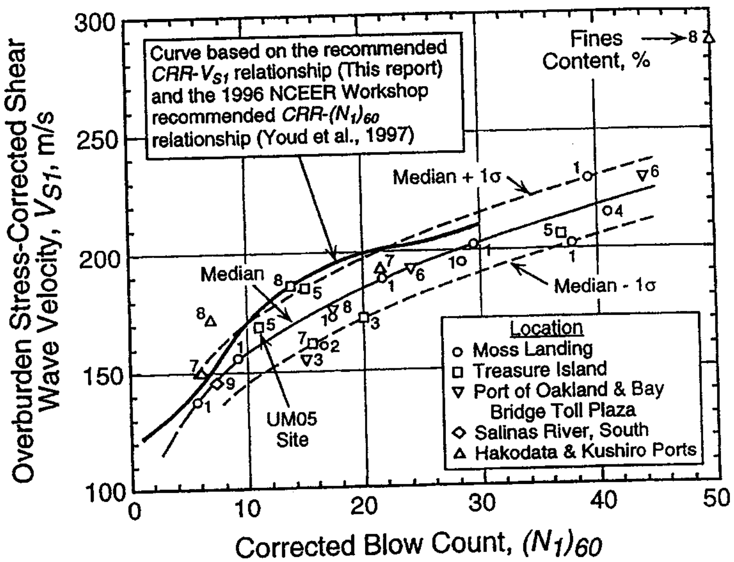
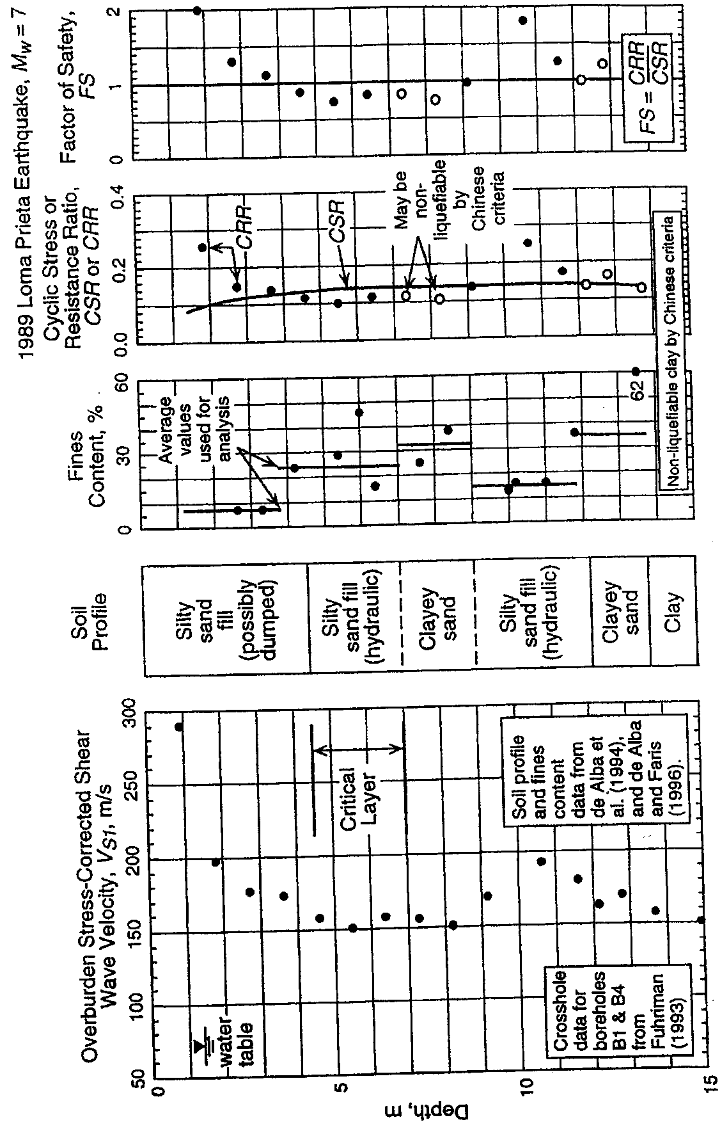


Relationships Between $(N_1)_{60}$ and V_{S1} for Clean Sands Implied by the Recommended CRR-V_{S1} Relationship (This Report) and the 1996 NCEER Workshop Recommended CRR-$(N_1)_{60}$ Relationship (Youd et al., 1997) with Field Data for Sands with Less than 10% Fines.



Application of the Recommended Procedure to the Treasure Island Fire Sation Site, Crosshole Test Array B1-B4 (Depth of 1.5 to 14 m).

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Correction to CRR for Cementation, Aging and Above-the-Water Table Conditions

$$CRR = \left\{ a\left(\frac{CV_{s1}}{100}\right)^2 + b\left(\frac{1}{V^*_{s1} - V_{s1}} - \frac{1}{V^*_{s1}}\right)\right\} MSF \quad (7)$$

where

C = a factor to correct for high values of V_{s1} caused by cementation, aging and negative pore-water pressure

Average estimates of C range from 0.6 to 0.8

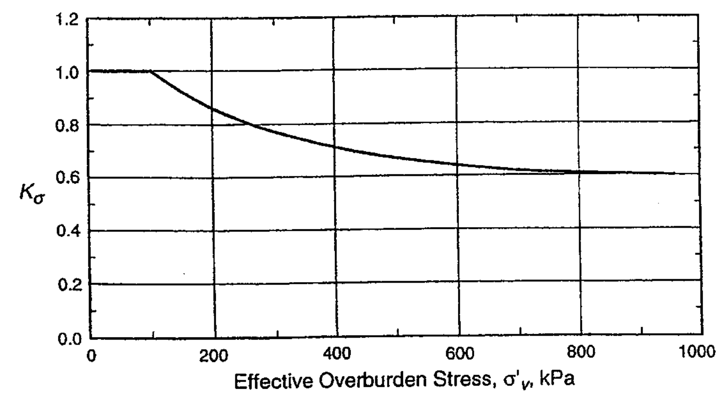
Correction for High Overburden Stress

$$CRR_1 = CRR * K_\sigma \quad (8)$$

where

CRR_1 = the cyclic resistance ratio at the reference overburden stress (100 kPa)

K_σ = correction factor (Seed, 1983)



Minimum Values of K_σ Recommended by the 1996 NCEER Workshop (after Youd et al., 1997; Harder and Boulanger, 1997).

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Liquefaction Evaluation Procedure Based on V_S

1. From available subsurface data, develop detailed profiles of shear wave velocity, soil type, fines content (particle less than 75 μm), and, if possible, soil density and penetration resistance.
2. Identify the depth of the ground water table, noting any seasonal fluctuations, artesian pressures, and the probable capillary zone.
3. Calculate total and effective overburden stresses for each measurement depth at which seismic testing has been performed.
4. Correct shear wave velocity measurements to the reference overburden stress of 100 kPa using Eq. 2.
5. Determine limiting values of overburden stress-corrected shear wave velocity for liquefaction occurrence, V_{s1}^*, for each measurement depth using Eq. 5. If the average fines content is unknown, assume 215 m/s for V_{s1}^*.

Liquefaction Evaluation Procedure Based on V_S continued

6. Determine the value of the correction factor C. The value of C can be assumed equal to 1, if the soil to be evaluated is uncemented, less than 10,000 year old, and lies below the ground water table when the seismic tests were conducted. If soil conditions are unknown and penetration data are not available, assume 0.6 for C.
7. Determine the design earthquake magnitude and expected peak horizontal ground surface acceleration.
8. For each measurement depth below the water table, calculate the cyclic stress ratio, as shown in Eq. 3. The stress reduction coefficient is estimated using Seed and Idriss (1971).
9. Plot values of V_{s1} and CSR, and the appropriate liquefaction resistance curves using Eqs. 4 , 5 and 6 with a = 0.022, b = 2.8, and n = -2.56. Liquefaction is predicted at the site if the data points plot to the left of the respective curve. No liquefaction is predicted if the data points plot to the right of the respective curve.

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Liquefaction Evaluation Procedure Based on V_S continued

10. Calculate the factor of safety, FS, against liquefaction at each measurement depth using:

$$FS = \frac{CRR}{CSR}$$

Liquefaction is predicted to occur when FS is less than 1. When FS is greater than 1, liquefaction is predicted not to occur. The acceptable value of FS will depend on several factors including: (1) the acceptable level of risk for the project, (2) the extent and accuracy of seismic measurements, (3) the availability of other site information, and (4) the conservatism in determining design earthquake magnitude and peak ground acceleration.

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