Use of Volumetric Strain in Liquefaction Damage Index Frameworks

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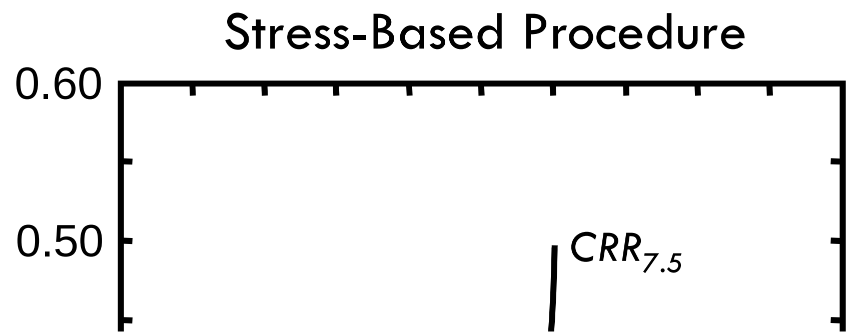
Outline

- Simplified Liquefaction Evaluation Procedure
- Liquefaction Potential Index (LPI)
  - Shortcomings of LPI Framework
- Alternative Liquefaction Damage Index Frameworks
  - One-dimensional volumetric reconsolidation settlement (S_{V1D})
  - Liquefaction Severity Number (LSN)
- Efficacy of Alternative Frameworks - ROC Analyses of CES Data
- Path Forward
- Summary/Conclusions

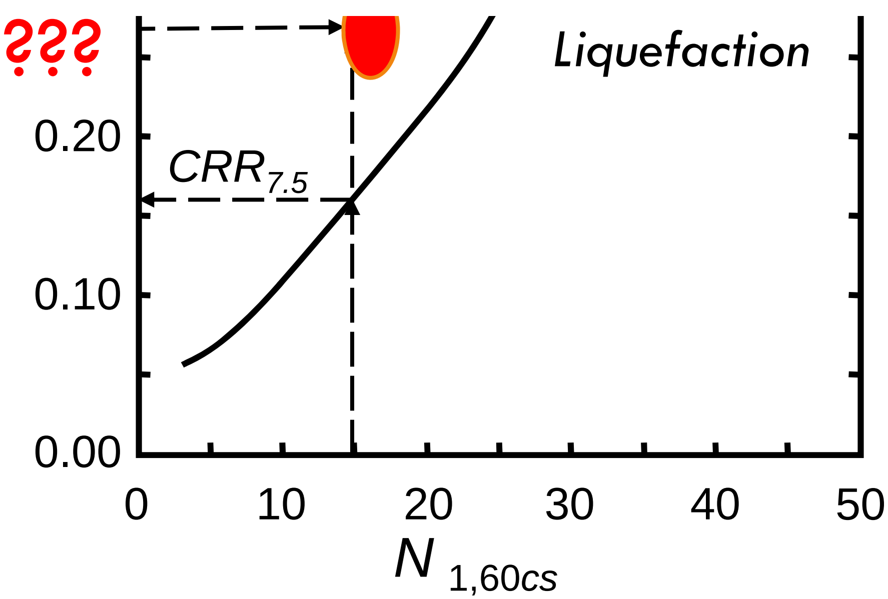
“Simplified” Liquefaction Evaluation Procedure

$$CSR^* = 0.65 \frac{a_{max}}{g} \frac{\sigma_v}{\sigma'_{vo}} r_d \frac{1}{MSF} \frac{1}{K_\sigma K_\alpha}$$



What value of FS is acceptable?

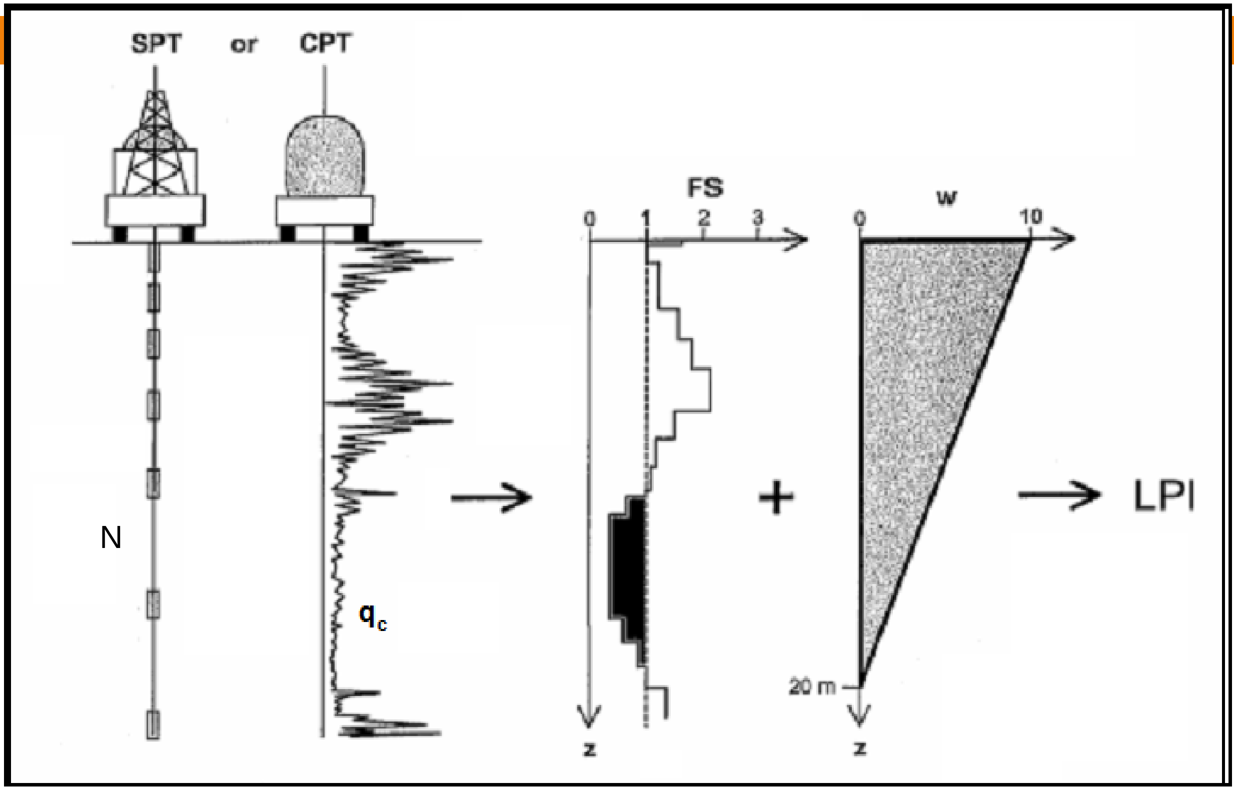
What about thickness and depth of the liquefied layer???



Factor of Safety Against Liquefaction:

$$FS = \frac{CRR_{7.5}}{CSR^*}$$

Liquefaction Potential Index (LPI)



$$LPI = \int_0^{20\ m} f(z) \cdot w(z)\, dz$$

$$f(z) = 0 \quad \rightarrow \quad for \quad FS(z) > 1$$

$$f(z) = 1 - FS(z) \quad \rightarrow \quad for \quad FS(z) \leq 1$$

$$w(z) = 10 - 0.5z; \ z \ in \ m$$

(Iwasaki et al. 1978)

Liquefaction Potential Index (LPI)

$$LPI = \int_0^{20\,m} f(z) \cdot w(z)\, dz$$

Limits: $LPI_{min} = 0$ (FS > 1 for $0 \le z \le 20$ m)

$LPI_{max} = 100$ (FS = 0 for $0 \le z \le 20$ m)

Damage: $LPI < 5$: Severe liquefaction manifestations <u>not expected</u>

$LPI > 15$: Severe liquefaction manifestation <u>expected</u>

(Iwasaki et al. 1978)

Shortcomings of LPI Framework

- Surficial manifestations of liquefaction can occur for FS > 1
- The consequences of a FS = 0.8, for example, will differ depending on the soil density (consequences will increase as density decreases)

The LPI framework <u>does not</u> account for either of these phenomena

Alternative Liquefaction Damage Index Frameworks

One-dimensional volumetric reconsolidation settlement (S_{V1D})

$$S_{V1D} = \int \varepsilon_v dz$$

(Zhang et al. 2002)

Liquefaction Severity Number (LSN)

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz$$

(van Ballegooy et al. 2014)

Alternative Liquefaction Damage Index Frameworks

One-dimensional volumetric reconsolidation settlement (S_{V1D})

Post-liquefaction volumetric strain – used as an index to account for consequences due to liquefaction as a function of FS and soil density

$$S_{V1D} = \int \varepsilon_v dz$$

(Zhang et al. 2002)

action Severity Number (LSN)

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz$$

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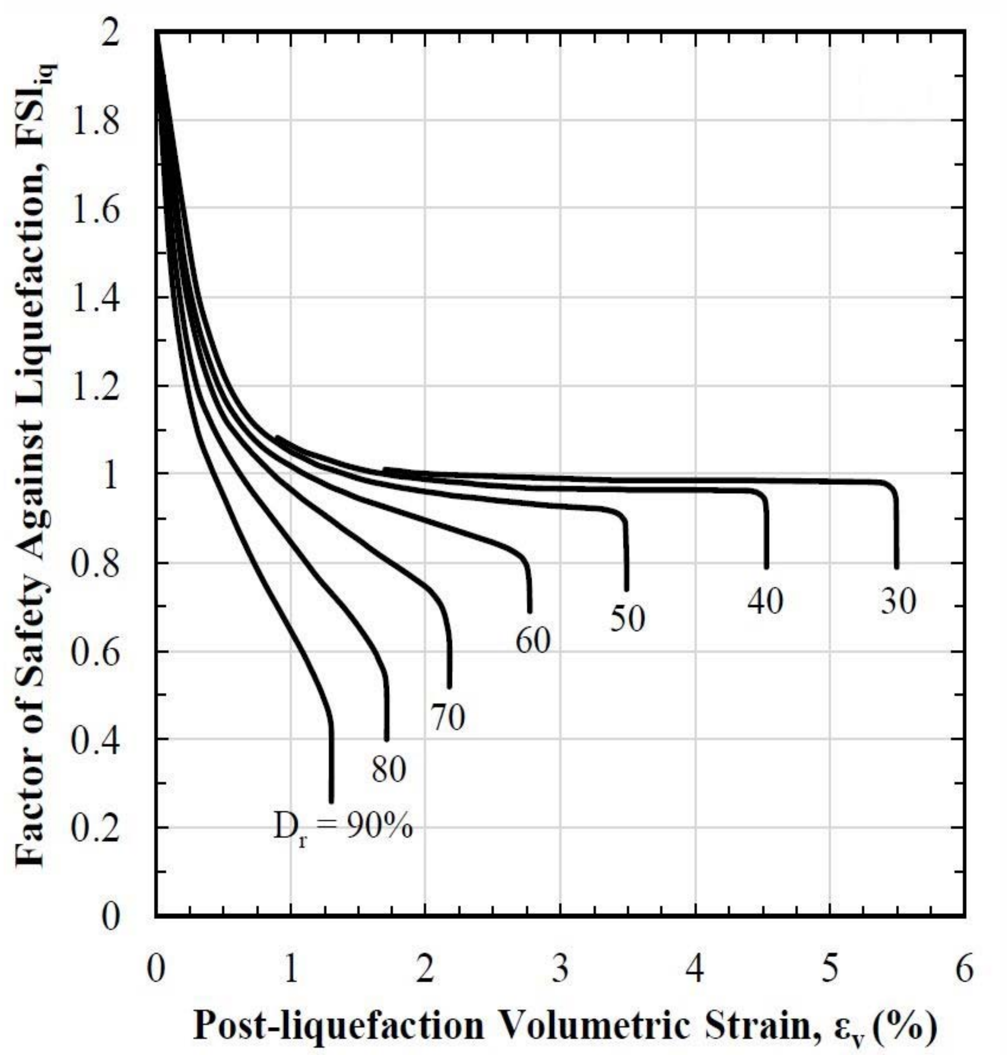
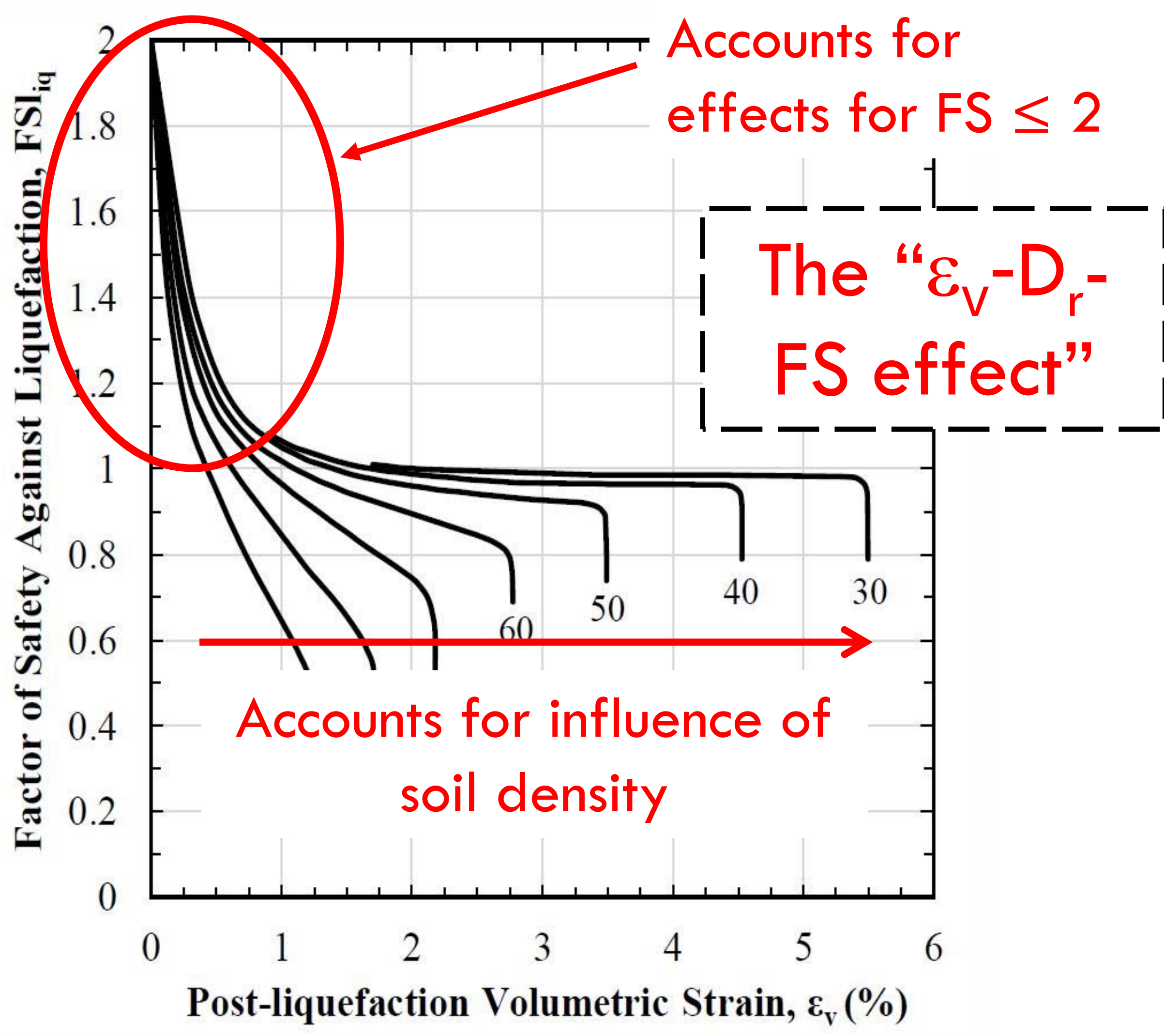
Post-liquefaction Volumetric Strain



(Ishihara and Yoshimine 1992)

Post-liquefaction Volumetric Strain



(Ishihara and
Yoshimine 1992)

Alternative Liquefaction Damage Index Frameworks

One-dimensional volumetric reconsolidation settlement (S_{V1D})

Focus of this presentation due to time limitations

$$S_{V1D} = \int \varepsilon_v dz$$

(Zhang et al. 2002)

Liquefaction Severity Number (LSN)

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz$$

(van Ballegooy et al. 2014)

Receiver Operator Characteristic (ROC) Analysis of CES Liquefaction Data

ID	Derived from Ishihara & Yoshimine 1992	D_r - q_{c1N} Correlation Utilized	Function(s)
S1	✓	Eq. (2)	Zhang et al. 2002
S2	✓	Eq. (3); C = 0.9	Available on request (a la Zhang et al. 2002)
S3	✓	Eq. (3); C = 0.9	Yoshimine et al. 2006
S4	✓	Eq. (3); C = 0.64	Yoshimine et al. 2006
S5	✓	Eq. (3); C = 1.55	Yoshimine et al. 2006
C1	×	N/A	$\varepsilon_v\ (\%) = \begin{cases} 1 & \text{for } FS_{liq} < 1 \\ 0 & \text{for } FS_{liq} \geq 1 \end{cases}$

(Maurer et al. 2015)

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Different equations for approximating Ishihara and Yoshimine (1992) ε_v-D_r-FS relationship

(Maurer et al. 2015)

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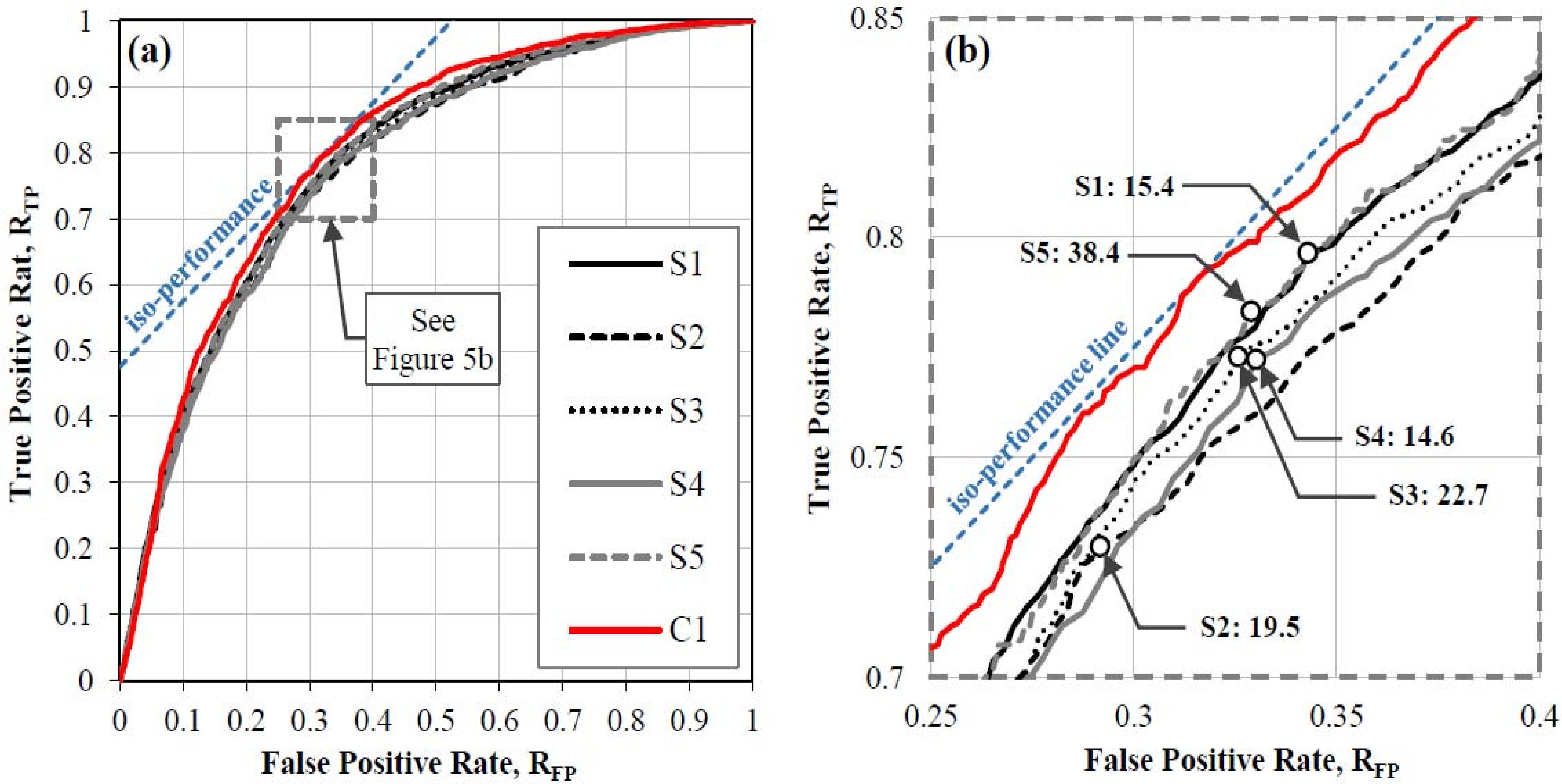
Control case that <u>does not</u> account for ε_v-D_r-FS effect

C1	×	N/A	$\varepsilon_v\ (\%) = \begin{cases} 1 & \text{for } FS_{liq} < 1 \\ 0 & \text{for } FS_{liq} \geq 1 \end{cases}$

(Maurer et al. 2015)

Receiver Operator Characteristic (ROC) Analysis of CES Liquefaction Data

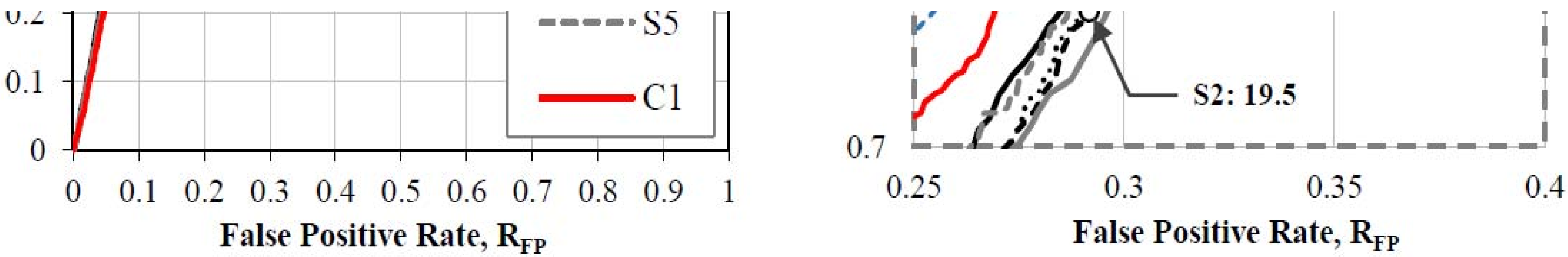


(Maurer et al. 2015)

Receiver Operator Characteristic (ROC) Analysis of CES Liquefaction Data

Not accounting for ε_v-D_r-FS effect results in better prediction of liquefaction severity for CES data than accounting for it!!!

WHY???

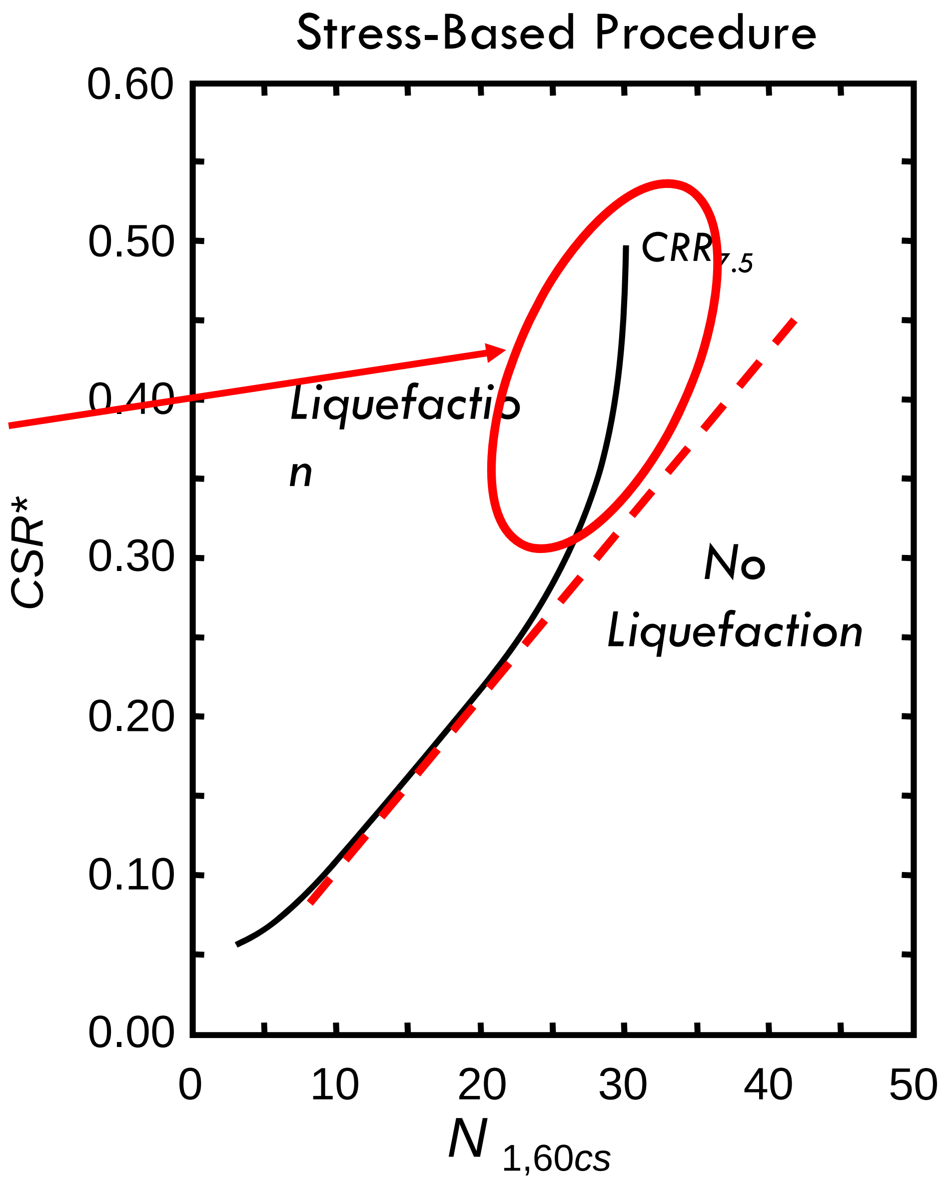


(Maurer et al. 2015)

“Simplified” Liquefaction Evaluation Procedure

Shape of $CRR_{7.5}$ curve likely a result of the dilative tendencies of dense soils minimizing surficial liquefaction manifestations, even when liquefaction is triggered

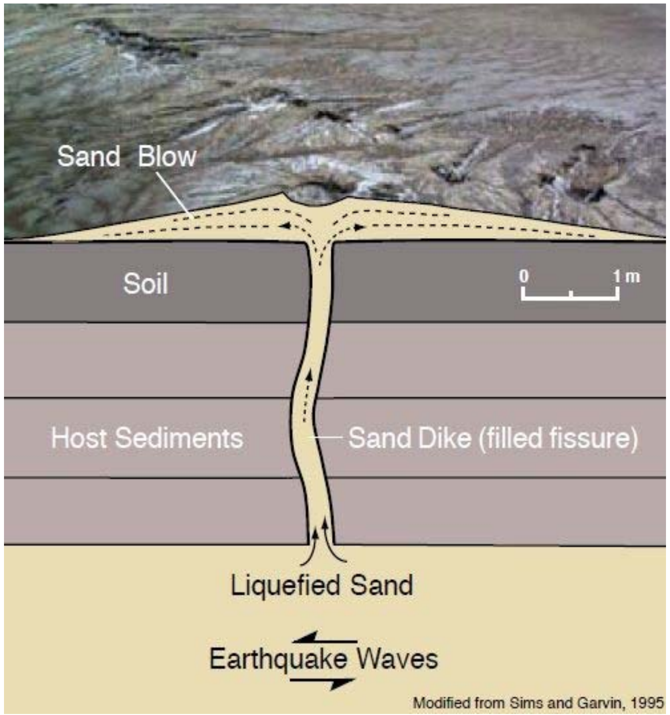
Inclusion of ε_v in Liquefaction Damage Index framework likely double counts ε_V-D_r-FS effect



Path Forward

Triggering curve and Liquefaction Damage Index framework need to be developed consistently (as opposed to independently as is currently the case).

Triggering models: tie surface manifestation to triggering; need manifestation mechanics to do so



Manifestation models (e.g., LPI & LSN): Tie triggering to surface manifestation; need manifestation mechanics to do so

Development of CRR Curve within Liquefaction Damage Index Framework

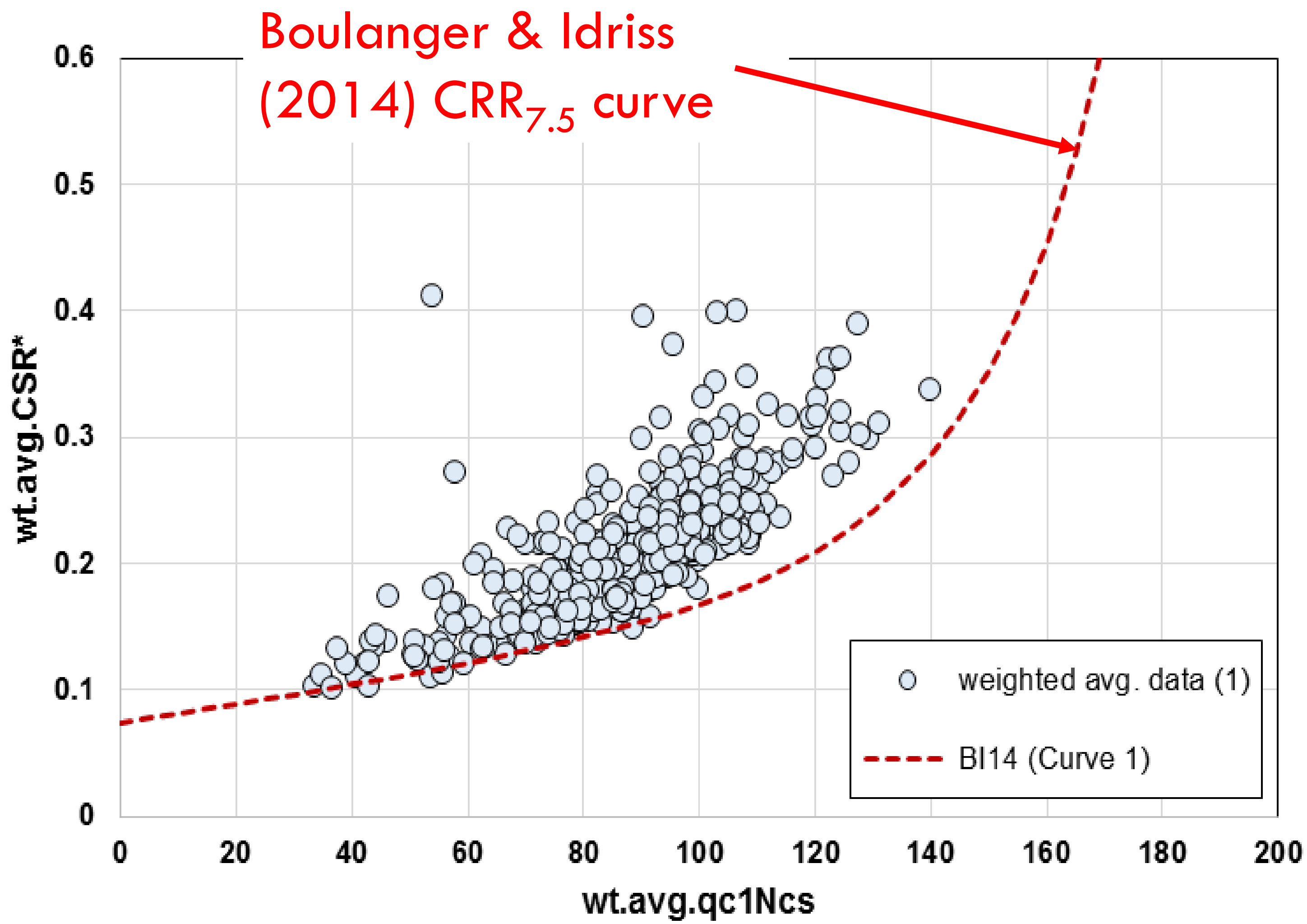
Example: Marginal surficial liquefaction manifestation "CRR" curve within LPI framework

$$Weighted\ avg\ CSR^* = \frac{\sum_{i=1}^{m} CSR_i^* \cdot w(z_i) \cdot F_i}{\sum_{i=1}^{m} w(z_i) \cdot F_i}$$

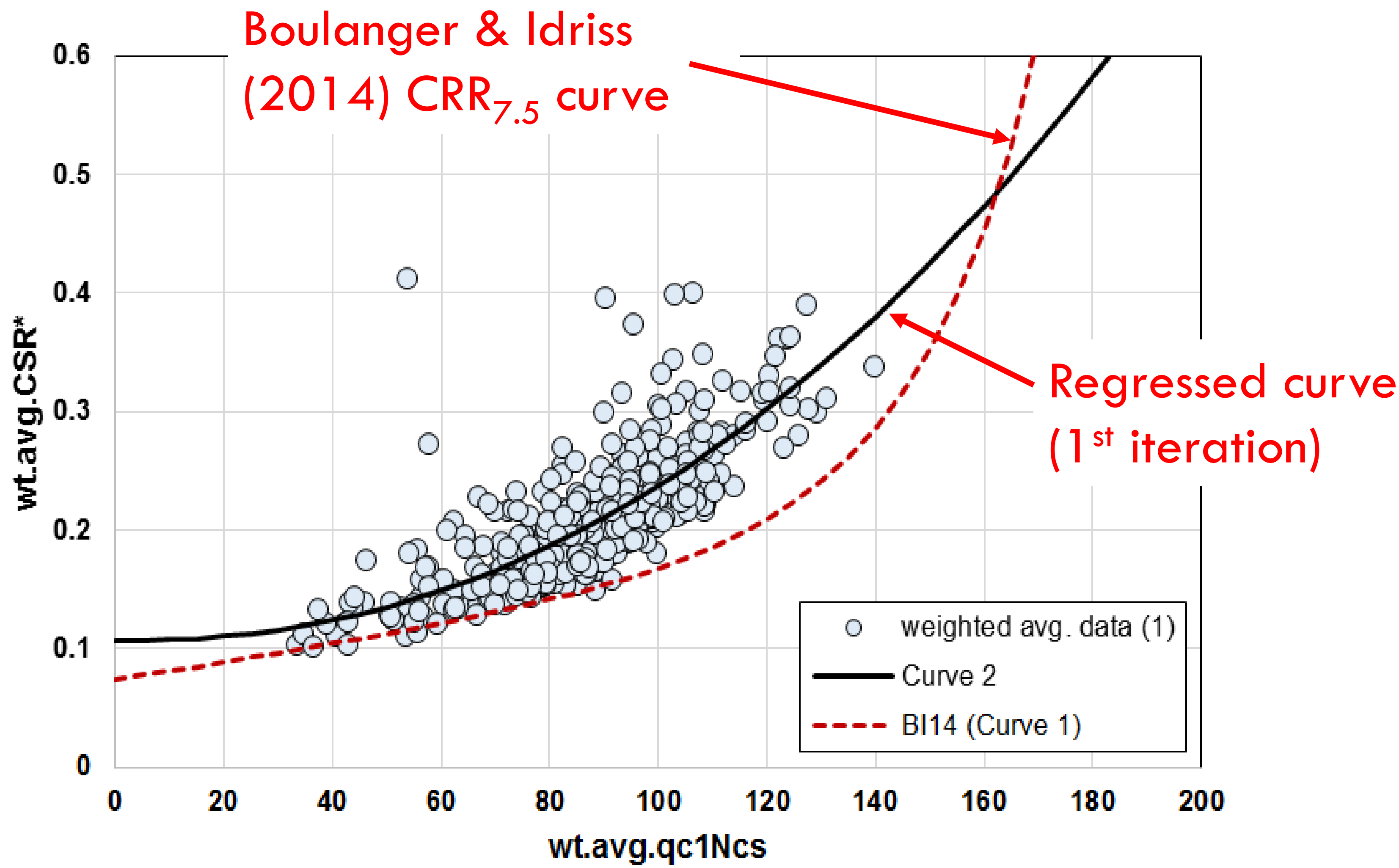
$$Weighted\ avg\ q_{c1Ncs} = \frac{\sum_{i=1}^{m} q_{c1Ncs\ i} \cdot w(z_i) \cdot F_i}{\sum_{i=1}^{m} w(z_i) \cdot F_i}$$

$$F_i = \begin{cases} 1.2 - FS_i & if \quad FS_i \leq 1.2 \\ 0 & otherwise \end{cases}$$

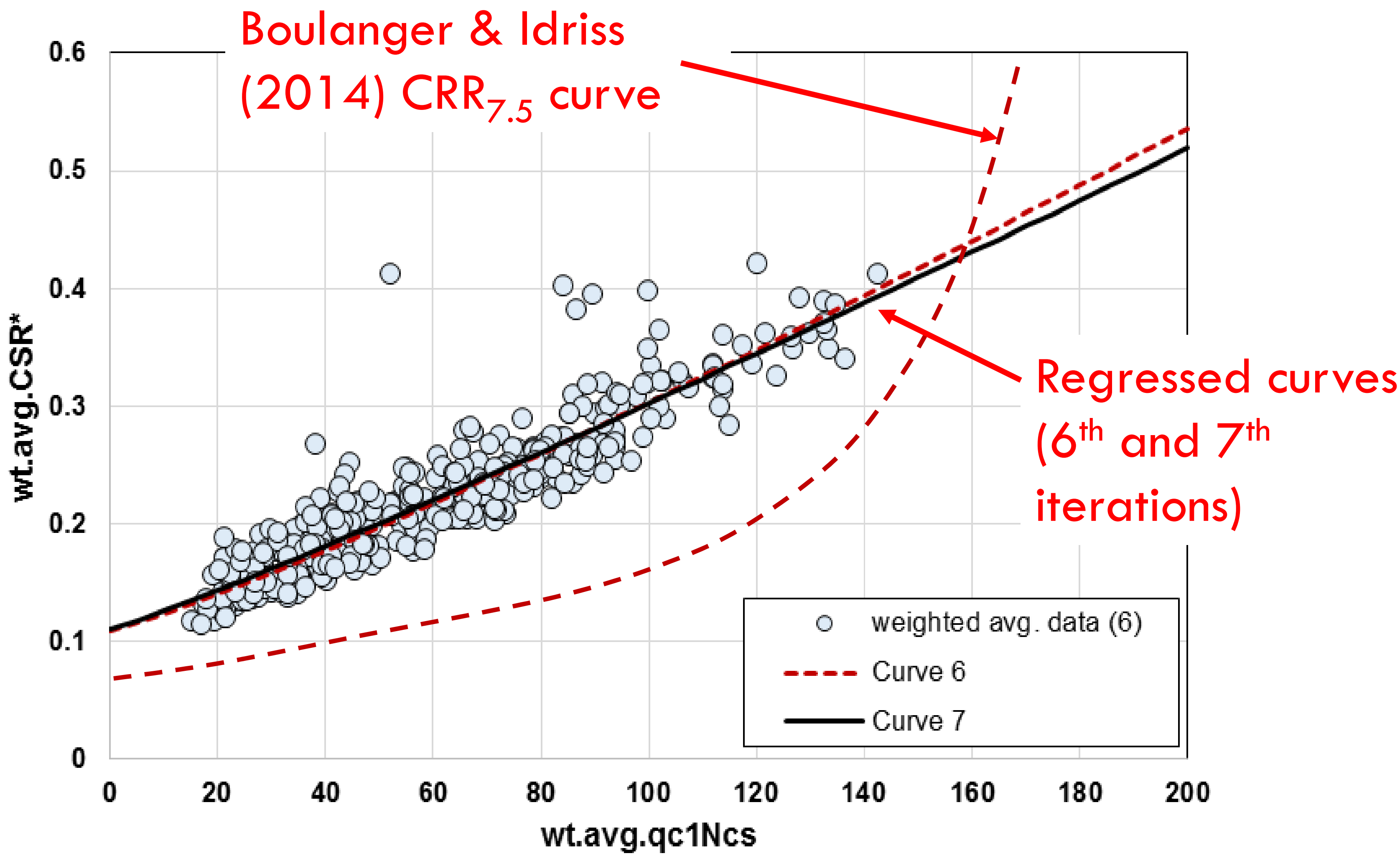
Development of CRR Curve within Liquefaction Damage Index Framework



Development of CRR Curve within Liquefaction Damage Index Framework



Development of CRR Curve within Liquefaction Damage Index Framework



Summary/Conclusions

- LPI framework fills the gap between liquefaction potential in an individual stratum at depth to the overall liquefaction damage potential.
- Several shortcomings of LPI framework: no consideration of the "ε_v-D_r-FS effect"
  - No consideration of damage potential of soils with elevated excess pore water pressures due to shaking, but where liquefaction was not triggered (i.e., FS > 1)
  - No consideration of soil density on potential consequences
- Alternative Liquefaction Damage Potential Index Frameworks have been proposed that account for the ε_v-D_r-FS effect
  - Their efficacy is less than frameworks that do not account for the ε_v-Dr-FS effect, likely due to the double counting of dilatational tendencies of dense soil
- Consistency needed: CRR curve needs to be developed within the Liquefaction Damage Index framework

Questions???

Thank You

(Mark Lincoln)

References

Ishihara, K., and Yoshimine, M. (1992). "Evaluation of settlements in sand deposits following liquefaction during earthquakes," Soils and Foundations, 32(1), 173–188.

Iwasaki, T., Tatsuoka, F., Tokida, K., and Yasuda, S. (1978). "A practical method for assessing soil liquefaction potential based on case studiesat various sites in Japan." Proc., 2nd Int. Conf. on Microzonation, National Science Foundation, Washington, DC.

Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B.A. (2015). "Influence of post-liquefaction strain potential estimation on the accuracy of liquefaction severity number (LSN) hazard assessments," Proc. 10th Pacific Conf. on Earthquake Engineering, 6-8 November 2015, Sydney, Australia

Yoshimine, M., Nishizaki, H., Amano, K., and Hosono, Y. (2006). "Flow deformation of liquefied sands under constant shear load and its application to analysis of flow slide in infinite slope," *Soil Dynamics and Earthquake Engineering,* 26, 253-264.

van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M.E., Cubrinovski, M., Bray, J.D., O'Rourke, T.D., Crawford, S.A., and Cowan, H. (2014). Assessment of liquefaction-induced land damage for residential Christchurch, *Earthquake Spectra*, 30(1): 31-55.

Zhang, G., Robertson, P.K., and Brachman, R. (2002). "Estimating Liquefaction Induced Ground Settlements from CPT," *Canadian Geotechnical Journal,* 39, 1168-1180.