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Examination of differences between three SPT-based seismic soil liquefaction triggering relationships

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ABSTRACT

The preceding companion paper presented the updating of the seismic soil liquefaction triggering relationship of Cetin et al. (2004) [1], and compared the resulting updated relationship with the earlier version. In this second paper, a detailed cross-comparison is made between three triggering relationships: (1) Seed et al. (1985) [2], as slightly updated by the NCEER Working Group (Youd et al., 2001 [3]), (2) Boulanger and Idriss (2012) [4], and (3) Cetin et al. (2017) [5]. Differences between these three triggering relationships, and the apparent causes of them are examined. Also studied are the impacts of these differences on levels of conservatism with regard to evaluation of liquefaction triggering hazard, and the resulting risks for engineering projects.

1. Introduction

The preceding companion paper of Cetin et al. [5] presented the updating of the seismic soil liquefaction triggering relationship of Cetin et al. [1], and compared the updated relationship with its earlier version. With the aim of developing a fair comparison framework, when compiling Cetin et al. [6] database, field case histories from relatively more recent events of 1999 Chi-Chi, 2008 Achaia-Ilia, Greece, 2010 Haiti, 2010 Chile-Maule, 2011 Tohoku, 2010–2011 New Zealand-Canterbury, 2012 Emilia-Romanga (Northern Italy), etc., earthquakes were excluded since they were also not included in Idriss and Boulanger [7] database. However, the presentation of a further expanded database with these additional new case histories will be the scope of another manuscript. In this second paper, a detailed cross-comparison is made between three triggering relationships: (1) Seed et al. [2] as slightly updated by the NCEER Working Group (Youd et al. [3]), (2) Boulanger and Idriss [4], and (3) Cetin et al. [5]. These three triggering relationships will be referred to hereafter as SEA1985, BI2012 and CEA2017, respectively. Differences between these three triggering relationships, and the apparent causes of these differences are examined. Also examined are the impacts of these differences on levels of conservatism with regard to evaluation of likelihood of triggering of liquefaction.

Fig. 1 shows the established soil liquefaction triggering "boundary curves" associated with each of these relationships. All three relationships have been re-plotted at the same scales to make visual cross-comparisons easier and more direct. The liquefaction triggering field case history data points plotted in each figure are those of the original authors, and all data points (as well as the boundary curves) are normalized to a fines-corrected "clean sand" reference condition of $N_{1,60,CS}$ rather than $N_{1,60}$.

Plotting all three relationships on the same scale is helpful with regard to making cross-comparisons, but it can be difficult to see in detail some of the differences between the boundary curves of these three relationships. Accordingly, Fig. 2(a) shows all three studies, with the BI2012 and CEA2017 relationships represented by contours of $P_L = 50\%$, and Fig. 2(b) repeats Fig. 2(a) but with these two probabilistic relationships represented by contours of $P_L = 20\%$. The SEA1985 relationship had no probabilistic basis, so the clean sand boundary curve for that relationship remains in the same position in both figures, and serves as a useful visual point of reference. All of these curves shown in Fig. 2 are presented on a "clean sand" basis (fines content ≤ 5%). As

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Notation list

a_{max}	Peak horizontal acceleration
C_N	Overburden correction
C_R	Correction factor for the rod length
CPT	Cone penetration test
CSR	Cyclic stress ratio
$CSR_{\sigma'_v,M_w,\alpha}$	Cyclic stress ratio at a depth where vertical effective stress and shear stress ratio are σ'_v and due to a M_w magnitude earthquake
$CSR_{\sigma'_v=1atm,M_w=7.5,\alpha=0}$	CSR normalized to σ'_v = 1 atm, M_w = 7.5 and α = 0
CRR	Cyclic resistance ratio
$d_{cr.}$	d = Critical depth for liquefaction
D_R	Relative density
FC	Fines content
g	Acceleration of gravity
K_o	Coefficient of earth pressure at rest
K_σ	Correction for overburden stress
K_{Mw}	Magnitude (duration) scaling factors
K_α	Correction for sloping sites
$N_{1,60}$	Standard penetration test blow count corrected for overburden, energy and procedural differences.
$N_{1,60,CS}$	Fines -corrected $N_{1,60}$ value
M	M_w = Moment magnitude
P_a	Atmospheric pressure (1 atm)
P_L	Probability of liquefaction
R	Distance to source (km) [31]
r_d	Stress reduction coefficient
S	Site class. S = 0 (for rock), S = 1 (for soil site) [31]
SPT	Standard penetration test
V_s	Shear wave velocity
$V_{s,12\,m}$	Shear wave velocity for the upper 12 m
γ_{max}	Maximum shear strain
$\gamma_{below\text{-}GWT}$	unit weight below ground water table
γ_{above_GWT}	unit weight above ground water table
α	initial static driving shear stress ratio; $\alpha = \tau_{hv,static} / \sigma'_v$
$\sigma_{N_{1,60}}$	Standard deviation of the $N_{1,60}$
$\sigma_{\ln(CSR_{\sigma'_v,\alpha,M_w})}$	Standard deviation of $\ln(CSR_{\sigma'_v,\alpha,M_w})$
$\sigma_{\ln(M_w)}$	Standard deviation of $\ln(M_w)$
σ_{FC}	Standard deviation of $\ln(FC)$
$\sigma_{\ln(\sigma'_v)}$	Standard deviation of $\ln(\sigma'_v)$
σ_ε	Standard deviation of the model uncertainty
σ'_v	Vertical effective stress
σ_v	Vertical total stress
θ	Limit state model parameters
τ_{av}	Average shear stress
$\tau_{hv,cyclic,peak}$	Peak cyclic horizontal shear stress
$\Delta N_{1,60}$	SPT penetration resistance correction for fines content

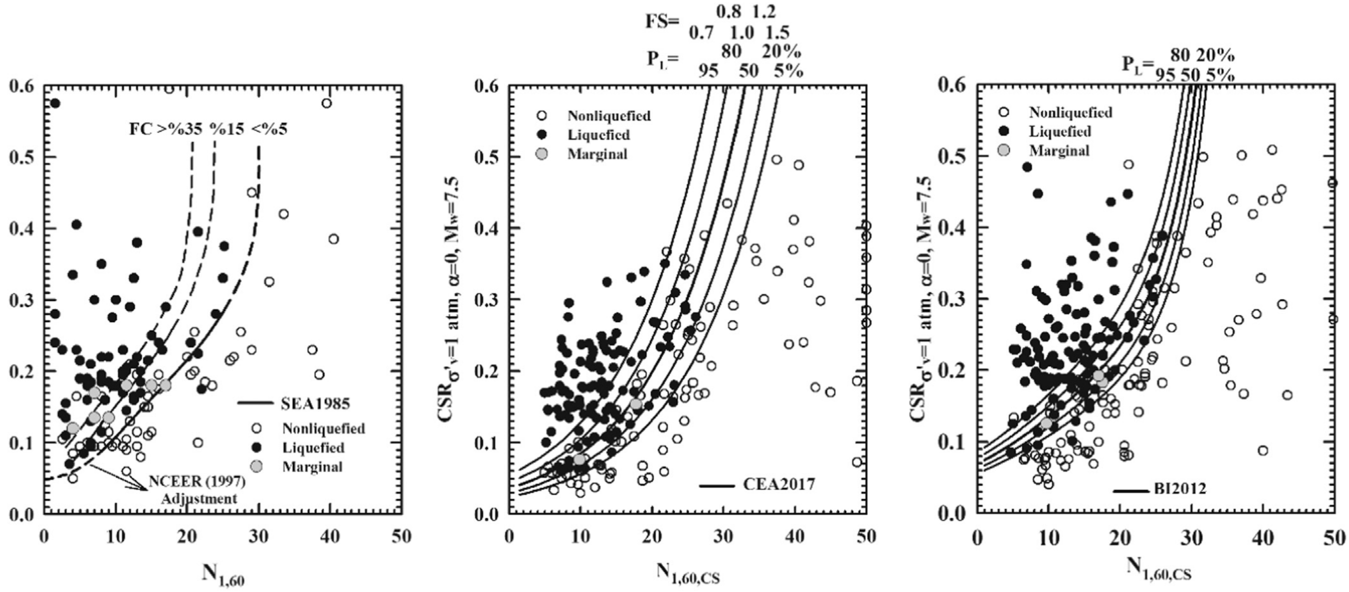

Fig. 1. Liquefaction triggering relationships as proposed by (a) SEA1985 as modified slightly by Youd et al. [3], (b) CEA2017 and (c) BI2012 (CSR values are plotted after correcting for typographical errors described in Boulanger and Idriss [8]).

shown in Fig. 2, there are significant differences between the triggering boundary curves at these two important levels of hazard or probability of liquefaction.

It must also be noted that examination of the boundary curves alone does not fully characterize overall levels of hazard or conservatism. Each of the three sets of boundary curves are developed to act in conjunction with a number of prescribed or recommended engineering protocols in terms of parameter assessment (e.g. evaluation of earthquake-induced cyclic stress ratio (CSR), $N_{1,60}$ etc.), and with a number of additional ("secondary") relationships that result in further adjustments for effective overburden stress (σ'_v), causative earthquake magnitude (M or M_w), and fines adjustments ($\Delta N_{1,60}$ as a function of fines content). These "secondary" relationships can also have potentially significant impacts on forward assessments of liquefaction hazard for engineering projects. They can either compound or partially offset levels of conservatism or unconservatism in the baseline boundary curves shown in Figs. 1 and 2, and their impacts differ over varying ranges of parameters. Accordingly, it is necessary to jointly examine both (1) the proposed sets of boundary curves, as well as (2) the secondary relationships, and (3) the recommended associated engineering protocols for forward analyses of projects, in evaluating differences between the three triggering relationships.

Figs. 1 and 2 also show that differences between the three triggering relationships are less pronounced at the "upper" portions of the boundary curves ($N_{1,60,CS}$ ≥ 20 blows/ft). It is important to note, however that (1) the ratios of the differences here (in terms of CSR) are