Soil Dynamics and Earthquake Engineering 113 (2018) 75–86

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

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

K. Onder Cetin[a,*], Raymond B. Seed[b], Robert E. Kayen[b], Robb E.S. Moss[c], H. Tolga Bilge[d], Makbule Ilgac[a], Khaled Chowdhury[b,e]

[a] Dept. of Civil Engineering, Middle East Technical University, Ankara, Turkey
[b] Dept. of Civil and Environmental Engineering, University of California, Berkeley, CA, USA
[c] California Polytechnic State University, San Luis Obispo, CA, USA
[d] GeoDestek Ltd., Ankara, Turkey
[e] US Army Corps of Engineers, South Pacific Division Dam Safety Production Center, Sacramento, CA, USA

ARTICLE INFO

Keywords:
Soil liquefaction
Liquefaction triggering relationship
Earthquake
Seismic hazard
Cyclic loading
Standard penetration test
In-situ test
Probability

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. [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 CEA2018, 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 CEA2018 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 shown in Fig. 2, there are significant differences between the triggering boundary curves at these two important levels of hazard or probability

* Corresponding author.
E-mail addresses: ocetin@metu.edu.tr (K.O. Cetin), kayen@berkeley.edu (R.E. Kayen).

https://doi.org/10.1016/j.soildyn.2018.03.013
Received 11 July 2017; Accepted 12 March 2018
Available online 05 June 2018

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; $\alpha = \tau_{hv,static} / \sigma'_v$
$\sigma_{N1,60}$	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

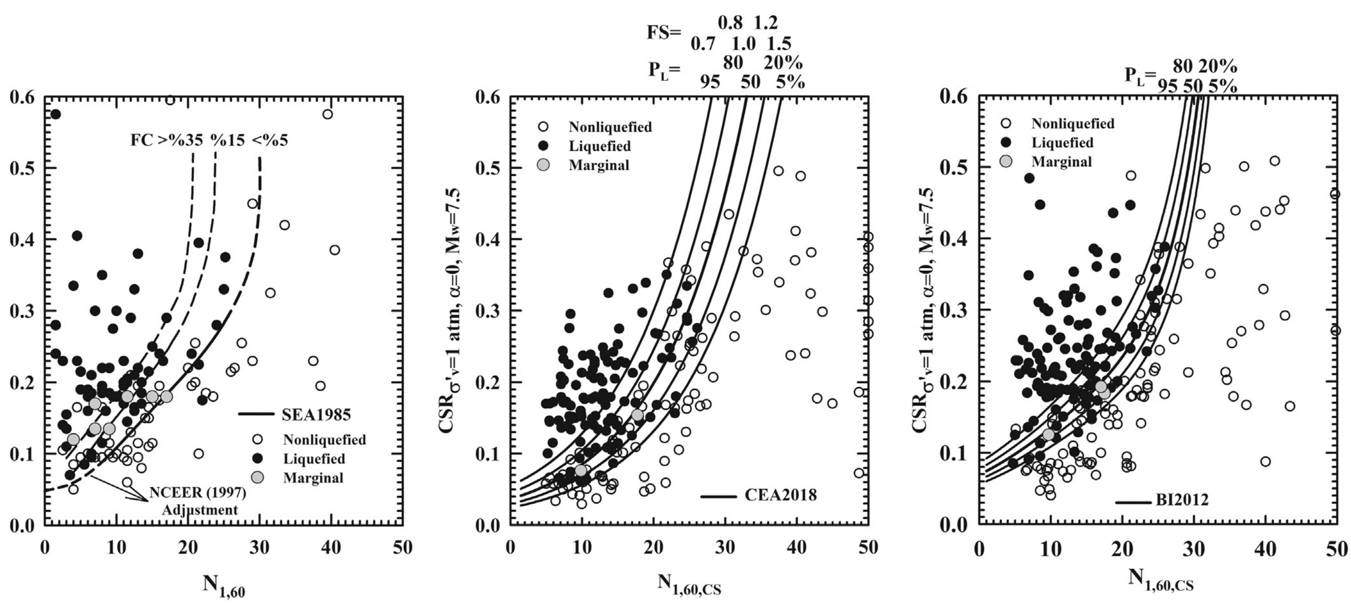

Fig. 1. Liquefaction triggering relationships as proposed by (a) SEA1985 as modified slightly by Youd et al. [3], (b) CEA2018 and (c) BI2012 (CSR values are plotted after correcting for typographical errors described in Boulanger and Idriss [8]).

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 lesser in magnitude than at the lower portions of the curves applicable to lower penetration resistances, and (2) differences at higher $N_{1,60,CS}$

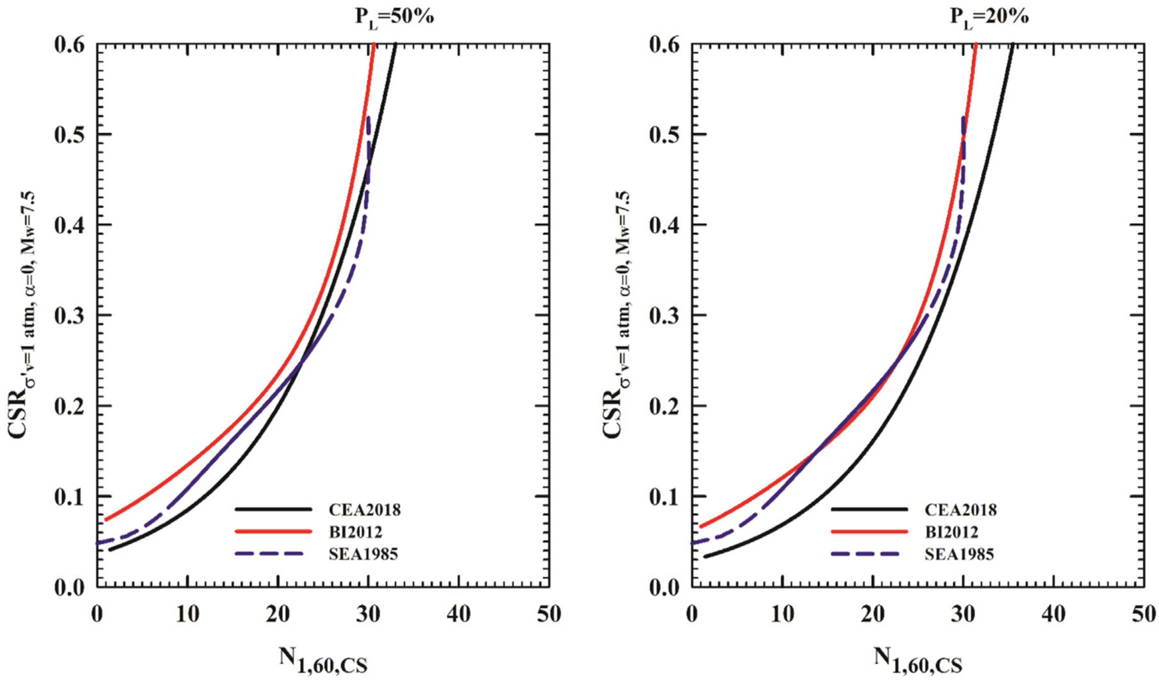

Fig. 2. Clean sand boundary curves ($N_{1,60,CS}$) for all three relationships co-plotted on the same two figures; (a) the deterministic curve of SEA1985 (as modified slightly by Youd et al. [3]) and the P_L = 50% contours of BI2012 and CEA2018, and (b) the deterministic curve of SEA1985 and the P_L = 20% contours of BI2012 and CEA2018.

values generally have lesser engineering implications because soils with higher corrected SPT $N_{1,60,CS}$ values have higher post-liquefaction strengths and tend to have more limited cyclic deformation potential as well.

For most engineered projects, it is soils with lower corrected SPT penetration resistances ($N_{1,60,CS}$ ≤ 20blows/ft) that are of principal concern. Unfortunately, it is in this lower range of $N_{1,60,CS}$ values, where the potential consequences can often be high, that the greatest differences between the three triggering relationships occur.

2. Examination of the six main differences between the three triggering relationships

An abbreviated summary of the six main differences between the three triggering relationships is presented in Supplementary material Table S1, which is a useful summary guide to the discussion that follows. Similarly, Supplementary material Fig. S1 provides a visual cross-comparison of input parameters of case histories present commonly in both the Idriss and Boulanger [7] and Cetin et al. [6] databases. Table 6 in the companion paper of Cetin et al. [5] presents a summary overview of average (mean) values of key parameters and indices, for each of the three databases of SEA1985, Idriss and Boulanger [7] and Cetin et al. [6], and this will also be useful in the discussions that follow. As part of these discussions, any effect which i) increases the CSR or ii) decreases the $N_{1,60,CS}$ median values of the case histories, or iii) both, will be referred to hereafter as "unconservative" since these effects will translate case history data points up and/or left, and consequently cyclic resistance ratio will be overestimated.

2.1. Differences in r_d relationships

Differences in the stress reduction (shear mass participation) factor, or r_d relationships, is the first of the issues listed in Table S1. The earlier work of Seed et al. [2,9] employed the r_d relationship developed by Seed and Idriss [10] in the "simplified" framework, in which CSR was evaluated by using Eq. (3) from the accompanying paper of Cetin et al.

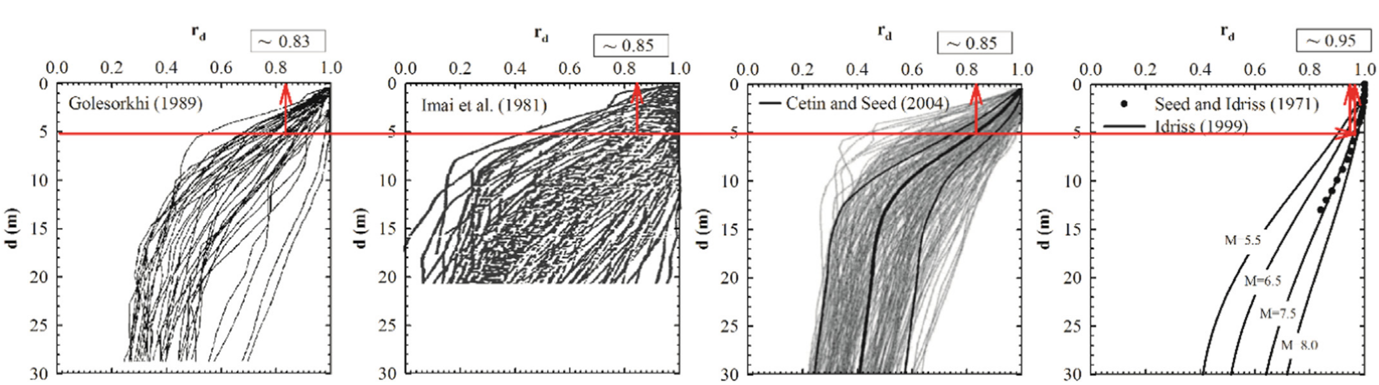

Fig. 3. Plots of r_d values calculated based on seismic site response analyses by (a) Golesorkhi [11], (b) Imai et al. [12], (c) Cetin and Seed [13], and (d) Seed and Idriss [10] and Idriss [14]. The red line and red arrows show the r_d values estimated at the approximate median critical depth of the databases of Idriss and Boulanger [7] and Cetin et al. [6].

[5] in back-analyses of case histories. To implement this simplified approach, first it was necessary to develop the "r_d curves". In early 1970's, the r_d curves were developed by analyzing a limited number of site profiles. Those profiles consisted of 100 feet (33 m.) of sand, and were not representative of the broad ranges of natural site conditions, which involves variable and often layered stratigraphy, present at many of the liquefaction field performance case history sites employed in the development the triggering relationship of SEA1985.

The resulting non-representativeness of the limited number of sand-only sites was then further compounded because at that early juncture, "input" ground motions were typically having lower intensities compared to the ones commonly used today. The r_d curves of Seed and Idriss [10] are considered to be non-representative of the field case history sites and the shaking levels of many of the case histories in the SPT-based soil liquefaction triggering catalog. These r_d values tend to systematically overestimate CSR. That, in turn, causes the field case history data points to be plotted "too high" (vertically) on plots like Fig. 1(a), which then unconservatively biases (i.e.: shifts liquefaction triggering boundary curves up) the resulting triggering relationship.

Prof. H. Bolton Seed's last Ph.D. student, Dr. Ramin Golesorkhi, performed one-dimensional site response analyses using both the equivalent linear approach and also fully nonlinear models, to evaluate these r_d effects and also to assess the ranges over which the equivalent linear analyses would be an adequately reliable proxy for nonlinear behaviors in a variety of other applications as well. Dr. Golesorkhi applied his r_d-related response analyses mainly to monolithic sites again comprised entirely of sand strata. Fig. 3(a) shows the r_d curves developed by Golesorkhi [11] based on his analyses at sand-only sites. This figure is re-scaled to the same vertical and horizontal axes as the other site response analysis results shown in Fig. 3(b), (c) and (d) for direct comparisons.

Imai et al. [12] had also advanced the assessment of r_d, and performed a total of 143 one-dimensional site response analyses based on multiple reflection theory by using 5 different input motions (with maximum horizontal accelerations varying in the range of 0.052–0.233 g), for a suite of layered soil sites (with actual stratigraphy) to investigate this issue. Their results are also presented in Fig. 3(b) and again scaled to matching axes.

Cetin and Seed [13] performed a significantly larger number of site response analyses to real sites with real stratigraphy as described in the companion paper to approximate nonlinear response effects. Results of these 2153 site response analyses are presented in Fig. 3(c). These results differed from the other three sets of r_d curves presented in Fig. 3 as (1) all 50 of the analyzed sites were actual ones, they were from the larger liquefaction field performance case history database, variable conditions and stratigraphy were covered so they were considered to be "representative", and (2) a suite of 42 carefully selected input motions was applied to all 50 of these sites (the input motions cover the range from low to high intensities of shaking from low to high magnitude causative events, and they include actual strong motions that are representative of near-, mid- and far-field events in each magnitude range. In addition, for 53 of the liquefaction field case history sites where a nearby strong motion recording was available to be scaled for use as an "input" motion, actual site- and earthquake event-specific site response analyses were performed. Regressions were then conducted to develop r_d relationships as a function of: (1) site stiffness and stratigraphy, (2) levels and intensity of shaking, (3) causative earthquake magnitude (as a proxy for duration effects), and (4) depth.

The dark dots in Fig. 3(d) show the middle values of the early recommended r_d curve of Seed and Idriss [10], which was not magnitude dependent. This early curve was developed from stiff monolithic (sand) sites lacking of layering or stratigraphy, and lower levels of shaking. Moreover, the associated range is narrow and does not span as broadly as the other three suites of analysis results. The differences are significant at the relatively shallow depths of principal interest for back-analyses of the liquefaction field performance case histories. As shown in Table 6 of the companion paper of Cetin et al. [5], the mean depth of critical strata tends to be in the order of approximately 5 m for the liquefaction field performance case history database.

The suite of four solid lines in Fig. 3(d) present the r_d curves developed and recommended by Idriss [14]. According to the information provided by Idriss and Boulanger [7], r_d curves of Idriss [14] were developed by performing one-dimensional equivalent linear seismic site response analyses. In these analyses, suites of input motions of three different magnitudes (M_w = 5.5, 6.5 and 7.5) with varying intensities were applied as input motions to six soil profiles, to conduct a total of 512 seismic site response analyses. Five of these six sites were again monolithically comprised of 100 feet (33 m.) of sand, underlain by "rock". Thus, it is considered they are non-representative of the liquefaction case history database sites, and they again produce overly "stiff" r_d behaviors. The sixth site was a modification of the USGS strong motion recording site at La Cienegain Los Angeles, California. This is a site with actual stratigraphy, but the V_s profile at this site was "modified", and due to this modification it produces even a "stiffer" r_d behavior (r_d values further to the right). Additionally, the "representative" r_d curves developed based on the results of these analyses were not selected at the mean or median values, but rather at the 65th-percentile values. This selection further shifted the resulting r_d curves further to the right and it is not complying with the use of mean input parameters within the maximum likelihood framework employed to develop a liquefaction triggering relationship.

As shown in Fig. 3, r_d curves of Idriss [14] are not in good overall agreement with the curves developed by the other three research groups, and they produce values that are biased to the high side at all depths.

An important pair of postulates affecting this and other elements of back-analyses of liquefaction performance field case histories for purposes of developing liquefaction triggering relationships are listed as follows;

Postulate 1. It is often true that decisions and approximations that would be "conservative" in forward engineering analyses of actual projects (e.g. over-estimation of r_d, and of resulting CSR values), are instead un-conservative when applied to the back-analyses of field performance case histories for purposes of developing triggering relationships.

As an example here, the over-estimation of r_d (and of CSR) that resulted from using curves developed for the non-representative and overly "stiff" site conditions would have been conservative in a forward analysis for an actual engineering project. But in back-analyses of liquefaction performance field case histories, the overestimation of r_d (and of resulting CSR's) serves instead to displace the plotted case histories vertically upwards on the eventual "boundary curve" plots (e.g. Fig. 1(a), (b) and (c)), producing an unconservative bias in the triggering relationships developed based on these data. This same principal applies to multiple other parameters and relationships, not just r_d and CSR, and so it will be discussed further throughout this manuscript.

Postulate 2. Engineers are often taught that it is important to "repeat the same mistakes going forward (executing engineering analyses of real projects) as were made going backwards (e.g.: back-analyzing field case histories for development of triggering relationships)". But it does not guarantee that errors or bias in the back-analyses will be suitably mitigated in forward engineering analyses for a specific site or engineering project.

Unconservative bias in back-analyses is not necessarily mitigated (or counter-balanced) by performing forward analyses using identical protocols. The overall bias from inappropriate back-analyses is largely "averaged" into the relationships developed, but forward analyses will be applied to a specific project site and conditions rather than to an "average" site with average conditions. It is true that some counter-balancing occurs if the "simplified" (e.g. the r_d-based) approach is used

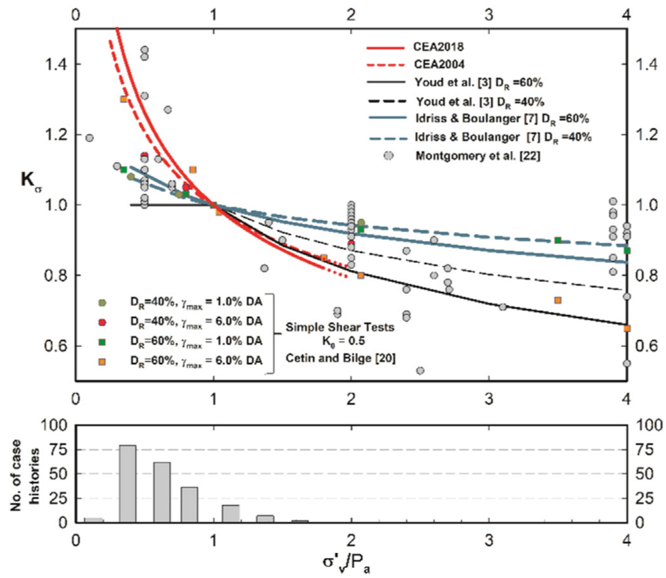

Fig. 4. The recommended K_σ relationships of (1) Youd et al. [3] as appended to the triggering relationship of SEA1985, (2) BI2012, and (3) CEA2018.

to evaluate CSR's in situ for forward analyses of an actual project, and if the same r_d curves are employed as were used for the back-analyses upon which the triggering curves are based. But the degree of counter-balancing is variable, and dependent upon the juxtaposition of actual site conditions vs. the "average" conditions in the liquefaction field performance database.

More importantly, for sites and projects of sufficient importance, or sufficient challenge and complexity, that site-specific seismic site response analyses (or even site-specific site and soil-structure interaction seismic response analyses) are warranted, in-situ CSR's are then directly (and correctly) calculated in these more detailed site- and project-specific forward analyses (employing higher-order seismic response analyses to directly calculate CSR at each point of interest, rather than employing the "simplified" r_d curves approach), and thus no counter-balancing (or compensating) error occurs in the forward analyses. This, in turn, means that the unconservative bias associated with the use of non-representative r_d curves in back-analyses and formulation of the triggering relationship is not totally compensated for in large, challenging, or complicated projects that can often be among those of greatest importance (e.g. large dams, major buildings, significant infrastructure, challenging site conditions, etc.). This issue was also recognized by Boulanger and Idriss [19] and their liquefaction triggering correlations were recommended to be used only with the same relationships that were used in the development of their correlations (e.g.: only with their r_d relationship; but not with a site-response-estimated r_d or CSR).

2.2. Differences in K_σ relationships

The second issue addressed in Table S1 is the development (or selection) of K_σ relationships for normalization of CSR's at arbitrary effective overburden stresses to "equivalent" CSR that would just trigger liquefaction at an effective vertical stress of σ'_v = 1 atm by using Eq. (1). K_σ is directly a function of vertical effective stress yet some studies also use relative density (or $N_{1,60,CS}$) while defining this stress scaling factor.

$$CSR_{\sigma'_v=1atm.,\alpha,M_w} = \frac{CSR_{\sigma'_v,\alpha,M_w}}{K_\sigma} = \frac{\tau_{\text{hv,cyclic,average}}}{\sigma'_v}\frac{1}{K_\sigma} = 0.65\cdot\frac{a_{\max}}{g}\cdot\frac{\sigma_v}{\sigma'_v}\cdot r_d\cdot\frac{1}{K_\sigma} \quad (1)$$

The early triggering relationships (e.g. Seed [15] etc.) were not normalized for vertical effective stress, because it was tacitly recognized that they were based on liquefaction field performance case histories for "shallow" soil strata; as discussed previously. The relationship of SEA1985 was the most recent of these early relationships, and it was also not normalized for K_σ effects. However, it had emerged as an important issue in the mid-1970's and the early 1980's because triggering relationships were increasingly being applied to analyses of major earth dams (with potentially liquefiable strata under high effective overburden stresses). Laboratory research and principles of critical state soil mechanics show that soils of a given density (or normalized SPT penetration resistance) would be more likely to liquefy at the same CSR if they were under higher initial effective overburden stress, because the higher effective stress would suppress cyclic dilation and increase cyclic compression on shear stress reversal during cyclic loading.

Accordingly, research efforts were undertaken to develop K_σ relationships based on laboratory undrained cyclic testing. By the second half of 1980's, (1) a body of laboratory test data were available, and K_σ relationships were being proposed by different sets of experts, and (2) it was becoming increasingly common practice to assume that the "shallow" liquefaction triggering relationships developed based on field performance case history data were suitably representative for conditions conforming to $\sigma'_v \leq 1$ atm, and then K_σ relationships would be applied to these triggering "curves" to extrapolate in order to evaluate liquefaction resistance (e.g. CRR) at higher initial effective stresses (greater depths) where $\sigma'_v > 1$ atm.

The NCEER Working Group (Youd et al. [3]) proposed a K_σ relationship of this type for application to the triggering relationship of SEA1985. This K_σ relationship was based on cyclic undrained laboratory test data, and K_σ was a function of both σ'_v and also relative density. That was a suitable approach based on the state of knowledge at that time. This K_σ relationship is shown in Fig. 4.

Boulanger [16], Boulanger and Idriss [17] and Idriss and Boulanger [7,18,19] produced less conservative K_σ relationships for extrapolating triggering curves that had been developed based on shallow data to higher overburden stresses. These K_σ relationships were again based on interpretations of available laboratory cyclic test data and are a function of both σ'_v and also $N_{1,60,CS}$. These relationships provide for a lesser rate of decrease in liquefaction triggering resistance (CRR) with increasing σ'_v. This is also a valid approach.

Cetin et al. [1,5] recognized the difficulties and uncertainties involved in extrapolating the results of (1) undrained cyclic triaxial tests, and (2) of undrained cyclic simple shear tests with uni-directional horizontal loading, both with uniform cycles, for evaluation of the fully-multi-directional (in a horizontal plane) and non-uniform cyclic shear loadings of principal interest for prediction of field behavior in real earthquakes. Accordingly, they preferred developing a K_σ relationship as part of the overall probabilistic regressions of the full liquefaction triggering field performance case history database, which intrinsically embodies these three-dimensional and irregular "real" world seismic cyclic loadings.

The resulting K_σ relationship of Cetin et al. [5] is a function of σ'_v only, and it is shown by the solid red line in Fig. 4. An additional variable was regressed, as part of the overall regression of the field case history data, to investigate whether an effect of $N_{1,60,CS}$ could be discerned from the large field case history database. However, only a very slight influence of $N_{1,60,CS}$ on K_σ could be distinguished by this effort.

Cetin and Bilge [20] performed a large number of undrained cyclic simple shear tests to investigate K_σ, and discovered that this scaling factor is strongly a function of the cyclic shear strain level at which "triggering" of liquefaction or cyclic mobility is deemed to have occurred. If the conventional levels of laboratory cyclic shear strain are employed as "triggering strain" criteria for all tests (regardless of density or $N_{1,60,CS}$), then the K_σ curves of Youd et al. [3], Idriss and Boulanger [7] and Cetin et al. [5], appear generally reasonable in form. However, the field case history data likely represent differing levels of cyclic strains. It should also be noted that denser strata (with higher $N_{1,60,CS}$ values) typically requires more limiting cyclic shear strain for triggering of liquefaction as discussed by Cetin and Bilge [21]. It could then be inferred, based on the laboratory data set of Cetin and Bilge [20] that a slightly "inverted" relationship between K_σ and $N_{1,60,CS}$ might be expected; with the effect that increasing $N_{1,60,CS}$ values affects K_σ in a manner slightly inverse to the trends posited by Youd et al. [3] and others, as was actually observed in the regression of the liquefaction triggering field case history database. However, there still exist significant uncertainty associated with this issue. Thus, pending additional investigation by other researchers, it was decided to take a middle position in developing the triggering relationship of CEA2018 and employ a K_σ relationship (1) that is a function of σ'_v only, (2) that is regressed from the overall field performance case history database, and (3) that is not necessarily recommended to be used outside the vertical effective stress range of the field performance case history database. As discussed in the companion paper, the K_σ relationship of Cetin et al. [5] is employed internally within the development of the triggering relationship, and it is used mainly to correctly "center" (or normalize) the relationship to a reference effective overburden stress of $\sigma'_v = 1$ atm. Extrapolation of the resulting normalized triggering relationship can then be accomplished by means of any of a number of other proposed K_σ relationships. This will be discussed further.

The histogram given in the lower part of Fig. 4 shows the distribution of vertical effective stresses in the field case history database of Cetin et al. [6], which is for these purposes very similar to that of Idriss and Boulanger [7]. The case history regression-based K_σ relationship of Cetin et al. [5] agrees reasonably well with the relationship proposed by Youd et al. [3] and available cyclic laboratory test results as presented in Fig. 4. On the other hand, The K_σ relationship proposed by Idriss and Boulanger [7] shown in Fig. 4 does not employ field case history data. Instead, it is based on the assessment of undrained cyclic laboratory test data and engineering judgment. For the purpose of enabling a direct visual comparison, available cyclic laboratory test results as compiled and interpreted by Montgomery et al. [22], which would be later referred by Boulanger and Idriss [8] to be in reasonable agreement with their K_σ relationship, are also shown in Fig. 4, along with additional data developed by Cetin and Bilge [20] based on undrained cyclic simple shear testing. The data set gathered and compiled by Montgomery et al. [22] was based on both cyclic triaxial and cyclic simple shear testing, with a majority of the data developed by cyclic triaxial testing.

There are significant uncertainties with regard to interpretation of cyclic triaxial test data for purposes of development of liquefaction triggering K_σ relationships for forward application to field conditions that will involve both non-uniform and three-dimensionally, randomly directionally varying in plan view (3-D) cyclic simple shear loadings. There are lesser levels of uncertainty in employing the more limited one-directional uniform cyclic simple shear test data that make up part of the data set compiled by Montgomery et al. [22] and all of the data developed by Cetin and Bilge [20], but these uncertainties are not negligible.

The K_σ curves of Youd et al. [3] were developed by a large group of researchers involving many of the world's top liquefaction experts. It is suggested that engineers might consider this overall situation (and Fig. 4) and then judge that the Youd et al. [3] curves still appear to be a reasonable and defensible basis for forward analyses for very high σ'_v. It is the view of the authors of this paper that more research is needed here, and that in the face of current uncertainty it would be good to avoid potentially serious unconservatism; especially at very high effective stresses, as those high stress levels often occur in conjunction with major dams or other critical and/or potentially high risk structures.

2.3. Differences in truncations of K_σ relationships

Truncation of K_σ is the third issue addressed in Table S1. As discussed earlier, it had often been assumed that the earlier "shallow" liquefaction triggering relationships (e.g. SEA1985) were appropriate to $\sigma'_v \leq 1$ atm, and as a result it had become somewhat standard practice to assume that those triggering curves were representative for $\sigma'_v \approx 1$ atm, but the field case history database of SEA1985 was actually more closely correlated with an overall average field case history stress level of $\sigma'_v = 0.67$ atm. Assuming that it was 1 atm, and then appending a K_σ relationship from 1 atm to progressively higher values of σ'_v had approximately the equivalent effect of "truncating" K_σ to $K_\sigma \leq 1.0$, as illustrated in Fig. 4 for the relationship recommended by Youd et al. [3]. Based on Postulates 1 and 2, the truncation of K_σ would be conservative for forward analyses of actual projects with low effective stresses. Yet, for back-analyses of liquefaction field case histories and for subsequent development of liquefaction triggering relationships, this type of truncation creates a significant unconservative bias in the resulting triggering relationships. Truncating at $K_\sigma \leq 1.0$ has the effect of increasing the overall average "normalized" CSR values which were back-calculated from the case histories, because (1) a majority of those cases had $\sigma'_v < 1$ atm, and thus $K_\sigma > 1.0$, and (2) in back-analyses the back-calculated CSR is multiplied by $1/K_\sigma$ before plotting the results in the triggering boundary curve plots of Fig. 1. That, in turn, means that truncation of K_σ biases the triggering boundary curves unconservatively by pushing CSR values vertically upwards in plots like those of Fig. 1(a) through (c).

Cetin et al. [1] addressed this issue and did not truncate K_σ values for back analyses of case histories and subsequent development of their triggering relationship to mitigate truncation error. However, a limit of $K_\sigma \leq 1.5$ was then recommended at very shallow depths for forward engineering assessments. Similarly, Cetin et al. [5] specifically did not apply a truncation of K_σ in processing the case history back analyses. However, for forward (design) assessments, it is recommended that K_σ to be limited (truncated) to $K_\sigma \leq 1.6$. This affects only soils at very shallow depths, and very low effective overburden stresses ($\sigma'_v < 0.25$ atm). Only 5 of the 210 field performance case histories back-analyzed by Cetin et al. [5] would have been affected by this $K_\sigma \leq 1.6$ truncation if it had been employed in the development of the triggering relationship, but it was not.

Idriss and Boulanger [23] elected to truncate their K_σ relationship at $K_\sigma \leq 1.0$, and later Idriss and Boulanger [19] truncated at $K_\sigma \leq 1.1$. Out of 230 cases 47 are affected (and unconservatively biased) due to this truncation. Without truncation these 47 case history points would have produced normalized CSR values that would have plotted lower on the CSR vs. $N_{1,60,CS}$ triggering curve plots. Examining their overall field case history database, it is observed that K_σ truncation effects appear to be more pronounced for $N_{1,60,CS} > 20$ blows/ft, and the resulting triggering curves would thus likely be somewhat more affected (unconservatively biased) at this larger range of $N_{1,60,CS}$ values due to this truncation.

There is no physical reason or basis for truncation of K_σ in back-analyses and development of triggering relationships. More significantly, it is simply a straightforward imposed constraint (or bias) that produces unconservative bias in the resulting triggering relationships. Both Postulates 1 and 2 apply here, and either (1) not correcting for K_σ effects (failing to "center" or normalize the triggering relationship correctly at $\sigma'_v = 1$ atm) as is commonly done when extrapolating the "shallow" relationship of SEA1985 to higher levels of effective overburden stress, or (2) truncating at either $K_\sigma \leq 1.0$ or $K_\sigma \leq 1.1$, as was done in the development of the triggering relationships of Idriss and Boulanger [23] and of BI2012, respectively, are considered as sources of unconservative bias in the liquefaction triggering relationships.

2.4. Differences in probabilistic treatment used in the development of the triggering relationships

Probabilistic treatment in the development of the triggering relationships is the fourth main difference between the three relationships addressed in Table S1. SEA1985 did not perform formal probabilistic regressions. Instead they plotted the data in several "bins", separating them based on fines contents, and then hand-drew three sets of boundary curves for data with (a) FC ≤ 5%, (b) 5% < FC < 35%, and (c) FC ≥ 35% based on engineering judgment. Prof. H. Bolton Seed had targeted these three boundary curves at approximately a 10–20% probability of liquefaction (Seed RB (1988) personnel communication), but he recognized that (1) the sparseness of the available field performance case history data, and (2) the lack of a formal probabilistic regression, raised questions as to the degree to which this target was actually met.

Boulanger and Idriss [4] state that their liquefaction triggering boundary curves are based on regressions performed by the maximum likelihood method. The formal application of the maximum likelihood method would require at least the following two attributes to be incorporated in the required assessments and analyses: (1) the regressions would have to be performed using functional shapes (or equational forms) providing both (a) suitable general characteristics and also (b) sufficient (regressable) degrees of freedom so that the overall relationship could suitably adapt its shape and position to conform to the dictates of the data, and (2) the regressions would have to employ correct and appropriate treatment of both (a) model error or uncertainty, and (b) input parameter uncertainty.

As shown in Fig. 1(c), the functional shape employed for the development of BI2012 "boundary curves" has an equation of a "bent" shape much like a boomerang, with somewhat more curvature near the middle and less at the two ends. This selected functional shape (equational form) has only one single regressable degree of freedom (model coefficient) which named as C_0 by Boulanger and Idriss [4]. As a result, based on regression, this shape can only translate in one single direction (vertically), but it cannot independently translate in two orthogonal directions (e.g. laterally and vertically), and rotate or adjust its bend or curvature. This lack of sufficient degrees of freedom represents a "stiff" regression, in which the resulting regressed relationship cannot well adapt itself to conform to the dictates of the database. This violates the first of the two requirements of a maximum likelihood regression as set forth above.

A second issue is that the input parameter uncertainty of each case history needs to be consistently incorporated, and then both input parameter uncertainties and overall model uncertainty need to be suitably handled. The performance of a maximum likelihood regression is governed by the need to correctly model both (a) model error, ε, and (b) input parameter variance or uncertainty of individual case histories (i.e.: uncertainties in $N_{1,60,i}$, $CSR_{\sigma'_v,\alpha,M_w,i}$, $M_{w,i}$, FC_i,$\sigma'_{v,i}$ of the i^{th}case history, represented by standard deviations designated as $\sigma_{N_{1,60},i}$, $\sigma_{\ln(CSR_{\sigma'_v,\alpha,M_w}),i}$, $\sigma_{\ln(M_w),i}$, $\sigma_{FC,i}$ and $\sigma_{\ln(\sigma'_v),i}$ etc.). Neither the model error nor the variance or uncertainty of individual case history input parameters were fully and systematically modeled within the maximum likelihood regressions performed by BI2012. Instead the standard deviation of the model error was assumed to be 0.13. As presented and discussed in Cetin [24], the model coefficients of liquefaction triggering relationships are also inter-correlated; hence assuming a value for one model coefficient (e.g.: assuming standard deviation of model error, σ_ϵ as 0.13) inevitably constrains the other model coefficients (e.g.: C_0 in BI2012), even if an attempt is made to independently (but actually conditionally) regress them due to intercorrelation of these coefficients.

Cetin et al. [5], in contrast, repeated the same level of effort that had previously been devoted to the estimation of individual input parameter error (or uncertainties) in processing and back-analyses of the field performance case histories by Cetin et al. [1]. The results differed slightly from the 2004 estimates due primarily to (1) differences in the case histories included in the database, and (2) differences in some of the details involved the back-analyses of the case histories. As discussed in the companion paper of Cetin et al. [5], it was then necessary to appropriately distribute the overall uncertainty between input parameter uncertainty and model error. An element of the solution here was to extend the regression (still by the maximum likelihood method) to include determination of the most appropriate (maximum likely best fit) distribution between input parameter uncertainty and model error. This was a challenging analytical effort. In the end, a total of seven model fitting coefficients (θ_1 to θ_6 and σ_ϵ) were regressed in a manner similar to that employed by Cetin et al. [1], and an eighth model coefficient (θ_7) addressing the relative distributions of input parameter uncertainty and model error was also (simultaneously) regressed in the same overall maximum likelihood regression as discussed in the companion manuscript of Cetin et al. [5].

As shown in Fig. 1(b) and (c) the resulting shapes of the median (P_L = 50%) boundary curves for the two regressed relationships differ significantly, and so do the associated contours of P_L = 5%, 20%, 50%, 80% and 95% for these two relationships. The "spread" of these probabilistic contours is a representation of the "uncertainty" (or model errors) of these two triggering relationships.

Fig. 5 is an enlarged view of Fig. 1(c), and it is annotated with a vertical dashed line at $N_{1,60,CS}$ = 20 blows/ft, so that the impacts of the three principal differences in the regression performed by BI2012 can be more clearly examined.

The first of these is the failure of the mean (P_L = 50%) triggering boundary curve to suitably "fit" the field case history data at low values of $N_{1,60,CS}$ ≤ 20 due primarily to the overly "rigid" equational shape selected and the lack of sufficient degrees of regressible model fitting parameters. Upon close inspection, even when weighting factors of 0.8 and 1.2 are applied to the "Liquefied" and "Non-Liquefied" cases, respectively, the uneven (unconservatively biased) positioning of P_L = 50%boundary curve in the range of $N_{1,60,CS}$ ≤ 20, relative to the data as developed and plotted by BI2012, can be visually observed.

Re-examining Fig. 1(b) and (c), it can be noted that both probabilistic relationships have P_L-based boundary curves that are relatively

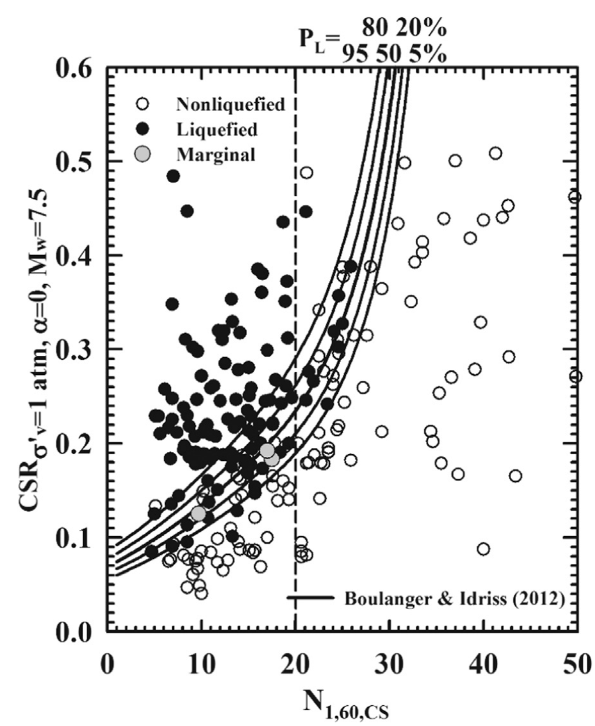

Fig. 5. The probabilistic triggering relationship boundary curves of BI2012, and their field case history data points.

closely spaced (indicating relatively low levels of uncertainty) in their bottom left corners. As the curves begin to rise, the uncertainty (and thus also the "spread" between the P_L-based curves) begins to increase. In the Cetin et al. [5] relationship, this spread continues to further increase as the curves rise to the top right extent of the figure. But in the BI2012 relationship, the spread between the P_L-based curves initially increases, and then begins to decrease again and the curves draw closer together in the top right corner.

Additional investigators have performed similar probabilistic regressions for liquefaction triggering relationships, employing a variety of different field liquefaction performance case history data sets. Significant examples include: Liao et al. [25], Youd and Noble [26], Toprak et al. [27] and Juang et al. [28].

Figs. S2(a) and S2(b) show two of these four additional relationships. Fig. S2(a) shows the relationship developed by Liao et al. [25], which was a noteworthy early effort of this type, by early experts in the field of geotechnical probability and reliability. Fig. S2(b) shows the more recent relationship developed by Juang et al. [28] by using the Bayesian mapping approach. All four of these previous relationships developed suites of probabilistic boundary curves with (1) significantly higher overall uncertainty, and (2) all four of them produced boundary curves with the lowest uncertainty in the lower left corner (at low penetration resistances) and with then progressively increasing model uncertainty towards the upper right corner, where the highest uncertainty occurs at the highest penetration resistances.

The authors of this current paper have, as an ensemble, been personally involved in developing a number of the liquefaction triggering field case histories in the databases discussed. An important lesson from those field investigations is the relatively high level of difficulty often involved in determining whether or not a site "triggered" with regard to liquefaction when penetration resistances are high ($N_{1,60,CS} \geq 20$–25 or so), because (1) these higher blowcount soils have limited cyclic strain potential, and (2) they undergo lesser levels of post-earthquake volumetric reconsolidation and so exude lesser levels of boil fluids and associated soil ejecta. As a result, uncertainty is intrinsically higher in this upper blowcount range as a result of uncertainty in characterizing observed field performance with regard to triggering (or non-triggering).

2.5. Differences in probabilistic treatment in the development of K_σ, K_{Mw}, and fines adjustments ($\Delta N_{1,60}$) relationships

Probabilistic treatment in the development of "secondary" relationships dealing with (1) effective overburden effects (K_σ), (2) causative magnitude (duration) scaling effects (K_{Mw}), and (3) fines adjustments ($\Delta N_{1,60}$), is the fifth of the major issues addressed in Table S1. SEA1985 employed no formal probabilistic approaches in the development of their main triggering curves, and they also used no formal probabilistic approaches in the development of their relationships for these three additional issues.

BI2012 preferred not to employ probabilistic regressions to develop, or assist in the development of, "secondary" relationships dealing with (1) effective overburden effects (K_σ), (2) causative magnitude scaling effects (K_{Mw}), and (3) fines adjustments ($\Delta N_{1,60}$). A combination of non-probabilistic regressions and engineering judgments were instead used to develop these three secondary relationships, and the resulting relationships are discussed in Table S1.

Cetin et al. [5] followed a significantly different set of approaches here. All three relationships (K_σ, K_{Mw}, and $\Delta N_{1,60}$) were developed as part of a combined overall regression of the full field case history database along with the development of other triggering relationship elements (e.g. the probabilistic triggering boundary curves, etc.). As a result, (1) the large field performance case history database was a dominant contributor to the defining of these "secondary" relationships, and (2) the resulting "secondary" relationships were intrinsically compatible with the overall probabilistic regressions performed, and the resulting probabilistically-based triggering relationships. Two of the resulting case history-based relationships (K_σ, and K_{Mw}) were then checked and were confirmed to agree suitably well with fundamentally different and independently developed laboratory testing-based relationships and data, as discussed previously.

2.6. Differences in transparency of case history processing and documentation

The sixth issue addressed in Table S1 is "Transparency", and with it the corollary issue of appropriate technical review. Transparency refers to the adequacy and transparency of documentation of (1) the background source data, (2) the selection, processing and analyses of those data, and (3) the many details and judgments made at each stage along the way in developing these types of complicated triggering relationships. Better, or worse, background documentation and transparency does not directly affect the likely bias of a given triggering relationship. But it makes it easier for other engineers and researchers to understand, and to back-check and review, the development of these types of important relationships.

Cetin et al. [1] tried to be comprehensively transparent in the presentation of the background development of their triggering relationship. As a result, it was studied by other engineers and investigators, and issues or errors were identified and challenged. As a consequence, Cetin et al. [5] were able to revise their derivations, employing a field case history database that was well-checked and vetted by other experts. That is an ideal outcome; and the authors of this paper would suggest that full and transparent documentation should be a fundamental requirement for all similar efforts to develop engineering analysis tools for important problems with broad ramifications for public safety.

SEA1985 had also provided what was, at that time, an open and transparent documentation of their data and analyses. Their case history database was significantly smaller than the more recent efforts, and the relationship developed was "simpler" and lacked a formal probabilistic basis. The level of documentation transparency was not as extensive as that of Cetin et al. [1], and hence full and complete independent examination of all details was not possible for a number of their case histories, but most cases could be suitably checked and examined. Moreover, the following steps taken in development of the triggering relationship were clearly explained.

The work of Idriss and Boulanger [23] could not be properly checked or technically reviewed due to lack of documentation. The missing background documentation was later presented as a U.C. Davis research report by Idriss and Boulanger [7]. With the release of this 2010 document, it was possible to know which case histories were included in the development of their liquefaction triggering relationships. Relatively complete background details were presented, and that could then be traced and checked for 101 of the 230 case histories used in their relationships. However, the remaining 129 case histories are difficult to be fully evaluated and back-analyzed.

2.7. Additional differences between the three triggering relationships

Table S2 lists 11 additional issues and factors that result in differences between the three triggering relationships. They are not all of the remaining factors. Instead they are selected either because they can make a potentially non-negligible difference in certain ranges of applications, or because engineers tend to ask about them and their effects. The issues discussed in Table S2 are generally less significant than those of Table S1. As this manuscript is over length, an indepth discussion of these additional differences are presented in Cetin et al. [6] which can be accessed online at http://users.metu.edu.tr/ocetin/Database_Report_2016.pdf, and they will not be repeated in full herein. Instead, only two of the additional eleven issues will be briefly discussed here. The additional factors discussed in Table S2 are numbered 7 through 17. Of these, Factor No's. 13 and 16 will be discussed below.

2.8. Fines adjustment, ($\Delta N_{1,60,CS}$)

Each of the three sets of triggering relationships employs a correction (or adjustment) for effects of fines content. The fines corrections developed and adopted by SEA1985, BI2012, Cetin et al. [1] and CEA2018 are presented and compared in Fig. 6.

There were significant differences in the procedures employed to develop these fines corrections, and in the case history data sets upon which they were based. Seed et al. [2] had sparse field case history data, and they manually plotted the data (in CSR vs. $N_{1,60}$ space) with the data "binned" into three sets of cases with (1) FC < 5%, (2) 5% ≤ FC ≤ 35% (assumed to represent approximately FC = 15%), and (3) FC > 35%. They then drew lines, by hand, based on engineering judgement, to develop the three triggering boundary curves shown in Fig. 1(a). No formal regressions were performed. Prof. H. Bolton Seed later became concerned that subsequent accumulating data suggested that the resulting (inferred) fines adjustments were a bit too large, and he employed a slightly lower set of fines adjustments ($\Delta N_{1,60}$) in his final paper (Seed [29]).

The basis of Boulanger and Idriss fines correction scheme cannot be fully traced. The presentation in Idriss and Boulanger [19] indicates that they initially repeated this same "binning" process, employing the plotting of three sets of binned data and then the hand-drawing of several sets of boundary curves based on engineering judgment, as a basis for inferring their new fines corrections.

Cetin et al. [1,5] developed fines corrections based on the overall (formal) probabilistic regressions of the large field performance case history database, so that these fines corrections are the only set of formally regressed fines corrections among the three sets of triggering relationships examined in this paper. The purpose of performing formal regressions is to develop keener and more reliable insights than what can be obtained based on visual judgments.

The fines adjustments ($\Delta N_{1,60}$) of SEA1985, shown in Fig. 6, are a function of $N_{1,60}$ (or CRR) and they are the largest of the four fines adjustment relationships shown. The fines adjustment of Idriss and Boulanger [18,19] does not vary as a function of $N_{1,60}$, and it is of intermediate size (generally lower than that of SEA1985 and generally a bit higher than that of CEA2018, except at very high values of $N_{1,60}$). On the other hand, the fines adjustments of Cetin et al. were regressed based on the field case history database. Fig. 6 reveals that the fines adjustments of SEA1985 were indeed a bit on the large side, and that there is somewhat better (but imperfect) agreement between the fines adjustments of Idriss and Boulanger [18,19] and those of CEA2018.

As shown in Table 6 of the companion paper Cetin et al. [5] and Fig. S1, the corresponding difference is only approximately 2.4% in the resulting overall "median" fines corrected $N_{1,60,CS}$ values for the data sets of Idriss and Boulanger [7] and Cetin et al. [6]. These are relatively modest, but non-zero, differences and they would be expected to have relatively modest effects on the overall triggering relationships developed. It is important to employ fines adjustments compatible with the triggering relationship selected.

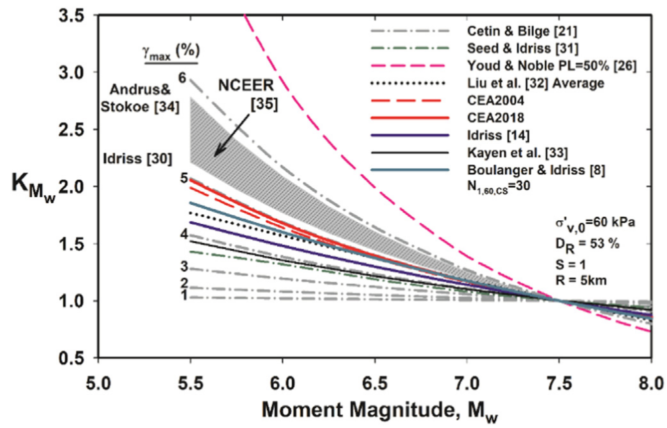

Fig. 7. Magnitude (duration) scaling factors.

2.9. Magnitude-correlated duration (K_{Mw}) correction

Scaling of the triggering relationships for numbers of equivalent uniform cycles of seismic loading (or duration of shaking) is another correction that affects liquefaction triggering assessments, particularly for small magnitude cases. Duration, or numbers of cycles, are correlated with causative earthquake magnitude, so the correction factor employed here is referred as K_{Mw}. As shown Fig. 7, there exist significant differences among K_{Mw} recommendations proposed by various research teams for very low magnitudes (e.g. M_w = 5.5), but differences can also be significant at very high magnitudes (e.g. M_w = 8.0 and greater).

The K_{Mw} relationships of (1) Idriss [30] which defines the lower bound of the range recommended by the NCEER Working Group (Youd et al. [3]) for application to the triggering relationship of SEA1985 and (2) BI2012 were both developed based on (i) laboratory undrained cyclic test data and (ii) processing of large numbers of strong ground motion recordings, and no use was made of the liquefaction triggering field case histories. The K_{Mw} relationships of Cetin et al. [1,5] are based on regressions of the large liquefaction triggering field case history

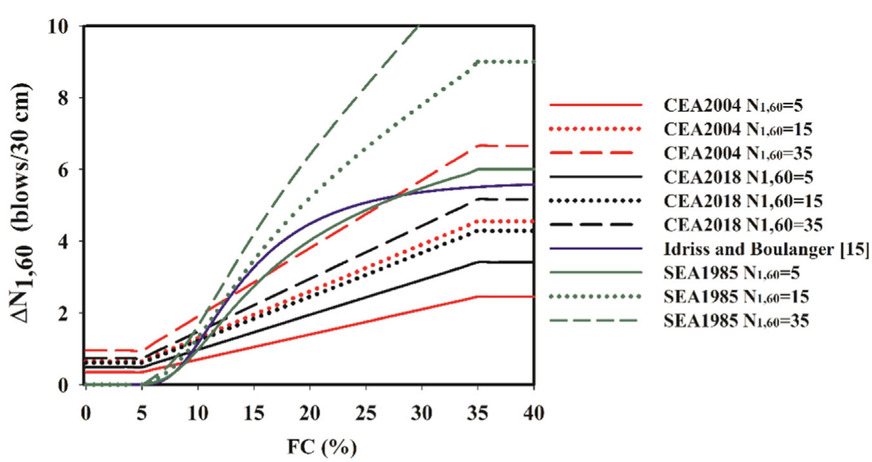

Fig. 6. Comparative illustration of fines correction.

databases, and make no use of laboratory data. As a result, these two sets of relationships are based on fully independent sets and types of data.

The relationship of CEA2018 is located between the relationships of Idriss [30] and Boulanger and Idriss [8], as shown in Fig. 7. There is relatively good agreement among these despite the very different approaches, and fully independent data sets, upon which they are based. In addition, all of the large field case history data sets discussed here have median values of magnitude approximately equal to 7.1. As a result, the impacts of K_{Mw} on differences between the triggering relationships is relatively small.

3. Conclusion

For a given $N_{1,60,CS}$ value, the corresponding cyclic resistance values (i.e.: CRR) associated with any target level of likelihood of liquefaction triggering based on the relationships of (1) SEA1985, (2) BI2012 and (3) Cetin et al. [5] are observed to be significantly different. These differences occur at essentially all locations on the triggering curves, but they are most pronounced at low $N_{1,60,CS}$ values. For conditions corresponding to σ'_v = 1 atm, the differences between the estimated CRR values reach as high as 50–80% in the critical region of $N_{1,60,cs}$ < 20 blows/ft within which the consequences of triggering of liquefaction can be especially significant due to low post-liquefaction strengths and high cyclic shear strain potential.

This paper has examined the principal sources and causes of differences between the three triggering relationships, addressing each source of differences in turn. It is now useful to summarize by addressing each of the three overall triggering relationships in turn.

3.1. SEA1985

SEA1985 was the last of the “first generation” of empirical triggering relationships based on field case histories, and it was the first essentially “complete” relationship of this type as it was the first comprehensive effort to address both (1) fines corrections, and (2) adjustments of measured SPT penetration resistances to account for variations in SPT equipment and procedures. Key attributes and issues associated with this early relationship include the following:

1. The field case history data set was sparse. Moreover, Seed et al. [2] had to accept and use some cases of lower quality, reliability or level of documentation (compared to the databases used in development of other two triggering relationships) due to the limited number of available cases. At the end, a total of 125 liquefaction field case histories were utilized in developing this triggering relationship.
2. The early “r_d” curves of Seed and Idriss [10] were used for back-analyses of the field case histories. These r_d curves had been developed based on one-dimensional site response analyses of simplified, monolithic, sand-only site conditions that were not representative of the more layered and complex site conditions present at many of the field case history sites. The acceleration levels applied to these sites were not sufficiently high as to encompass the levels of shaking of some of the case histories. Use of these non-representative r_d curves produced estimates of back-calculated CSR that were systematically biased to the high side, tending to push the resulting CSR values vertically upwards on the triggering plots, and producing a source of unconservative bias in the resulting triggering relationship.
3. No normalization for effective overburden stress was performed (no K_σ corrections were applied) because this triggering relationship was recognized to be generally applicable to “shallow” site conditions corresponding to most of the liquefaction triggering field case histories. Because the most “representative” vertical overburden stress of the overall case history database, and thus the triggering relationship as well, was more nearly σ'_v = 0.67 atm than σ'_v = 1 atm, not correcting for K_σ effects was largely equivalent to “truncation” of K_σ to $K_\sigma \leq 1.0$. Due to this “truncation”, CSR's of cases with σ'_v < 1 atm (a majority of the cases) move vertically upwards on the triggering plots and it introduced a significant source of unconservative bias developed relationship.
4. The early fines adjustments of this relationship were not developed based on regression, but instead they were estimated based on manual plotting of the field data and engineering judgment. The sparse available field data led to an initial level of fines adjustments that the late Prof. Seed later came to view as somewhat unconservative (too large) as additional liquefaction triggering field data continued to become available. That was later confirmed by the subsequent relationships developed by both Boulanger and Idriss [4] and by Cetin et al. [1,5] which developed smaller fines corrections based on the significantly larger field case history databases available to them.
5. There was no formal probabilistic basis for this triggering relationship. Thus, it is not known with any accuracy what level of probability of liquefaction triggering is represented by the “deterministic” triggering curve developed. Accordingly, this relationship cannot be used directly in performing probabilistic assessments of liquefaction triggering hazard, nor in associated/resulting risk evaluations.
6. This early triggering relationship was presented and documented in a manner that was open and transparent for its time, but the level of transparency was incomplete and so it was difficult to fully back-check some elements of the work.

3.2. BI2012

This relationship began as the Idriss and Boulanger [18,22] triggering relationship, and it has subsequently been modified to produce the current relationship of BI2012. Changes have been incremental, and the character of the overall relationship remains largely intact. Key attributes and issues associated with this relationship include the following:

1. Boulanger and Idriss largely accepted and adopted the significantly enlarged case history database of Cetin et al. [1], which involves 197 field performance cases, and then added 33 additional cases to develop a database of 230 cases. The result was a significantly larger database of generally higher overall quality compared to the one employed by SEA1985. On the other hand, some of the 33 cases added by Boulanger and Idriss (2010) subsequently failed to meet the screening criteria employed by Cetin et al. [6] and were not used in that study. However, overall the databases of Idriss and Boulanger [7] and Cetin et al. [6] were largely similar, and quality was generally good in both.
2. Similar to SEA1985, BI2012 also employed r_d curves that were developed based on analyses of overly “stiff” site conditions. These were newly developed r_d curves, but they had strikingly similar attributes to those previously employed by SEA1985, and the use of these non-representative r_d curves again produced estimates of back-calculated CSR that were systematically biased to the high side, tending to push the resulting CSR values vertically upwards on the triggering plots. This, again, introduced a source of unconservative bias in the resulting triggering relationship developed. This issue was also recognized by Boulanger and Idriss [19] and their liquefaction triggering correlations were recommended to be used only with the same relationships that were used in the development of their correlations (e.g.: only with their r_d relationship; but not with a site-response-estimated r_d or CSR).
3. Boulanger and Idriss were aware of the need for normalization for effective overburden stress effects, and so K_σ correction relationships were developed and applied. It was decided to truncate K_σ to a value of $K_\sigma \leq 1.1$ in processing their case history data. This

truncation affected 47 of the 230 case histories, and in a similar manner as the inadvertent truncation of K_σ implicit in the use of the triggering relationship of SEA1985. As a result, this truncation of K_σ again emerges a source of unconservative overall bias in this triggering relationship. Boulanger and Idriss developed their own K_σ relationship, and this relationship was also less conservative than previous relationships when applied to back-analyses of field case histories.

4. The initial fines corrections of Idriss and Boulanger [18] were again based on plotting binned sub-sets of the field case history data and engineering judgment, as SEA1985 had done. The resulting fines adjustments are significantly smaller (more conservative) than those of SEA1985, and they are on average somewhat larger than those of Cetin et al. [5]. These fines adjustments are not a function of $N_{1,60}$, as is the case for the fines adjustments of both SEA1985 and Cetin et al. [5], and this appears to result in locally unconservative (oversized) fines adjustments at very low $N_{1,60}$ values. Yet, this localized issue does not appear to significantly affect the overall triggering relationship at higher $N_{1,60}$ values.
5. Formal probabilistic regressions were performed to develop this overall triggering relationship, but an unconservative "fit" to the field data was observed due to "stiffly" regressed model and model uncertainty was underestimated at all locations. Both of these issues were particularly pronounced at higher values of $N_{1,60,CS} \geq 20$.
6. The K_σ relationship proposed by BI2012 was based on laboratory undrained cyclic test data, rather than regressions of the field case history database, and it differs from the K_σ relationship developed by Cetin et al. [5]. Compared to the other K_σ relationships, it is less conservative for (i) use in back-analyses of field case histories and development of triggering relationships, and (ii) forward engineering analyses for cases with very high effective overburden stresses.
7. Documentation and transparency was lacking when the initial relationship of Idriss and Boulanger [18,19,22] was first published. As a result, their work could not be properly evaluated and fully checked. Improved documentation was eventually provided by Idriss and Boulanger [7], but independent checking of the processing and back-analyses of the remaining 129 field case histories continues to be difficult to impossible.

3.3. CEA2018

1. Cetin et al. [1] developed systematic screening criteria to evaluate the suitability and reliability of potential candidate case histories. They applied those criteria to the case history database of SEA1985, and consequently eliminated 35 of the 125 cases. They next examined more than 200 potential new candidate field case histories, and based on the same screening criteria they adopted only 110 of those. Cetin et al. [6] deleted 3 cases, and then screened 33 additional cases added by BI2012 and found 13 of them to meet the screening criteria. These cases were added and producing a final database with 210 field performance case histories, all of them systematically screened for quality and reliability.
2. CEA2018 employed r_d curves of Cetin and Seed [13] which had been developed based on 2153 site response analyses of 50 actual sites from the case history database. These probabilistic based relationship was defined as a function of site conditions (layering and stiffness) as well as intensity and duration of shaking. They were used in the assessment of CSR in 162 of the field case histories. The remaining 48 case histories were back-analyzed by means of site- and event-specific one – dimensional site response analyses using (1) available nearby ground motion records from the actual earthquakes (scaled to transpose them to the local site), and (2) actual site stratigraphy and soil properties. The resulting back-calculated values of CSR for all 210 case histories were thus specifically unbiased best-estimates with case-specific uncertainties also evaluated. Moreover, they are compatible for use in forward engineering analyses employing either (1) "simplified" (r_d-based) evaluations of CSR's, or (2) direct determination of CSR's by means of event-specific seismic response analyses.
3. No truncation of K_σ was employed. Back-calculated CSR values for all case histories were therefore correctly normalized for effective overburden stress effects, and so were the overall database and the resulting triggering curves developed.
4. Fines corrections were developed based on formal probabilistic regressions of the large liquefaction field performance case history database.
5. Formal probabilistic regressions of the field case history database were performed to develop the resulting probabilistic liquefaction triggering relationship. Suitable degrees of freedom were available in the regression so that the triggering curves could conform themselves to the dictates of the large field database, and the very difficult and time-consuming task of evaluating and treating both individual parameter uncertainties as well as overall model uncertainty were suitably performed. As a result, this triggering relationship provides an unbiased framework for application to probabilistic liquefaction triggering and overall risk evaluations.
6. Because the initial work of Cetin et al. [1] was transparently well-documented, the back-analyses, assumptions, etc. involved in those studies were well examined by other researchers. Issues, questions, and challenges resulting from the examinations and reviews were thus able to be implemented to develop (1) a resulting database that is more closely reviewed, and (2) regressed updated triggering relationships that benefitted from both challenges and discussions of details of the previous work. A similar level of transparency and documentation is aimed for the updated work of CEA2018.
7. The K_σ relationship employed in development of the overall triggering curves was based on regression of the large field case history database, and so was specifically appropriate over the range of vertical effective stresses well represented in this database ($0.25\ \text{atm} \leq \sigma'_v \leq 1.8\ \text{atm}$). This K_σ relationship was used to "center" or normalize the overall triggering curves to a condition representative of $\sigma'_v = 1\ \text{atm}$ Having accomplished that in an unbiased manner, the resulting triggering curves can then be extrapolated to much higher effective vertical stresses employing suitable K_σ relationships of the engineer's choice. A discussion of the merits of various K_σ relationships for extrapolation to higher effective vertical stresses is presented in this paper, in conjunction with Fig. 4.
8. Documentation of the data and analyses involved in the development of the new triggering relationship of Cetin et al. [5] is again presented in a complete and transparent manner, so that other engineers and researchers can thoroughly examine and check all details.

Re-examining the trigging relationship plots of Fig. 1(a), (b) and (c) more closely, with the benefit of the discussions above, it can now be clearly seen that the case history data tend to plot higher on the plots in Fig. 1(a) and (b), than in Fig. 1(c). It can also be noticed that the triggering curves plot higher (especially for $N_{1,60,CS} < 20$). The main reasons for this are now hopefully well understood.

The triggering curves of both SEA1985 and BI2012 can be demonstrated to produce higher cyclic resistance ratio values (i.e.: unconservatively biased), especially at $N_{1,60,CS} < 20$. Despite a number of other relatively more minor issues, the governing factors leading to this unconservatism are the use of unrepresentatively i) higher r_d and ii) lower K_σ values in the processing of case history data.

This unconservatism can be expected to be most significant for engineering projects where, (1) critical strata have representative values of $N_{1,60,CS} < 20$, (2) site-specific seismic site response (or site response and soil-structure interaction) analyses are performed to directly calculate CSR values, rather than using the "simplified (r_d-based) approach, and/or (3) liquefaction of soils with σ'_v significantly greater than 1 atmosphere is of potential concern.

As a concluding remark, one of the most significant underlying messages of this manuscript is likely the importance of fully transparent documentation of the background details and data involved in the types of back-analyses and regressions, etc. employed in the development of these complex types of engineering analysis tools. This enables the other engineers and researchers (and oversight agencies) to fully review and understand the work, which is important for engineering analysis tools with significant ramifications with regard to public safety. That lesson is already being implemented. A multi-year Next Generation Liquefaction (NGL) program coordinated through the Pacific Earthquake Engineering Research Center (PEER) is now underway and involving an unusually large number of researchers in an effort designed to develop improved liquefaction triggering relationships. The NGL effort is currently targeted at producing new triggering relationships over the next five years, or so, and experience from the NGA program suggests that (1) there may be some delays, and (2) the eventual results are likely to be well-reviewed and well-checked new engineering analysis tools, with good communal support within both the research and practice communities.

In the meantime, engineers will continue to have to sort through the thicket of confusion surrounding the existing liquefaction triggering relationships. It is the hope of the authors that the materials presented in this paper, and in the companion paper by Cetin et al. [5], will be helpful in that regard.

Acknowledgements

The authors are deeply grateful to the many engineers and researchers who developed the invaluable liquefaction triggering field performance case history data upon which these types of correlations are based. We are also grateful to the many engineers and colleagues who encouraged this current work, and whose discussions and comments were of great value.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.soildyn.2018.03.013.

References

[1] Cetin KO, Seed RB, Der Kiureghian A, Tokimatsu K, Harder Jr LF, Kayen RE, et al. SPT-Based probabilistic and deterministic assessment of seismic soil liquefaction potential. ASCE J Geotech Geoenviron Eng 2004;130(12):1314–40.

[2] Seed HB, Tokimatsu K, Harder LF, Chung RM. The influence of SPT procedures in soil liquefaction resistance evaluations. J Geotech Eng ASCE 1985;111(12):1425–45.

[3] Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, et al. Liquefaction resistance of soils. Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. J Geotech Geoenviron Eng 2001;127(10):817–33.

[4] Boulanger RW, Idriss IM. Probabilistic standard penetration test–based liquefaction–triggering procedure. J Geotech Geoenviron ASCE 2012;138(10):1185–95.

[5] Cetin KO, Seed RB, Kayen RE, Moss RES, Bilge HT, Ilgac M, et al. SPT-based probabilistic and deterministic assessment of seismic soil liquefaction triggering hazard. Soil Dyn Earthq Eng 2017. [in review].

[6] Cetin KO, Seed RB, Kayen RE, Moss RES, Bilge HT, Ilgac M. et al. Summary of SPT-Based field case history data of the updated 2016 database. METU Soil Mechanics and Found Eng Research Center. Report no: METU/GTENG 08/16-01; 2016.

[7] Idriss IM, Boulanger RW. SPT-based liquefaction triggering procedures. (Report UCD/CGM-10/02). Davis, CA: Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California; 2010. p. 136.

[8] Boulanger RW, Idriss IM. CPT and SPT based liquefaction triggering procedures. (Report No. UCD/CGM-14/01). Davis, CA: Center for Geotechnical Modeling, Department of Civil and Environmental Engineering, University of California; 2014. p. 134.

[9] Seed HB, Tokimatsu K, Harder LF, Chung RM. The influence of SPT procedures in soil liquefaction resistance evaluations, (Earthquake Engineering Research Center Report No. UCB/EERC-84/15). Berkeley, CA: Dept. of Civil and Environmental Engineering, University of California at Berkeley; 1984.

[10] Seed HB, Idriss IM. Simplified procedure for evaluating soil liquefaction potential. J Soil Mech Found Div, ASCE 1971;97:1249–73. [SM9, Proc. Paper 8371].

[11] Golesorkhi R. Factors influencing the computational determination of earthquake-induced shear stresses in sandy soils [Dissertation submitted in partial fulfillment of the requirement for the degree of doctor of philosophy]. University of California at Berkeley; 1989.

[12] Imai T, Tonouchi K, Kanemori T. The simple evaluation method of shear stress generated by earthquakes in soil ground, report no 3. Bur Pract Geol Investig 1981:39–58.

[13] Cetin KO, Seed RB. Nonlinear shear mass participation factor (r_d) for cyclic shear stress ratio evaluation. Soil Dyn Earthq Eng J 2004;24(2):103–13.

[14] Idriss IM. An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential. In: Proceedings of TRB workshop on new approaches to liquefaction, Publication No. FHWA-RD-99-165, Federal Highway Administration; 1999.

[15] Seed B. Evaluation of soil liquefaction effects on level ground during earthquakes, Liquefaction Problems in Geotechnical Engineers, Preprint 2725, presented at the ASCE National Convention, Philadelphia; 1976. p. 1–104.

[16] Boulanger RW. High overburden stress effects in liquefaction analyses. J Geotech Geoenviron Eng ASCE 2003;129(12):1071–82.

[17] Boulanger RW, Idriss IM. State normalization of penetration resistance and the effect of overburden stress on liquefaction resistance. In: Proceddings of 11th international conference on soil dynamics and earthquake engineering and 3rd international conference on earthquake geotechnical engineering, Univ of California, Berkeley, CA; 2004.

[18] Idriss IM, Boulanger RW. Semi-empirical procedures for evaluating liquefaction potential during earthquakes. In: Doolin D, editor. Proceedings of 11th international conference on soil dynamics and earthquake engineering and 3rd International conference on earthquake geotechnical engineering, 1. Stallion Press; 2004. p. 32–56.

[19] Idriss IM, Boulanger RW. Soil liquefaction during earthquakes. Monograph MNO-12. Oakland, CA: Earthquake Engineering Research Institute; 2008. [261 pp].

[20] Cetin KO, Bilge HT. Stress scaling factors for seismic soil liquefaction engineering problems: a performance-based approach. In: Proccedings of international conference on earthquake geotechnical engineering from case history to practice in honor of Prof. Kenji Ishihara, Istanbul, Turkey; 2013.

[21] Cetin KO, Bilge HT. Performance-based assessment of magnitude (duration) scaling factors. J Geotec Geoenviron Eng ASCE 2012;138(3):324–34.

[22] Montgomery J, Boulanger RW, Harder Jr. LF. Examination of the Kσ overburden correction factor on liquefaction resistance. J Geotech Geoenviron Eng 2014. http://dx.doi.org/10.1061/(ASCE)GT.

[23] Idriss IM, Boulanger RW. Semi-empirical procedures for evaluating liquefaction potential during earthquakes. J Soil Dyn Earthq Eng 2006;26:115–30.

[24] Cetin KO. Reliability-based assessment of seismic soil liquefaction initiation hazard [Dissertation submitted in partial fulfillment of the requirement for the degree of doctor of philosophy]. University of California at Berkeley; 2000.

[25] Liao SSC, Veneziano D, Whitman RV. Regression models for evaluating liquefaction probability. J Geotech Eng ASCE 1988;114(4):389–409.

[26] Youd TL, Noble SK. Magnitude scaling factors. In: Proceedings of NCEER workshop on evaluation of liquefaction resistance of soils, Nat Ctr For Earthquake Engrg Res, State Univ of New York at Buffalo; 1997. p. 149–65.

[27] Toprak S, Holzer TL, Bennett MJ, Tinsley JC. CPT- and SPT-based probabilistic assessment of liquefaction potential. In: Proceedings of seventh U.S.-Japan workshop on earthquake resistant design of lifeline facilities and countermeasures against liquefaction; 1999.

[28] Juang CH, Jiang T, Andrus RD. Assessing probability-based methods for liquefaction potential evaluation. J Geotech Geoenviron Eng ASCE 2002;128(7):580–9.

[29] Seed HB. Design problems in soil liquefaction. J Geotech Eng ASCE 1987;113(8):827–45.

[30] Idriss IM. Seed memorial lecture. University of California at Berkeley; 1995.

[31] Liu AH, Stewart JP, Abrahamson NA, Moriwaki Y. Equivalent number of uniform stress cycles for soil liquefaction analysis. J Geotech Geoenviron Eng 2001;127(12):1017–26.

Further reading

[1] Seed HB, Idriss IM. Ground motion and soil liquefaction during earthquakes. Oakland, CA: Earthquake Engineering Res. Insitute Monograph; 1982.

[2] Kayen R, Moss RES, Thompson E, Seed RB, Cetin KO, Kiureghian A, et al. Shear-wave velocity-based probabilistic and deterministic assessment of seismic soil liquefaction potential. J Geotech Geoenviron Eng 2013;139(3):407–13.