



# Regionalization of Liquefaction Triggering Models

Russell A. Green<sup>(✉)</sup>

Virginia Tech, Blacksburg, VA 24061, USA  
rugreen@vt.edu

**Abstract.** The stress-based simplified liquefaction triggering procedure is the most widely used approach to assess liquefaction potential worldwide. However, empirical aspects of the procedure were primarily developed for tectonic earthquakes in active shallow-crustal tectonic regimes. Accordingly, the suitability of the simplified procedure for evaluating liquefaction triggering in other tectonic regimes and for induced earthquakes is questionable. Specifically, the suitability of the depth-stress reduction factor ( $r_d$ ) and magnitude scaling factor (MSF) relationships inherent to existing simplified models is uncertain for use in evaluating liquefaction triggering in stable continental regimes, subduction zone regimes, or for liquefaction triggering due to induced seismicity. This is because both  $r_d$ , which accounts for the non-rigid soil profile response, and MSF, which accounts for shaking duration, are affected by the characteristics of the ground motions, which can differ among tectonic regimes, and soil profiles, which can vary regionally. Presented in this paper is a summary of ongoing efforts to regionalize liquefaction triggering models for evaluating liquefaction hazard. Central to this regionalization is the consistent development of tectonic-regime-specific  $r_d$  and MSF relationships. The consistency in the approaches used to develop these relationships allows them to be interchanged within the same overall liquefaction triggering evaluation framework.

**Keywords:** Liquefaction triggering · Simplified procedure · Earthquakes

## 1 Introduction

The stress-based “simplified” liquefaction evaluation procedure is the most widely used approach to evaluate liquefaction triggering potential worldwide. Analysis of fifty well-documented liquefaction case histories from the 2010–2011 Canterbury, New Zealand, earthquake sequence showed that the three commonly used Cone Penetration Test (CPT)-based simplified liquefaction triggering models (i.e., [1–3]), performed similarly, with the Idriss and Boulanger [3] model performing slightly better than the others. The same conclusion was obtained from the analysis of several thousand case studies from the Canterbury earthquake sequence, wherein the models were used in conjunction with surficial liquefaction manifestation severity indices (e.g., Liquefaction Potential Index: LPI [4]) to evaluate the severity of liquefaction [5, 6].

Despite the conclusions from the comparative studies using the New Zealand data, the suitability of the existing variants of the simplified models for use in evaluating liquefaction triggering in stable continental or subduction zone tectonic regimes is questionable. Additionally, the suitability of existing models for evaluating liquefaction potential due to induced earthquakes is also questionable. This is because the simplified procedure is semi-empirical, with the empirical aspects of it derived from data from tectonic earthquakes in active shallow-crustal tectonic regimes (e.g., California, Turkey, and portions Japan and New Zealand). As a result, existing variants of the simplified procedure may not be suitable for use in evaluating liquefaction triggering when the geologic profiles/soil deposits or ground motion characteristics differ significantly from those used to develop some of the empirical aspects of the models. Specifically, the depth-stress reduction factor ( $r_d$ ) and magnitude scaling factor (MSF) relationships inherent to existing variants of the simplified liquefaction evaluation models are significantly influenced by the characteristics of the geologic profiles and ground motions.

In this paper, ongoing efforts by the author and his collaborators to develop region-specific  $r_d$  and MSF relationship are summarized. Relationships are being developed for tectonic earthquakes in stable continental regimes (e.g., the central-eastern US: CEUS) and subduction zone events (e.g., the Pacific Northwest, PNW of the US), and induced earthquakes in the Groningen region of the Netherlands due to natural gas extraction and in Midwest of the US (MWUS: Oklahoma, Texas, and Kansas) due to deep waste water disposal. The significance of the differences in these regional relationships is shown by the ratios of the factors of safety against liquefaction triggering computed using the various preliminary region-specific relationships and those from active shallow-crustal tectonic regimes.

## 2 Background

### 2.1 Overview of the Simplified Model

In the simplified procedure, the seismic demand is quantified in terms of Cyclic Stress Ratio (CSR), which is the cyclic shear stress ( $\tau_c$ ) imposed on the soil at a given depth in the profile normalized by the initial vertical effective stress ( $\sigma'_{vo}$ ) at that same depth. The word “simplified” in the procedure’s title originated from the proposed use of a form of Newton’s Second Law to compute  $\tau_c$  at a given depth in the profile, in lieu of performing numerical site response analyses [7, 8]. The resulting “simplified” expression for CSR is given as:

$$CSR = \frac{\tau_c}{\sigma'_{vo}} = 0.65 \left( \frac{a_{max}}{g} \right) \left( \frac{\sigma_v}{\sigma'_{vo}} \right) r_d \quad (1)$$

where:  $a_{max}$  = maximum or peak horizontal acceleration at the ground surface;  $g$  = acceleration due to gravity;  $\sigma_v$  and  $\sigma'_{vo}$  = total and initial effective vertical stresses, respectively, at the depth of interest; and  $r_d$  = depth-stress reduction factor that accounts for the non-rigid response of the soil profile.

Additional factors are applied to Eq. 1, the needs for which were largely determined from results of laboratory studies, to account for the effects of the shaking duration

(MSF: Magnitude Scaling Factor, where the reference motion duration is for a moment magnitude,  $M_w$ , 7.5 earthquake in an active shallow-crustal tectonic regime), initial effective overburden stress ( $K_\sigma$ , where the reference initial effective overburden stress is 1 atm), and initial static shear stress ( $K_\alpha$ , where the reference initial static shear stress is zero, e.g., level ground conditions). The resulting expression for the normalized CSR (i.e.,  $CSR^*$ : CSR normalized for motion duration for a  $M_w$  7.5 active shallow-crustal event, 1 atm initial effective overburden stress, and level ground conditions) is given as:

$$CSR^* = \frac{CSR}{MSF \cdot K_\sigma \cdot K_\alpha} = 0.65 \left( \frac{a_{max}}{g} \right) \left( \frac{\sigma_v}{\sigma'_{vo}} \right) r_d \frac{1}{MSF \cdot K_\sigma \cdot K_\alpha} \quad (2)$$

Case histories compiled from post-earthquake investigations were categorized as either “liquefaction” or “no liquefaction” based on whether evidence of liquefaction was or was not observed. The normalized seismic demand (or normalized Cyclic Stress Ratio:  $CSR^*$ ) for each of the case histories is plotted as a function of the corresponding normalized in-situ test metric, e.g., Standard Penetration Test (SPT):  $N_{1,60cs}$ ; Cone Penetration Test (CPT):  $q_{c1Ncs}$ ; or small strain shear-wave velocity ( $V_S$ ):  $V_{S1}$ . In this plot, the “liquefaction” and “no liquefaction” cases tend to lie in two different regions of the graph. The “boundary” separating these two sets of case histories is referred to as the Cyclic Resistance Ratio ( $CRR_{M7.5}$ ) and represents the capacity of the soil to resist liquefaction during the reference event and initial stress conditions (i.e., a  $M_w$  7.5 active shallow-crustal event, 1 atm initial effective overburden stress, and level ground conditions). This boundary can be expressed as a function of the normalized in-situ test metrics.

The factor of safety against liquefaction ( $FS_{liq}$ ) is defined as the capacity of the soil to resist liquefaction for the reference conditions divided by the normalized seismic demand:

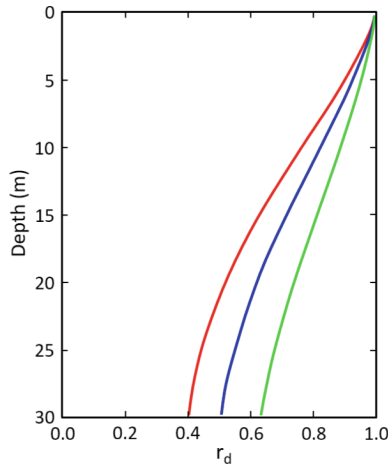
$$FS_{liq} = \frac{CRR_{M7.5}}{CSR^*} \quad (3)$$

The ability of the soil to resist liquefaction during earthquake shaking can be considered an inherent property of the soil, independent of earthquake shaking characteristics. However, because  $CRR_{M7.5}$  was developed from case histories from active shallow-crustal tectonic earthquakes, the seismic demand imposed on the soil needs to be “corrected” so that it is consistent with the reference conditions. In the simplified liquefaction evaluation procedure, the potential differences in ground motion characteristics manifest in the  $r_d$  and MSF relationships used to compute  $CSR^*$  (Eq. 2). Both  $r_d$  and MSF are discussed in detail in the following.

## 2.2 Depth-Stress Reduction Factor

As stated above,  $r_d$  is an empirical factor that accounts for the non-rigid response of the soil profile. For illustrative purposes, the  $r_d$  relationship developed by Idriss [9] and used in both the Idriss and Boulanger [3] and the Boulanger and Idriss [10] simplified liquefaction evaluation models is shown in Fig. 1. The Idriss [9]  $r_d$  relationship is a function of earthquake magnitude and depth, with  $r_d$  being closer to one for all depths for

larger magnitude events (note that  $r_d = 1$  for all depths corresponds to the rigid response of the profile). This is because larger magnitude events have longer characteristic periods (e.g., [11]) and hence, longer wavelengths. As a result, even a soft profile will tend to respond as a rigid body if the characteristic wavelength of the ground motions is significantly longer than the height of the profile. Accordingly, the correlation between earthquake magnitude and the frequency content of the earthquake motions significantly influences the  $r_d$  relationship. Additionally, the dynamic response characteristics of the geologic profile, to include the impedance contrast between bedrock and the overlying soil, also influences  $r_d$ . This raises questions regarding the universality of existing  $r_d$  relationships that were developed using motions recorded during moderate to major tectonic events ( $5 < M_w < 8$ ) in active shallow-crustal regimes and geologic profiles characteristic of California. Specifically, it is uncertain regarding whether or not such relationships are suitable for evaluating liquefaction triggering in other tectonic regimes, for induced earthquakes, or geologic profiles that significantly differ from those used to develop the existing  $r_d$  relationships.

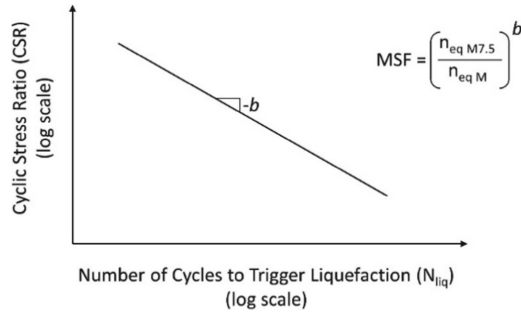


**Fig. 1.**  $r_d$  factor used to account for the non-rigid response of the soil column. The red, blue, and green lines were computed using the Idriss [9]  $r_d$  relationship for  $M_w 5.5$ ,  $M_w 6.5$ , and  $M_w 7.5$  events, respectively.

### 2.3 Magnitude Scaling Factor: MSF

As stated above, MSF account for the influence of the strong motion duration on liquefaction triggering. For historical reasons, the influence of ground motion duration on liquefaction triggering is expressed relative to that of a  $M_w 7.5$  shallow-crustal event in an active tectonic regime. Towards this end, MSF have traditionally been computed as the ratio of the number of equivalent cycles for the reference event ( $n_{eq M7.5}$ ) to that of the event of interest ( $n_{eq M}$ ), raised to the power  $b$  [i.e.,  $MSF = (n_{eq M7.5}/n_{eq M})^b$ ]. Commonly, the Seed et al. [12] variant of the Palmgren–Miner (P–M) fatigue theory

is used to compute  $n_{eq\ M}$  and  $n_{eq\ M7.5}$  (collectively referred to as  $n_{eq}$  henceforth) from earthquake motions recorded at the surface of soil profiles. Additionally, the value of  $b$  is commonly obtained from laboratory test data.  $b$  is the negative slope of a plot of  $\log(CSR)$  vs.  $\log(N_{liq})$ , as shown in Fig. 2;  $N_{liq}$  is the number of cycles required to trigger liquefaction in a soil specimen subjected to sinusoidal loading having an amplitude of CSR, typically determined using cyclic triaxial or cyclic simple shear tests.



**Fig. 2.** For liquefaction evaluations, the Seed et al. [12] variant of the P-M fatigue theory has most commonly been used to compute the equivalent number of cycles ( $n_{eq}$ ). Per this approach, the negative of the slope of a CSR vs.  $N_{liq}$  curve (or  $b$ -value) developed from laboratory tests is used to relate the “damage” induced in a soil sample from a pulse having one amplitude to that having a different amplitude. The  $b$ -value is also used to relate  $n_{eq}$  and MSF

There are several shortcomings inherent to the Seed et al. [12] variant of the Palmgren–Miner (P-M) fatigue theory used to compute  $n_{eq}$  and how the  $b$ -value used to compute MSF is determined. These include:

- Because the Seed et al. [12] approach for computing  $n_{eq}$  is based on motions recorded at the surface of the soil profile, both the magnitude and uncertainty in  $n_{eq}$ , and hence MSF, are assumed to be constant with depth. However, Green and Terri [13] have shown that  $n_{eq}$  can vary with depth in a given profile, and Lasley et al. [14] showed that while the median values of  $n_{eq}$  computed for a large number of soil profiles and ground motions remains relatively constant with depth, the uncertainty in their values varies with depth.
- Pulses in the acceleration time history having an amplitude less than  $0.3 \cdot a_{max}$  are assumed not to contribute to the triggering of liquefaction, and thus are not considered in the computation of  $n_{eq}$ . Using a relative amplitude criterion to exclude pulses is contrary to the known nonlinear response of soil which is governed by the absolute amplitude of the imposed load, among other factors. The use of a relative amplitude exclusion criterion with tectonic earthquake motions may inherently bias the resulting MSF, limiting its validity for use with motions having different characteristics (e.g., motions from induced earthquakes).
- Each of the two horizontal components of ground motion is treated separately, inherently assuming that both components have similar characteristics. However, analysis of recorded motions has shown this is not always the case, particularly for motions

in the near fault region of tectonic events (e.g., [15–17]). Also, the horizontal components of the induced motions recorded in the Groningen region of the Netherlands have been shown to exhibit very strong polarization [18].

- $b$ -values used to compute MSF are commonly derived from multiple laboratory studies performed on various soils, and it is uncertain whether all these studies used a consistent definition of liquefaction in interpreting the test data. As a result, the  $b$ -values entail a considerable amount of uncertainty [19]. Additionally, previously used  $b$ -values are not necessarily in accord with those inherent to the shear modulus and damping degradation curves used in the equivalent linear site response analyses to develop the  $r_d$  and  $n_{eq}$  relationships (elaborated on subsequently).
- Recent studies have shown that the amplitude (e.g.,  $a_{max}$ ) and duration (e.g.,  $n_{eq}$ ) of earthquake ground motions are negatively correlated (e.g., [14, 20, 21]). Few, if any, of the MSF relationships developed to date have considered this.

Some of the above listed shortcomings likely will be more significant to the liquefaction hazard assessment than others, but it is difficult to state a-priori which ones these are. Furthermore, even for tectonic earthquakes in active shallow-crustal regimes, the validation of MSF is hindered by the limited magnitude range of case histories in the field liquefaction databases, with the majority of the cases being for events having magnitudes ranging from  $M_w 6.25$  to  $M_w 7.75$  [22]. Specific to liquefaction hazard assessment for induced earthquakes, MSF for small magnitude events are very important, particularly given that published MSF values vary by a factor of 3 for  $M_w 5.5$  [23], with this factor increasing if the proposed MSF relations are extrapolated to lower magnitudes.

### 3 Development of Regional $r_d$ and MSF Relationships

#### 3.1 Regional-Specific Relationships

Region-specific  $r_d$  and MSF relationships are being developed using approaches outlined below. The approaches are consistently being implemented across tectonic regimes and for tectonic vs. induced events. As a result, any bias inherent to the relationships should be consistent across all relationships, which is essential to allow use of these relationships in conjunction with the same  $CRR_{M7.5}$  curve.

#### 3.2 Regional $r_d$ Relationships

Region-specific  $r_d$  relationships are being developed using an approach similar to that used by Cetin [24]. Equivalent linear site response analyses are being performed using soil profiles and ground motions representative of: (1) active shallow-crustal events (e.g., western US: WUS); (2) shallow-crustal events in the stable continental setting (e.g., CEUS); (3) mega-thrust subduction zone events (e.g., PNW); (4) induced events resulting from deep waste water disposal in the MWUS; and (5) induced events resulting from natural gas production in the Groningen region of the Netherlands. In all cases ground motions representative of the respective source mechanisms and soil profiles representative of the respective regions are being compiled. Several functional forms for

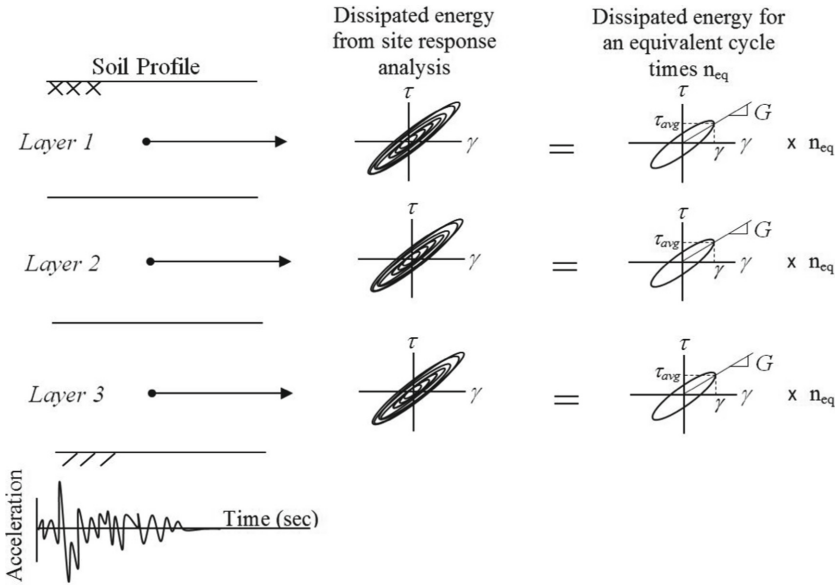
the region-specific  $r_d$  relationships are being examined in regressing the results from the site response analyses for each region, with the final form of regressed  $r_d$  relationship for each region being selected by balancing simplicity and low standard deviation of the regressed equation.

### 3.3 Regional MSF Relationships

The development of region-specific MSF relationships that overcome all the shortcomings listed in Sect. 2.3 is not as straightforward as developing the new  $r_d$  relationships. The reason for this is that there are many more issues with how  $n_{eq}$  and MSF relationships have been developed than there are for how  $r_d$  relationships have been developed. As a result, new approaches for computing  $n_{eq}$  and MSF need to be developed, as opposed to implementing an existing approach using a more comprehensive dataset and a more rigorous regression analysis.

Well-established fatigue theories have been proposed for computing  $n_{eq}$  for materials having varying phenomenological behavior; reviews of different approaches for computing  $n_{eq}$  are provided in Green and Terri [13], Hancock and Bommer [25], and Green and Lee [26], among others. Developed specifically for use in evaluating liquefaction triggering, the approach proposed by Green and Terri [13] is selected herein for developing the region-specific  $n_{eq}$  relationships. This approach is an alternative implementation of the P-M fatigue theory that better accounts for the nonlinear behavior of the soil than the Seed et al. [12] variant. In this approach, dissipated energy is explicitly used as the damage metric.  $n_{eq}$  is determined by equating the energy dissipated in a soil element subjected to an earthquake motion to the energy dissipated in the same soil element subjected to a sinusoidal motion of a given amplitude and a duration of  $n_{eq}$ . Dissipated energy was selected as the damage metric because it has been shown to correlate with excess pore pressure generation in saturated cohesionless soil samples subjected to undrained cyclic loading (e.g., [27, 28]). Furthermore, from a microscopic perspective, the energy is thought to be predominantly dissipated by the friction between sand grains as they move relative to each other as the soil skeleton breaks down, which is requisite for liquefaction triggering.

Conceptually, the Green and Terri [13] approach for computing  $n_{eq}$  is shown in Fig. 3. Stress and strain time histories at various depths in the soil profile are obtained from a site response analysis. By integrating the variation of shear stress over shear strain, the cumulative dissipated energy per unit volume of soil can be computed (i.e., the cumulative area bounded by the shear stress-shear strain hysteresis loops).  $n_{eq}$  is then determined by dividing the cumulative dissipated energy for the entire earthquake motion by the energy dissipated in one equivalent cycle. For historical reasons, the shear stress amplitude of the equivalent cycle ( $\tau_{avg}$ ) is taken as  $0.65 \cdot \tau_{max}$  (where  $\tau_{max}$  is the maximum induced cyclic shear stress,  $\tau_c$ , at a given depth), and the dissipated energy associated with the equivalent cycle is determined from the constitutive model used in the site response analysis.

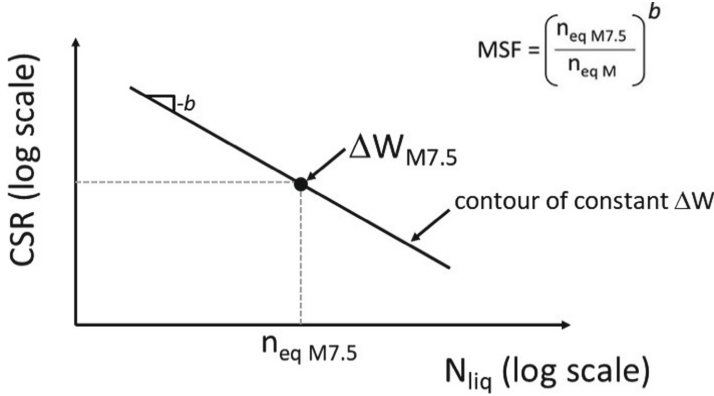


**Fig. 3.** Illustration of the proposed procedure to compute  $n_{eq}$  [13]. In this procedure, the dissipated in a layer of soil, as computed from a site response analysis, is equated to the energy dissipated in an equivalent cycle of loading multiplied by  $n_{eq}$

The same soil profiles and ground motions being compiled for developing the region-specific  $r_d$  relationships are being used to develop the region-specific  $n_{eq}$  relationships, thus ensuring consistency between the relationships. As with the region-specific  $r_d$  relationships, several functional forms for the  $n_{eq}$  relationships are being examined in regressing the results from the site response analyses for each region, with the final form of regressed  $n_{eq}$  relationship for each region being selected by balancing simplicity and low standard deviation of the equation.

As mentioned previously,  $MSF = (n_{eq} M_{7.5} / n_{eq} M)^b$  where the value of  $b$  is commonly obtained from laboratory test data (i.e.,  $b$  is the negative slope of a plot of  $\log(CSR)$  vs.  $\log(N_{liq})$ , as shown in Fig. 2). However, it is also possible to compute  $b$ -values from contours of constant dissipated energy computed using modulus reduction and damping (MRD) curves [29], as illustrated in Fig. 4. Assuming that the relationship between  $CSR$  and  $N_{liq}$  is a contour of constant dissipated energy, the  $b$ -value representing this relationship can be computed by estimating  $CSR$  for a range of  $N_{liq}$  values from the dissipated energy per unit volume of soil for a  $M_w 7.5$  active shallow-crustal event ( $\Delta W_{M7.5}$ ). Towards this end, the same approach used in equivalent-linear site response analysis can be used to compute  $\Delta W_{M7.5}$ : using a visco-elastic constitutive model in conjunction with MRD curves (e.g., Ishibashi and Zhang [30]). This approach results in the following equation:





**Fig. 4.** A CSR vs.  $N_{liq}$  curve can be computed from shear modulus and damping degradation curves assuming the curve is a contour of constant dissipated energy.  $\Delta W_{M7.5}$  can be computed using Eq. 4 and the remaining portions of the curve can be computed for different amplitudes of loading by simply computing the number of cycles for the assumed loading amplitude required for the dissipated energy to equal  $\Delta W_{M7.5}$ .

$$\Delta W_{M7.5} = \frac{2\pi D_\gamma \left( CRR_{M7.5} \cdot K_\gamma \cdot \sigma'_{vo} \right)^2}{G_{max} \left( \frac{G}{G_{max}} \right)_\gamma} n_{eqM7.5} \quad (4)$$

where  $K_\gamma$  accounts for the overburden per Green et al. [31] and is analogous to the overburden correction factor,  $K_\sigma$ ;  $G_{max}$  is the small-strain shear modulus; and  $D_\gamma$  and  $(G/G_{max})_\gamma$  are the damping and shear modulus ratios, respectively, associated with a given value of shear strain,  $\gamma$ .

Because the relationship between CSR vs.  $N_{liq}$  is assumed to be a contour of constant dissipated energy, the remaining portions of the curve can be computed for different amplitudes of loading (i.e., CSR) by simply computing the number of cycles for the assumed loading amplitude required for the dissipated energy to equal  $\Delta W_{M7.5}$ . In this approach, the  $\Delta W$  for one cycle of loading (i.e.,  $\Delta W_1$ ) having amplitude CSR is computed as:

$$\Delta W_1 = \frac{2\pi D_\gamma \left( CSR \cdot \sigma'_{vo} \right)^2}{G_{max} \left( \frac{G}{G_{max}} \right)_\gamma} \quad (5)$$

and the  $N_{liq}$  corresponding to this CSR amplitude is  $\Delta W_{M7.5}/\Delta W_1$ .

Although an estimate of  $G_{\max}$  is necessary to compute  $\Delta W_{M7.5}$  or  $\Delta W_1$  individually, because it appears in both the numerator and the denominator when computing  $N_{liq} = \Delta W_{M7.5}/\Delta W_1$ , it cancels out. Accordingly, the value of  $N_{liq}$  (and  $b$ -value) computed from MRD curves in this manner is not contingent on  $G_{\max}$ .

Values of  $D_\gamma$  and  $(G/G_{\max})_\gamma$  can be determined using any published, applicable MRD curves. The Ishibashi and Zhang [30] curves, hereafter denoted IZ, are being used in this study. These MRD curves are dependent on the initial mean effective stress,  $\sigma'_{mo}$ , and soil type or plasticity index, PI. For liquefiable soils, PI is being assumed to equal zero and  $\sigma'_{mo}$  is being computed as a function of the at-rest lateral earth pressure coefficient,  $K_o$ , which is assumed to equal 0.5.

Using this procedure,  $b$ -values are being regressed for a range of  $q_{c1Ncs}$  and  $\sigma'_{vo}$  values. Values of  $q_{c1Ncs}$  were correlated to  $D_r$  using the following expression [3, 32] [33]:

$$D_r = 0.478(q_{c1Ncs})^{0.264} - 1.063 \quad (6)$$

In general,  $b$ -values remain relatively constant with increasing  $D_r$  and  $\sigma'_{vo}$ . An average  $b$ -value from the IZ MRD curves for  $\sigma'_{vo} = 100$  kPa is 0.28. Note that although the  $b$ -values showed some sensitivity to changes in  $D_r$  and  $\sigma'_{vo}$ , the ranges of  $b$ -values (0.25–0.31) have only a mild impact on MSF. It is noted that using the same MRD curves to compute  $b$  as are also being used in the site response analyses to develop the  $r_d$  and  $n_{eq}$  relationships, ensuring consistency among all the relationships.

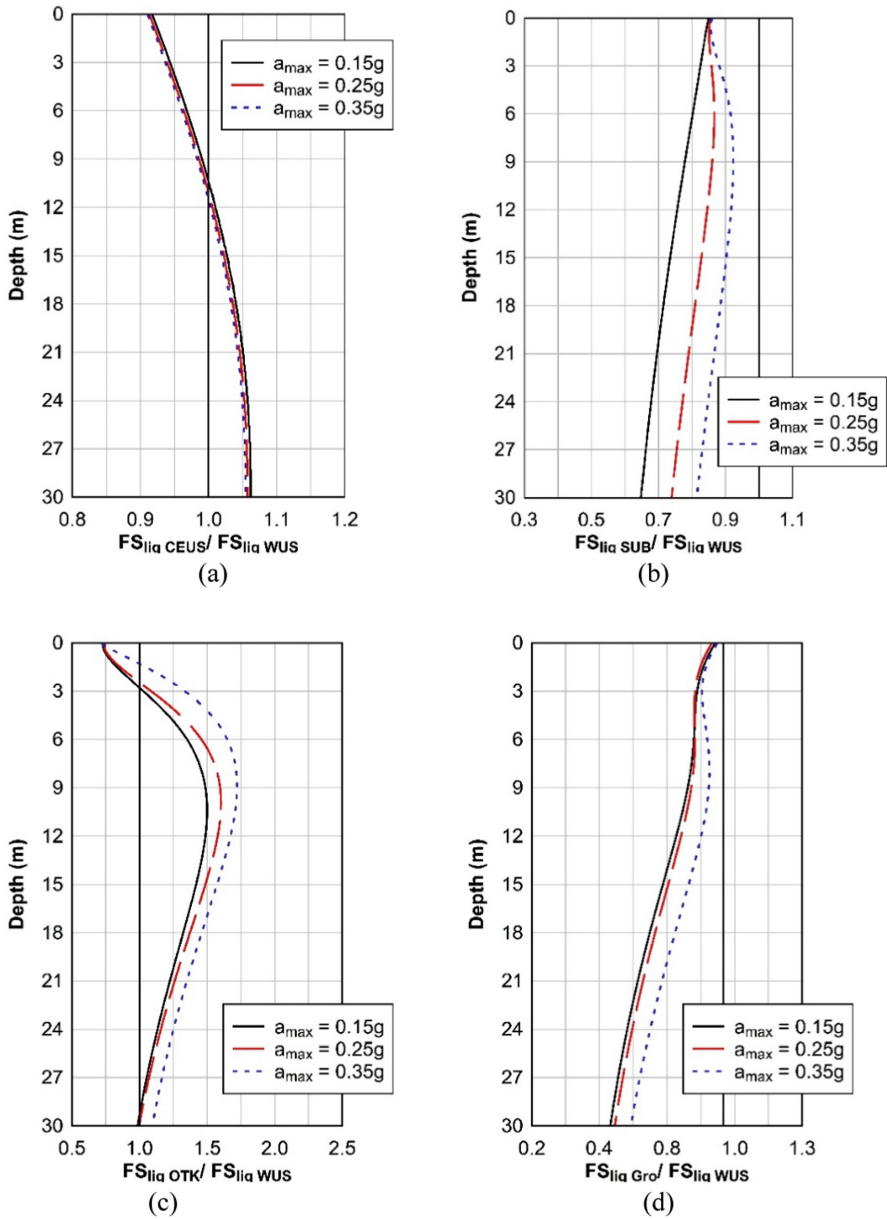
#### 4 Ratios of $FS_{liq}$

To assess the significance of the region-specific  $r_d$  and MSF relationships on the liquefaction triggering predictions, the ratios of the  $FS_{liq}$  computed using the region-specific relationships and relationships for the reference tectonic regime (i.e., active shallow-crustal regimes) are examined. Because it is assumed that the ability of the soil to resist liquefaction during earthquake shaking is an inherent property of the soil, the ratio of  $FS_{liq}$  for the CEUS and WUS, for example, becomes:

$$FS_{liq\ ratio} = \frac{\frac{CRR_{M7.5}}{0.65 \frac{a_{max}}{g} \frac{\sigma_y}{\sigma_{vo}} r_d CEUS \frac{1}{MSF_{CEUS} \cdot K_\gamma \cdot K_\alpha}}}{\frac{CRR_{M7.5}}{0.65 \frac{a_{max}}{g} \frac{\sigma_y}{\sigma_{vo}} r_d WUS \frac{1}{MSF_{WUS} \cdot K_\gamma \cdot K_\alpha}}} = \frac{r_{dWUS}}{r_{dCEUS}} \bullet \frac{MSF_{CEUS}}{MSF_{WUS}} \quad (7)$$

Plots of  $FS_{liq\ ratio}$  computed using preliminary region-specific  $r_d$  and MSF relationships are shown in Fig. 5. Specifically,  $FS_{liq\ ratio}$  are shown for tectonic events in stable continental regimes (e.g., CEUS: Fig. 5a), tectonic subduction zone events (e.g., PNW: Fig. 5b), induced earthquakes in the MWUS (i.e., Oklahoma, Texas, and Kansas: OTK) (Fig. 5c), and induced earthquakes in the Groningen region of the Netherlands (Fig. 5d).

Values of  $FS_{liq\ ratio}$  that are less than one imply that the use of the simplified models developed for tectonic events in active shallow-crustal regimes will over-predict the liquefaction hazard. In contrast, values of  $FS_{liq\ ratio}$  that are greater than one imply that the use of the simplified models developed for tectonic events in active shallow-crustal



**Fig. 5.** Preliminary  $FS_{liq}$  ratios for: (a) stable continental tectonic events: CEUS  $M_w 6.5$  tectonic event; (b) subduction zone tectonic events: PNW  $M_w 8.5$  tectonic event; (c) MWUS (i.e., Oklahoma, Texas, and Kansas: OTK)  $M_w 5.25$  induced event; and (d) Groningen region of the Netherlands:  $M_w 5.25$  induced event. In all cases, soil deposits were assumed comprising loose uniform sand deposits with the ground water table at a depth of  $\sim 2$  m

regimes will under-predict the liquefaction hazard. Accordingly, based on the plots in Fig. 5, use of liquefaction triggering models developed for active shallow-crustal tectonic regimes will result in a higher computed liquefaction hazard for subduction zone events in the PNW and for induced earthquake in the Groningen region of the Netherlands than the actual liquefaction hazard. Additionally, use of liquefaction triggering models developed for active shallow-crustal tectonic regimes will result in a higher computed liquefaction hazard for tectonic events in the CEUS and for induced earthquake in the MWUS at shallower depths and lower liquefaction hazard at deeper depths than the actual liquefaction hazard. In some of the cases, the liquefaction is significantly under- or over-predicted. These trends provide the impetus to develop and use regionally applicable liquefaction triggering models in assessing liquefaction hazards.

While the plots of the computed  $FS_{liq \text{ ratio}}$  shown in Fig. 5 show trends in over- or under-prediction of the liquefaction hazard in various tectonic regimes or tectonic vs. induced earthquakes using models developed for active shallow-crustal tectonic events, region-specific  $r_d$  and MSF relationships can be used to directly evaluate the liquefaction hazard in a given region. Specifically, the region-specific  $r_d$  and MSF relationships can be used to compute  $CSR^*$ , which in turn can be used in conjunction with the  $CRR_{M7.5}$  curve determined from case histories from active shallow-crustal tectonic events, to compute  $FS_{liq}$  in a given region. This is because  $CRR_{M7.5}$  is considered to be an inherent property of the soil and because consistent approaches are being used to develop all the region-specific relationships. As a result, any bias inherent to these relationships will be consistent among all relationships, which is essential to allow use of the region-specific relationships in conjunction with the same  $CRR_{M7.5}$  curve. The exceptions to the assumption that  $CRR_{M7.5}$  is an inherent property of the soil is if the mineralogy or age of the soil of interest differs from that represented in the case history database used to develop the  $CRR_{M7.5}$  curve. In these cases, corrections need to be applied to the  $CRR_{M7.5}$  curve, but for the purpose of this study, these exceptional conditions are not considered.

## 5 Summary and Conclusions

The stress-based “simplified” liquefaction evaluation procedure is the most widely used approach to evaluate liquefaction triggering potential worldwide. However, the suitability of the existing variants of the simplified models for use in evaluating liquefaction triggering in tectonic regimes other than active shallow-crustal regimes is questionable. Additionally, the suitability of existing models for evaluating liquefaction potential due to induced earthquakes is also questionable. This is because the simplified procedure is semi-empirical, with the empirical aspects of it derived from data from tectonic earthquakes in active shallow-crustal tectonic regimes (e.g., California, Turkey, and portions Japan and New Zealand). As a result, existing variants of the simplified procedure may not be suitable for use in evaluating liquefaction triggering when the geologic profiles/soil deposits or ground motion characteristics differ significantly from those used to develop some of the empirical aspects of the models.

In this paper, ongoing efforts by the author and his collaborators to develop region-specific  $r_d$  and MSF relationship were summarized. Relationships are being developed

for tectonic earthquakes in the central-eastern US (CEUS) and subduction zone events in the Pacific Northwest (PNW) of the US, and induced earthquakes in the Groningen region of the Netherlands due to natural gas extraction and in Midwest of the US (MWUS: Oklahoma, Texas, and Kansas) due to deep waste water disposal.

The significance of the region-specific relationships is shown by the ratios of the factors of safety against liquefaction triggering computed using the various preliminary region-specific relationships and those from active shallow-crustal tectonic regimes. Based on preliminary relationships developed by the author and his collaborators, use of liquefaction triggering models developed for active shallow-crustal tectonic regimes will result in a higher computed liquefaction hazard for subduction zone events in the PNW and for induced earthquake in the Groningen region of the Netherlands than the actual liquefaction hazard. Additionally, use of liquefaction triggering models developed for active shallow-crustal tectonic regimes will result in a higher computed liquefaction hazard for tectonic events in the CEUS and for induced earthquake in the MWUS at shallower depths and lower liquefaction hazard at deeper depths than the actual liquefaction hazard. In some of the cases, the liquefaction is significantly under- or over-predicted. These trends provide the impetus to use develop and use regionally applicable liquefaction triggering models in assessing liquefaction hazards.

**Acknowledgements.** The author has collaborated with many researchers on various aspects of this project, to include: Adrian Rodriguez-Marek, Julian Bommer, Peter Stafford, Jan van Elk, Brett Maurer, Kristin Ulmer, James K. Mitchell, Tyler Quick, Balakumar Anbazhagan, Sam Lasley, Ellen Rathje, and Balakumar Anbazhagan, among others. The input from these collaborators is gratefully acknowledged. This research was funded by National Science Foundation (NSF) grants CMMI-1825189 and CMMI-1937984, U.S. Geological Survey (USGS) awards G18AP00094 and G19AP00093, and NAM. This support is gratefully acknowledged. However, any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author and do not necessarily reflect the views of NSF, USGS, NAM or the listed collaborators.

## References

1. Robertson, P.K., Wride, C.E.: Evaluating cyclic liquefaction potential using cone penetration test. *Can. Geotech. J.* **35**(3), 442–459 (1998)
2. Moss, R.E.S., Seed, R.B., Kayen, R.E., Stewart, J.P., Der Kiureghian, A., Cetin, K.O.: CPT-based probabilistic and deterministic assessment of in situ seismic soil liquefaction potential. *J. Geotechnical Geoenvironmental Eng.* **132**(8), 1032–1051 (2006)
3. Idriss, I.M., Boulanger, R.W.: Soil liquefaction during earthquakes. Monograph MNO-12, Earthquake Engineering Research Institute, Oakland, CA, p. 261 (2008)
4. Iwasaki, T., Tatsuoka, F., Tokida, K., Yasuda, S.: A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan. In: 2nd International Conference on Microzonation, pp. 885–896. Nov 26–Dec 1, San Francisco, CA, USA (1978)
5. Green, R.A., Maurer, B.W., Cubrinovski, M., Bradley, B.A.: Assessment of the relative predictive capabilities of CPT-based liquefaction evaluation procedures: lessons learned from the 2010–2011 canterbury earthquake sequence. In: Proceedings of the 6th International Conference on Earthquake Geotechnical Engineering (6ICEGE), Christchurch, New Zealand, 2–4 November (2015)

6. Maurer, B.W., Green, R.A., Cubrinovski, M., Bradley, B.: Assessment of CPT-based methods for liquefaction evaluation in a liquefaction potential index framework. *Géotechnique* **65**(5), 328–336 (2015)
7. Whitman, R.V.: Resistance of soil to liquefaction and settlement. *Soils Found.* **11**(4), 59–68 (1971)
8. Seed, H.B., Idriss, I.M.: Simplified procedure for evaluating soil liquefaction potential. *J. Soil Mechanics Found Division* **97**(SM9), 1249–1273 (1971)
9. Idriss, I.M.: An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential. In: *Proceedings of the TRB workshop on new approaches to liquefaction*, Publication No. FHWA-RD-99-165, Federal Highway Administration, Washington, DC (1999)
10. Boulanger, R.W., Idriss, I.M.: CPT and SPT based liquefaction triggering procedures. Rep. No. UCD/CGM-14/01. Davis, CA: Univ. of California at Davis (2014)
11. Green, R.A., Lee, J., Cameron, W., Arenas, A.: Evaluation of various definitions of characteristic period of earthquake ground motions for site response analyses. In: *Proceedings of the 5th International Conference on Earthquake Geotechnical Engineering*, Santiago, Chile, 10–13 January 2011 (2011)
12. Seed, H.B., Idriss, I.M., Makdisi, F., Banerjee, N.: Representation of irregular stress time histories by equivalent uniform stress series in liquefaction analysis. Report Number EERC 75–29, Earthquake Engineering Research Center, College of Engineering, University of California at Berkeley, Berkeley, CA (1975)
13. Green, R.A., Terri, G.A.: Number of equivalent cycles concept for liquefaction evaluations: revisited. *J. Geotechnical Geoenvironmental Eng.* **131**(4), 477–488 (2005)
14. Lasley, S., Green, R.A., Rodriguez-Marek, A.: Number of equivalent stress cycles for liquefaction evaluations in active tectonic and stable continental regimes. *J. Geotechnical and Geoenvironmental Eng.* **143**(4), 04016116 (2017)
15. Green, R.A., Lee, J., White, T.M., Baker, J.W.: The significance of near-fault effects on liquefaction. In: *Proceedings of 14th world conference on earthquake engineering*, Paper no. S26–019 (2008)
16. Carter, W.L., Green, R.A., Bradley, B.A., Cubrinovski, M.: The influence of near-fault motions on liquefaction triggering during the canterbury earthquake sequence. In: Orense, R.P., Towhata, I., Chouw, N. (eds.) *Soil Liquefaction during Recent Large-Scale Earthquakes*, Taylor & Francis Group, pp. 57–68. England, London (2014)
17. Carter, W.L., Green, R.A., Bradley, B.A., Wotherspoon, L.M., Cubrinovski, M.: Spatial variation of magnitude scaling factors during the 2010 Darfield and 2011 Christchurch, New Zealand. Earthquakes. *Soil Dynamics Earthquake Eng.* **91**, 175–186 (2016)
18. Bommer, J.J., et al.: Framework for a ground-motion model for induced seismic hazard and risk analysis in the Groningen gas field, the Netherlands. *Earthq. Spectra* **33**(2), 481–498 (2017)
19. Ulmer, K.J., et al.: A critique of b-values used for computing magnitude scaling factors. In: *Proceedings of geotechnical earthquake engineering and soil dynamics V (GEESD V)*, Austin, TX, 10–13 June (2018)
20. Bradley, B.A.: Correlation of significant duration with amplitude and cumulative intensity measures and its use in ground motion selection. *J. Earthquake Eng.* **15**, 809–832 (2011)
21. Bommer, J.J., et al.: Developing an application-specific ground-motion model for induced seismicity. *Bull. Seismol. Soc. Am.* **106**(1), 158–173 (2016)
22. NRC: State of the art and practice in the assessment of earthquake induced soil liquefaction and consequences. Committee on earthquake induced soil liquefaction assessment, National Research Council, The National Academies Press, Washington, DC (2016)

23. Youd, T.L., 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. Geotechnical and Geoenvironmental Eng.* **127**(4), 297–313 (2001)
24. Cetin, K.O.: Reliability-based assessment of seismic soil liquefaction initiation hazard. Ph.D. Thesis, University of California at Berkeley, Berkeley, CA (2000)
25. Hancock, J., Bommer, J.J.: The effective number of cycles of earthquake ground motion. *Earthquake Eng. Struct. Dynam.* **34**, 637–664 (2005)
26. Green, R.A., Lee, J.: Computation of number of equivalent strain cycles: a theoretical framework. In: Lade, P.V., Nakai, T. (eds.) *Geomechanics II: Testing, Modeling, and Simulation*, ASCE Geotechnical Special Publication 156, pp. 471–487 (2006)
27. Green, R.A., Mitchell, J.K., Polito, C.P.: An energy-based excess pore pressure generation model for cohesionless soils. In: Smith, D.W., Carter, J.P.: (eds) *Proceedings of the John Booker memorial symposium—developments in theoretical geomechanics*. A. A. Balkema, Rotterdam, pp. 383–390 (2000)
28. Polito, C.P., Green, R.A., Lee, J.: Pore pressure generation models for sands and silty soils subjected to cyclic loading. *J. Geotechnical Geoenvironmental Eng.* **134**(10), 1490–1500 (2008)
29. Green, R.A., et al.: Addressing limitations in existing ‘simplified’ liquefaction triggering evaluation procedures: application to induced seismicity in the Groningen gas field. *Bull. Earthq. Eng.* **17**(8), 4539–4557 (2019)
30. Ishibashi, I., Zhang, X.: Unified dynamic shear moduli and damping ratios of sand and clay. *Soils Found.* **33**(1), 182–191 (1993)
31. Green, R.A., Bradshaw, A., Baxter, C.D.P.: Accounting for Intrinsic Soil Properties and State Variables on Liquefaction Triggering in Simplified Procedures. *J. Geotech. Geoenvironmental Eng.* **148**(7), 04022056 (2022)
32. Salgado, R., Boulanger, R.W., Mitchell, J.K.: Lateral stress effects on CPT liquefaction resistance correlations. *J. Geotechnical and Geoenvironmental Eng.* **123**(8), 726–735 (1997)
33. Salgado, R., Mitchell, J.K., Jamiolkowski, M.: Cavity expansion and penetration resistance in sands. *J. Geotechnical Geoenvironmental Eng.* **123**(4), 344–354 (1997)