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# Assessment of the cyclic strain approach for evaluating liquefaction triggering

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ABSTRACT

The cyclic strain approach was proposed in the 1980s as a potential alternative to the stress-based simplified liquefaction evaluation procedure. However, despite its fundamental basis and many positive attributes, it has not been embraced by practice. One reason for this may be the need to perform cyclic laboratory tests on undisturbed/reconstituted samples to develop a relationship among excess pore water pressure, cyclic strain amplitude, and number of applied strain cycles. Herein an alternative implementation of the strain-based procedure is proposed that circumvents this requirement, using a strain-based pore pressure generation model in lieu of laboratory test data. To assess the efficacy of the alternative implementation, several hundred small strain shear wave velocity ($V_s$) and Standard Penetration Test (SPT) field liquefaction case histories are evaluated. The results are compared with both field observations and with predictions from the stress-based procedures. It was found that the stress-based approach yielded considerably more accurate predictions compared to the cyclic strain approach. One likely reason for this is the strain-based procedure's inherent and potentially fatal limitation of ignoring the decrease in soil stiffness due to excess pore pressure when representing the earthquake loading in terms of shear strain amplitude and number of equivalent cycles.

## 1. Introduction

The primary objective of the study presented herein is to evaluate the efficacy of the strain-based liquefaction triggering evaluation procedure implemented using a pragmatic variant of the procedure originally proposed by Dobry et al. [11]. Liquefaction is a phenomenon that results from the contractive tendencies of loose to medium dense soils when sheared. For saturated cohesionless soils, this tendency results in the transfer of the overburden stress to the pore fluid, with the commensurate increase in pore water pressure and decrease in effective confining stress. Liquefaction has occurred in most major earthquakes and has caused significant damage to infrastructure (e.g., Cubrinovski and Green [8]; Cubrinovski et al. [9]; Green et al. [15]; Olson et al. [33]; Stringer et al. [40]; among many others).

The most widely used procedure for evaluating liquefaction triggering potential is the simplified stress-based procedure originally proposed by Whitman [44] and Seed and Idriss [37]. This procedure is semi-empirical and has undergone periodic updates as a result of findings from new laboratory studies and/or the collection and analysis of additional field case history data (e.g., Youd et al. [46]; Cetin et al. [6]; Idriss and Boulanger [16]). Inherent to this procedure is the quantification of the seismic demand imposed on the soil expressed in terms of cyclic shear stress.

Despite the popularity of the stress-based procedures, multiple studies have shown that excess pore water pressure better correlates to cyclic strain than to cyclic stress (e.g., Fig. 1) (e.g., Martin et al. [25]; Dobry et al., [11]; Byrne [3]). The reason for this is the relative movement of soil particles, which is requisite for excess pore water pressure generation, relates to the induced strain, regardless of amplitude of the stress applied to soil. As a result, Dobry et al. [11] proposed a strain-based liquefaction triggering evaluation procedure. Although the Dobry et al. [11] procedure generally received a positive reception by liquefaction researchers, it has failed to be adopted into practice. One reason for this is likely the requirement to perform strain-controlled cyclic laboratory tests on undisturbed and/or reconstituted specimens. This is in contrast to the simplified stress-based procedures wherein in-situ test metrics are the primary parameters used to evaluate liquefaction potential, with laboratory index tests and grain size distribution analyses having supporting roles if their performance is deemed necessary (e.g., use of measured fines content, FC, versus apparent FC in conjunction with the Cone Penetration Test, CPT, stress-based simplified procedure).

Herein an alternative approach to implementing the Dobry et al. [11] strain-based procedure is proposed which circumvents the need for

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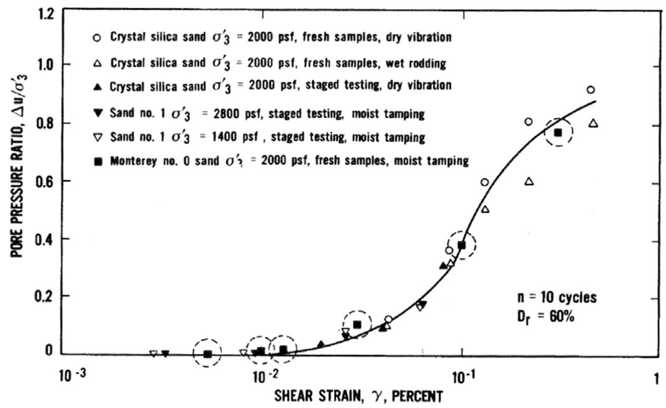


**Fig. 1.** Porewater pressure buildup in cyclic triaxial strain-controlled tests, after ten loading cycles, as a function of cyclic shear strain, for various normally consolidated saturated sands at $D_r$ = 60% and for various pressures (Dobry et al. [11]).

performing strain-controlled cyclic laboratory tests. Per this procedure, a strain-based numerical excess pore pressure generation model is used in lieu of developing analogous relationships from laboratory tests. The soil parameters required to implement the procedure include: relative density ($D_r$), secant shear modulus (G), and grain size distribution characteristics of the soil (i.e., FC and coefficient of uniformity: $C_u$); note that focus herein is on soils that are susceptible to liquefaction (i.e., non-plastic soils) and thus Plasticity Index (PI) is not needed. These required parameters are not too different from those required to implement the stress-based simplified procedures and can be estimated using simple relationships or conservative assumptions.

To assess the efficacy of the proposed variant of the Dobry et al. [11] strain-based procedure, earthquake liquefaction case histories in the small strain shear wave velocity ($V_s$) database, which consists of 415 case histories compiled by Kayen et al. [20], and in the Standard Penetration Test (SPT) database, which consists of 230 case histories compiled by Boulanger et al. [2], are evaluated. Accordingly, the efficacy of the strain-based procedure can be assessed both in an absolute sense (i.e., with respect to field observations) and in a relative sense (i.e., relative to the efficacy of stress-based procedures). Additionally, using the two types of liquefaction case history databases in the assessment allows the significance of using one type of in-situ test metric, versus the other, to estimate needed parameters.

The following sections present the background information related to both the cyclic stress and cyclic strain approaches. Next, the steps used to implement the proposed variant of the strain-based procedure are outlined, and an overview of the liquefaction case history databases used in the assessment is given. The results from the assessment are then presented and discussed.

## 2. Background information

### 2.1. Liquefaction evaluation procedures

#### 2.1.1. Simplified stress-based approach

As stated in the Introduction, the simplified stress-based procedure is widely used for evaluating liquefaction triggering. Per this procedure the seismic demand is quantified in terms of Cyclic Stress Ratio (CSR), which is the cyclic shear stress ($\tau_c$) imposed at a given depth in the soil 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. The resulting "simplified" expression for CSR is:

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

where: $a_{max}$ = maximum horizontal acceleration at the ground surface; g = acceleration due to gravity; $\sigma_v$ and $\sigma'_{vo}$ = total and initial effective vertical stresses, respectively; 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 need for which were largely based on results from laboratory studies, to account for durational effects of the shaking (MSF: Magnitude Scaling Factor, where the reference motion duration is for a moment magnitude 7.5 earthquake, $M_w$7.5), initial effective overburden stress ($K_\sigma$, where the reference initial effective overburden stress is 1 atm), and initial static shear stress ($K_\alpha$, where the 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 event, 1 atm initial effective overburden stress, and level ground conditions) is given by Eq. (2):

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

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 at the sites. By plotting CSR* for each of the case histories as a function of the corresponding in-situ test metric (e.g., SPT N-value or $V_s$), normalized for clean sand conditions and an initial effective overburden stress of 1 atm etc., it can be observed that 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 an $M_w$7.5 event. This boundary can be expressed as a function of the normalized in-situ test metrics.

Consistent with the conventional definition for factor of safety (FS), the FS against liquefaction ($FS_{Liq}$) is defined as the capacity of the soil to resist liquefaction divided by the seismic demand:

$$FS_{Liq} = \frac{CRR_{M7.5}}{CSR^*} \tag{3}$$

As discussed subsequently in this paper, the efficacies of the deterministic variants of the Kayen et al. [20] $V_s$-based and Idriss and Boulanger [17] SPT-based simplified liquefaction evaluation procedures are used herein to compare with that of the proposed variant of the Dobry et al. [11] strain-based procedure.

#### 2.1.2. Dobry et al. [11] strain-based approach

Early studies showed that volumetric strain in a given soil subjected to cyclic loading under drained conditions almost uniquely correlates with the amplitude of the applied cyclic shear strain ($\gamma_c$), rather than the applied $\tau_c$ (e.g., Silver and Seed [36]). The corollary of this finding is that the excess pore pressure ratio ($r_u$: $r_u = \Delta u/\sigma'_{vo}$, where $\Delta u$ is the excess pore water pressure) in a given saturated soil subjected to cyclic loading under undrained conditions almost uniquely correlates with the amplitude of the applied $\gamma_c$, rather than the applied $\tau_c$ (e.g., Martin et al. [25]). Building on these findings, Dobry et al. [11] proposed a strain-based approach for evaluating liquefaction triggering potential, as an alternative to the stress-based approach.

Starting with the simplified equation to compute $\tau_c$, Dobry et al. [11] proposed a simplified equation to compute $\gamma_c$:

$$\gamma_c = \frac{\tau_c}{G} \tag{4}$$

$$\gamma_c = 0.65(\frac{a_{max}}{g})\frac{\sigma_v r_d}{G_{max}(G/G_{max})_{\gamma_c}} \tag{5}$$

where: G = secant shear modulus of the soil; $G_{max}$ = small-strain ($\gamma_c \le 10^{-4}$%) secant shear modulus of the soil; and $(G/G_{max})_{\gamma c}$ = normalized