A comparative study of deterministic approach for assessing liquefaction potential

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Abstract. SPT-based methods have been developed to evaluate liquefaction potential due to seismic loading. This method was evolved over time modified and updated by some researchers. This paper performed a comparative analysis of deterministic approach for assessing liquefaction potential. The selected case study site is in Taiwan which subjected to the 1999 Chi-Chi Earthquake. Furthermore, the oldest and most well-known method proposed by Seed et al. [3] was selected to identify the liquefaction potential. Moreover, a method from Idriss and Boulanger. [6] in which stated as the most suitable method for a certain case in Indonesia, was also conducted. The recent updated method of Cetin et al. [12] which has considered some seismic parameter from the recent seismic events was also utilized in quantifying liquefaction potential. Despite the fact that liquefaction potential is expressed by the factor of safety in deterministic method, some liquefaction parameters including $r_d$ (stress reduction coefficient), CSR (Cyclic stress ratio), ($N_{160}$), (fines-corrected $N_{60}$ value) and FS (factor of safety) were quantified by these methods and then compared. The results show that $r_d$ and CSR calculated by Cetin et al. [12] is lower than that of Seed et al. [3] and Idriss and Boulanger [6]. The FS from Idriss and Boulanger [6] is lower as compared to the two methods; Seed et al. [3] and Cetin et al. [12].

1. Introduction

Soil liquefaction is one of the secondary hazardous of earthquake. Soil liquefaction, phenomenon induced by shaking of earthquake, is the increment of pore water pressure causes the soil lose its shear strength significantly. Moreover, it can lead to ground failures which cause structural damage and loss of life. Thus, soil liquefaction is a topic of considerable interest to civil engineers particularly geotechnical engineers. Liquefaction potential of soil can be assessed by utilizing two general types of approaches: (1) use of laboratory testing of undisturbed samples, and (2) use of empirical relation based on in-situ tests, such as cone penetration test (CPT), standard penetration test (SPT), shear wave velocity (Vs), and Becker penetration test [1]. However, the use of laboratory testing is sufficiently difficult and costly to be performed. Whereas, empirical approach based on in-situ tests is more common in practice and quite feasible to be performed. Among these in-situ tests, the oldest and still the most frequently used to evaluate the liquefaction potential of soil is SPT. SPT-based methods to assess soil liquefaction potential will be focused in this study.

Numerous SPT-based methods to evaluate liquefaction potential have been developed by some researchers. The SPT-based method for evaluating soil liquefaction potential which has been used over the last four decades was originally proposed by Seed and Idriss [2]. Actually, this method was evolved
over time modified and updated by some researchers. A modification proposed by Seed et al. [3] is one of the most commonly accepted and used in practice which was confirmed by the discussion in NCEER Working Group [4, 5]. Seed et al. [3] employed 126 case history data points were screened for data quality by the original investigators, and so represented an excellent starting point. Although widely used in practice, this method is somewhat dated, and does not make use of an increasing body of field case history data from seismic events that have occurred since 1984.

After two decades, Idriss and Boulanger [6] proposed SPT-based method procedures to investigate liquefaction potential. In substance, Idriss and Boulanger [6] is the updated version of Idriss and Boulanger [7]. Idriss and Boulanger [7] primarily used cases summarized in the databases compiled by Seed et al [8] and cetin et al. [9,10] were screened for data quality. Those databases were then updated by Idriss and Boulanger [6] to derive updated triggering correlation. The updated database includes considerably more case histories and that the updated database continues to support the previously derived triggering correlation. The total number of case histories in the updated database is 230, of which 115 cases had surface evidence of liquefaction, 112 cases had no surface evidence of liquefaction, and 3 cases were at the margin between liquefaction and no liquefaction. Unsurprisingly, a study from mase [11] performed reliability study of SPT-based liquefaction analysis stated that Idriss and Boulanger [6] is the most suitable method with the smallest error weighted factor, although the case study is specified for liquefaction case due to earthquake of magnitude \( M_{w} = 8.4 \) in Bengkulu City, Indonesia.

After a decade, Cetin et al. [12] cast new regression model for seismic soil liquefaction triggering based on the data improvements. Some improvements were made by compiling the databases from Cetin et al. [9], Idriss and Boulanger [13-14]. Some databases of Cetin et al. [9] were excluded due to some reasons. Meanwhile, Idriss and Boulanger [13] SPT database has 230 case histories, and many are those have been screened and compiled by Cetin et al. [9]. Idriss and Boulanger [13] has added a new group data consist of 33 case histories. More recently, Boulanger and Idriss [14] compiled 24 additional cases. Thus, there are 57 new cases which were then re-evaluated by Cetin et al. [15-16] with screening criteria of Cetin et al. [9]. The screening results showed that 13 of the new Idriss and Boulanger [13-14] case histories are satisfied the Cetin et al. [9] screening criteria, and were added to the database utilized in Cetin et al. [12]. According to this updated data bases, Cetin et al. [12] developed an equation for liquefaction assessment in which only the coefficients are different from the Cetin et al. [9].

Assessment of liquefaction potential can be addressed by using deterministic and probabilistic approach. In a deterministic approach, the occurrence of soil liquefaction is defined by the factor of safety (FS). The FS is defined as the ratio of cyclic resistance ratio (CRR) over cyclic stress ratio (CSR). Moreover, if the FS is smaller than or equal to 1 then the soil liquefaction is predicted to occur. Differently, no soil liquefaction is concluded to occur if FS > 1. The purpose of this study is to make a comparative analysis of liquefaction potential expressed as \( r_d \), CSR, \( (N_1)_{a(SCS) \text{, and factor of safety (FS) according to several methods proposed by Seed et al. [3], Idriss and Boulanger [6], and Cetin et al. [12].}}

2. Liquefaction assessment methods

2.1. Seed et al. [3]
Evaluation of liquefaction potential basically take account two parameters: (1) the level of cyclic loading on the soil caused by the earthquake, expressed as CSR; and (2) the resistance of the soil to liquefaction, expressed as a CRR. However, the differences between one and the other methods are the considered parameters to compute them. According to Seed et al. [3], the CSR and CRR were depended on magnitude \( M_{s} \), peak horizontal ground surface acceleration \( a_{max} \), \( r_d \), effective overburden, \( (\sigma') \), fines content (FC), and SPT blow count, N (as shown in Figure 1).

2.2. Idriss and boulanger [6]
Idriss and Boulanger [6] proposed a liquefaction potential analysis by considering some parameters, including the:

- \( r_d \) and \( K_{o} \) (correction for cyclic stress ratios)
- Earthquake magnitude affects the MSF (magnitude scaling factor) and $r_d$.
- N-SPT correction factors, such as $C_R$ (Correction for sampler configuration details), $C_N$ (Overburden correction factor for penetration resistances), $C_S$ (correction for sampler configuration), $C_B$ (correction for borehole diameter), $C_E$ (correction for hammer energy ratio – ER).
- Effective overburden, $(\sigma'v)$ affects the $C_N$.
- Fines content affects the CRR and has poorly defined effects on all the other relationships.

**Figure 1. Flowchart of Seed’s method**

**Figure 2. Flowchart of Idriss and Boulanger’s method**
2.3. Cetin et al. [12]

A recent liquefaction triggering curves was presented by Cetin et al. [12] by updating the data bases. This method is the slightly different as compare to Seed et al [3] and Idriess and Boulanger [6] since the FS is calculated from PL (Probability of triggering of liquefaction) which is calculated first. As compared with some studies from over a decade ago, this new SPT-based triggering curves proposed by Cetin et al [12] have shifted to slightly higher CSR-levels for a given $(N_{l})_{LCS}$ greater than 15 blows/ft, but the correlation curves remain necessarily unaffected at $(N_{l})_{LCS}$ values less than 15 blows/ft. The procedures to use Cetin et al. [12] are clearly documented in Cetin et al. [17].

- $rd$-values estimated by using the predictive $rd$ relationship developed by Cetin and Seed [1]. The consistent use of $rd$ relationship of Cetin and Seed [1] is presented on an illustrative seismic soil liquefaction triggering problem in Cetin et al. [17]. $rd$ requires the estimation of a representative shear wave velocity for upper 12 m of the soil site.

$$rd = \frac{14 - 23.013 - 2.949 \alpha_{max} + 0.999 M_w + 0.0525 V_s 12m}{14 - 23.013 - 2.949 \alpha_{max} + 0.999 M_w + 0.0525 V_s 12m} \times 16.258 + 0.201 e^{0.341(0.785 V_s 12m + 7.586)}$$

- $(N_{1.60})$ (standard penetration test blow count value corrected for overburden, energy, equipment and procedural factors) values are the product of the averaged $N$ values for a stratum corrected for effective normal stress $(C_S)$, hammer energy $(C_E)$, equipment rod length $(C_R)$, equipment sampler $(C_S)$, borehole diameter $(C_B)$, and procedural effects to fully standardized $(N_{1.60})$ values as given below:

$$N_{1.60} = NC_G C_E C_R C_S C_B$$

- The resulting (new) recommended seismic soil liquefaction triggering relationships are presented in the following equation and the new model coefficients are $\theta_1=0.00167$, $\theta_2=27.352$, $\theta_3=3.958$, $\theta_4=0.089$, $\theta_5=16.084$, $\theta_6=11.771$, $\theta_7=0.392$, $\sigma_v=2.95$.

$$P_L(N_{1.60}, CSR \sigma'_{\nu, \alpha=0,M_w}, \sigma'_{\nu}, FC) = \Phi(-) \frac{(N_{1.60}(1+\theta_1 FC) - \theta_2 \ln(CSR \sigma'_{\nu, \alpha=0,M_w}) - \theta_3 \ln(\frac{\sigma'_v}{\sigma_c}) + \theta_4 FC + \theta_5)}{\sigma_c}$$

$$CRR(N_{1.60}, M_w, FC, P_L) = \exp(-) \frac{(N_{1.60}(1+\theta_1 FC) - \theta_2 \ln(M_w) - \theta_3 \ln(\frac{\sigma'_v}{\sigma_c}) + \theta_4 FC + \theta_5 + \sigma_c \Phi^{-1}(P_L))}{\theta_6}$$

$$FS = \frac{CRR(P_L=50\%)}{CRR(P_L)} = \exp[-0.251 \Phi^{-1}(P_L)]$$

$$CSR = 0.65rd \frac{a_{max} \sigma'_v}{g \sigma_v}$$

$$CSR_{T5} = CSR \frac{1}{K_a} \frac{1}{K_{MW} K_a} \leq 0.6$$

$$K_a = \frac{\alpha_{\nu}^T}{\rho_d} \theta_3 / \theta_6; 0.8 \leq K_a \leq 1.6, K_{MW} = \left(\frac{M_w}{7.5}\right)^{-\theta_2 / \theta_6}; 5.5 \leq M_w \leq 8.4$$

3. Research method

A sample site selected for this analysis is located at the south western plain of Taiwan. The simplified geological profile of the site consists of five layers as listed in Table 1 [18]. The ground water table is 2.0 m below the ground surface. For liquefaction analysis, only two sandy soil layers, which are located at G.L.-2.0 to -6.0m (Layer 2) and G.L.-8.0~12.0m (Layer 4), are considered to be liquefiable. Hence, the analysis presented below is focused on these two layers. A scenario earthquake of magnitude $M_w=7.6$ Chi-Chi earthquake was used in the calculations. Analyses were carried out for $a_{max}$ levels at 1g. Thereafter, the liquefaction potential was analyzed by conducting three methods; Seed et al. [3], Idriess and Boulanger [6], and Cetin et al. [12].
Table 1. Simplified geological profile of the site [18]

| Depth (m) | N-SPT | Soil Types | ɣ (KN/m³) | Fines (%) |
|-----------|-------|------------|-----------|-----------|
| 1         | 12    | SM         | 19.2      | 5         |
| 2         | 12    | SM         | 19.2      | 5         |
| 3         | 12    | SM         | 19.3      | 5         |
| 4         | 12    | SM         | 19.3      | 5         |
| 5         | 12    | SM         | 19.3      | 5         |
| 6         | 12    | ML         | 19.4      | 57        |
| 7         | 5     | ML         | 19.4      | 57        |
| 8         | 5     | ML         | 19.4      | 57        |
| 9         | 15    | SM         | 19.3      | 5         |
| 10        | 15    | SM         | 19.3      | 5         |
| 11        | 15    | SM         | 19.3      | 5         |
| 12        | 15    | SM         | 19.3      | 5         |

4. Results and discussion

A comparative study of these methods for identifying liquefaction potential can be focused on some parameters. Since in general, basically the assessment procedures of liquefaction potential from each method are the same. However, the differences are the considered parameter and the equation to compute them. Four parameters will be compared in to simplify this comparative study.

The first parameter will be discussed is $r_d$, in which all methods are considering this parameter to calculate the CSR. $r_d$ was computed by using method proposed by Seed et al. [3], Idriss and Boulanger [6], and Cetin et al. [12]. $r_d$ were then plotted with respect to the depth as shown in Figure 3. Obviously, it shows the value of $r_d$ decreases as depth increasing. Moreover, the $r_d$ from Cetin et al. [12] is smaller as comparing to that of Seed et al. [3] and Idriss and Boulanger [6]. It had been suspected that the differences in the $r_d$, $K_a$, and $C_N$ relationships may have played a significant role, but it was found that they had a relatively minor effect on the resulting liquefaction triggering correlations [13].

Figure 4. shows the comparison of CSR computed by Seed et al. [3], Idriss and Boulanger [6], and Cetin et al. [12]. The line CSR versus Depth of Seed et al. [3], and Idriss and Boulanger [6] are coincident at the depth of 1.0 to 8.0 m and slightly different at the depth of 8.0 to 12.0 m. Moreover, the line CSR versus Depth from Cetin et al. [12] coincides with the line from Seed et al. [3], and Idriss and Boulanger [6] at the depth of 1.0 to 3.0 m. However, after depth of 3 m, the CSR of Cetin et al. [12] is smaller than that of the other methods.

The comparison of $(N_{1})_{60CS}$ calculated by three methods can be seen in Figure 5. The line CSR vs Depth from Seed et al. [3], and Cetin et al. [12] is coincident at the depth of 9.0 to 12.0 m. Moreover, the line CSR vs Depth from Idriss and Boulanger [4], and Cetin et al. [12] is coincident at the depth of 6.0 to 8.0 m. In general, the $(N_{1})_{60CS}$ of Seed et al. [3] is slightly greater from that of the other methods.

Figure 6. shows the comparison of FS form these three methods. Some certain depths, 1.0 to 2.0 m is definitely not liquefiable since the water table is 2.0 m below the ground surface and the depth of 6.0 to 8.0 m is not sandy soil. According to Figure 6, all the soil layers are liquefiable except those certain depths. Surprisingly, the FS from Seed et al. [3] resembles to the FS from and Cetin et al. [12]. Meanwhile, the FS from Idriss and Boulanger [6] is lower as compared to the two methods; Seed et al. [3], and Cetin et al. [12].
5. Conclusions
In summary, liquefaction is considered as one of critical issues in geotechnical engineering. Some SPT-based methods have been developed to evaluate liquefaction potential. This paper presents a comparison analysis of liquefaction potential expressed as factor of safety (FS) according to several methods.
proposed by Seed et al. [3], Idriss and Boulanger [6], and Cetin et al. [12]. Some comparisons of liquefaction parameters have been performed, including $r_d$, CSR, $(N_d)_{socs}$, and FS. $r_d$ and CSR calculated by Cetin et al. [12] is lower than that of Seed et al. [3] and Idriss and Boulanger [6]. The $(N_d)_{socs}$ of Seed et al. [3] is slightly greater from that of the other methods. Surprisingly, the FS from Idriss and Boulanger [6] is lower as compared to the other two methods; Seed et al. [3], and Cetin et al. [12]. It is necessary to consider more databases for comparative study.

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