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Developing the FC and GC dependent Liquefaction Triggering Curve using In-Situ Correlation of SPT-N and Vs with these Factors

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ABSTRACT: Liquefaction triggering analysis, based on SPT-N or Vs measurements, incorporates empirical corrections for fines content (FC) or gravel content (GC). These corrections vary among the studies due to limited case history databases. This study proposes the FC or GC corrections by modelling the maximum liquefiable SPT-N ($(N_1)_{60,max}$) or stress-normalized maximum liquefiable Vs ($Vs_{1,max}$) within the liquefaction triggering curves. The FC correlations on SPT-N are extracted from field exploration to model $(N_1)_{60,max}$. The resulting curves adjusted by the FC-dependent $(N_1)_{60,max}$ demonstrate trends comparable to those observed in case history databases. Similarly, the modelling $Vs_{1,max}$, based on field correlations between GC and Vs, produces outcomes aligned with case history data. These findings indicate that the proposed method could be utilized to develop various correction factors for regional liquefaction triggering curves, provided that regional correlations between SPT-N or Vs and influencing factors are established.

KEYWORDS: Liquefaction triggering curve, fines content, gravel content, SPT-N, Vs.

1 INTRODUCTION

The "simplified procedure" (Seed & Idriss, 1971) has been the standard method for soil liquefaction triggering analysis since 1970. It estimates liquefaction cyclic resistance ratio (CRR) based on standard penetration test blowcounts (SPT-Ns). Over the years, the procedure has been continuously modified by various studies (e.g., Boulanger & Idriss, 2014; Cetin et al., 2004; Idriss & Boulanger, 2010; Seed et al., 1985; Seed et al., 2003; Youd et al., 2001) by expanding case histories from different earthquakes worldwide. Cone penetration test (CPT)-based (Ecemis and Karaman, 2014; Geyin and Maurer, 2021; Hu and Liu, 2019; Juang et al., 2008; Robertson and Campanella, 1985) and shear wave velocity (Vs)-based approaches (Andrus and Stokoe, 2000; Kayen et al., 2013; Zhou et al., 2020) have been also developed following the similar framework.

Seed et al. (1985) found that the CRR increases as the fines content (FC) rises with the same stress-normalized SPT-N $(N_1)_{60}$ value. Ishihara (1993) discussed FC correction derived from past studies to obtain a consistent CRR for clean sand. Youd et al. (2001) proposed an updated FC correction, and Idriss and Boulanger (2006) further improved it by introducing a correction term, ΔN, as a function of FC added to $(N_1)_{60}$ to derive $(N_1)_{60,cs}$ (clean sand equivalence of corrected SPT blowcount). Meanwhile, Seed et al. (2003) and Cetin et al. (2004) presented an FC correction (K_s) to derive $(N_1)_{60,cs}$.

The aforementioned FC corrections, either by Ks and ΔN, were derived on the liquefaction case history database. However, the obtained FC corrections may have some bias and uncertainties because these databases are limited in both size and the uniformity of their FC distribution.

In predicting the liquefaction potential of gravelly soils using Vs-based curve, a number of studies (Cao et al., 2013; Chang, 2016; Rollins et al., 2020) have identified inaccuracies when applying triggering curves originally developed for sands. This is because gravels exhibit higher Vs values than sands under equivalent relative density and effective stress conditions (Cao et al., 2013; Chang, 2016; Hu, 2021). Therefore, some adjustment of Vs-based triggering boundaries may be desirable for gravelly soil. Recently, Hu (2021) and Rollins et al. (2022) proposed Vs-based liquefaction resistance boundaries for gravelly soils using larger databases than those used in the earlier studies (Andrus and Stokoe 2000, Kayen et al. 2013). However, a quantitative GC correction has not yet been established, as the available liquefaction databases still lack sufficient cases covering a broad range of gravel content.

This study aims to propose a novel method to develop the FC and GC dependent liquefaction triggering curve using in-situ correlation of SPT-N and Vs with these factors. Unlike the conventional approach that relies on limited liquefaction database, the proposed method take advantage of enriched in-situ data to enhance the liquefaction assessment. Moreover, this method is particularly appealing for low-to-medium seismicity regions with characteristic soils where liquefaction case histories are scarce.

2 METHOD

2.1 *SPT-N based liquefaction triggering curve*

Hwang et al. (2003) developed a liquefaction triggering curve by the hyperbolic function (HBF) based on the case history data from the Chi-Chi Earthquake. The model uses the following equation for CRR with three parameters:

$$\mathrm{CRR} = A + \frac{B \times (N_1)_{60,cs}}{1 - (N_1)_{60,cs}/C} \tag{1}$$

where A, B and C are three model parameters. Fig. 1 shows the schematic of HBF. The parameter of A corresponds to CRR at $(N_1)_{60,cs}$ of 0. It typically ranges from 0.06 to 0.10 in the past studies (Boulanger and Idriss, 2014; Cetin et al., 2004; Idriss and Boulanger, 2010; Seed et al., 1985; Seed et al., 2003; Youd et al., 2001). C corresponds to an upper bound of liquefiable $(N_1)_{60,cs}$ ($(N_1)_{60,\max}$), which is conceivably in the range of 25–45. Beyond this range, the soil will not liquefy due to shear-induced dilation behavior of dense soil. The three model parameters suggested by Hwang et al. (2021) are A=0.07, B=0.0042, and C=42, respectively.

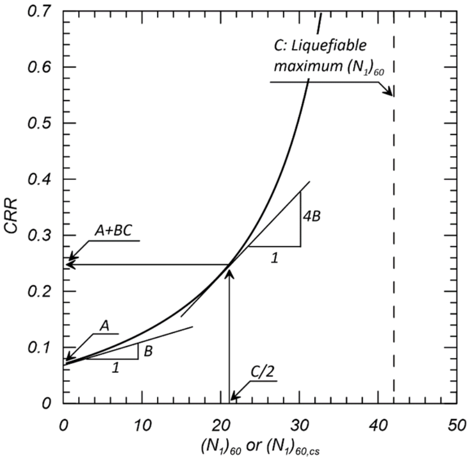

Fig. 1. Schematic of HBF

2.2 *Vs based liquefaction triggering curve*

Andrus and Stokoe (2000) proposed a Vs-based liquefaction resistance boundary as the reference clean sand curve, which is formulated as:

$$\mathrm{CRR} = \mathrm{a}\left(\frac{V_{s1}}{100}\right)^2 + b\left(\frac{1}{V_{s1}^* - V_{s1}} - \frac{1}{V_{s1}^*}\right) \tag{2}$$

where a=0.022, b=0.8, V_{s1} is stress-normalized V_s and V_{s1}^* (or $V_{s1,\max}$) is upper limit of V_{s1} that the soil will not liquefy due to shear-induced dilation behavior of dense soil. V_{s1}^* typically range from 215 m/s to 200 m/s as FC increases from 5% to 35%.

2.3 *Adjustment of liquefaction triggering curve*

Past studies have shown that SPT-N tends to decrease with FC given a relative density (D_R) (Cubrinovsk and Ishihara, 1999). Therefore, its influence on CRR given $(N_1)_{60}$ may be mostly captured by adjusting C (an upper bound of liquefiable blowcount) in the following equation for different FC ranges.

$$\mathrm{CRR} = A + \frac{B \times (N_1)_{60}}{1 - (N_1)_{60}/C} \tag{3}$$

Notably, $(N_1)_{60}$ is not corrected with FC by Ks or ΔN in Eq. (3). In contrast, the boundary curve shifts left as C is lowered, which results in a higher liquefaction resistance with a given $(N_1)_{60}$. C is modelled by using FC as follow:

$$C = C_{cs} \cdot min\left[1, \left(\frac{FC}{5}\right)^d\right] \tag{4}$$

where, A and B in Eq. (3) are remained constant (i.e., 0.07 and 0.0042, respectively).

For the Vs-based curve in Eq. (2), V_{s1}^*, similar to C in HBF representing upper limit of liquefiable Vs, is adjusted to modify CRR curve. As V_{s1}^* is lower, CRR curve also shift left, indicating an increase of CRR. Therefore, once the correlation of V_{s1}^* on GC is obtained, CRR can be adjusted.

3 IN-SITU CORRELATION

3.1 *In-situ database*

The Engineering Geological Database (EGDT) was constructed for the Taiwan Strong Motion Instrumentation Program (TSMIP). The EGDT contains comprehensive data, including stratum descriptions and results from soil physical property tests such as grain size distribution, uniformity coefficient (Cu), coefficient of gradation, void ratio, water content, specific gravity, unit weight, liquid limit, and plasticity index (PI). The database also includes soil classification, P- and S-wave velocities, and SPT-N values. EGDT provides sufficient information for developing empirical correlations between engineering properties and for evaluating the influence of various factors on these properties.

3.2 *SPT-N and FC correlation*

Based on EGDT, Tsai et al. (2019) observed that *N* decreases with FC given the effective vertical stress (σ'_v) based on the regression analysis. Moreover, they found the correlation of SPT-N with basic soil properties as follows:

$$\begin{aligned} \ln N = {} & 0.9 + 0.58\ln(\sigma'_v) \\ & - 0.27\ln(\mathrm{FC}) \\ & - 0.37\ln(\mathrm{PI}) + 0.4\ln(\mathrm{OCR}) \end{aligned} \tag{5}$$

Therefore, the d in Eq. (4) is found to be −0.27. The negative correlation indicates N decrease as FC increase. A lower absolute d value indicates a less influence of FC on the penetration resistance and the liquefaction resistance.

3.3 *Vs and GC correlation*

Based on EGDT, Tsai et al. (2024) proposed Vs prediction model for gravelly soil based on the regression analysis and found:

$$\begin{aligned} & \ln V_s = 4.438 + 0.214\ln(\sigma_v') \\ & - 0.0135\ln(\mathrm{FC}) \\ & - 0.163\ln(\mathrm{PI}) + 0.285\ln(\mathrm{OCR}) - 0.360\ln(e) \\ & + 0.0471\ln(\mathrm{GC}) + 0.0110\ln(\mathrm{Cu}) \end{aligned} \tag{6}$$

where, e is void ratio. Moreover, the additional inter parameter corelation are found as follow

$$\mathrm{Cu} = 10.21\exp(0.0426\mathrm{GC}) \tag{7}$$

$$\mathrm{e} = 1 - 0.095\ln(\mathrm{GC}) \tag{8}$$

Therefore, the model indicates that Vs increases as GC (or Cu) increases due to an increasing number of particle-to-particle contacts.

Based on Eq. (6), $V_{s1,eq}^*$ to account for GC effect under the same σ_v' is calculated as follows:

$$V_{s1,eq}^* = V_{s1}^* / (GC^{-0.047} \cdot Cu^{-0.011} \cdot e^{0.36}) \tag{9}$$

This equation implicitly assumes PI=1, OCR=1, and FC=1. Given V_{s1}^*= 215 m/s for FC < 5% suggested by Andrus and Stokoe (2000), $V_{s1,eq}^*$ is obtained per Eq. (9) and input into Eq. (2) to adjust the V_{s1} triggering curves accounting for the GC and Cu effects. Using this approach, $V_{s1,eq}^*$ increases to 245, 272, 295, 320 m/s, respectively, for GC = 10, 30, 50, 70% as Cu corresponds to 16, 37, 86, 200 and e corresponds to 0.72, 0.65, 0.56. 0.48 per Eq (7) and Eq (8).

4 RESULTS

4.1 *FC-dependent triggering curve*

Fig. 2 compares the FC-dependent resistance curves from this study and Hwang et al. (2021) for different FC ranges. Fig. 2 also presents the liquefaction (blue) and non-liquefaction (red) cases in the database complied by Hwang et al. (2021). Using d=−0.27 in Eqs. (4) and (3) yields a similar boundary to Hwang et al., (2021). This result indicates that the inherent reduction in N due to FC could be possibly applied to adjust boundary curve if the model of CRR curve includes the parameter which has a physical meaning associated with N (e.g., C in Eq. (1) represents the maximum liquefiable $(N_1)_{60}$). Potentially, the proposed method can update the CRR curves with local experimental studies, such as by conducting SPT calibration chamber tests using local materials by ranging FC.

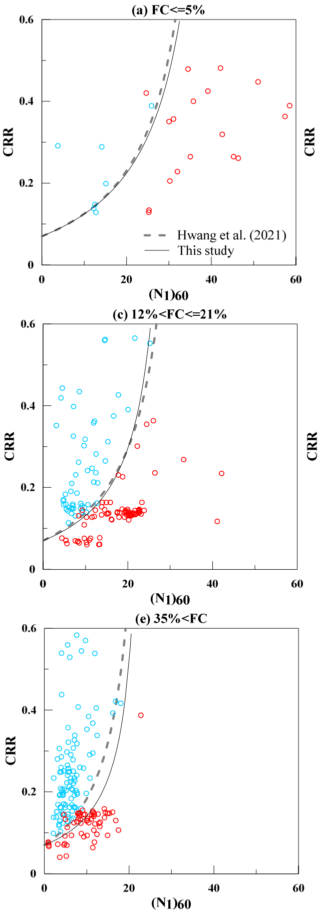

Fig. 2. Comparison of the FC-dependent resistance curves from this study and Hwang et al. (2021) (a) FC<=5% (b) 5%<FC<=12% (c) 12%<FC<=21% (d) 21%<FC<=35% (e) FC>35%

4.2 *GC-dependent triggering curve*

To validate the adjusted V_{s1} based liquefaction resistance boundaries, we used the databased compiled by Hu (2021), who collected 203 cases of liquefaction and non-liquefaction of gravelly soils from 17 earthquakes. To this database, we added cases involving gravelly soils (GC around 40~60%) from the 1976 Friuli earthquake reported by (Rollins et al., 2020). Cyclic stress ratios (CSR) for these case histories were computed consistently using the method described by Andrus and Stokoe (2000).

Fig. 3 compares the original Andrus and Stokoe (2000) clean sand (equivalent) liquefaction resistance curves, the Rollins et al. (2022) resistance curve for gravelly soil, and the modified Andrus and Stokoe (2000) resistance curves (using Eq. (2)) with liquefaction and non-liquefaction case histories in the databased compiled by Hu (2021). Moreover, we added cases involving gravelly soils (GC around 40~60%) from the 1976 Friuli earthquake reported by (Rollins et al., 2020). As illustrated Fig. 3, the liquefaction resistance boundary shifts to the right (higher V_{s1}) as GC increases. Furthermore, the case history data illustrate that the reference clean sand liquefaction triggering curve (Andrus and Stokoe, 2000) is not able to separate liquefied from non-liquefied data, even for GC < 20% cases. Rollins et al. (2022) developed a single liquefaction resistance curve for gravelly soils that is a clear improvement over the original Andrus and Stokoe (2000), but the single liquefaction resistance curve does not capture the apparent variation in liquefaction resistance with GC. In contrast, the proposed liquefaction triggering curves (Eq. (9)) reasonably envelope the liquefied cases (although several non-liquefied cases are mis-classified). Notably, the proposed curves for GC ~ 20% to 60% are quite comparable to the Rollins et al. (2022) single boundary.

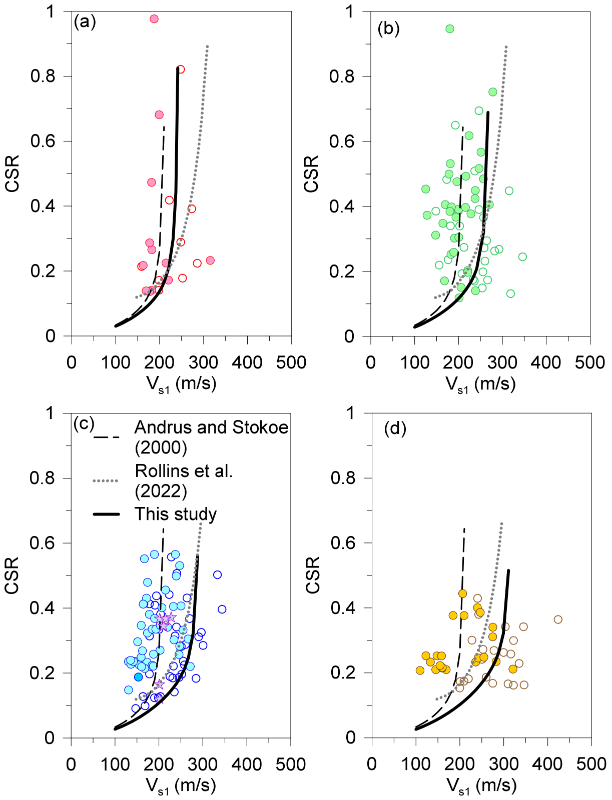

Fig. 3. Comparison of the GC-dependent resistance curves with case case history data (a) GC ≤ 20%, (b) 20% < GC ≤ 40%, (c) 40% < GC ≤ 60%, (d) 60% < GC. [Note: circle symbols represent data from Hu (2021); star symbols represent data from Rollins et al. (2020). Solid symbols and hollow symbols indicate liquefied and non-liquefied cases, respectively.]

5 CONCLUSIONS

Liquefaction triggering analysis, typically based on Standard Penetration Test (SPT-N) or shear wave velocity (Vs) measurements, conventionally incorporates empirical corrections for fines content (FC) or gravel content (GC). These corrections are predominantly derived from case history databases, which inherently limits their general applicability and accuracy.

This study introduces a novel approach to determine FC or GC corrections by directly modeling the maximum liquefiable SPT-N ($(N_1)_{60,max}$) or stress-normalized maximum liquefiable Vs ($Vs_{1,max}$) within the framework of liquefaction triggering curves. To model ($(N_1)_{60,max}$), correlations between SPT-N and FC are meticulously extracted from extensive field exploration data collected in Taiwan. The resultant CRR curves, when adjusted by the FC-dependent $(N_1)_{60,max}$, exhibit trends comparable to those derived from traditional case history databases.

Similarly, the modeling of $Vs_{1,max}$, informed by field correlations between GC and Vs, yields outcomes consistent with liquefaction case history data. As GC increases, the curves shift rightward, indicating a lower liquefaction resistance. These findings collectively suggest that the proposed methodology offers a robust alternative for developing diverse correction factors applicable to regional liquefaction triggering curves, contingent upon the establishment of reliable regional correlations between SPT-N or Vs and other influential factors.

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