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Influence of mis-assignment of groundwater level on liquefaction assessment of soils

Influence de la mauvaise affectation du niveau des eaux souterraines sur l'évaluation de la liquéfaction des sols

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ABSTRACT: This paper discusses unexpected influences of the miss-assignment of groundwater table in the analysis of soil liquefaction. In viewing that the groundwater table (GWT_0) during subsurface exploration for evaluating cyclic resistance ratio (CRR) of soils is sometimes mistakenly assumed the same as the groundwater table (GWT) for computing cyclic stress ratio (CSR) due to seismic shaking, the results of liquefaction analysis may thus be erroneous. If the GWT_0 is assigned higher than the actual level, than the CRR, and the associated factor of safety (F_L), would be overly predicted. Alternatively, if the GWT_0 is assigned lower than its actual one, than the CRR and F_L would be underestimated. If the groundwater table during exploration is mistakenly assigned as the groundwater table for computing cyclic stress ratio (i.e., $GWT_0 = GWT$; or "one-groundwater, 1-GW, scenario"), then the variation in groundwater tables will lead to the changes in CRR and CSR in the same sense. Owing to different rates of change, however, the computed factor of safety ($F_L = CRR/CSR$), and the associated liquefaction potential index (LPI), may sometimes result in an unexpected situation. Namely, an increase in the groundwater tables would cause an unanticipated increase in the computed factor of safety and a decrease in the associated liquefaction potential index. Based on results of current study, the LPI could be reduced by 10~30% if 1-GW scenario is assumed and GWT_0 is 3m higher than the actual level; or alternatively, the LPI would be increased by 5~45% if GWT_0 is 3m lower than the actual one.

RÉSUMÉ: Cet article examine les influences inattendues de la mauvaise affectation de la nappe phréatique dans l'analyse de la liquéfaction des sols. En considérant que la nappe phréatique (GWT_0) pendant l'exploration souterraine pour évaluer le rapport de résistance cyclique (CRR) des sols est parfois supposée à tort la même que la nappe souterraine (GWT) pour le calcul du rapport de contrainte cyclique (CSR) en raison des secousses sismiques , les résultats de l'analyse de liquéfaction peuvent donc être erronés. Si le GWT_0 est attribué à un niveau supérieur au niveau réel, le CRR et le facteur de sécurité associé (F_L) seraient surévalués. Alternativement, si le GWT_0 est attribué plus bas que son réel, le CRR et F_L seraient sous-estimés. Si la nappe phréatique pendant l'exploration est affectée par erreur comme la nappe phréatique pour le calcul du ratio de stress cyclique (c.-à-d. $GWT_0 = GWT$; ou «une eau souterraine, 1-GW, scénario»), la variation des nappes souterraines entraînera aux évolutions du CRR et CSR dans le même sens. Cependant, en raison de taux de changement différents, le facteur de sécurité calculé ($F_L = CRR/CSR$) et l'indice de potentiel de liquéfaction (LPI) associé peuvent parfois entraîner une situation inattendue. À savoir, une augmentation des nappes phréatiques entraînerait une augmentation imprévue du facteur de sécurité calculé et une diminution de l'indice de potentiel de liquéfaction associé. Sur la base des résultats de l'étude actuelle, LPI pourrait être réduit de 10 à 30% si le scénario de 1 GW est supposé et que GWT_0 est 3 m plus élevé que le niveau réel; ou bien, LPI serait augmenté de 5 ~ 45% si GWT_0 est 3 m plus bas que le réel.

KEYWORDS: Liquefaction analysis, groundwater level, CRR, CSR, LPI.

1 ROUTINE LIQUEFACTION ANALYSIS PROCEDURE

The SPT-N-based analysis methods have been widely adopted in liquefaction assessment of soils (Seed & Idriss 1971; Tokimatsu & Yoshimi 1983; Seed et al. 1985; JRA 1996; Youd et al. 2001). These methods generally involve separate calculations of the soil liquefaction resistance and the earthquake force action.

Fig. 1 shows a typical example of the calculation procedures, where the soil liquefaction resistance, expressed in terms of cyclic resistance ratio, or CRR, is evaluated based on the groundwater table (GWT_0) and hammer energy ratio (ER) at the time of drilling; and the earthquake force action, expressed in terms of cyclic stress ratio, or CSR, is estimated based on the assumed groundwater table (GWT) when the earthquake is acting.

The factor of safety against liquefaction (F_L) at a certain depth of concern can then be computed by $F_L = CRR/CSR$. As for the entire depth of borehole, the liquefaction potential (LPI) is commonly assessed by a depth-weighting procedure as proposed by Iwasaki et al. (1982), where $LPI = \int(1 - F_L)(10 - 0.5z)dz$ for a depth interval from the surface up to normally 20m deep.

It is clear that these two groundwater tables, namely GWT_0 and GWT, should not be confused, since they serve for different purposes, as mentioned by Youd et al. (2001) and Chang et al. (2011). As shown in Fig. 1, we notice that a rise in GWT_0 will reduce the effective overburden pressure σ'_{v0} at the location of SPT, which will amplify the N-value correction and hence an increase in CRR. Likewise, a rise in GWT will reduce the effective overburden pressure σ'_v at the depth of concern for estimating earthquake shear force and hence increase CSR.

A misuse of the groundwater table at the time of drilling (GWT_0) is often found by assigning it the same as the groundwater table during earthquake loading, namely, $GWT_0 = GWT$, or so-called "one groundwater (1-GW)" scenario. With this situation, the same rise or drop in the groundwater tables would lead to unexpected results in F_L and LPI. As shown in Fig. 2, a rise in both groundwater tables (1-GW scenario) would generally decrease F_L profiles. In some situations, however, the results are contradictory. The unexpected results are generally found to be at the shallower ground and for higher SPT-N deposits.

The aims of this paper are therefore to examine the one-groundwater (1-GW) scenario and to quantify its influence on the liquefaction assessment of soils. The examinations are performed based on single boreholes located in either a sandy or silty deposit, as well as a study site with an area of 116.4 Km^2 and a total number of boreholes of 331.

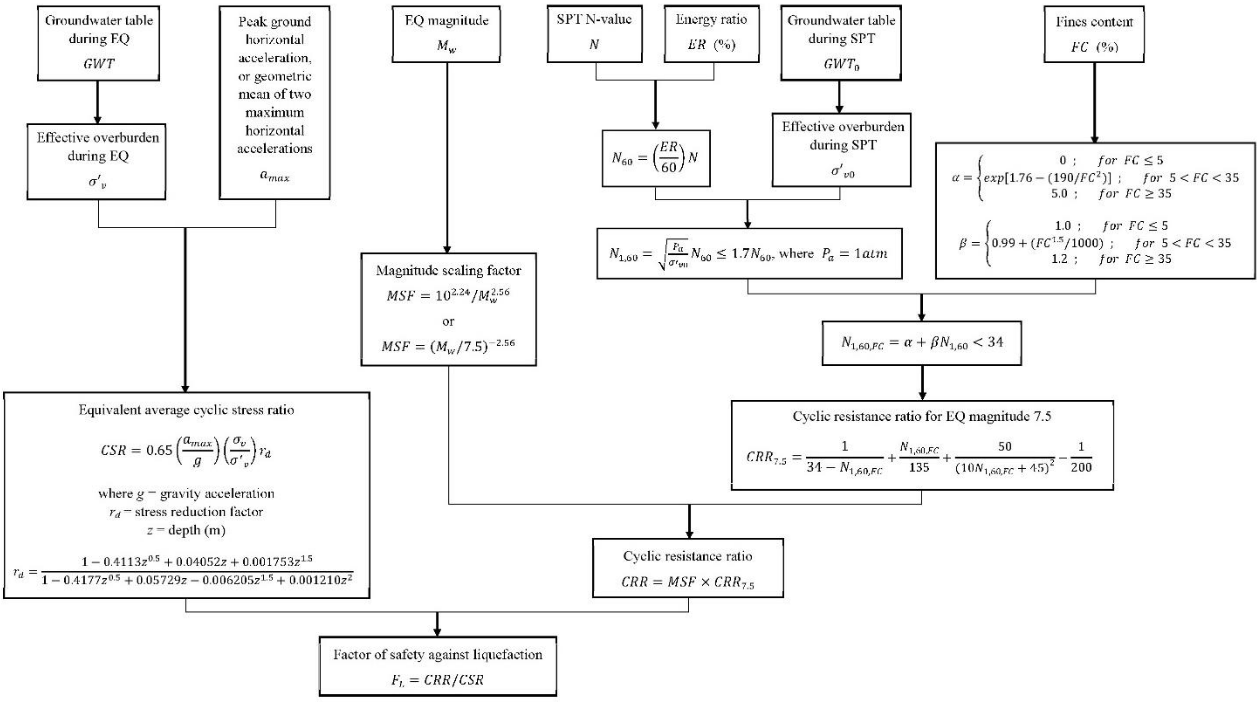

Figure 1. SPT-N-based soil liquefaction analysis flow chart by Seed/NCEER method (Youd et al. 2001).

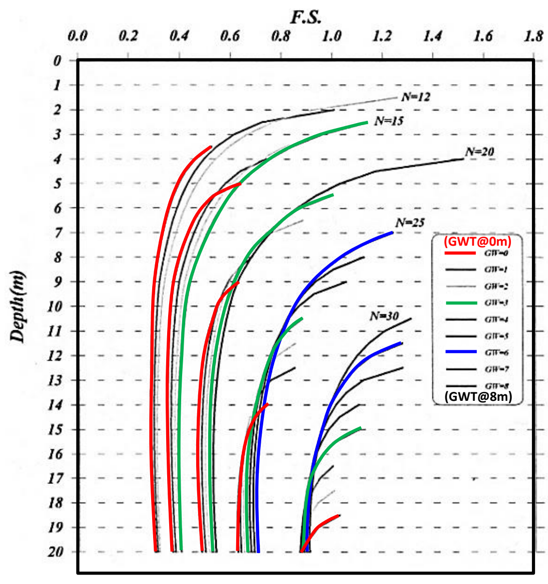

Figure 2. Results of computed $F_L{\sim}Depth$ profile based on 1-GW assumption (M=7.5, PGA=0.5g, FC=10%, uniform SPT-N deposit, Seed/NCEER method) (revised from Lin et al. 2001).

2 LIQUEFACTION ASSESSMENT OF A BOREHOLE IN A SANDY DEPOSIT

The borehole, W5-3, is located in Huwei Township of Yunlin County, Taiwan, which is one of the boreholes conducted in Phase I liquefaction study of the county, a part of the national-wise liquefaction project started in 2017 (REI 2019). Table 1 indicates the material data of the borehole, with the measured groundwater table during drilling, $GWT_{0,\mathrm{actual}}$, at a depth of 3.80 m.

Table 1. Material data at Borehole W5-3, a sandy deposit in Huwei Township, Yunlin County, Taiwan

Depth (m)	SPT-N	γ_m (kN/m^3)	FC (%)	PI (%)	USCS
-1.5	4	14.52	10	0	SP-SM
-3.0	5	17.36	28	0	SM
-4.5	8	18.74	13	0	SM
-6.0	10	20.01	8	0	SW-SM
-7.5	6	19.03	6	0	SP-SM
-9.0	16	19.23	5	0	SP
-10.5	9	19.13	7	0	SP-SM
-12.0	18	18.84	4	0	SP
-13.5	16	18.74	8	0	SP-SM
-15.0	10	18.34	7	0	SP-SM
-16.5	8	17.95	9	0	SW-SM
-18.0	13	20.99	14	0	SM
-19.5	15	20.40	10	0	SW-SM

Note: $GWT_{0,actual}$= -3.80m

Liquefaction assessment is based on project requirements with a design earthquake magnitude $M_w = 7.1$, a peak ground acceleration of the site $a_{max} = 0.308g$, and a site-specific hammer energy ratio $ER = 82\%$. The groundwater table during earthquake, GWT, is considered with a depth range of -1 ~ -7 m, approximately ± 3 m of $GWT_{0,\text{actual}}$. Factors of safe against liquefaction at various depths of the deposit are calculated based on Seed / NCEER method (Youd et al. 2001) and the liquefaction potential index is assessed by using Iwasaki procedure (Iwasaki et al. 1982).

Results of the assessment are indicated in Fig. 3 and Table 2. Fig. 3 shows the computed F_L profiles with various assignment of GWT. The dashed or dotted lines in the figure are for Case I with 1-GW assumption (i.e., $GWT_0 = GWT$), while the solid lines are for Case II where the groundwater table during drilling (GWT_0) is determined based on the onsite measurement ($GWT_{0,\text{actual}}$) and is dissimilar to the assigned groundwater tables during earthquake (GWT).

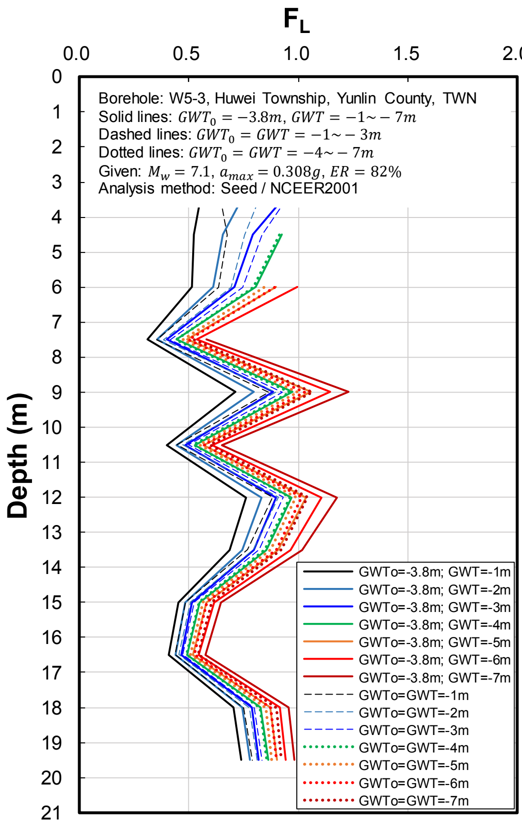

Figure 3. Computed $F_L \sim Depth$ profiles at Borehole W5-3, a sandy deposit in Huwei Township, Yunlin County, Taiwan, with or without 1-GW assumption.

As seen in the figure, the misuse of groundwater table during drilling by the 1-GW scenario (dashed or dotted lines) may cause computed factors of safety against liquefaction at various depths either too high or too low than the scenario (solid lines) with decoupled groundwater assignments (i.e., $GWT_0 \neq GWT$), leading to less variation in the F_L profiles due to the influence of GWT.

It is further noticed that if the 1-GW scenario is used and the groundwater table during drilling is higher than its actual level measured onsite (i.e., $GWT_{0,\text{actual}}$), then the computed factor of safety against liquefaction will higher than it should be, as shown by the dashed lines in Fig. 3, and hence results in a lower prediction in the liquefaction potential as indicated Table 2. For this borehole, the miss-assignment of GWT_0 by 3m higher than the actual level will decrease the liquefaction potential prediction by about 15%.

Similarly, if the 1-GW scenario is adopted and the groundwater table during drilling is lower than its actual level, then the computed factor of safety against liquefaction will be lower than it should be, as seen by the dotted lines in Fig. 3, and leads to a higher prediction in the liquefaction potential as shown in Table 2. For this borehole, the miss-assignment of GWT_0 by 3m lower than the actual level will increase the liquefaction potential prediction by about 20%.

Table 2. Results of liquefaction potential assessment at Borehole W5-3, a sandy deposit in Huwei Township, Yunlin County, Taiwan, with or without 1-GW assumption

GWT (m)	LPI (%) Case I (1-GW) $GWT_0 = GWT$ $GWT = -1\sim-7m$	LPI (%) Case II $GWT_0 = -3.80m$ $GWT = -1\sim-7m$	Error in LPI computation $\frac{(Case.1 - Case.2)}{Case.2}$ (%)
-1	38.95	46.20	-15.7
-2	23.55	28.60	-17.7
-3	19.08	20.93	-8.8
-4	16.40	15.94	2.9
-5	13.70	12.38	10.6
-6	12.36	10.11	22.2
-7	10.53	8.91	18.2

Note: M_w=7.1, a_{max}=0.308g, ER=82%, Seed/NCEER method

3 LIQUEFACTION ASSESSMENT OF A BOREHOLE IN A SILTY-CLAYEY DEPOSIT

The borehole, X4-8, is located in Tuku Township of Yunlin County, Taiwan, which is also one of the boreholes conducted in the project discussed previously (REI 2019). Table 3 indicates the material data of the borehole, with the measured groundwater table during drilling, $GWT_{0,\text{actual}}$, at a depth of 2.50 m.

Table 3. Material data at Borehole X4-8, a silty-clayey deposit in Tuku Township, Yunlin County, Taiwan

Depth (m)	SPT-N	γ_m (kN/m^3)	FC (%)	PI (%)	USCS
-1.5	3	19.23	86	0	ML
-3.0	5	19.03	88	0	ML
-4.5	4	18.64	85	3	ML
-6.0	4	18.25	60	0	ML
-7.5	8	18.84	36	0	SM
-9.0	13	18.44	33	0	SM
-10.5	5	17.95	93	33	CH
-12.0	10	18.54	76	0	ML
-13.5	5	18.44	97	22	CL
-15.0	4	18.74	93	7	ML
-16.5	3	18.44	95	4	ML
-18.0	5	18.15	99	13	CL
-19.5	9	17.66	50	0	ML

Note: $GWT_{0,actual}$= -2.50m

Same as the previous borehole, the conditions of liquefaction assessment are based on project requirements. The groundwater table during earthquake, GWT, is considered with a depth range of 0 ~ -6 m, approximately ±3 m of $GWT_{0,\text{actual}}$. Factors of safe against liquefaction as well as liquefaction potential index are assessed by the same methods as mentioned previously (Youd et al. 2001; Iwasaki et al. 1982).

Results of the assessment are indicated in Fig. 4 and Table 4. Fig. 4 shows the computed F_L profiles with various assignments of GWT. As before, the dashed or dotted lines in the figure are for Case I with 1-GW assumption (i.e., $GWT_0 = GWT$), while the solid lines are for Case II where the groundwater table during drilling (GWT_0) is determined based on the onsite measurement ($GWT_{0,\text{actual}}$) and is dissimilar to the assigned groundwater tables during earthquake (GWT).

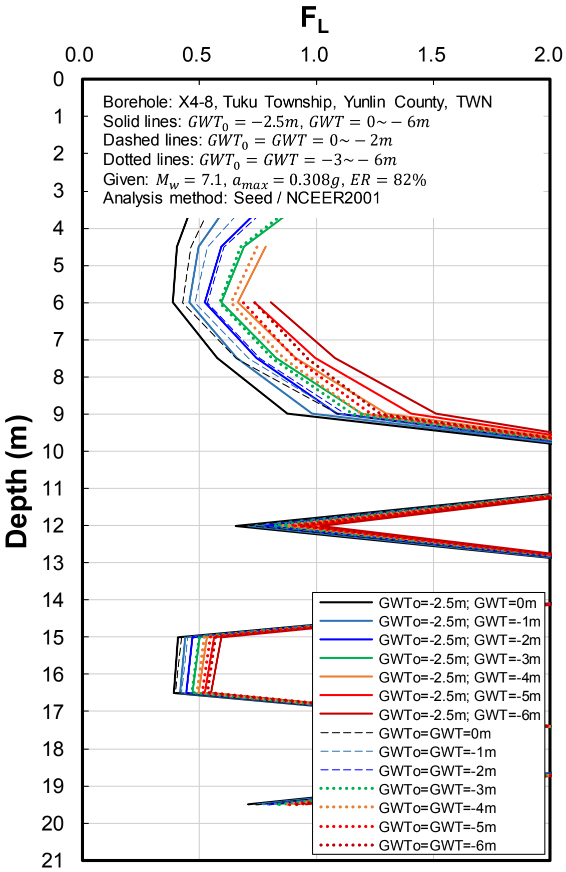

Figure 4. Computed $F_L \sim Depth$ profiles at Borehole X4-8, a silty-clayey deposit in Tuku Township, Yunlin County, Taiwan, with or without 1-GW assumption.

As seen in the figure, the misuse of groundwater table during drilling with the 1-GW scenario (dashed or dotted lines) again causes computed factors of safety against liquefaction at various depths either too high or too low than the scenario (solid lines) with decoupled groundwater assignments (i.e., $GWT_0 \neq GWT$).

If the 1-GW scenario is used and the groundwater table during drilling is higher than its actual level measured onsite (i.e., $GWT_{0,\text{actual}}$), then the computed factor of safety against liquefaction will higher than it should be, as shown by the dashed lines in Fig. 4, and results in a lower prediction in the liquefaction potential as indicated Table 4. For this borehole, the miss-assignment of GWT_0 by 3m higher than the actual level will decrease the liquefaction potential prediction by about 15%.

Alternatively, if the 1-GW scenario is adopted and the groundwater table during drilling is lower than its actual level, then the computed factor of safety against liquefaction will be lower than it should be, as seen by the dotted lines in Fig. 4, and leads to a higher prediction in the liquefaction potential as shown in Table 4. For this borehole, the miss-assignment of GWT_0 by 3m lower than the actual level will increase the liquefaction potential prediction by about 30%.

Table 4. Results of liquefaction potential assessment at Borehole X4-8, a silty-clayey deposit in Tuku Township, Yunlin County, Taiwan, with or without 1-GW assumption

GWT (m)	LPI (%) Case I (1-GW) $GWT_0 = GWT$ $GWT = -0\sim-6m$	Case II $GWT_0 = -2.50m$ $GWT = -0\sim-6m$	Error in LPI computation $\frac{(Case.1 - Case.2)}{Case.2}$ (%)
0	38.62	43.09	-10.4
-1	28.27	30.92	-8.6
-2	18.15	19.00	-4.5
-3	14.50	13.76	5.4
-4	12.09	10.58	14.2
-5	7.76	6.01	29.2
-6	6.42	4.78	34.1

Note: M_w=7.1, a_{max}=0.308g, ER=82%, Seed/NCEER method

4 LIQUEFACTION ASSESSMENT OF A STUDY AREA WITH MORE THAN 300 BOREHOLES

4.1 *Influence of miss-assignment of groundwater tables*

The influence of misuse of groundwater table by 1-GW scenario is also examined through a study area which covers Huwei and Tuku Townships of Yunlin County, Taiwan, an investigation site of the Phase I liquefaction project mentioned previously (REI 2019). The total area of the investigation is 116.4 Km^2 and the number of boreholes is 331, which includes 121 existing boreholes collected in the available reports and 210 supplementary boreholes conducted in this project.

As mentioned, the project requirements include a design earthquake magnitude $M_w = 7.1$, a peak ground acceleration $a_{max} = 0.308g$ for Type III ground ($V_{s30} < 180m/s$) or $a_{max} = 0.280g$ for Type II ground ($180m/s < V_{s30} < 270m/s$), and a site-specific hammer energy ratio $ER = 82\%$ for supplementary boreholes and an estimated hammer energy ratio $ER = 72\%$ for existing boreholes. The groundwater table during earthquake, GWT, is considered as the average of monitoring data during the 1-year period of the project, which is generally close to the measured values of GWT_0. As before, factors of safe against liquefaction are calculated based on Seed / NCEER method (Youd et al. 2001) and the liquefaction potential index is assessed by using Iwasaki procedure (Iwasaki et al. 1982).

Results of the assessment are shown in Fig. 5 and Table 5. Fig. 5 illustrates the computed liquefaction potential indices (LPI) of the 331 boreholes for the scenarios with or without 1-GW assumption, i.e., Case I vs. Case II. The results indicate, with the 1-GW scenario (Case I) and the groundwater tables during drilling (GWT_0) 3m higher than the actual levels, the assessed liquefaction potentials will be underestimated, as shown by the red triangles on the lower side of diagonal in the figure. Table 5 indicates the area with computed $LPI < 15$ (i.e., green and yellow areas) will be increase and the area for $LPI > 15$ (i.e., red area) will be decreased, as the result of 1-GW scenario in Case I. The average decrement in LPI in the study area will be 17.3% due to 1-GW scenario and the GWT_0 3m higher than the actual levels.

Conversely, with the condition of 1-GW scenario and GWT_0 3m lower than the actual levels, the assessed liquefaction potentials will be overestimated, as shown by the blue crosses on the upper side of diagonal in the Fig. 5. Table 5 indicates the area with computed $LPI < 5$ (i.e., green area) will be decreased and the area for $LPI > 5$ (i.e., yellow and red areas) will be increased, as the result of 1-GW scenario in Case I. The average increment in LPI in the study area will be 24.3% due to 1-GW scenario and the GWT_0 3m lower than the actual levels.

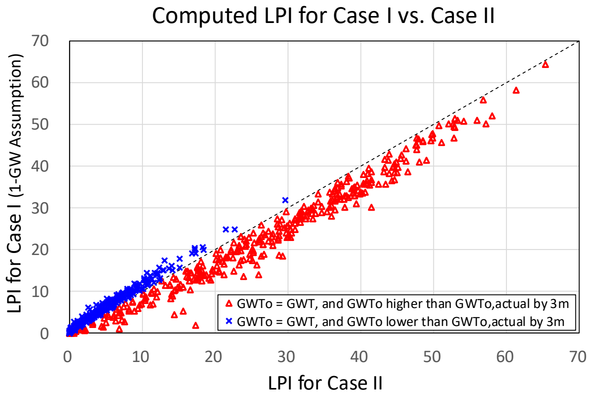

Figure 5. Computed liquefaction potentials for 331 boreholes in Huwei and Tuku areas in cases with or without 1-GW assumption.

Table 5. Liquefaction potential assessment results for 331 boreholes in Huwei and Tuku Townships, Yunlin County, Taiwan, with or without 1-GW assumption

Scenario	LPI level	Computed areas (Km²) Case I (1-GW) $GWT_0 = GWT$	Case II $GWT_0 \neq GWT$	Change in computed area (%)	Average change in LPI (%)
$GWT = GWT_{0,actual}$ + 3m (3m higher)	0~5	12.232	7.495	+4.07	-17.32
	5~15	22.419	17.796	+3.97	
	>15	81.792	91.152	-8.04	
		Sum: 116.443	Sum: 116.443	Sum: 0.00	
$GWT = GWT_{0,actual}$ - 3m (3m lower)	0~5	55.178	70.929	-13.53	+24.34
	5~15	58.866	44.428	+12.40	
	>15	2.399	1.086	+1.13	
		Sum: 116.443	Sum: 116.443	Sum: 0.00	

Note: Design EQ, M_w=7.1, a_{max}=0.308g (for Type III ground) or a_{max}=0.280g (for Type II ground), ER=82% (for 210 supplementary boreholes) or ER=72% (for 121 existing boreholes), Seed/NCEER method for analysis, IDW interpolation method for contouring

4.2 *Influence of assumption in hammer energy ratio*

The 331 boreholes adopted in the Phase I project as mentioned include 121 existing boreholes and 210 supplementary boreholes. The existing boreholes are obtained from various sources of data, and the associated hammer energy ratios (ER) for the correction of SPT-N values in these boreholes are practically unavailable. Based on very limited inspection data conducted previously in Taiwan, a preliminary estimate of $ER = 72\%$ is recommended by Lin et al. (2001) and adopted in the Yunlin liquefaction project as well as the analyses in Section 4.1 of this paper for the existing boreholes.

Since Phase I liquefaction project in Yunlin requires an auto-drop hammer system and the measurement of hammer energy during SPT operations, the hammer energy ratio is determined in the project with $ER = 82\%$ for the supplementary boreholes (REI 2019). Fig. 6 shows the auto-drop hammer system and the hammer energy inspection assembly adopted in this project.

Figure 6. Auto-drop hammer system and hammer energy inspection arrangement adopted in the Phase I soil liquefaction study in Huwei & Tuku Township, Yunlin County, Taiwan.

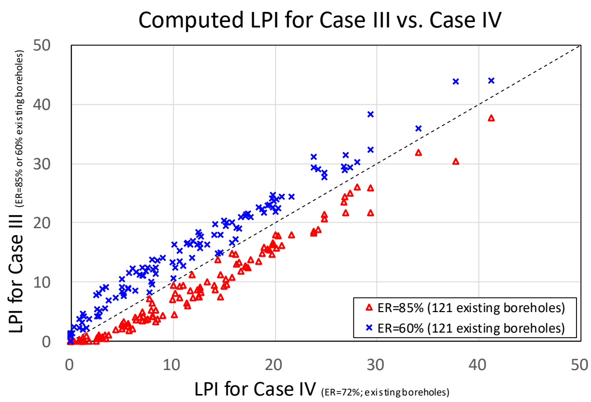

Figure 7. Computed liquefaction potentials in Huwei and Tuku areas with different assignments of energy ratio for the 121 existing boreholes.

Due to uncertainty in ER-value for the existing boreholes and its potential influence on the computed F_L and LPI, a liquefaction assessment is conducted for the 121 existing boreholes with ER-values ranged from 60% to 85%, approximately $\pm12\%$ of the preliminary estimate of 72%.

Results of the assessment are illustrated in Fig. 7. As noted in the analysis flowchart in Fig. 1, an increase in ER will enhance the correction of SPT-N value, which in turn increases CRR and F_L, and decreases LPI. Fig. 7 shows an increase in ER for the existing boreholes will decrease the LPI estimates, as shown by red triangles on the lower side of diagonal in the figure. The average decrement in LPI will be about 33% for the increase in ER by 13% (72% → 85%) for the 121 existing boreholes of this study.

Conversely, a decrease in ER for the existing boreholes will increase the LPI estimates, as shown by blue crosses on the upper side of diagonal in Fig. 7. The average increment in LPI will be about 44% for the decrement in ER by 12% (72% → 60%) for the 121 existing boreholes of this study.

5 CONCLUSIONS

This paper discusses miss-assignment of the groundwater table for drilling (GWT_0) and its potential influence on the liquefaction assessment of soils. Some key points and findings of the paper are summarized below:

- In routine liquefaction analyses of soils based on SPT-N approach, separate assessments of soil liquefaction resistance (CRR) and earthquake force action (CSR) are required. CRR is evaluated based on the groundwater table at the time of drilling (GWT_0) and CSR is estimated by the assumed groundwater table when earthquake is acting (GWT). These two groundwater tables serve different purposes and should not be confused in the analysis.
- In often cases, the groundwater table for drilling is misused the same as the groundwater table during earthquake, i.e., $GWT_0 = GWT$, or so-called "one-groundwater (1-GW) scenario", leading to variations of the groundwater tables, and the associated CRR and CSR as well, in the same sense, and hence resulting in unexpected estimates of the factor of safety against liquefaction (F_L) and the liquefaction potential index (LPI).
- Results of current study and other similar study conducted by the authors (Chang et al. 2020) indicate the LPI could be reduced by 10~30% if 1-GW scenario is assumed and GWT_0 is 3m higher than the actual level. Conversely, the LPI could be increased by 5~45% if 1-GW scenario is assumed and GWT_0 is 3m lower than the actual one.
- In examination of the influence of hammer energy (ER) on liquefaction assessment of soils, the study indicates the average decrement in LPI would be about 33% for the increase in ER by 13% (72% → 85%). Alternatively, the average increment in LPI will be about 44% for the decrement in ER by 12% (72% → 60%).

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