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Hany Shehata
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ISSN 2366-3405 ISSN 2366-3413 (electronic)
Sustainable Civil Infrastructures
ISBN 978-3-030-62907-6 ISBN 978-3-030-62908-3 (eBook)
https://doi.org/10.1007/978-3-030-62908-3

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

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SSIGE Official Publications 2020: Part 1

Assignment of Groundwater Table in Liquefaction Analysis of Soils

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Abstract. This paper discusses the issue and potential influences of miss-assignment of groundwater table in the analysis of soil liquefaction. In viewing that the groundwater table ($\boldsymbol{GWT}_0$) during subsurface exploration or testing 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 $\boldsymbol{GWT}_0$ is assigned higher than the actual level, the ***CRR*** and the associated factor of safety ($\boldsymbol{F_L}$), would be overly predicted. Alternatively, if the $\boldsymbol{GWT}_0$ is assigned lower than its actual one, the ***CRR*** and $\boldsymbol{F_L}$ would be underestimated. If the groundwater table during exploration or testing is mistakenly assigned the same as the groundwater table for computing cyclic stress ratio (i.e., $\boldsymbol{GWT}_0 = \boldsymbol{GWT}$; or "one-groundwater-table, ***OGT***, scenario"), then the variation in the 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 ($\boldsymbol{F_L} = \boldsymbol{CRR}/\boldsymbol{CSR}$), and the associated liquefaction potential index (***LPI***), may sometimes result in an unexpected situation. Namely, a rise 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 with assumption of ***OGT*** scenario, the ***LPI*** could be reduced by 10–30% if $\boldsymbol{GWT}_0$ is 3 m higher than the actual level; or alternatively, the ***LPI*** would be increased by 5–45% if $\boldsymbol{GWT}_0$ is 3 m lower than the actual one.

1 Introduction

Commonly adopted liquefaction analysis procedures, including methods based on $SPT - N$, $CPT - q_c$, and V_s, etc., involve separate evaluations of the cyclic resistance ratio (*CRR*) of soils and the cyclic stress ratio (*CSR*) due to seismic shaking (Youd

H. Shehata and M. Badr (Eds.): *Advancements in Geotechnical Engineering*, SUCI, pp. 3–18, 2021.
https://doi.org/10.1007/978-3-030-62908-3_1

et al. 2001; Seed et al. 1985; Robertson and Wride 1998; Andrus and Stokoe 2000). A factor of safety (F_L) against soil liquefaction at a particular depth of concern is obtained by the ratio of the above two evaluations, i.e., $F_L = CRR/CSR$. To assess liquefaction potential of a soil deposit, a depth-weighted approach is usually adopted with the consideration of liquefaction potential decreasing with the depth. In view of liquefaction incidents that had often observed within 20 m below the ground surface, Iwasaki et al. (1982) proposed a depth-weighted procedure, as shown below, by integrating the calculated factors of safety with depth, which has become most-widely used as the definition of liquefaction potential index (LPI or P_L):

$$\begin{aligned} LPI\ or\ P_L &= \int_0^{20m} F \cdot w(z)dz \\ \text{where } F &= 1 - F_L \qquad \ldots \text{ for } F_L \le 1.0 \\ F &= 0 \qquad\qquad\ \ \ldots \text{ for } F_L > 1.0 \\ w(z) &= 10 - 0.5z \end{aligned} \tag{1}$$

Iwasaki et al. (1982) further classified the assessed LPI or P_L into different categories: (1) $0 \le LPI \le 5$, for low liquefaction risk; (2) $5 < LPI \le 15$, for high liquefaction risk; and (3) $15 < LPI$, for very high liquefaction risk.

Figure 1 indicates a typical flowchart in conducting a liquefaction analysis. As can be seen, two groundwater data are required. The groundwater table, GWT_0, measured during the subsurface exploration and testing (e.g., SPT or CPT) is adopted for the assessment of CRR of soils, and the groundwater table,GWT, is assigned for the design earthquake condition and for the estimation of CSR due to seismic shaking. These groundwater tables are dissimilar and should not be confused, since they serve different purposes for the analysis and would have diverse effects on the assessment. Generally, the influences of GWT_0 and GWT on the computed factor of safety, F_L, and liquefaction potential index, LPI, would follow the trends as bellows (referring to Fig. 1 for symbols):

$$(GWT_0 \uparrow) \to \left(\sigma'_{v0} \downarrow\right) \to (N_1 \uparrow) \to (CRR \uparrow) \to (F_L \uparrow) \to (LPI \downarrow) \tag{2}$$

$$(GWT \uparrow) \to \left(\sigma'_v \downarrow\right) \to (CSR \uparrow) \to (F_L \downarrow) \to (LPI \uparrow) \tag{3}$$

It is clear that both groundwaters would influence the associated CRR and CSR in the same sense. One might expect an increase in the groundwater tables would soften the ground (or decrease effective stresses), thus reduce factor of safety against liquefaction and increase liquefaction potential. In view of the definition of factor of safety ($F_L = CRR/CSR$), however, a decrease in F_L by the increasing groundwater tables would not be certain, which would depend on the rates of change of GWT_0 and GWT on F_L. Supposed the rate of change of GWT_0 on F_L is more significant than that of GWT, then the same rise in both groundwater tables would lead to an increase in F_L, a situation appears contradictory with the intuition.

Whereas in general practices of liquefaction analysis, the groundwater table, GWT_0, during subsurface exploration and testing is often not employed for computing effective stresses σ'_{v0}, SPT blow counts N_1, and associated CRR. Instead, the groundwater table, GWT, assigned for design earthquake condition and for estimating cyclic stress ratio due

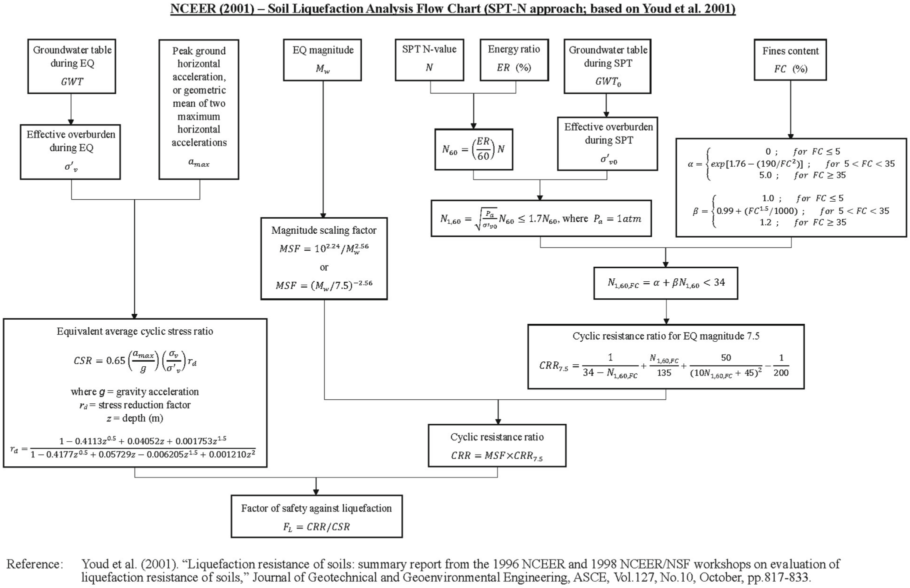


Fig. 1. Seed and NCEER SPT-N liquefaction analysis flowchart based on Youd et al. (2001)

to seismic shaking, is used in replacement of GWT_0 to compute σ'_{v0}, N_1 and CRR. The assignment of $GWT_0 = GWT$, termed hereafter as "one-groundwater-table" or OGT scenario, would be erroneous, since the CRR of soils is not properly evaluated by the groundwater table at the time of drilling or testing, and the incorrect GWT_0 might result in unanticipated F_L assessments as mentioned previously.

Figure 2 illustrates abnormal situations in the assessment of factor of safety due to OGT assumption. The factor of safety profiles are computed at various depths of a soil deposit with uniform $SPT - N$ distributions and different groundwater tables. As seen, the rise in the groundwater table would generally decrease the computed factor of safety. It is noticed, however, the rise in groundwater table could also lead to unexpected increases in the computed factor of safety, causing intersections of the factor of safety profiles as shown in the figure. These abnormal situations appear obvious for the cases with higher groundwater tables and shallower depths.

Figure 3 also indicates abnormal situations of the computed factor of safety, as dashed lines in the figure, due to the OGT assumption, where SPT blow counts are corrected with respect to GWT. Without OGT assumption, the GWT_0 would be irrelevant to GWT, and N_1 is solely determined by GWT_0, which is kept as a constant herein. Results demonstrate the computed factor of safety profiles without OGT assumption, as solid lines in the figure, are consistent as expected, where the rise in GWT will cause a decrease in F_L, and vice versa; with no intersection of the factor of safety profiles.

As discussed, the groundwater tables, GWT_0 and GWT, should not be misused in the liquefaction analysis of soils. Actually, this warning has been given by Youd et al. (2001) with the statements: "*The effective overburden pressure* σ'_{v0} *applied in (9;* $C_N = \left(P_a/\sigma'_{v0}\right)^{0.5}$*) and (10;* $C_N = 2.2/(1.2+\sigma'_{v0}/P_a)$*) should be the overburden pressure at*

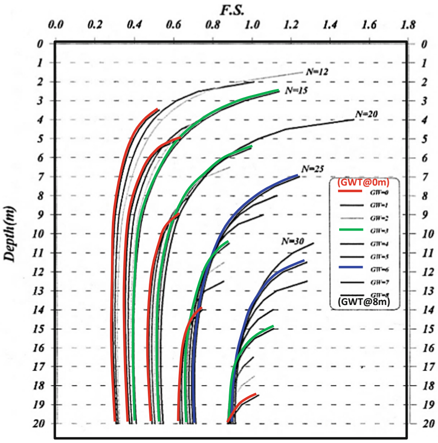


Fig. 2. Abnormal results of calculated factor of safety profiles due to one-groundwater-table assumption ($M = 7.5$, $PGA = 0.5g$, $FC = 10\%$, uniform $SPT - N$ deposits, Seed/NCEER2001 method) (Lin et al. 2001)

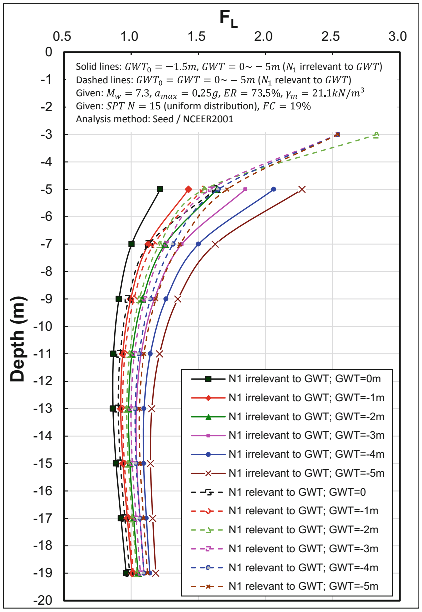


Fig. 3. Calculated factor of safety profiles due to OGT and non-OGT assumptions ($M = 7.3$, $PGA = 0.25g$, $FC = 19\%$, uniform deposit $SPT - N = 15$, Seed/NCEER2001 method) (Chang et al. 2011)

the time of drilling and testing. Although a higher groundwater level might be used for conservatism in the liquefaction resistance calculations, the C_N factor must be based on the stresses present at the time of the testing." (Note: C_N is a correction factor for $SPT - N$ values). In many occasions, however, the misuses of GWT_0 were found in routine practices of liquefaction analysis; part of reasons might have been due to the uncertainty or shortage of groundwater measurement data in the borehole logs that prevents proper assessments of cyclic resistance of soils (Wang et al. 2019).

The misuse of groundwater tables in liquefaction analysis has been addressed by Wang et al. (2019), based on the borehole data obtained from a recent liquefaction assessment project in Taipei basin. Preliminary results indicated the difference in the evaluated liquefaction potentials with or without OGT assumption would appear to be small. However, this finding was not conclusive since the groundwater tables, GWT_0, were measured during site explorations in flood seasons, which were generally close to the groundwater tables, GWT, assigned for the liquefaction analyses.

In accordance, the aims of this paper are to further address the issue of misuse of groundwater tables in liquefaction analysis of soils and to examine potential influences due to the misuse on the assessment of factor of safety and associated liquefaction potential. Several cases are employed for the examinations, including a fictitious borehole, actual boreholes, and a study site with an area of about 120 km^2 and a borehole number of more than 300.

2 Liquefaction Assessments of a Fictitious Borehole

A fictitious borehole is adopted to examine the influence of OGT assumption on the computed factor of safety and liquefaction potential. The borehole is assumed in a uniform stratum with a constant $SPT - N$ value of 10 and a fines content of 20%. The design earthquake is assumed with $M_w = 7.3$ and $a_{max} = 0.25g$. Seed/NCEER $SPT - N$ based method (Youd et al. 2001) is adopted for liquefaction analysis of soils at various depths and the depth-weighted procedure by Iwasaki et al. (1982) is employed for assessment of liquefaction potential in soil deposit up to 20 m deep.

Results of OGT scenario are compared with those of non-OGT scenario, in which the groundwater table, GWT, for estimating cyclic stress ratio due to seismic shaking is assumed varied from the ground surface to a depth of –5 m. Considering the groundwater table, GWT_0, for assessment of cyclic resistance of soils that could be higher or lower than its actual level of –2.5 m, the comparisons are discussed separately with results shown in Figs. 4 and 5, as well as in Tables 1 and 2, respectively.

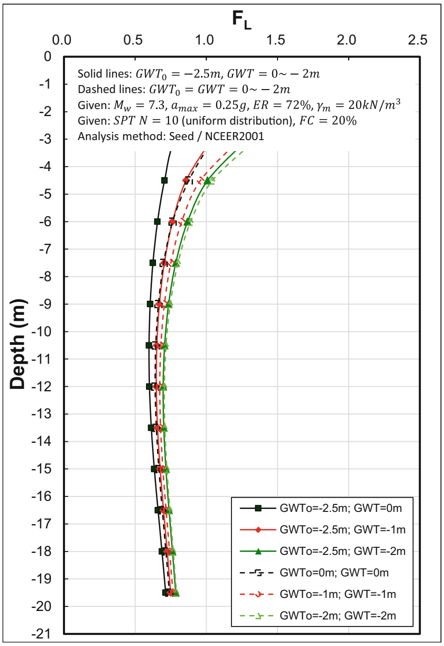


Fig. 4. Calculated factor of safety profiles with OGT (dashed lines) and without OGT (solid lines) assumptions and where the dashed lines are assigned with GWT_0 higher than its actual level of –2.5 m

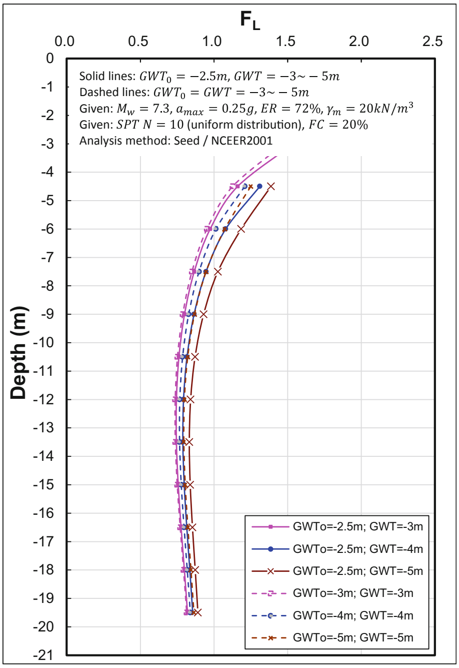


Fig. 5. Calculated factor of safety profiles with *OGT* (dashed lines) and without *OGT* (solid lines) assumptions and where the dashed lines are assigned with GWT_0 lower than its actual level of –2.5 m

Table 1. Calculated liquefaction potential indices with *OGT* (case I-A) and without *OGT* (case II-A) assumptions and where case I-A is assigned with GWT_0 higher than its actual level of –2.5 m

GWT	*LPI* or *PL* (%)		Error in *LPI* computations for case I-A
	Case I-A	Case II-A	
	$GWT_0 = GWT$	$GWT_0 = -2.5$ m	
	$GWT = 0 \sim -2$ m	$GWT = 0 \sim -2$ m	
0	18.46	26.46	−30.2%
−1 m	15.19	18.37	−17.3%
−2 m	12.43	13.11	−5.1%

Figure 4 and Table 1 indicate the results of *OGT* scenario (dashed lines; Case I-A) and the associated non-*OGT* scenario (solid lines; Case II-A), where the groundwater table, GWT_0, in the *OGT* scenario is higher than its actual level of –2.5 m. It is noticed when GWT_0 is mistakenly assigned the same as *GWT* and also higher than its actual

Table 2. Calculated liquefaction potential indices with *OGT* (case I-B) and without *OGT* (case II-B) assumptions and where case I-B is assigned with GWT_0 lower than its actual level of –2.5 m

GWT	*LPI* or *PL* (%)		Error in *LPI* computations for case I-B
	Case I-B	Case II-B	
	$GWT_0 = GWT$	$GWT_0 = -2.5\,\text{m}$	
	$GWT = -3 \sim -5\,\text{m}$	$GWT = -3 \sim -5\,\text{m}$	
$-3\,\text{m}$	10.18	9.50	7.2%
$-4\,\text{m}$	8.10	6.73	20.4%
$-5\,\text{m}$	6.54	4.48	46.2%

level (i.e., *OGT* scenario; dashed lines; Case I-A), the *CRR* of soils would be overestimated, leading to a higher estimation of F_L and a lower estimation of *LPI*; a situation appears contradictory with the intuition. For the fictitious example discussed herein, the computed *LPI* would be decreasing (i.e., less conservative) by 5–30%, if GWT_0 is 3 m higher than the actual level.

Figure 5 and Table 2 indicate the results of *OGT* scenario (dashed lines; Case I-B) and the associated non-*OGT* scenario (solid lines; Case II-B), where the groundwater table, GWT_0, in the *OGT* scenario is lower than its actual level of –2.5 m. It is noticed when GWT_0 is mistakenly assigned the same as *GWT* and also lower than its actual level (i.e., *OGT* scenario; dashed lines; Case I-B), the *CRR* of soils would be underestimated, leading to a lower estimation of F_L and a higher estimation of *LPI*; a situation appears contradictory with the intuition. For the fictitious example discussed herein, the computed *LPI* would be increasing (i.e., more conservative) by 5–45%, if GWT_0 is 3 m lower than the actual level.

The above discussions indicate the *OGT* assumption would be erroneous in liquefaction assessment of soils, leading to estimated factors of safety or liquefaction potentials contradictory with the intuitions. The fictitious example shows the liquefaction potential would be underestimated by 5–30%, if *OGT* is assumed and GWT_0 is higher than the actual level by 3 m. Alternatively, the liquefaction potential would be overestimated by 5–45%, if *OGT* is assumed and GWT_0 is lower than the actual level by 3 m.

3 Liquefaction Assessments of Actual Boreholes

The influences of *OGT* assumption on the computed factor of safety and liquefaction potential are further examined through actual boreholes drilled as a part of a field investigation program for the liquefaction study project in Huwei and Tuku Townships of Yunlin County, Taiwan, in 2019 (REI 2019). Two boreholes are selected from clayey or sandy deposits, and results of examination are discussed in the following subsections.

3.1 A Borehole in a Clayey Deposit

Borehole X6-1 is located in Huwei Township of Yunlin County, Taiwan. Table 3 indicates the material data, soil classifications and *SPT* blow counts within 20 m deep of the hole.

As seen, the borehole is in a clayey-silty deposit with relatively few sandy layers. Soil materials of the deposit are generally soft with $SPT - N$ values less than 10. The groundwater level GWT_0 measured during subsurface exploration is at –2.80 m.

Table 3. Material stratification and data at borehole No. X 6–1, in a clayey deposit of Huwei township, Yunlin county, Taiwan

Depth (m)	SPT N value	γ_m (kN/m^3)	FC (%)	LL (%)	PI (%)	USCS
−1.5	5	18.4	92	29	10	CL
−3.0	4	18.6	96	28	8	CL
−4.5	3	18.3	92	31	12	CL
−6.0	10	18.7	48	–	NP	SM
−7.5	5	18.3	48	–	NP	SM
−9.0	4	18.1	96	41	22	CL
−10.5	8	18.8	92	–	NP	ML
−12.0	6	18.2	93	42	19	CL
−13.5	5	18.5	95	–	NP	ML
−15.0	5	18.1	60	–	NP	ML
−16.5	10	18.6	34	–	NP	SM
−18.0	6	19.5	58	–	NP	ML
−19.5	16	18.2	31	–	NP	SM
Note: $GWT_{0,actual} = -2.80\,\text{m}$						

A design earthquake with $M_w = 7.3$ and $a_{max} = 0.25g$ is assigned and a SPT hammer energy ratio $ER = 72\%$ is chosen. As before, Seed/NCEER $SPT - N$ based method (Youd et al. 2001) is adopted for the analysis and the depth-weighted procedure by Iwasaki et al. (1982) is employed for assessment of liquefaction potential. The examination on the influences of OGT assumption is performed with the analysis groundwater tables GWT varied from the ground surface to a depth of –6 m, which are approximately 3 m above or below the actual groundwater table during drilling at a depth of –2.80 m.

Results of the examination are shown in Table 4. For OGT scenario (Case I) and GWT_0 higher than its actual level, the computed liquefaction potentials will be underestimated. The computed LPI would decrease by about 20% if GWT_0 is 3 m higher than the actual level. Alternatively, for OGT scenario (Case I) and GWT_0 lower than its actual level, the computed liquefaction potentials will be overestimated. The computed LPI would increase by about 30% if GWT_0 is 3 m lower than its actual level. These findings are consistent with discussions in the previous section.

Table 4. Errors in liquefaction potential assessment due to one-groundwater-table assumption (case I) for borehole No. X 6–1, in a clayey deposit of Huwei township, Yunlin county, Taiwan

GWT	*LPI* or *PL* (%)		Error in *LPI* computations for case I
	Case I	Case II	
	$GWT_0 = GWT$	$GWT_0 = -2.8\,\text{m}$	
	$GWT = 0 \sim -6\,\text{m}$	$GWT = 0 \sim -6\,\text{m}$	
0 m	13.80	16.97	−18.7%
−1 m	11.92	13.92	−14.4%
−2 m	10.70	11.04	−3.1%
−3 m	9.54	9.46	0.8%
−4 m	8.40	7.88	6.6%
−5 m	7.28	6.30	15.6%
−6 m	6.16	4.79	28.6%

Note: $GWT_{0,actual} = -2.80\,\text{m}$

Analysis assumptions: $M_w = 7.3$, $a_{max} = 0.25g$, $ER = 72\%$

Analysis method: Seed/NCEER SPT-N-based method (Youd et al. 2001)

3.2 A Borehole in a Sandy Deposit

Borehole X2-2 is located in Tuku Township of Yunlin County, Taiwan. Table 5 indicates the material data, soil classifications and *SPT* blow counts within 20 m deep of the hole. As seen, the borehole is in a sandy deposit with relatively few silty layers. Soil materials of the deposit are generally loose to medium dense with $SPT - N$ values ranged about 5–15. The groundwater level GWT_0 measured during subsurface exploration is at –4.10 m.

A design earthquake with $M_w = 7.3$ and $a_{max} = 0.25g$ is assigned and a *SPT* hammer energy ratio $ER = 72\%$ is chosen. As before, Seed/NCEER $SPT - N$ based method (Youd et al. 2001) is adopted for the analysis and the depth-weighted procedure by Iwasaki et al. (1982) is employed for assessment of liquefaction potential. The examination on the influences of *OGT* assumption is performed with the analysis groundwater tables *GWT* varied from depths of –1 m to –7 m, which are approximately 3 m above or below the actual groundwater table during drilling at a depth of –4.10 m.

Results of the examination are shown in Table 6. For *OGT* scenario (Case I) and GWT_0 higher than its actual level, the computed liquefaction potentials will be underestimated. The computed *LPI* would decrease by about 10% if GWT_0 is 3 m higher than the actual level. Alternatively, for *OGT* scenario (Case I) and GWT_0 lower than its actual level, the computed liquefaction potentials will be overestimated. The computed *LPI* would increase by about 10% if GWT_0 is 3 m lower than its actual level. These findings are consistent with discussions in the previous section.

Table 5. Material stratification and data at borehole No. X 2–2, in a sandy deposit of Tuku township, Yunlin county, Taiwan

Depth (m)	SPT N value	γ_m (kN/m^3)	FC (%)	LL (%)	PI (%)	USCS
−1.5	6	15.6	32	–	NP	SM
−3.0	6	15.7	5	–	NP	SP-SM
−4.5	3	17.7	5	–	NP	SP-SM
−6.0	9	19.3	7	–	NP	SP-SM
−7.5	2.5	17.7	63	–	NP	ML
−9.0	9	18.1	76	30	6	ML
−10.5	1.5	16.7	97	32	4	ML
−12.0	2	18.4	72	–	NP	ML
−13.5	16	19.0	14	–	NP	SM
−15.0	15	19.5	20	–	NP	SM
−16.5	11	18.6	8	–	NP	SP-SM
−18.0	11	18.5	8	–	NP	SP-SM
−19.5	17	19.6	7	–	NP	SP-SM

Note: $GWT_{0,actual} = -4.10\,\mathrm{m}$

4 Assessment of a Study Area with >300 Boreholes

The influences of *OGT* assumption on the computed factor of safety and liquefaction potential are also examined through a regional liquefaction study program carried in Huwei and Tuku Townships as mentioned previously (REI 2019). The study area, with about 120 km^2 in size and more than 300 boreholes, is chosen; in viewing that the examination could consider the variability of borehole data as well as the influence of *OGT* assumption on the distribution of liquefaction potentials at the site.

The total number of boreholes considered herein is 331, including 121 existing boreholes and 210 supplementary boreholes carried in the project (REI 2019). Based on current codes of Taiwan (MOI 2011 & 2017), a design earthquake is assigned with $M_w = 7.1$ at the project site and the peak ground acceleration is determined in accord with the type of soil deposit where the borehole is located, i.e., $a_{max} = 0.280g$ for Type III ground (soft deposits; $V_{s30} < 180m/s$) or $a_{max} = 0.308g$ for Type II ground (firm deposits; $V_{s30} = 180 \sim 270m/s$). It is noticed, however, most of the boreholes considered herein are situated in Type III ground, and only few are for Type II deposits.

The groundwater tables, $GWT_{0,proj}$, for assessing cyclic resistance of soils are based on the measurement during exploration and testing of the boreholes. Without a long-term monitoring data, the groundwater tables, GWT, for estimating cyclic stress due to shaking are assumed 3 m above or below the $GWT_{0,proj}$ at the borehole locations. In *OGT* scenario, the GWT_0 is assumed the same as GWT, and would not be the same

Table 6. Errors in liquefaction potential assessment due to one-groundwater-table assumption (case I) for borehole No. X 2–2, in a sandy deposit of Tuku township, Yunlin county, Taiwan

GWT	*LPI* or *PL* (%)		Error in *LPI* computations for case I
	Case I	Case II	
	$GWT_0 = GWT$	$GWT_0 = -4.1$ m	
	$GWT = -1 \sim -7$ m	$GWT = -1 \sim -7$ m	
−1 m	38.33	42.89	−10.6%
−2 m	33.35	36.73	−9.2%
−3 m	29.22	30.57	−4.4%
−4 m	23.81	23.93	−0.5%
−5 m	15.19	14.42	5.3%
−6 m	13.42	12.27	9.4%
−7 m	10.76	10.21	5.4%

Note: $GWT_{0,actual} = -4.10$ m
Analysis assumptions: $M_w = 7.3$, $a_{max} = 0.25g$, $ER = 72\%$
Analysis method: Seed/NCEER SPT-N-based method (Youd et al. 2001)

as $GWT_{0,proj}$. The energy ratio for *SPT* hammer is assumed as 72% for the existing boreholes. For supplementary boreholes, however, an energy ratio of 82% is assigned based on onsite calibrations for this project.

As before, Seed/NCEER $SPT - N$ based method (Youd et al. 2001) is adopted for liquefaction analysis and the depth-weighted procedure by Iwasaki et al. (1982) is employed for assessment of liquefaction potential. For liquefaction potential contour plotting, an interpolation technique by Inversed Distance Weighting, or IDW, is used.

Figures 6 and 7 show the results of *OGT* scenario (Case I-A) and the associated non-*OGT* scenario (Case II-A), where the groundwater table GWT_0 in the *OGT* scenario is higher than the project level $GWT_{0,proj}$ by 3 m. As shown in Fig. 6, when GWT_0 is mistakenly assigned the same as *GWT* and also higher than the project level (i.e., Case I-A), the computed *LPI* would be underestimated, with all the computation points falling on lower side of the diagonal line where *LPI* s are equal in Cases I-A and II-A. The average error in *LPI* computation of Case I-A is –17.3% (underestimated liquefaction potentials), for all the 331 boreholes evaluated.

Figure 7 shows distributions in area of computed liquefaction potentials for Cases I-A and II-A. The liquefaction potentials are divided into three levels, based on Iwasaki et al. (1982), where "$LPI \leq 5$" is for low liquefaction risk and shown in GREEN color, "$5 < LPI \leq 15$" is for high liquefaction risk and shown in YELLOW color, and "$15 < LPI$" is for very high liquefaction risk and shown in RED color. As seen, the computed liquefaction potentials for Case I-A are generally decreasing due to *OGT* assumption and GWT_0 higher than the project level. In terms of computed areas, the

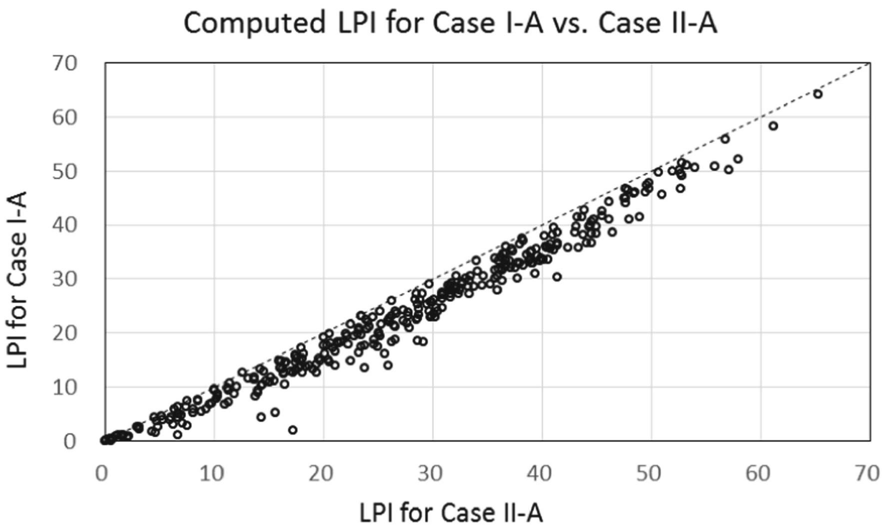
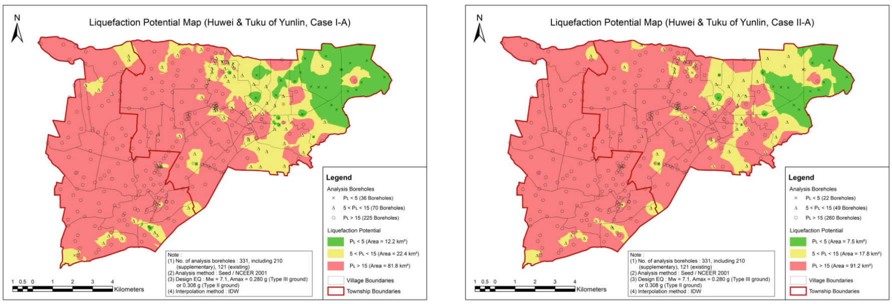


Fig. 6. Calculated indices of liquefaction potential with *OGT* (case I-A) and without *OGT* (case II-A) assumptions where the GWT_0 in case I-A is higher than its actual level by 3 m

Case I-A ($GWT_0 = GWT$)
($GWT_0 = GWT_{0,actual} + 3m$; $GWT = GWT_{0,actual} + 3m$)

Case II-A ($GWT_0 \neq GWT$)
($GWT_0 = GWT_{0,actual}$; $GWT = GWT_{0,actual} + 3m$)



LPI Category	Computed Area in Case I-A	
	(km^2)	(%)
LPI ≦ 5	12.2	**10.5**
5 < LPI ≦ 15	22.4	**19.2**
15 < LPI	81.8	**70.3**
Sum:	116.4	100.0

Changes in Area

+4.1% ( )
+3.9% ( )
-8.0% ( )

LPI Category	Computed Area in Case II-A	
	(km^2)	(%)
LPI ≦ 5	7.5	6.4
5 < LPI ≦ 15	17.8	15.3
15 < LPI	91.2	78.3
Sum:	116.4	100.0

Fig. 7. Calculated areas of liquefaction potential category with *OGT* (case I-A) and without *OGT* (case II-A) assumptions where the GWT_0 in case I-A is higher than its actual level by 3 m

decrement in liquefaction potentials could be attributed to 8.0% reduction in RED zone, as well as 3.9% and 4.1% increments in YELLOW and GREEN zones, respectively.

Figures 8 and 9 show the results of *OGT* scenario (Case I-B) and the associated non-*OGT* scenario (Case II-B), where the groundwater table GWT_0 in the *OGT* scenario is lower than the project level $GWT_{0,proj}$ by 3 m. As shown in Fig. 8, when GWT_0 is mistakenly assigned the same as *GWT* and also lower than the project level (i.e., Case I-B), the computed *LPI* would be overestimated, with all the computation points falling on upper side of the diagonal line where *LPI* s are equal in Cases I-B and II-B. The average error in *LPI* computation of Case I-B is +24.3% (overestimated liquefaction potentials), for all the 331 boreholes evaluated.

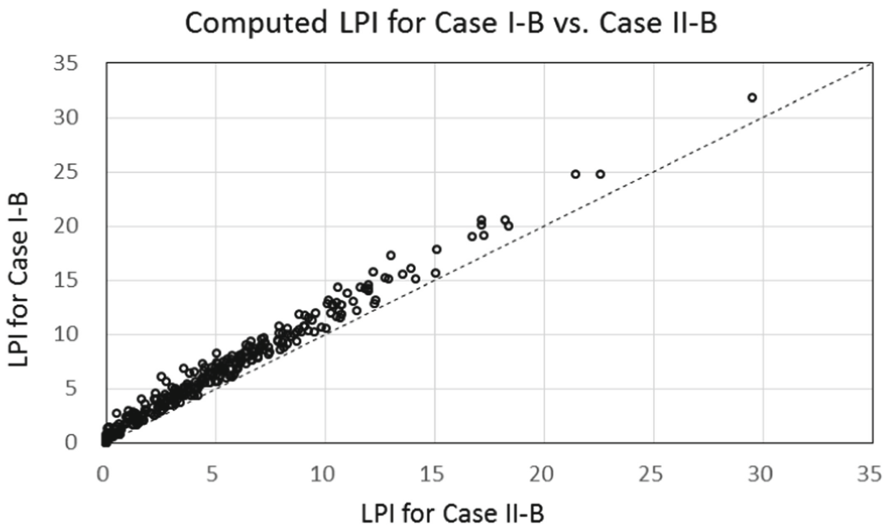
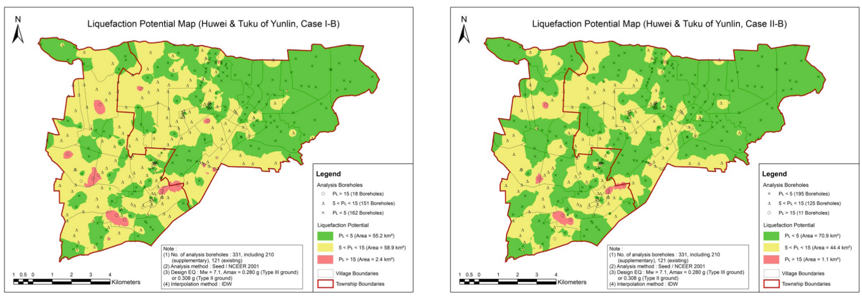


Fig. 8. Calculated indices of liquefaction potential with *OGT* (case I-B) and without *OGT* (Case II-B) assumptions where the GWT_0 in case I-B is lower than its actual level by 3 m

Case I-B ($GWT_0 = GWT$)
($GWT_0 = GWT_{0,actual} - 3m$; $GWT = GWT_{0,actual} - 3m$)

Case II-B ($GWT_0 \neq GWT$)
($GWT_0 = GWT_{0,actual}$; $GWT = GWT_{0,actual} - 3m$)



LPI Category	Computed Area in Case I-B	
	(km²)	(%)
LPI ≦ 5	55.2	47.4
5 < LPI ≦ 15	58.8	50.5
15 < LPI	2.4	2.1
Sum:	116.4	100.0

Changes in Area

-13.5% ( )
+12.4% ( )
+1.1% ( )

LPI Category	Computed Area in Case II-B	
	(km²)	(%)
LPI ≦ 5	70.9	60.9
5 < LPI ≦ 15	44.4	38.1
15 < LPI	1.1	1.0
Sum:	116.4	100.0

Fig. 9. Calculated areas of liquefaction potential category with *OGT* (case I-B) and without *OGT* (case II-B) assumptions where the GWT_0 in case I-B is lower than its actual level by 3 m

Figure 9 shows distributions in area of computed liquefaction potentials for Cases I-B and II-B. Similarly, the liquefaction potentials are divided into three levels, i.e., GREEN ($LPI \leq 5$), YELLOW ($5 < LPI \leq 15$), and RED ($15 < LPI$). As seen, the computed liquefaction potentials for Case I-B are generally increasing due to *OGT* assumption and GWT_0 lower than the project level. In terms of computed areas, the increment in liquefaction potentials could be attributed to 1.1% and 12.4% increases in RED and YELLOW zones, respectively, as well as 13.5% reduction in GREEN zone.

5 Conclusions

This paper addresses the issue of misuse of groundwater table in the evaluation of soil liquefaction. The groundwater table during subsurface exploration and testing, GWT_0, is used for assessment of cyclic resistance (or strength) of soils, but is often times assigned the same as the groundwater table assumed in the analysis, *GWT*, for estimating cyclic stress (or load) due to seismic shaking. The misuse would lead to erroneous results which contradict with the intuitions. Some key points and findings of the study are summarized as follows:

- Routine liquefaction analysis procedures generally involve separate evaluations of cyclic resistance ratio of soils (*CRR*) and cyclic stress ratio due to seismic shaking (*CSR*). A factor of safety against liquefaction (F_L) is obtained by the ratio of the above two, at a given depth of concern, and then integrated with depth to assess the liquefaction potential index (*LPI*) for the deposit.
- The groundwater table during exploration and testing (GWT_0) is used to calculate the effective stress and to assess the resistance or strength of soils, *CRR*, at the depth of concern. The increase in GWT_0 will decrease effective stress, which in turn will increase *CRR* and F_L, and thus decrease *LPI*.
- The groundwater table assumed in the analysis (*GWT*) is used to calculate the effective stress and to estimate the load of shaking, *CSR*, at the time earthquake. The increase in *GWT* will decrease effective stress, which in turn will increase *CSR*, decrease F_L, and thus increase *LPI*.
- These groundwater tables serve different functions in the analysis, so as to their influences on the assessed safety factor and liquefaction potential. Hence, GWT_0 and *GWT* should not be misused.
- General practices in liquefaction analysis would often times assign GWT_0 the same as *GWT*, called as one-groundwater-table (*OGT*) scenario; in which GWT_0, and *CRR* of soils as well, will go with *GWT* assumed in the analysis for estimation of *CSR*. Due to different rates of change of groundwater tables on the computed of safety factor and liquefaction potential, results of assessment would be erroneous.
- With *OGT* assumption and GWT_0 higher than actual level, the *CRR* of soils would be overestimated, thus leading to overestimated F_L and underestimated *LPI*. Alternatively, with *OGT* assumption and GWT_0 lower than actual level, the *CRR* of soils would be underestimated, and thus leading to underestimated F_L and overestimated *LPI*. Both of the above are erroneous and contradictory to intuitions.

- Based on results of current study, the *LPI* could be reduced by 10–30% for the case of *OGT* scenario and GWT_0 is 3 m higher than the actual level; or alternatively, the *LPI* could be increased by 5–45% for the case of *OGT* scenario and GWT_0 is 3 m lower than the actual one.

Acknowledgement. The authors would like to thank following peoples for discussions on the issue of one-groundwater-table in liquefaction analysis of soils: Professor T.S. Ueng of NTU, Taiwan, Professors C.H. Chen and J.H. Hwang of NCREE, Taiwan, Dr. C.C. Lu of NCREE, Taiwan, Mr. C.H. Wang of MAA, Taiwan, and the participants of 07/2018 NCREE seminar on the groundwater table issue for soil liquefaction. The opinions and insights provided through these discussions had been valuable and helpful in clarification of the issue that often times being neglected. The authors would also like to thank the Government of Yunlin County to provide borehole data for verification of the issue.

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