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Evaluation of Liquefaction Hazards in Soil Layers alongTabriz Metro Line 1 based on Practical Methods

Rouzbeh Dabiri, Sadaf Mahmoudi Azar

Department of Civil Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran.

*Correspondence should be addressed to Rouzbeh Dabiri, Department of Civil Engineering, Tabriz Branch, Islamic Azad University, Tabriz, Iran. Tel: +989141161400; Fax: +xxxxxxxxx; Email: rouzbehdabiri@gmail.com.

ABSTRACT

Settlements in the ground and deep soil layers can occur after the liquefaction phenomenon—these deformations damage structures, buildings, and lifelines. Several practical methods have recently been proposed based on fields and laboratory data for evaluating volumetric strain (settlement) and maximum shear strain due to liquefaction. The present study mainly aimed to compare liquefaction potential assessment findings in terms of risk intensity and settlement values of soil layers after liquefaction using Standard Penetration Test (SPT) and Energy Methods along Tabriz Metro Line 1. Thus, 31 boreholes along the path were selected in this regard. Then, the liquefaction potential of soil layers was assessed based on the above-mentioned methods, and the liquefaction potential risk index was determined as well. Finally, the settlement value of soil layers was evaluated according to the two proposed methods' findings. The findings showed that both processes were relatively correlated, and the energy method proposed higher liquefaction potential risk compared to the SPT procedure.

Keywords: Energy, Liquefaction, Settlement, Standard Penetration Test, Tabriz Metro Line 1

1. INTRODUCTION

Settlements and reductions in the soil particles of layers happen when loose and saturate sandy soil layers are subjected to earthquake loading. These conditions can cause severe damages to structures, buildings, metro, underground structures, and lifelines. In the dry sand, settlement happens very quickly due to earthquake shaking and constant effective stress. Therefore, settlement and reductions in the volume of soil particles are completed before the earthquake. In the saturated sand and when the drainage is limited, the production of excess pore water pressure in soil layers is the major effect of earthquake shaking in constant-volume conditions. In this state, the settlement and dissipate of excess pore water pressure simultaneously occur in soil layers. This trend can continue even after the end of the earthquake. Therefore, the settlement in saturated soil layers requires longer time, although it depends on permeability, compressibility, and drainage path length. Different field tests are used to evaluate the liquefaction potential of soil layers, including the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Shear Wave Velocity (Vs). Given that the SPT test has several advantages such as past measurements at liquefaction sites, detecting the variability of soil deposits and the retrieved soil sample is useful compared to other field tests for liquefaction resistance assessment [1]. Considering the risk of settlement, the present study sought to evaluate liquefaction potentials in soil layers along Tabriz Metro Line 1 based on practical methods.

2. MATERIALS AND METHODS

2.1. SETTLEMENT DUE TO LIQUEFACTION

If the saturated granular soil layer goes under earthquake loading, it can compress volume reductions in the absence of drainage possibility due to an increase in pore water pressure. In addition, the pore water pressure in the soil layers equals the total stress if it increases due to continuous shaking. Based on the concept of effective stress, it can be considered that:

$$\sigma' = \sigma - u \tag{1}$$

Where σ´, σ, and *u* represent the effective stress, the total stress, and the pore water pressure, respectively. If σ is equal to *u*, σ´ equals zero. In this condition, the saturated granular soils can be in a liquid situation, and the shear strength demonstrates a decrease. Such a condition is called “liquefaction”. The liquefaction of saturated sandy and granular soils during an earthquake is a damaging factor for buildings, underground structures, dams, retaining walls, and the like. Further, ground settlement, sand boiling, lateral spreading, cyclic mobility, and building distortion can be observed due to the liquefaction phenomenon in saturated soil layers. Several factors influence the occurrence of liquefaction, including the magnitude of an earthquake and its duration, the void ratio, the relative density, the fines content and soil types, the ratio of over consolidation, and the range of shear stress inflicted on the mass of the soil [1]. As mentioned above, various field methods are applied to evaluate the liquefaction phenomenon. SPT [2, 3], CPT [4], and seismic for measuring the velocity of the shear wave can be listed among these field methods [5-7]. On the other hand, recent methods for evaluating liquefaction are based on absorbed strain energy due to an earthquake in the soil. Several studies have evaluated the liquefaction potential of the soils using the energy theory [8-12]. Based on numerical models, some studies also proposed statistical theories for the energy method [13-15]. The tendency of the sand to become compressed under an earthquake vibration has been studied as well. The soil layer compression appears as a settlement on the ground surface. In addition to damaging vital piles commonly buried in lower depths, the settlement due to an earthquake causes fatigue in the structures located on shallow foundations and the destruction of the facilities serving the structures located on the piles. Moreover, the dried sand compaction occurs rapidly. The settlement of a sand mass typically completes after an earthquake, while the settlement of the saturated sand requires a longer time. Additionally, the settlement occurs when the pore pressure caused by an earthquake is dissipated. Varying from a few minutes to several days, the required time for settlement depends on the permeability, density, and strength of the soil, and the length of the drainage course. Thus, determining the settlement caused by an earthquake is difficult. The errors between 25 and 50% are common in the static settlement prediction, increasing in the case of more complicated loadings of an earthquake [16]. In addition, the rate of the settlement in sand layers is evaluated based on the field test in the two parts, dry [17, 18] and saturate layers [19-21]. Shimomura et al. [22] have recently proposed a new method for assessing settlement due to liquefaction in the soil layer using the energy of the probable earthquake. In this study, Davis and Brill’s method [8] was used for evaluating the liquefaction potential of soil layers based on the energy. Then, the findings were compared with Idriss and Boulanger’s [2] process based on SPT blow counts. The liquefaction potential index for both methods was calculated using the method by Iwasaki et al. [23, 24]. Then, settlement and volumetric strain in soil layers in dry and saturate states were estimated according to Tokimatsu and Seed’s [19] method for SPT. Similarly, Shimomura’s [22] procedure was employed in the energy process, and Tabriz Metro Line 1 was selected as the study area.

2.2. GENERAL CONDITION IN THE STUDY AREA

In general, 31 boreholes along Tabriz Metro Line 1 were collected to evaluate the liquefaction potential and estimate the probable settlement in soil layers in the study area. Approximately the length of Tabriz Metro Line 1 is equal to 17.2 Km. As shown in Figure 1, a part of this path is located underground

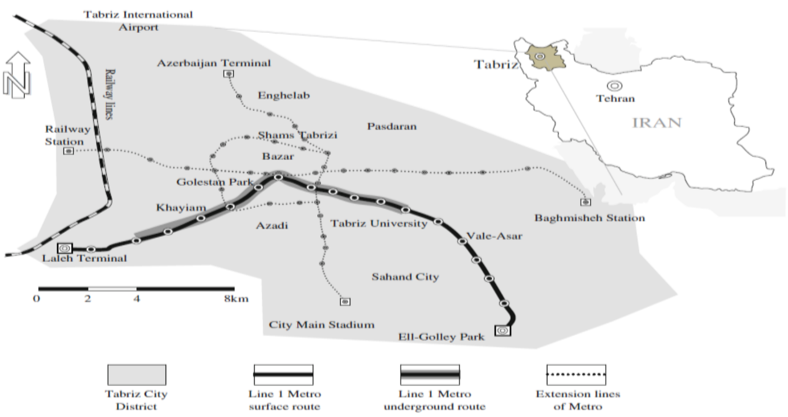


Figure 1. The general layout of the Tabriz Metro network [25]

Tabriz Metro Line 1 starts from the Elgoli area in the southeast of Tabriz and passes Shahid Beheshti Square and Bazar in the downtown. As the final destination, it reaches the Laleh area in the southwest of Tabriz. Further, the groundwater level is a very important factor in evaluating the liquefaction potential of soil layers. Groundwater depth variations in Tabriz are depicted in Figure 2a. The variation of groundwater along the path is estimated to be 7 to 18 m (Figure 2b).

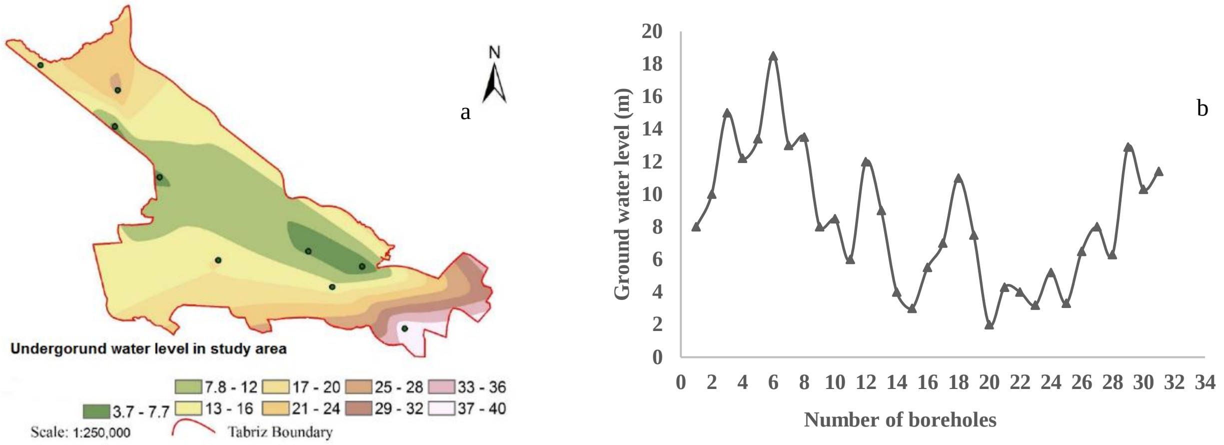


Figure 2. Variation of underground water level, a: In Tabriz [21]; b: In boreholes along Tabriz Metro Line 1.

2.3. ANALYSIS OF LIQUEFACTION

First, the liquefaction potential should be studied to evaluate the settlement due to liquefaction in soil layers in the study area. Peak ground acceleration (PGA) is considered as another important factor in liquefaction analysis. Tabriz North Fault is one of the most active faults in the northwest of Iran and is relatively close to Tabriz Metro Line 1. The length of Tabriz North Fault between Bostan Abad and Sofiean, where most historical earthquakes have happened, is nearly 90 km. Therefore, the PGA = 0.35g (475 years is the return period and a useful life 50 years), and Mw = 7.5 are considered according to the Iranian Code of Practice for the Seismic Resistant Design of Buildings.

2.3.1. Liquefaction Analysis (SPT) Method

The soils' liquefaction potential in the study area was assessed based on the simplified method proposed by Idriss and Bolanger (2010). In this method, the cyclic stress ratio (CSR) value is estimated, expressing the rate of the severity of the earthquake load in an Mw=7.5. It is evaluated using Equation No.2.

$$CSR_{7.5} = 0.65 \frac{a_{max}}{g} \cdot \frac{\sigma_V}{\sigma'_V} \cdot r_d \cdot \frac{1}{MSF} \tag{2}$$

Where a_{max}, g, σ_V, and σ'_V denote the PGA, the acceleration of gravity, the total stress in-depth in the question, and effective stress in the same depth, respectively. Moreover, the coefficient of the shear stress reduction was estimated using the Idriss [26] method. Magnitude Scale Factor (MSF) is the earthquake MSF that is calculated based on the studies by Andrus and Stoke (1997) using Equation No.2. Mw is the earthquake magnitude.

$$MSF = \left(\frac{M_W}{7.5} \right)^{-3.3} \tag{3}$$

Then, simplified and modified methods proposed by Seed et al. [1] were used to determine the cyclic resistance ratio (CRR) of the soils. In this step, the findings from the SPT were modified based on Equation (4), which was proposed by Skempton [27].

$$(N_1)_{60} = NSPT \times C_N \times C_E \times C_B \times C_R \times C_S \tag{4}$$

Where N_{SPT} and C_N show the number of the standard penetration resistance test and the coefficient of the overburden stress, respectively. Additionally, C_E, C_S, and C_B represent the coefficient of the hammer energy, the coefficients of the sampling method, and the borehole diameter, respectively. Similarly, C_R stands for the coefficient of the rod length, and $(N_1)_{60}$ is the modified number of the SPT. Next, according to the presented proposal by Idriss and Boulanger [2], the overburden tension correction factor (C_N) was determined using Equation No.5 as follows.

$$C_N = \left(\frac{P_a}{\sigma'_V}\right)^m \leq 1.7, P_a = 100kPa \tag{5}$$

$$m = 0.784 - 0.0768\sqrt{(N_1)_{60}}$$

Where Pa = 100kPa is the atmospheric pressure and σ'_V and effective stress at the intended depth, respectively, and $(N_1)_{60}$ represents the corrected number of the SPT. The equivalent of SPT in the clean sand ($(N_1)_{60CS}$) was determined after modifying its number. Then, CRR was assessed by applying Equations No.6 and No.7.

$$(N_1)_{60CS} = (N_1)_{60} + \Delta(N_1)_{60} \tag{6}$$

$$\Delta(N_1)_{60} = 1.63 + \exp\left(1 + \frac{9.7}{FC + 0.1}\right) - \left(\frac{15.7}{FC + 0.1}\right)^2$$

$$CRR = \exp(\left(\frac{(N_1)_{60cs}}{14.1}\right) + \left(\frac{(N_1)_{60CS}}{126}\right)^2 - \left(\frac{(N_1)_{60CS}}{23.6}\right)^3 + \left(\frac{(N_1)_{60CS}}{25.4}\right)^4 - 2.8) \tag{7}$$

2.3.2. Liquefaction Assessment Based on Energy Method

In contrast to other methods where stress or strain is used to determine CRR or CSR, in the energy procedure, a logical process exists for evaluating the liquefaction potential of soil layers due to two reasons. First, seismologists have proposed some relationships for estimating the released energy of an earthquake. Further, suitable correlations exist between dissipated energy and pore pressure. Therefore, the energy method for evaluating liquefaction in soil layers has two advantages as follows.

1. Energy is a scalar quantity. Therefore, there is no need to determine the history of stress and strain due to an earthquake in soil layers.

2. The energy method includes stress, strain, and geotechnical properties of soil layers.

Davis and Brill [8] applied three assumptions to determine the imported energy (demand) or trigger factor and estimated the energy of an earthquake based on the Gutenberg-Richter relationship. The energy value is a proportion of ($1/r^2$) where (r) is the distance between the site and the epicenter of an earthquake. This model of attenuation in energy dissipation includes no damping materials, but merely includes a geometric form of the wavefront. Furthermore, there is a linear relationship between excess pore water pressure and dissipated energy. Moreover, the dissipated energy due to the material is a proportion of ($1/(\sigma'_{v0})^{0.5}$). The triggering factor is calculated using Equation No.8.

$$Demand = \left[\frac{r^2 \cdot \sigma'^{1.5}_{vo}}{10^{1.5Mw}}\right]^{-1} \tag{8}$$

Where r, Mw, and σ'_{vo} represent the distance between the site and the epicenter (m), the magnitude of an earthquake, and the effective vertical stress in the study area (kPa), respectively. Additionally, demand can be determined using the corrected SPT data. According to Davis and Brill's [8] procedure, the capacity value of soil layers can be evaluated based on Equation No.9.

$$Capacity = \left[\frac{450}{N_1^2}\right]^{-1} \tag{9}$$

In the liquefaction potential evaluation based on the energy method, a critical state occurs when the energy due to the earthquake reaches a site more than the threshold value, which shows the resistance of soil layers. In this study, Google Earth satellite images were used for measuring the distance between the study area (Tabriz Metro Line 1) and the epicenter. It should be noted that the epicenter was assumed in the center of Tabriz north fault. The distance of boreholes along Tabriz Metro Line 1 from the assumed epicenter on the fault (Central part of Tabriz north fault) is calculated, and the demand and capacity of soil layers were determined using Equations 8 and 9 (Figure 3).

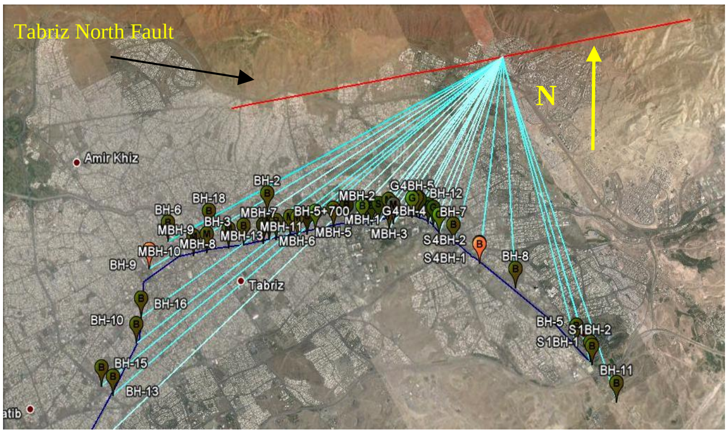


Figure 3. Determining of R based on the distance between the central part of Tabriz North Fault and boreholes in the study area

2.3.3. Correction of CCR

In both methods, if the amount of the effective vertical stress at the intended depth is more than 100 kPa, the CRR value is modified using Equation No.10.

$$CRR_j = K_\sigma \times CRR \quad (10)$$

Where CRR_j is the corrected CRR. Furthermore, Kσ denotes a coefficient based on effective vertical stress and is calculated using Equation (11) as follows [28].

$$K_\sigma = \left(\frac{\sigma'_V}{100}\right)^{f-1} \quad (11)$$

2.3.4. Safety Factor (FS)

Fs against liquefaction in soil layers is computed using Equation No.12. Liquefaction occurs when the amount is Fs ≤ 1. There is no probability of the occurrence of liquefaction when it is Fs >1.

$$F_S = \frac{CRR_j}{CSR} \quad (12)$$

2.3.5. Liquefaction Potential Index (LPI)

Previous researchers suggested several methods for assessing the rate of liquefaction and the level of its occurrence. One of the common methods was proposed by Iwasaki et al. [23, 24], which is presented as Equation No.13.

$$LPI = \int_0^{20} W(Z) \times F(Z).dz \quad (13)$$

$$F(Z) = 1 - F_S \text{ For Fs} < 1 \quad (13a)$$

$$F(Z) = 0 \text{ For Fs} \geq 1 \quad (13b)$$

$$W(Z) = 10 - 0.5Z \text{ For } Z < 20 \text{ m} \quad (13c)$$

$$W(Z) = 0 \text{ For } Z > 20 \text{ m} \quad (13d)$$

2.4. ANALYSIS OF SETTLEMENT

In the present study, the amount of settlement or the volumetric strain in the soil after liquefaction was calculated in two parts in soil layers above the groundwater level and under the water table (in the saturated model) as follows.The method by Tokimatsu and Seed [19] was used to determine the soil above the water table level in boreholes. Then, the following procedure was used to compute the volumetric strain (ε_v) in the upper layers of the groundwater level in borehole logs (34 boreholes) along Tabriz Metro Line 1.1. Using the formula provided by Idriss-Boulanger [2], the relative density (D_r) on the soil layer was determined according to some standard penetration resistance tests.

$$D_r = \sqrt{\frac{(N_1)_{60}}{46}}.100 \quad (14)$$

2. Similarly, the cyclic shear strain in the intended layer was determined using the formula provided by Tokimatsu and Seed [19] as follows.

$$\gamma_{cyc} = 0.65.\frac{a_{\max}}{g}.\frac{\sigma_v}{G_{\max}}.rd \quad (15)$$

Where rd and a_{max} are the stress reduction factor and the PGA, respectively. In addition, σ_v represents the total stress at the intended depth, and G_{max} is the maximum shear modulus calculated by Equation No.16 that proposed by Tokimatsu and Seed [19] based on kN/m^2.

$$G_{max} = 4400.((N_1)60)^{0.33}.(\sigma_V^{'})^{0.5}) \quad (16)$$

3. After calculating the volumetric strain (ε_v) in each layer of the soil, the settlement value of soil layers in borehole logs was determined through Equation No.17.

$$\Delta H = (\frac{\varepsilon_v}{100}) \times h \quad (17)$$

Where h demonstrates the thickness of the intended layer. Finally, the total of the settlement of each soil layer above the groundwater level was accumulated in meters for each borehole log. Further, Tokimatsu and Seed's [19] method was used to specify soil settlement and volumetric strain below the groundwater level in 34 boreholes of the study area. The applied procedure is as follows.1. The cyclic stress ratio (CSR) due to an earthquake was estimated using Equation No.2 for each soil layer of boreholes at the underground water level.

2. Then, the clean sand equivalent to the number of $(N_1)_{60CS}$ standard penetration resistance tests for soil layers below the water table was determined using Equation No.7.

3. The volumetric strain rate (ε_v) was calculated by determining the CSR and $(N_1)_{60CS}$ for each soil layer.

4. Finally, after calculating the volumetric strain (ε_v) in each layer of the soil, settlement values were computed in meters for each layer of boreholes using Equation No.17. The total amount of the settlement in layers below the water table was calculated as well.

Moreover, the total value of the settlement was calculated after accumulating the amount of the settlements of soil layers upper and lower than the groundwater level in each borehole of the study area. Then, Shimomura's [22] procedure was used to evaluate the volumetric strain (or the settlement) due to liquefaction in saturated soil layers according to the energy method

1. The induced energy due to an earthquake in the soil layer for liquefaction was calculated according to Equation No.18:

$$LogW = 2.002 + 0.0044\sigma_c^{'} + 0.011Dr \quad (18)$$

Where W and σ'$_c$ represent the induced energy in the soil layer and the effective confining stress in depth-study, respectively, and *Dr*, as described in Equation (14), shows the relative density in the soil layer.

2. Furthermore, the volumetric strain in soil layers at the underground water table was evaluated using Equations No.19 to 22.

$$\varepsilon_v = a.W / \sigma_c^{'} \ (\varepsilon_v < \varepsilon_{vmax}) \quad (19)$$

$$\varepsilon_v = \varepsilon_{v\max} \ (\varepsilon_v = \varepsilon_{vmax}) \quad (20)$$

$$\varepsilon_{v\max} = 0.003.(CAPACITY)^{-1.4} \quad (21)$$

$$a = 0.0105.(CAPACITY)^{-3.1} \quad (22)$$

Where ε_v and ε_{vmax} are the volumetric strain in the soil layer and the maximum volumetric strain, respectively. Additionally, capacity, as shown in Equation No.8, is the resistance of the soil layer against liquefaction.

3. Finally, after calculating the volumetric strain (ε_v) in each layer of the soil, settlement values were determined in meters for each layer of boreholes using Equation No.17, and then the total value of the settlement in layers below the water table was calculated as well. Moreover, the total value of the settlement was computed after accumulating the settlements of soil layers upper and lower than the groundwater level in each borehole of the study area.

3. RESULTS AND DISCUSSION

The findings of this study can be expressed in two parts as follows. Part one: The consequences of liquefaction analysis applying two practical methods in the study area:

1. In general, 34 boreholes were collected along Tabriz Metro Line 1. According to the unified classification, soil types included 30 gravels, 140 sands, 73 silts, and 26 clays. The distribution of uncorrected N_{SPT} values is illustrated in Figure 4. As shown, N_{SPT} varies between 10 and 70. In addition, the variations of the safety factor (Fs) in soil layers versus liquefaction based on two methods are depicted in Figure 5 (a, b). Based on the data, approximately 67% of soil layers have a safety factor of less than 1 in the SPT method. Contrarily, about 90% of soil layers have liquefaction potentials in the energy procedure.

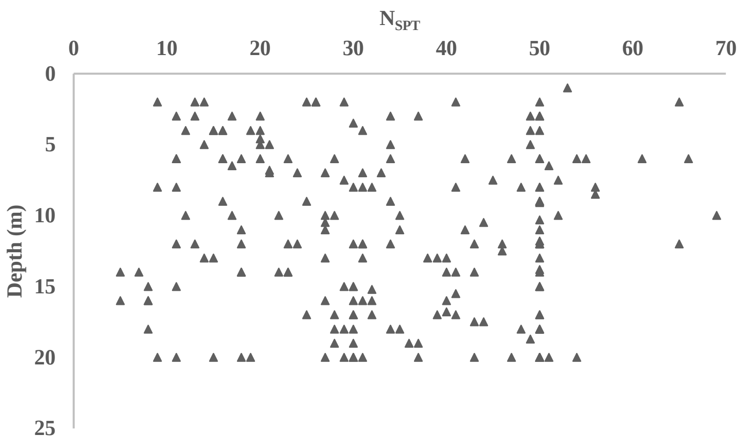


Figure 4. Variations of SPT values in the study area.

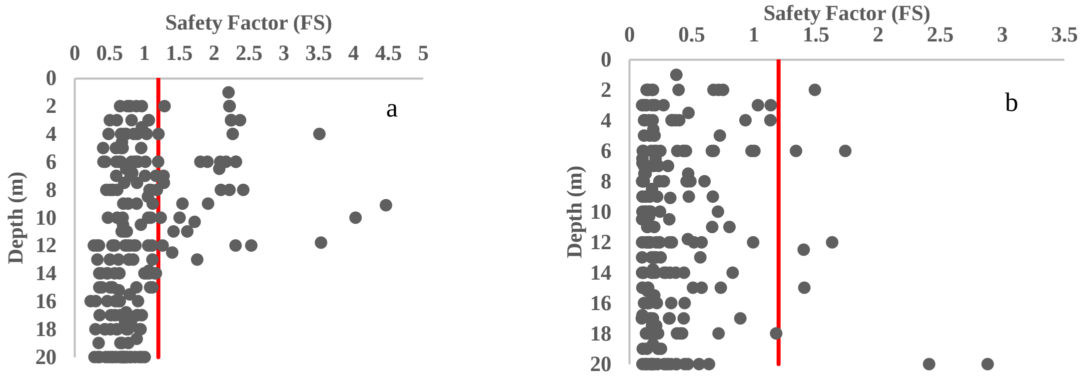


Figure 5. Variations of the safety factor of soil layers against liquefaction in the study area
Note. SPT: Standard Penetration Test; a: SPT method; b: Energy procedure.

2. The values of the cyclic resistance ratio (CRR) in soil layers were compared using the two practical methods (Figure 6). As displayed, the resistance of soil layers against liquefaction based on the energy method is less than that of the SPT procedure. Thus, there is relative harmony between the findings of both methods. According to the diagram, the liquefaction hazard in soil layers based on the energy procedure is extremely high. In other words, the energy method is conservative.

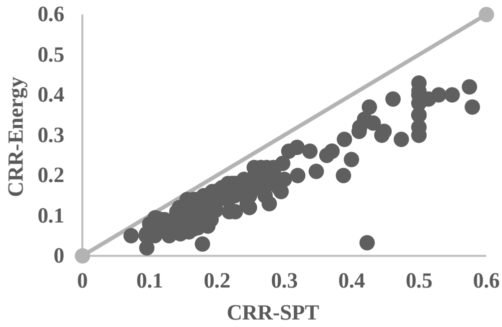


Figure 6. Comparison of CRR values based on SPT, and energy procedure in soil layers against liquefaction in the study area (*Note*. CRR: Cyclic resistance ratio; SPT: Standard Penetration Test).

3. Figure 7 depicts the liquefaction potential index (LPI) values in boreholes along Tabriz Metro Line 1 and based on the above-mentioned practical procedures. Based on the findings of the distribution and based on Iwasaki's [39, 40] criterion, this energy procedure explains liquefaction hazards with high rates in comparison with the SPT method. As illustrated in Figure 8 (similar to Figure 6), relative harmony is found between the two methods. However, LPI values in the energy method are more than the ones in SPT. In other words, as shown in Figure 7, liquefaction hazards in the central (bazaar) and southwest (Kuye Laleh) parts of Tabriz Metro Line 1 have moderate to high rates of liquefaction risk, respectively. However, liquefaction risk is low in the Elgoli area and the southeast part of the path.

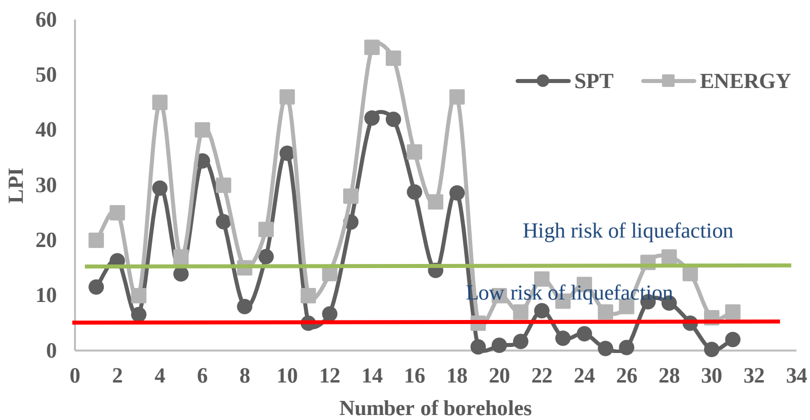


Figure 7. Comparison of LPI values in boreholes according to energy and SPT methods along the path (*Note*. LPI: Liquefaction potential index; SPT: Standard Penetration Test).

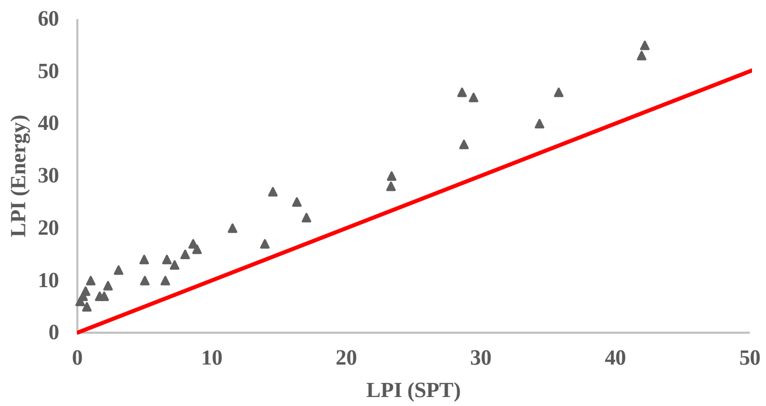


Figure 8. Distribution of LPI values according to energy and SPT methods in the study area (*Note*. LPI: Liquefaction potential index; SPT: Standard Penetration Test).

4. As previously mentioned, LPI in the study area was evaluated according to Iwasaki's [39, 40] procedure for both practical methods. As shown in Table 1 and based on Idriss and Boulanger's [3] rule analysis results, nearly 64% of boreholes are located in medium and high rates in terms of liquefaction risk. Moreover, 34% of boreholes have extensively high liquefaction risk. Contrarily, approximately 48 and 52% of boreholes have medium-to-high and very high risks in liquefaction using the energy method, respectively. Then, the number of soil layers having liquefaction risk in boreholes was evaluated separately. Based on the findings in Table 2, the number of soil layers, including liquefaction risk based on the energy method analysis, is more than that of the SPT procedure.5. To compare the rate of conformity better, and the match between the findings of both methods in the same soil layer, the value of the safety factor is evaluated and presented in Table 3. Generally, both methods demonstrate a 58% match in terms of liquefaction hazards or no liquefaction. However, both procedures have a 42% similarity in explaining liquefaction/no liquefaction potential of soil layers. Accordingly, relatively good agreements exist between both practical methods. It should be mentioned that gravel specimens have silt and clay in the study area. According to the unified soil classification method, specimens are in GM (Silty gravel) and GC (Clayey gravel) category. As regards the number of GM, the samples were more than GC. Therefore, GM-type soil layers were considered in liquefaction analyses in the present research, the details of which are presented in Tables 1 and 2.

Table 1. The number of boreholes with Liquefaction Hazards Based on Both Methods with Considering to Soil Types.

LPI	LPI=0	0‹ LPI‹5	5‹ LPI ‹15	LPI › 15
Idriss and Boulanger's method				
Number	-	10	10	11
Percent	-	32	32	34
Energy method				
Number	-	1	14	15
Percent	-	3	45	52

Note. LPI: Liquefaction potential index.

Table 2. The number of Layers with Liquefaction Hazards Based on Both Methods with Considering to Soil Types.

Number of layers					
Soil type	**Total**	**liquefaction in SPT method**	**liquefaction in Energy method**	**No liquefaction in SPT method**	**No liquefaction in energy method**
Gravel	30	10	25	20	5
Sand	140	57	105	83	35
Silt	73	31	49	42	24

Note. SPT: Standard penetration test.

Table 3. Conformity of the Findings of Both Methods in the Same Soil Layer.

Description					
Soil type	Number of layer	Liquefaction in both methods	No Liquefaction in both methods	Rate of conformity	Rate of unconformity
Gravel	30	10	**5**	50%	%50
Sand	140	48	30	56%	%44
Silt	73	27	20	%64	%36
Total	243	85	55	%58	%42

Part two: The outcomes of the settlement (volumetric strain) evaluation due to liquefaction occurrence in soil layers in the study area

1. The values of the settlement in soil layers in dry and saturated conditions (above and below groundwater table) were evaluated based on the studies by Tokimatsu and Seed [30] and Shimomura [38]; the related data are depicted in Figure 9 (a, b, and c). Generally, the comparative analysis of the diagrams represents that the rate of the settlement is extremely low in soil layers above the groundwater table due to probable liquefaction. Contrarily, settlement amounts are high in soil layers below the groundwater table (Figures 9b and 9c), although the settlement rate based on the energy method is a little more compared to the SPT procedure.

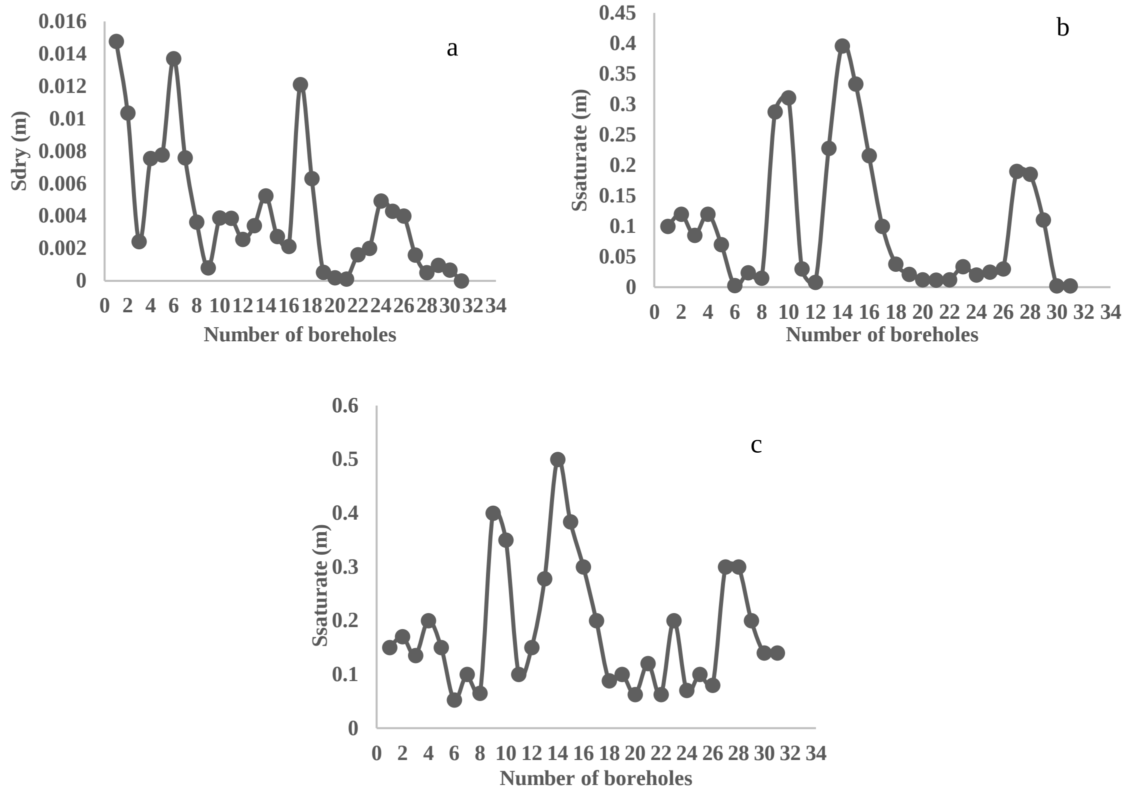
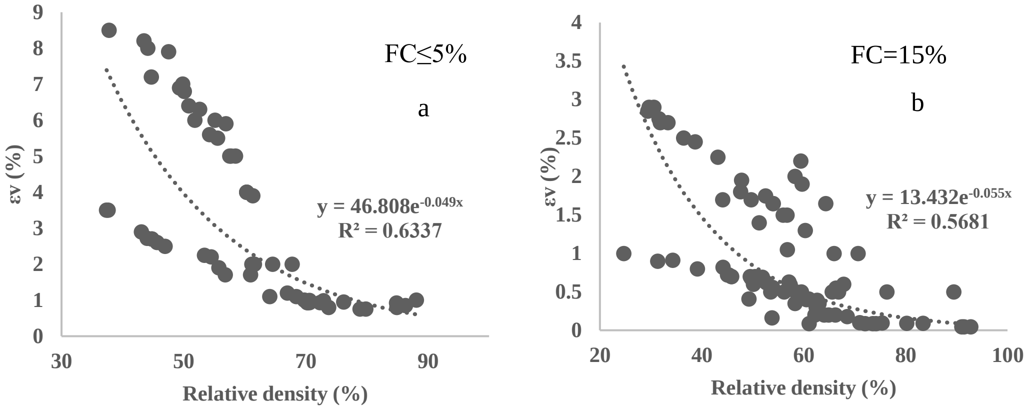


Figure 9. Variations of settlement in dry and saturated soil layers in boreholes in the study area (*Note*. a: Dry position; b: Saturate position; c: Saturate position (based on the energy method)).

2. Figure 10 (a, b, & c) displays the effects of fines content and relative density on the volumetric strain in saturated soil layers in the study area based on Tokimatsu and Seed's method [30]. Based on the findings, an increase in soil layers' fines content leads to a decrease in the rate of volumetric strain. Furthermore, when relative density in soil layers enhances, the volumetric strain represents a reduction. As shown, relative density in saturated soil layers with fines content less than 5% is more effective in the volumetric strain value compared to soils with high fines (i.e., FC ≥ 35%).



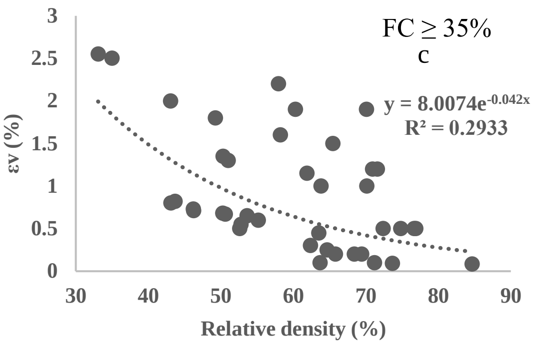


Figure 10. Variations of volumetric strain in saturated soil layers in boreholes in the study area according to Tokimatsu and Seed's method (*Note*. a: FC ≤ 5%; b: FC = 15%; c: FC ≥ 35% (Mw = 7.5)).

3. Similar to the previous process, the variations of volumetric strain versus relative density in different fines contents of saturated soil layers were determined according to the energy method findings and the method of Shimomura et al. [38]. It was also observed that liquefaction hazards decrease by an increase in the fines content of soil layers and a decrease in the void ratio of soil particles. However, a comparison of the diagrams in Figures 10 and 11 revealed that the volumetric strain rate of soil layers in the energy method was more than that of Tokimatsu and Seed's [30] procedure. Nonetheless, the role of relative density in volumetric strain and settlement due to liquefaction decreased in both methods by increasing fines content in saturated soil layers.

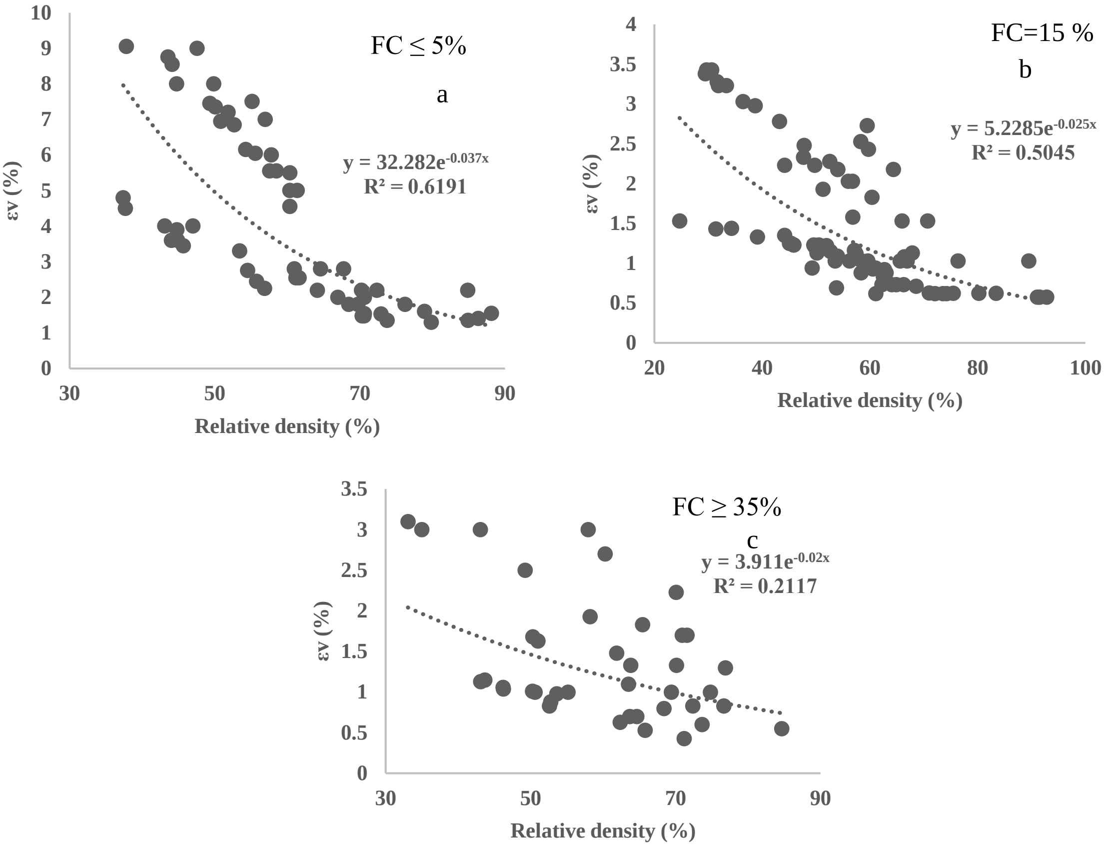


Figure 11. Variations of volumetric strain in saturated soil layers in boreholes in the study area according to energy procedure (*Note*. a: FC ≤ 5%; b: FC = 15%; c: FC ≥ 35% (Mw = 7.5)).

4. Figure 12 (a, b, & c) illustrates the variations of volumetric strain versus the cyclic shear strain (γ_{cyc}) due to the probable earthquake in the study area in saturated soil layers according to Tokimatsu and Seed's [19] method. As depicted, the probability of volumetric strain and settlement occurrence enhances in accordance with the growth in the maximum shear strain. Conversely, increasing the fines content in soil layers results in a decrease in volumetric strain values. Moreover, the correlation between γ_{cyc} and volumetric strain in saturated soil layers with fines content

less than 5% is more compared with soils with FC over 35%. This situation demonstrates that locating fines particles between liquefaction resistance of granular soils increases while the probability of settlement indicates a reduction.

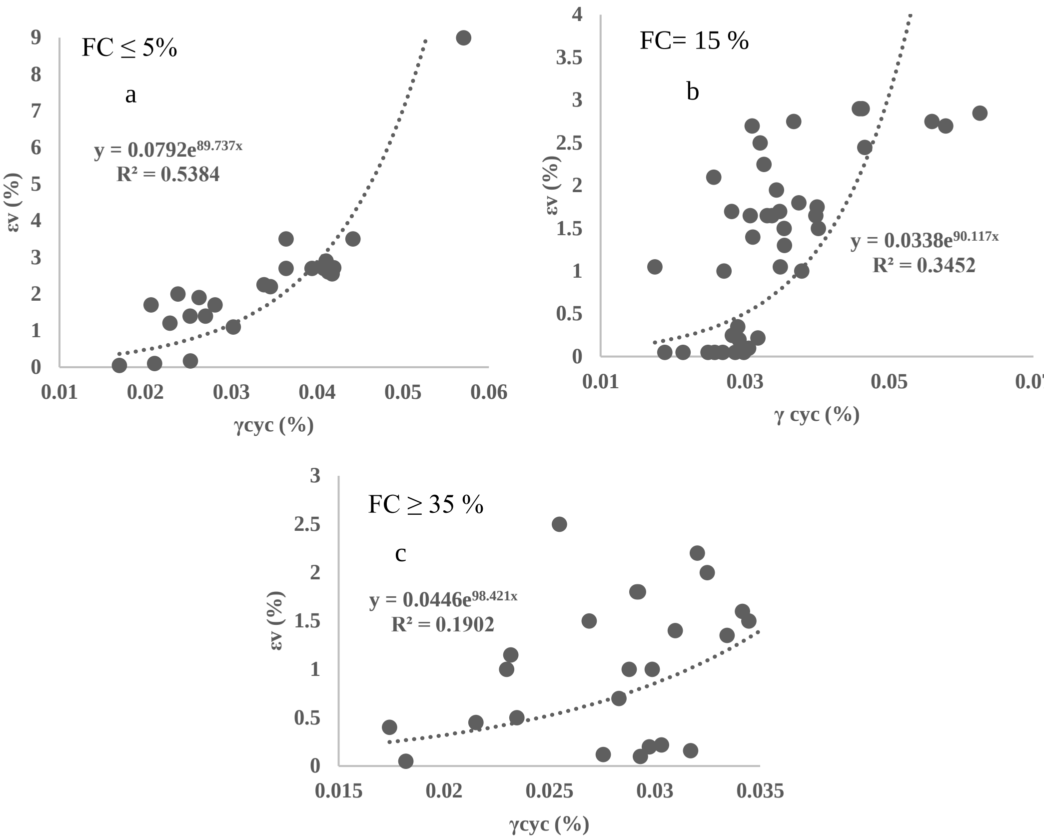
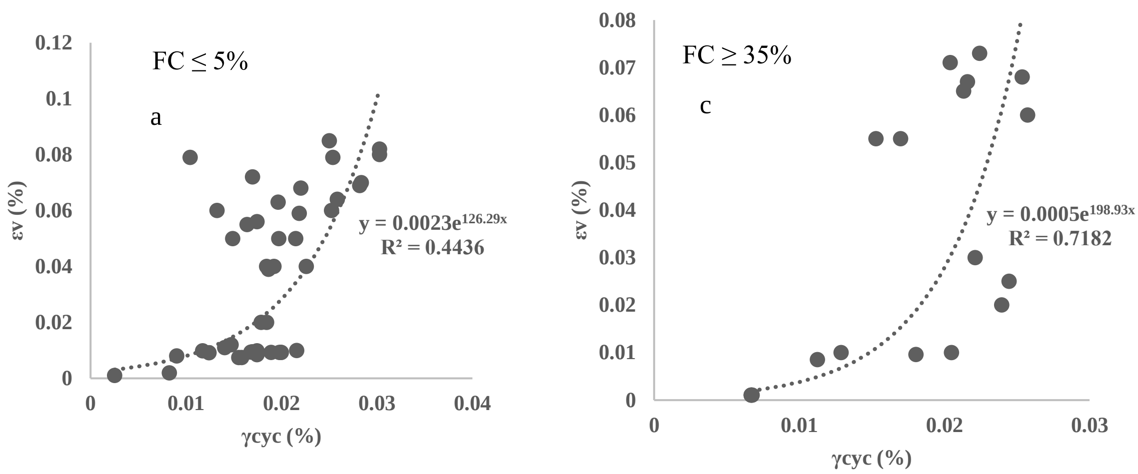


Figure 12. Variations of volumetric strain versus cyclic shear strain in saturated soil layers in boreholes in the study area according to energy procedure (*Note*. a: FC ≤ 5%; b: FC = 15%; c: FC ≥ 35% (Mw = 7.5)).

5. In the next phase of the study, volumetric strain effects on the cyclic shear strain (γ_{cyc}) in soil layers above the groundwater table are displayed in Figure 13 (a, b, & c). Based on the findings, in dry soil layers, volumetric strain increases by the growth in γ_{cyc} while it decreases by an increase in fines content. However, comparing the values of the volumetric strain in soil layers in dry and saturated positions showed that the amount of the volumetric strain in soil layers below the groundwater table was more than the one in dry conditions. As shown, contrary to saturated conditions, in dry soil layers, when γ_{cyc} affects soil layers with high fines content (i.e., FC ≥ 35%) due to a probable earthquake, these layers have more volumetric strain and settlement. This could be attributed to the soil skeleton structure of particles and geotechnical properties.



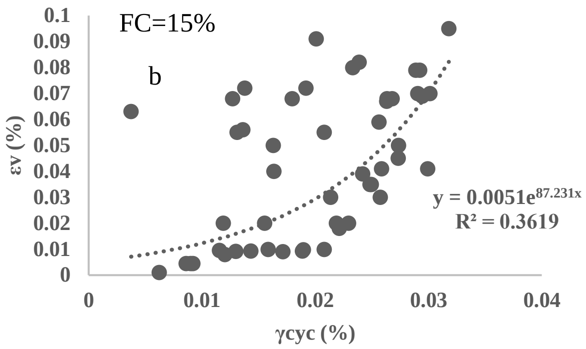


Figure 13. Variations of volumetric strain versus the maximum shear strain in soil layers in boreholes above the groundwater table in the study area according to energy procedure (*Note*. a: FC ≤ 5%; b: FC = 15%; c: FC ≥ 35% (Mw = 7.5)).

6. Figure 14a depicts the total settlement values of soil layers in boreholes in the study area, according to Tokimatsu and Seed's [19] method. In addition, the variations of LPI based on both procedures are illustrated in Figure 14b. A suitable correlation can be observed comparing the two procedures. As shown, increasing LPI leads to an increase in the total settlement and vice versa.

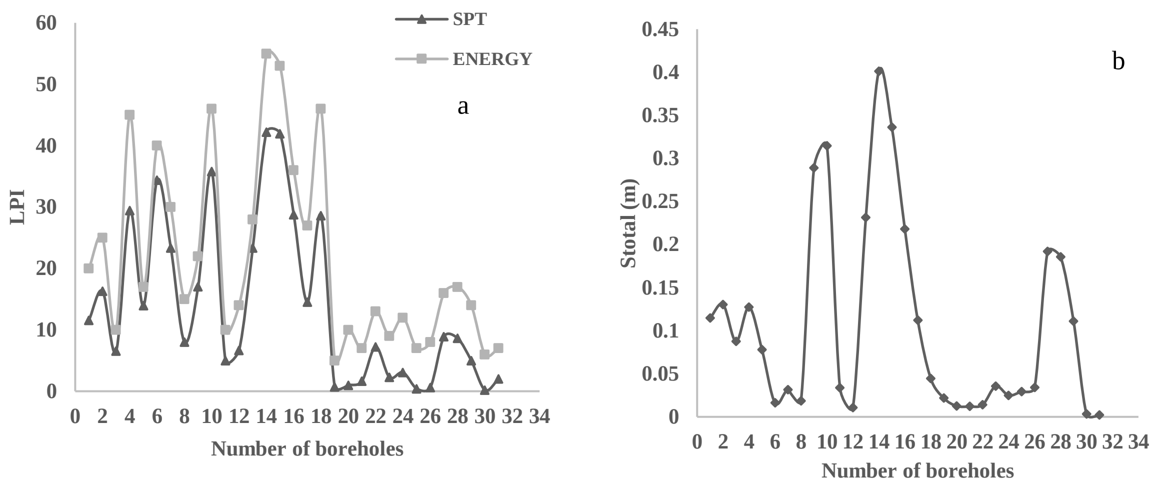


Figure 14. Comparison between total settlements in soil layers after liquefaction, and LPI values (*Note*. LPI: Liquefaction potential index; SPT: Standard penetration test; a: LPI based on SPT and energy methods; b: Total settlement).

4. CONCLUSION

The present study aimed to compare the findings of potential liquefaction evaluations, in terms of risk intensity, and settlement after liquefaction in soil layers along Tabriz Metro Line 1, based on Standard Penetration Test (SPT) data and the Energy method. First, the liquefaction potential was determined based on SPT findings and according to Idriss and Boulanger's (2010) method. Then, David and Brill's [8] procedure was applied to estimate liquefaction risk based on the energy theorem. Then, the liquefaction potential index (LPI) was evaluated for both practical methods by applying the procedure of Iwasaki et al. [23, 24]. Finally, probable settlement due to liquefaction in soil layers was determined according to Tokimatsu and Seed [19] and Shimomura [22]. The main findings of this study are as follows.

1. There was relatively good agreement between the two methods with regard to potential liquefaction evaluations, particularly in sandy and silty soil layers. However, the fundamental theory in both methods was different. In addition, the energy procedure relied on the release of earthquake energy and the distance between the epicenter of the earthquake and the site. Meanwhile, the liquefaction potential of soil layers was evaluated as a point in the SPT method.

2. The LPI determination in soil layers showed that liquefaction risk based on the energy procedure was slightly more than that of the SPT method. Nonetheless, the distance of Tabriz Metro Line 1 from Tabriz North Fault could be an effective factor in energy method findings.

3. The findings related to the probable settlement in soil layers due to liquefaction demonstrated a rather good agreement between the two practical methods. However, this value was higher in the energy method compared to the SPT procedure.

The evaluation of liquefaction potential hazards and settlement in soil layers based on the energy procedure is a new method. On the other side, a settlement is an earthquake geotechnical phenomenon, and different factors are effective in its occurrence, including fines content, relative density, groundwater table level, and the like. This study was conducted using field data. Therefore, further research is warranted to use experimental designs in order to increase the accuracy of findings and discover a proper relationship for evaluating settlement based on the energy method.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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