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Effects of Building Construction Overburden on Liquefaction Potential of Soils

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Abstract

As one of the significant phenomena in earthquake geotechnical engineering, liquefaction can cause severe damages. A number of factors play a role in the occurrence of liquefaction such as magnitude of earthquake, void ratio, relative density, and fines content percentage. The impact of building construction overburdens on liquefaction is of paramount importance. The present study was aimed at evaluating the effects of overburden resulting from building construction on liquefaction potential of saturating soil layers along Tabriz Metro Line 2. Fifty-four boreholes and geotechnical information were collected from the research site. Overburden values were considered to be 100 kPa, 200 kPa, 300 KPa, and 400 KPa equivalents to 5-, 10-, 15-, and 30-story building, respectively. The assessment of liquefaction potential of soil layers was carried out using the standard penetration test (SPT) method. Furthermore, liquefaction potential index (LPI) of soil layers was evaluated. The findings demonstrated that overburden can affect liquefaction resistance of soil layers. With increasing overburden, safety factor against liquefaction became less than one in nearly 80% of soil layers. The rate of growth in LPI of boreholes in the research site was found to be roughly 70%. Hence, an increase in overburden elevated liquefaction hazards in the research site.

Keywords: *Fines content, Liquefaction, Liquefaction Potential Index, Overburden, Tabriz Metro Line* 2

1. Introduction

Liquefaction is one of the most important events in earthquake geotechnical engineering leading to destructive damages. By raising pore water pressure in saturating loose granular soil layers (e.g., fine gravel or sand) and clay (in a special situation) and by reducing volume as a result of the earthquake or seismic loading, effective confining stress decreases. In this condition, the shear strength of soil sharply declined and equals zero. This phenomenon leads to lateral spreading, settlement, sand boiling, and water leakage from voids in the ground. Several elements influence the occurrence of liquefaction including magnitude of earthquake, void ratio, relative density, and fines content percentage. Building construction overburdens are highly influential in liquefaction occurrence. Based on observing damages of structures due to previous earthquakes, it can be realized that overburden resulting from building construction does not have a negative effect on soil layers response and behavior. Structures on the ground may prevent the occurrence of some events. However, building construction can influence liquefaction occurrence in saturating soil layers. Rollins and Seed [1] indicated that the required cyclic stress ratio (CSR) for happening liquefaction in soil layers near and under structures can be different from the one needed for soil layers far from structures. Structures and building on ground influence soil layers and liquefaction occurrence as the factor of static shear stress in lateral soil layers (kα), the factor of vertical effective stress in layers (kσ), over consolidated ratio (kOCR), and soil-structure interaction [1-3]. Various studies have been conducted on the effects of the building construction overburden on liquefaction potential of soil layers. Numerical studies include Lopez and Modarresi (2008) [4], Shush Pasha and Bagheri (2012) [5], and Khatibi

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et al. (2012) [6]. Experimental studies include Whitman and Lambe (1985) [7], Pillai (1991) [8], and ArdashiriL ajimi et al. (2015) [9]. Finally, field studies consist of Watanabe (1966) [10], Ishihara et al. (1980) [11], Yoshimi and Tokimatsu (1997) [12], and Boulanger (2003) [13]. In recent years, different laboratory and field tests methods have been proposed for evaluating liquefaction resistance of soil layers. Field test methods involve using SPT [14-16], CPT [17], seismic tests, and shear wave velocity [18-20].In this study, the research site was Tabriz Metro Line 2. For a number of studies were conducted to determine geotechnical properties and liquefaction potential hazards of the research site [21-23]. The main propose of the present study was to evaluate overburdens resulting from building constructions and their impacts on liquefaction potential of soil layers, which was a lacuna in the literature. The effects of overburdens on soil layers were calculated using Boulanger method [13]. By applying Idriss and Boulanger (2010) process [14], the liquefaction potential of soil layers were evaluated based on SPT data. Liquefaction potential index (LPI) was assessed through Iwasaki et al.'s method [24, 25] with both overburden presence and without overburden. Finally, comparisons were made between the results of this study and those of similar studies.

2. Geology and General Condition of the Research Site

To examine the effects of overburden resulting from building construction on saturate soil layers' liquefaction potential, 54 boreholes were collected along Tabriz Metro Line 2. Having an approximate length of 22 km, line 2 of Tabriz Metro, starts at the western part of Tabriz and passes through Qaramalek, Qara- aqaj, and Bazar located in the city center. The line passes through Daneshsara Square and goes under the Mehranroud River leading to Abbasi Street and Shahid Fahmide Square. The line runs along Shahaid Fahmide Square toward Baghmisheh town. Turning its path, it goes toward the southeast of the city and finally terminates in front of Tabriz International Exhibition Center. This route is level starting from Baghmisheh own, but it gets jagged in the east having hilly topography. In the eastern part, the difference between the highest and the lowest points along the route is about 140 meters. The position of the route is illustrated in Figure 1 (a, b).

The level of the groundwater can be deemed as one of the main factors in assessing liquefaction potential of the soil. It should be noted that, along the route of Line 2 of Tabriz Metro, the level of groundwater changes. In one of the drilled boreholes, the water in the Artesian condition had over flown the surface of the borehole, while in other boreholes, waters, was not found above a considerable depth. The results indicated that groundwater level changes were not drastic after being static, and the higher level of the groundwater could be ascribed to the spring season. Overall, the depth of the groundwater was found to vary from 2 to 30 meters. The balance of the groundwater decreased from east to west, showing that the water flow was from east to west corresponding to the slope of Tabriz plain. Groundwater depth variations in the city of Tabriz are presented in Figure 2. Additionally, the level of groundwater in boreholes along Tabriz Metro Line 2is illustrated in Figure 3.

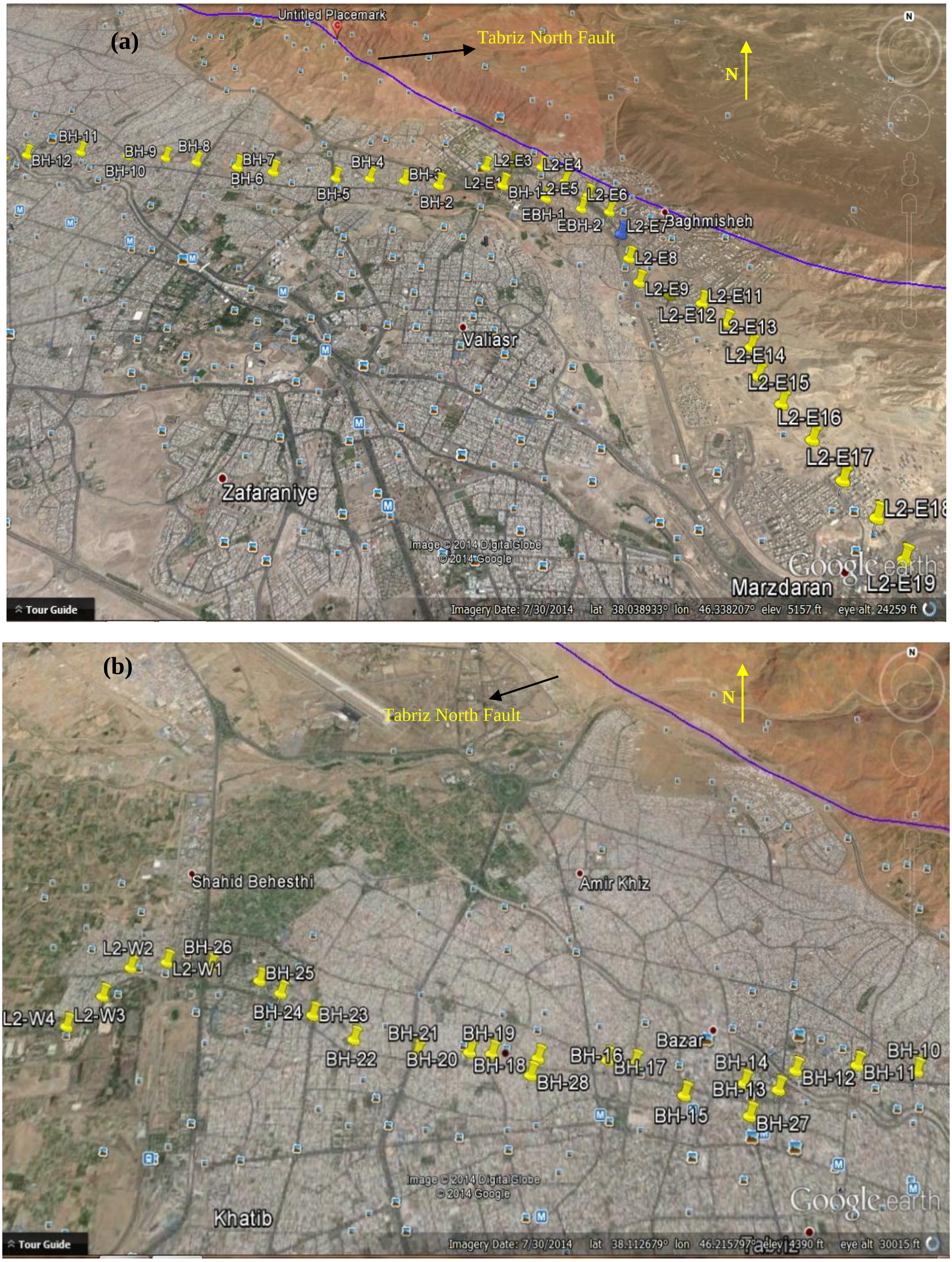


Figure 1. (a, b). Boreholes' position along Tabriz Metro Line 2 [26]

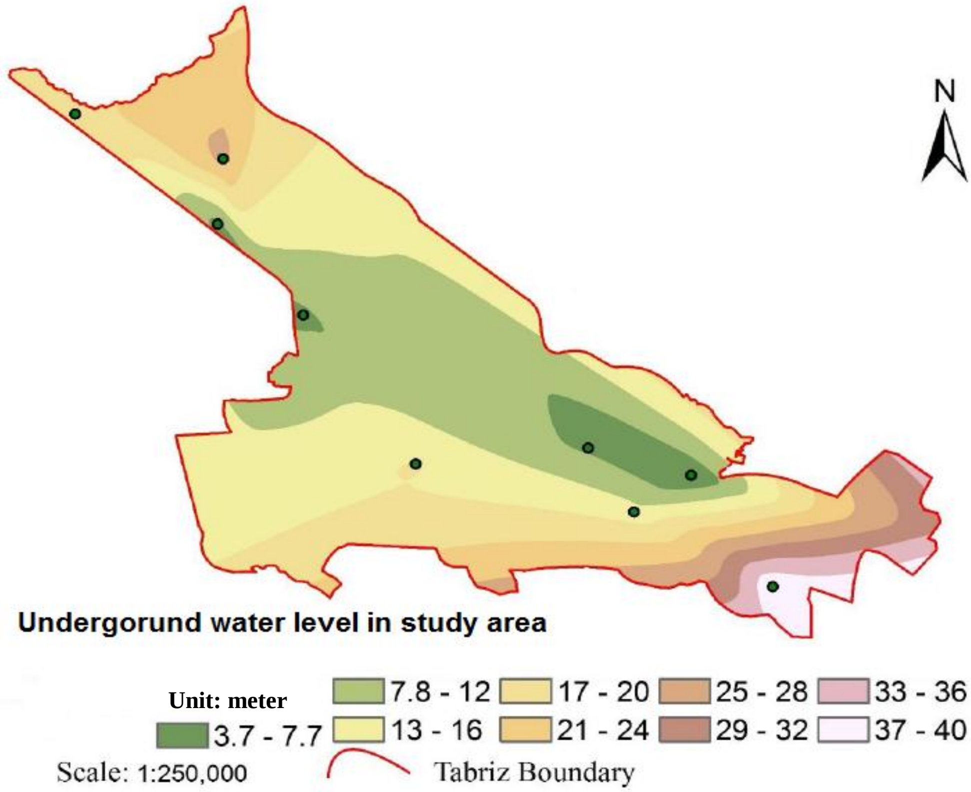


Figure 2. Variation of underground water level in Tabriz city [27].

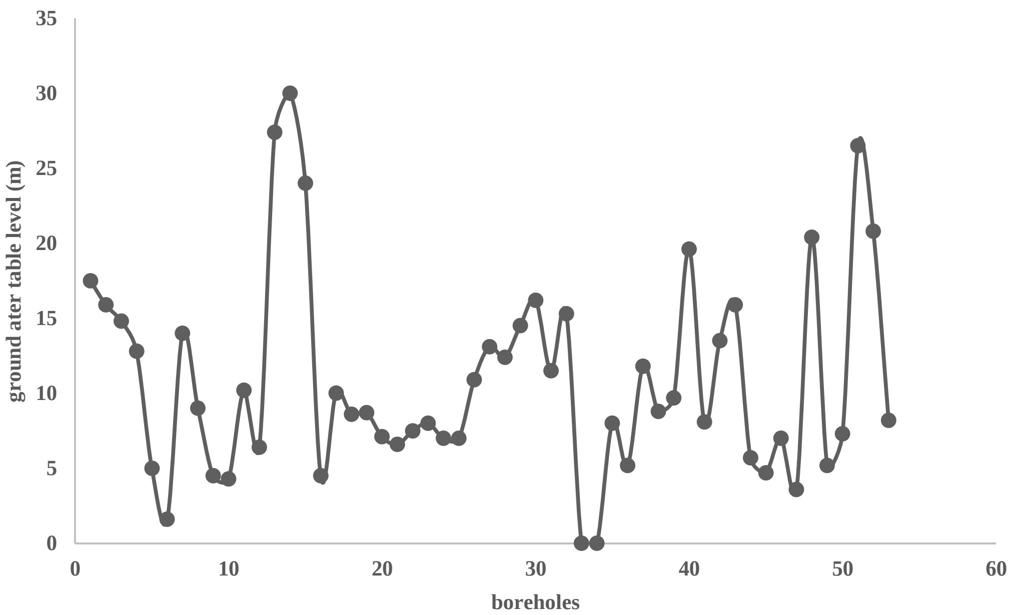


Figure 3. Variation of underground water level in boreholes along Tabriz Metro Line 2.

3. Liquefaction Potential Analysis

An assessment of the peak ground acceleration (PGA) of the research site is required to analyze boreholes and identify the liquefaction potential and to determine the rate of settlement in layers of soil. The length of Tabriz North fault from Bostanabad to Sofian is at least 90 km, however, it seems to run toward the southeast and the northwest. Therefore, according to the Iranian Code of Practice for Seismic Resistant Design of Buildings [28], the PGA equal to 0.35g (475 years is the return period and a useful life of 50 years), and Mw equal to 7.5 were considered (Figure 4).

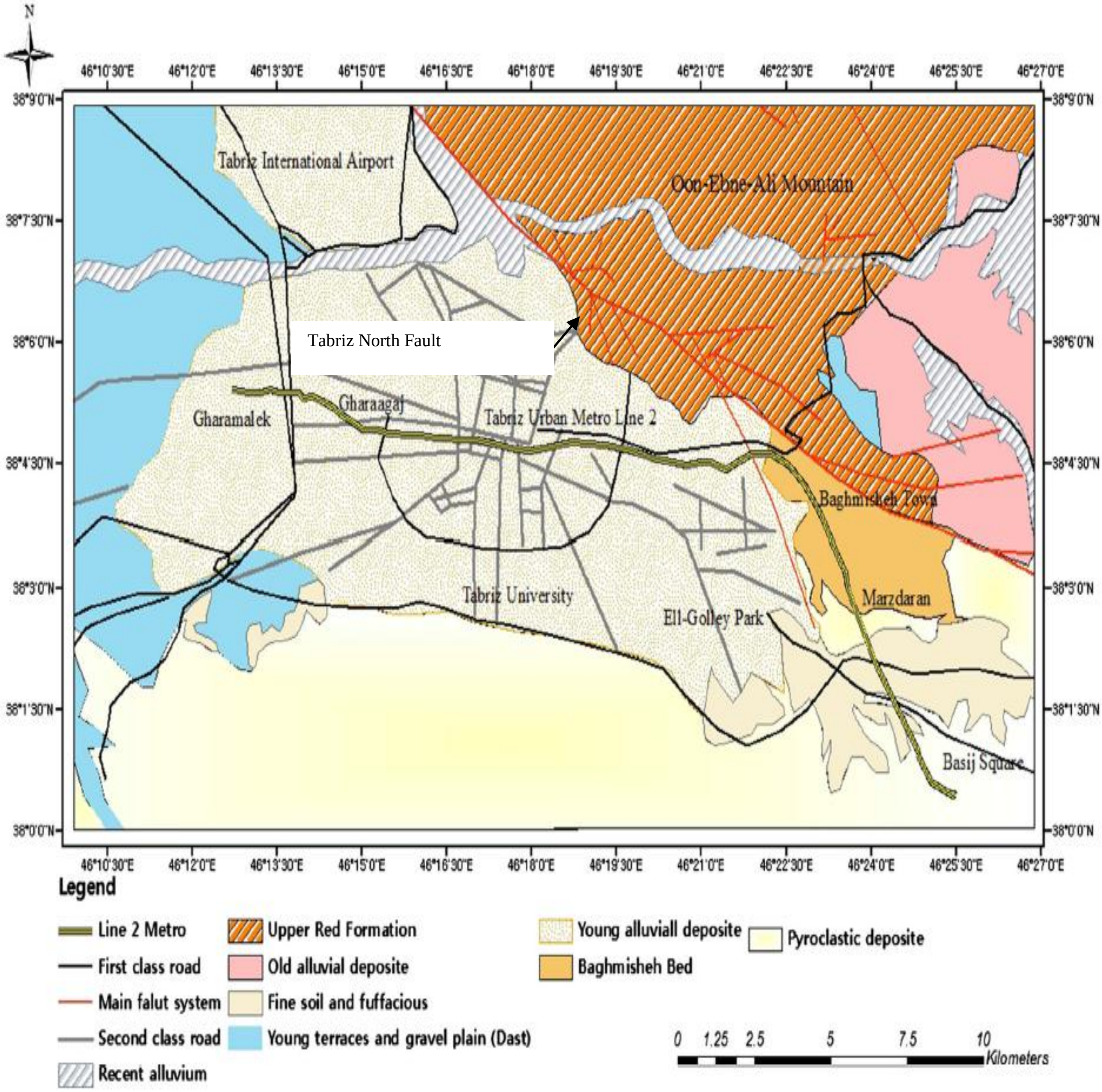


Figure 4. Geology map and Tabriz north fault's location in the study area [22]

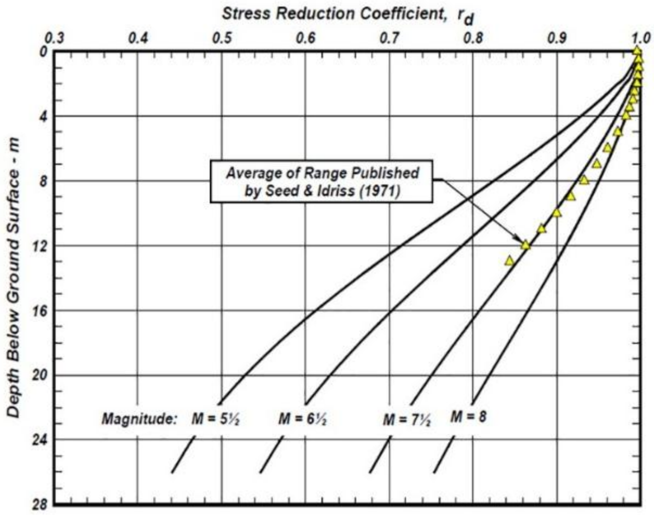


Figure 5. Variations of stress reduction coefficient with depth and earthquake magnitudes [16].

The assessment of the liquefaction potential of e soil in the study area was carried out based on the simplified method proposed by Idriss and Bolanger [16]. In this method, the value of the cyclic stress ratio (CSR) is estimated expressing the rate of the severity of the earthquake load in an Mw=7.5. That is calculated using the following equation:

$$CSR_{7.5} = 0.65.\frac{a_{max}}{g}.\frac{\sigma_V}{\sigma'_V}.r_d.\frac{1}{MSF} \quad (1)$$

Where amax is the peak ground acceleration, g is acceleration of gravity, σ^V is total stress in the depth in the question, σ'^V is effective stress in the same depth, and rd is coefficient of shear stress reduction as illustrated in Figure 5. MSF (Magnitude Scale Factor) refers to earthquake magnitude scale factor calculated based on Andrus and Stoke's (1997)[19] study using equation 2. Mw refers to earthquake magnitude.

$$MSF = \left(\frac{M_W}{7.5}\right)^{-3.3} \quad (2)$$

In order to determine the cyclic resistance ratio (CRR) of the soils, simplified and modified versions of the method proposed by Seed et al. [3] were used. In this step, the results obtained from the standard penetration test were modified based on the following equation proposed by Skempton [29]. Value of parameters can be observed in Table 1.

$$(N_1)_{60} = N_{SPT} \times C_N \times C_E \times C_B \times C_R \times C_S \quad (3)$$

Where, NSPT, is the number of standard penetration resistance test, CN is coefficient of the over burden stress, CE is the coefficient of the hammer energy, CS is the coefficient of the sampling method, CB is the coefficient of the bore hole diameter, CR is the coefficient of the rod length, and (N1)60is the modified number of the standard penetration test. Next, as suggested by Idriss and Boulanger [15], the overburden tension correction factor (CN) was determined using the following equation.

$$C_N = (\frac{Pa}{\sigma'_V})^{\alpha} \leq 1.7 \quad (4)$$

$$\alpha = 0.784 - 0.0768 \times \sqrt{(N_1)_{60}} \quad (5)$$

Where Pa = 100kPa, is the atmospheric pressure, σ′V is the effective stress at the depth in question, and (N1)60 is corrected the number of standard penetration test. After modifying the number of the standard penetration test, its equivalent in clean sand ((N1)60CS) was determined. Then, cyclic resistance ratio (CRR) was assessed through the following equations (Figure 6):

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

Table1. Correction factor of SPT [29]

Overburden Pressure		C_N	$\left(P_a / \sigma'_v\right)^{0.5}$ $C_N \leq 1.7$
Energy ratio	Donut Hammer Safety Hammer Automatic-Trip Donut- Type Hammer	C_E	0.5 to 1.0 0.7 to 1.2 0.8 to 1.3
Borehole diameter	65 mm to 115 mm 150 mm 200 mm	C_B	1.0 1.05 1.15
Rod length	3 m to 4 m 4 m to 6 m 6 m to 10 m 10 m to 30 m > 30 m	C_R	0.75 0.85 0.95 1.0 〈1.0
Sampling method	Standard sampler Sampler without liners	C_S	1.0 1.1 to 1.3

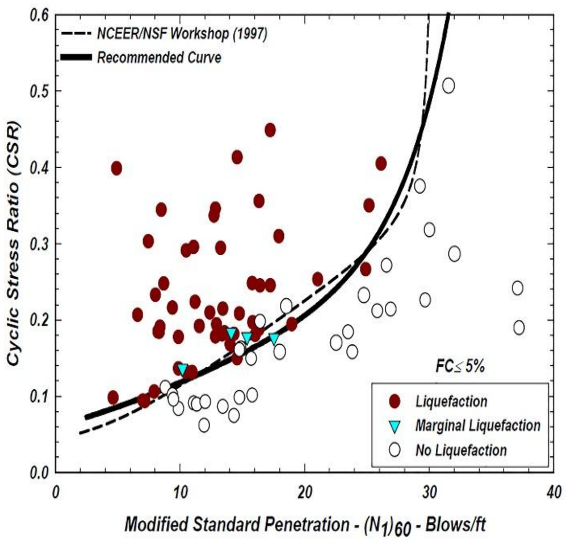


Figure 6. Liquefaction resistance curve for themagnitude7.5 earthquakes [16].

$$\Delta(\mathrm{N}_1)_{60} = 1.63 + \exp\left(1 - \frac{9.7}{\mathrm{FC}+0.1}\right) - \left(\frac{15.7}{\mathrm{FC}+0.1}\right) \tag{7}$$

$$\mathrm{CRR} = \exp\left(\left(\frac{(\mathrm{N}_1)_{60CS}}{14.1}\right) + \left(\frac{(\mathrm{N}_1)_{60CS}}{126}\right)^2 - \left(\frac{(\mathrm{N}_1)_{60CS}}{23.6}\right)^3 + \left(\frac{(\mathrm{N}_1)_{60CS}}{25.4}\right)^4 - 2.8\right) \tag{8}$$

Where FC refers to equal fines content in soil layer.

In the calculation of the CRR, if the amount of effective vertical stress at the depth in question is more than 100 KPa, the CRR value is modified by using the following equation:

$$\mathrm{CRR}_j = \mathrm{K}_\sigma \times \mathrm{CRR} \tag{9}$$

In this equation, the CRRj refers to corrected cyclic resistance ratio. The Kσ parameter is a coefficient based on the effective vertical stress calculated as follows [30]:

$$\mathrm{K}_\sigma = \left(\frac{\sigma'_V}{100}\right)^{f-1} \tag{10}$$

Where Kσ is the overburden correction factor, σ´V is the effective vertical stress, and f is an exponent that is a function of site conditions including relative density, stress history, aging, and over-consolidation ratio. For the relative densities between 40% and 60%, f= 0.7-0.8, and for the relative densities between 60% and 80%, f= 0.6-0.7 (Figure 7).

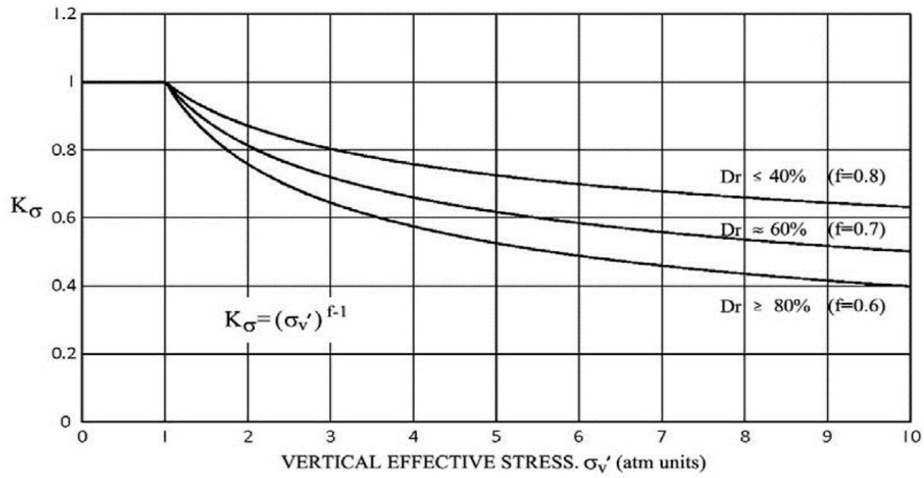


Figure 7. Variations of Kσ values versus effective overburden stress [30].

Safety factor (Fs) against liquefaction in soil layers is calculated using the following equation:

$$F_S = \frac{CRR_j}{CSR} \tag{11}$$

Liquefaction occurs when Fs ≤ 1. For Fs>1, there is no probability of the occurrence of liquefaction.

3.1. Liquefaction Potential Index (LPI)

Several methods are suggested for the assessments of the rate of liquefaction and itslevel of occurrence. One of the common methods is proposed by Iwasaki et al. [24], [25] presented in the following equation:

$$LPI = \int_0^{20} W(Z) \times F(Z).\,dz \tag{12}$$

$$F(Z) = 1 - F_S \quad \text{For Fs < 1} \tag{12a}$$

$$F(Z) = 0 \quad \text{For Fs} \geq 1 \tag{12b}$$

$$W(Z) = 10 - 0.5Z \quad \text{For Z < 20 m} \tag{12c}$$

$$W(Z) = 0 \quad \text{For Z > 20 m} \tag{12d}$$

Where is the depth of midpoint in question layer. The liquefaction intensity is stated between zeros and 100. The liquefaction risk can be obtained using Table 2 based on the liquefaction potential index (LPI) value.

Table 2. Liquefaction potential index (LPI) and its describes [24]

LPI-Value	Liquefaction risk and investigation/ Required countermeasures
LPI=0	Liquefaction risk is very low. Detailed investigation is not generally needed. (very low)
0<LPI≤ 5	Liquefaction risk is low. Further detailed investigation is needed, especially for important structures. (low)
5<LPI≤ 15	Liquefaction risk is high. Further detailed investigation is needed for structures. A countermeasure of liquefaction is generally needed. (high)
LPI> 15	Liquefaction risk is very high. Detailed investigation and countermeasures are needed. (very high)

3. 2. Effects of Overburden Resulting from Building Construction

In this study, based on the method proposed by Boulanger in 2003 [13] to evaluate influence on construction overburden on liquefaction resistance in soil layers, equation No.10 was modified as follows:

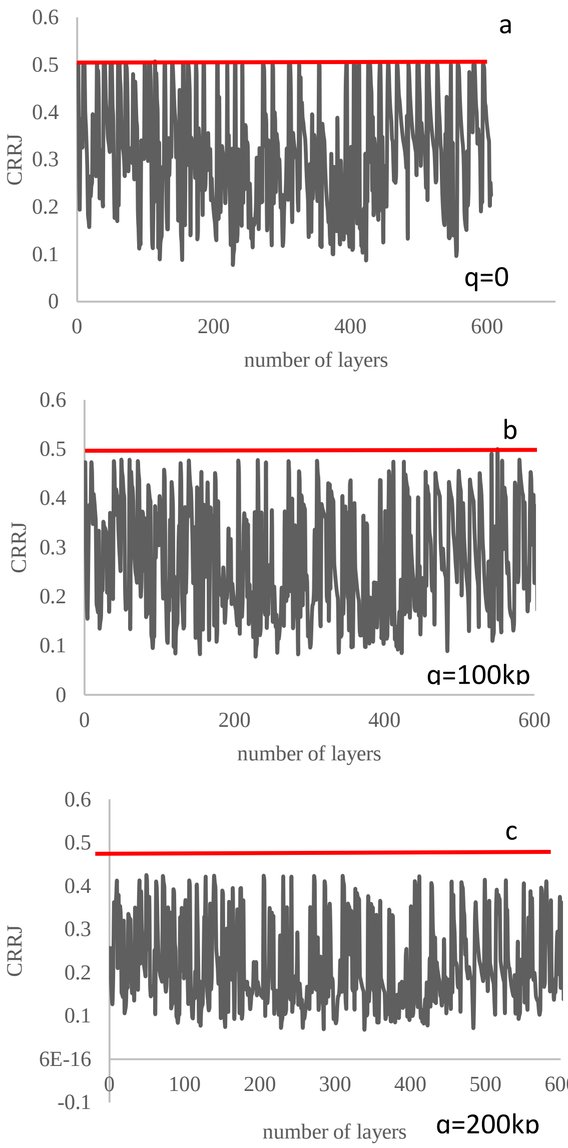
$$k_\sigma = 1 - C_\sigma . L_n(\frac{\sigma'_V}{P_a}) \tag{13}$$

Where Cσ is constant factor equal to 0.185, σ´V is the effective vertical stress, and Pa = 100 KPa is the atmospheric pressure. In this study, based on Iran National Regulation Code No.6 [31], the amount of overburdens of buildings with 5, 10, 15, and 30 stories was considered to be equivalent to 100 KPa, 200kPa, 300 KPa, and 400 kPa, respectively.

4. Results

4.1. Effects of overburden on CRR_j

In the research site, 54 boreholes were collected. Generally, 522 soil layers' geotechnical information was evaluated. It was observed that soil layers' types were 33 to the gravel, 175 to the sand, 210 to the silt, and 104 to the clay. The effects of overburden values on corrected cyclic resistance ratio (CRRJ) in soil layers are presented in Figure 8. As shown in Figure 8a, when q=0, almost 20% of soil layers' CRRj was less than 0.5 (lower bound of no liquefaction). As illustrated in Figure 8b, when q=100 KPa, about 80% of CRRj was less than 0.5. Therefore, resistance of soil layers against liquefaction was reduced, and consequently, liquefaction hazards increased. Based on Figures 8c, 8d, and 8e, it can be observed that with an increase in overburden effects in soil layers, about 80% of layers' CRRj was less than 0.38, indicating that liquefaction potential highly increased.



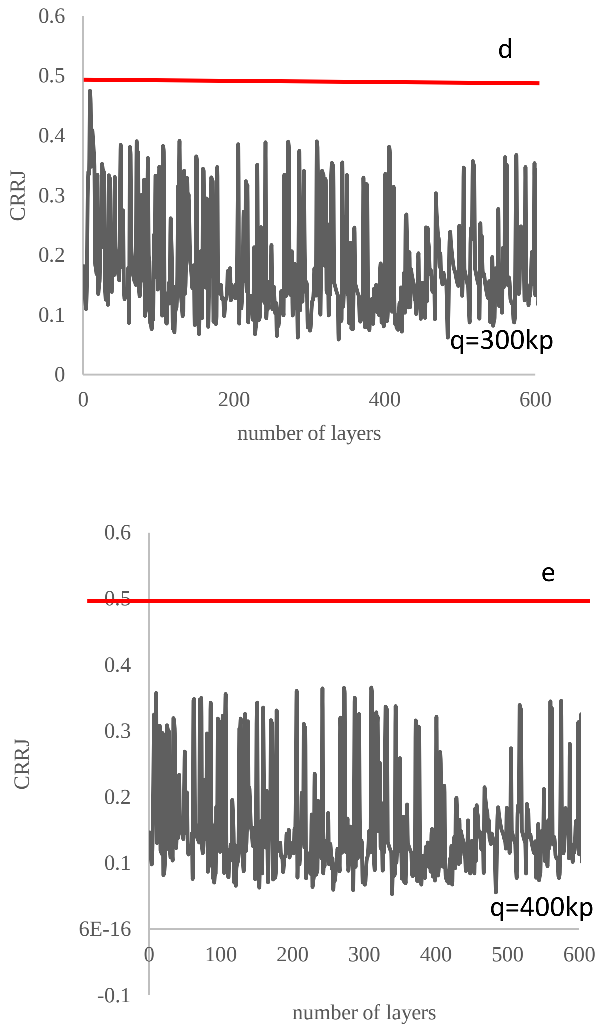
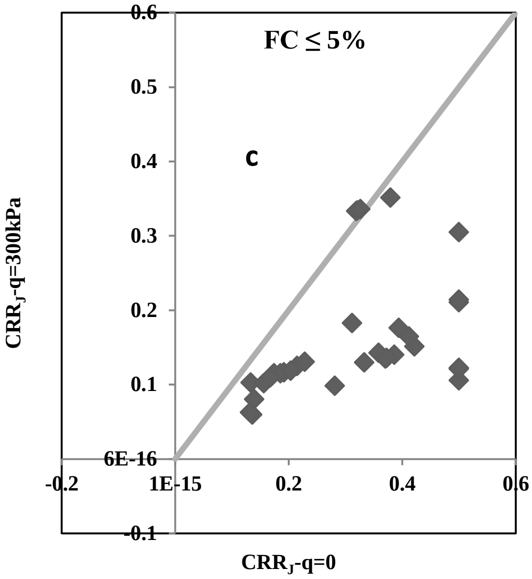
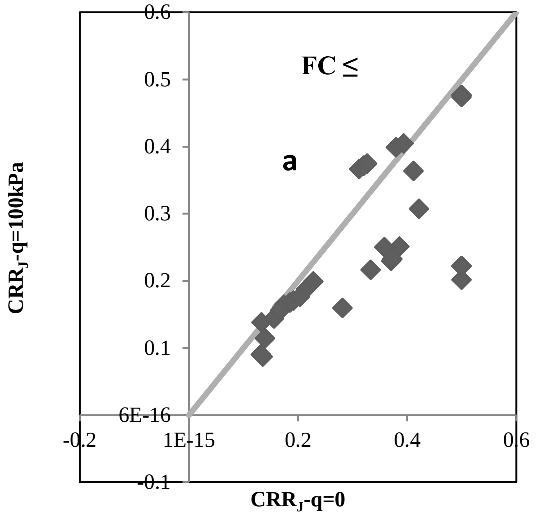
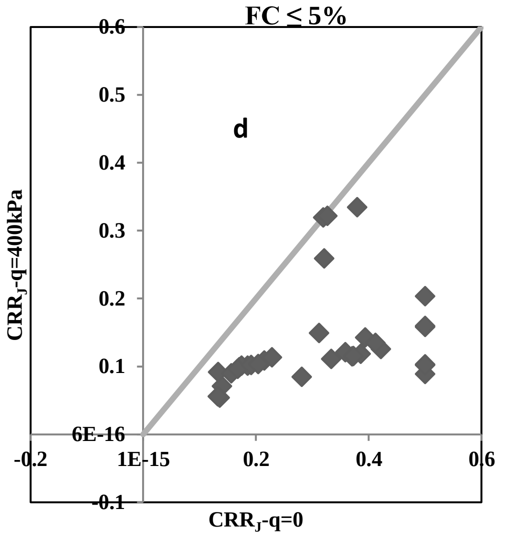


Figure 8. (a, b, c, d, and e). Effects of overburden on corrected cyclic resistance ratio (CRRj) in soil layers: a-q=0, b-q=100kPa, c-q=200kPa, d-q=300kPa, e-q=400kPa

In without overburden and overburden conditions, corrected cyclic resistance ratio (CRRj) of soil layers was compared with CRRj in q = 0.The results based on fines content percent (less than 5%, 15%, and more than 35%) are presented in Figures 9, 10, and 11.As Figures illustrate, in low values of overburden (q=100kPa), fewer effects were observed in CRRj, and almost 40% of data were next to middle line. However, with gradual raising of overburden values, CRRj was placed in the middle line. In summary, as mentioned earlier, with increasing overburden, in all of fines content, resistance versus liquefaction in soil layers have been decreased.







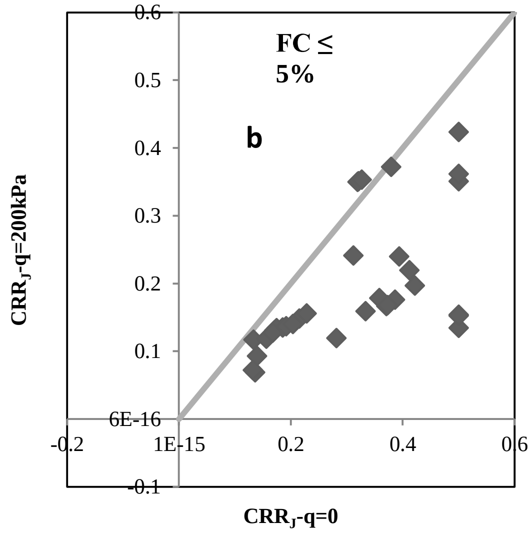


Figure 9. (a, b, c, d). Effects of overburden on corrected cyclic resistance ratio (CRRJ) in soil layers (FC ≤ 5%): a-q=100kPa, b-q=200kPa,
c- q= 300kPa, d-q=400kPa

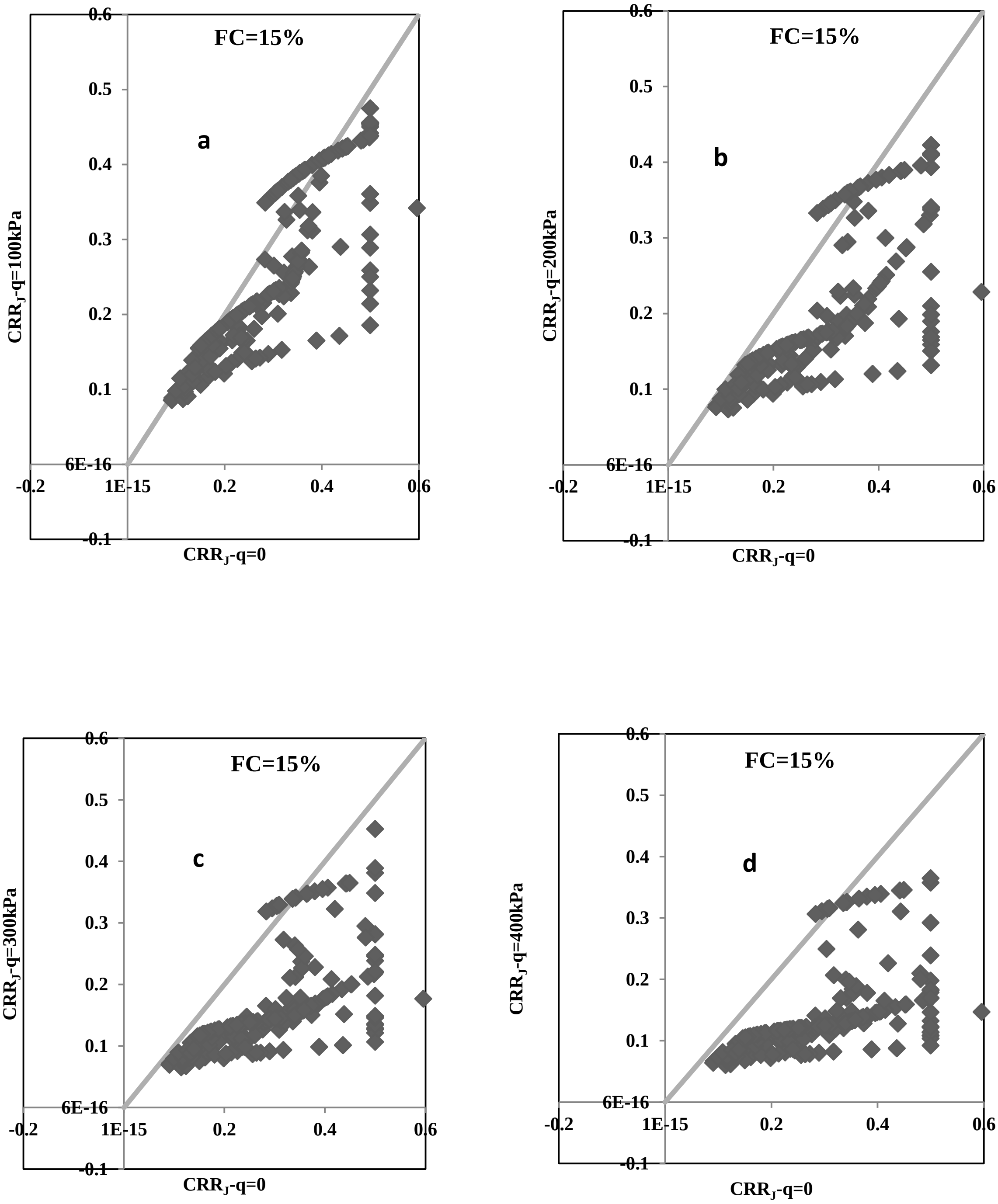


Figure 10. (a, b, c, d). Effects of overburden on corrected cyclic resistance ratio (CRRJ) in soil layers (FC= 15%):
a-q=100kPa, b-q=200kPa,
c- q= 300kPa,d-q=400kPa

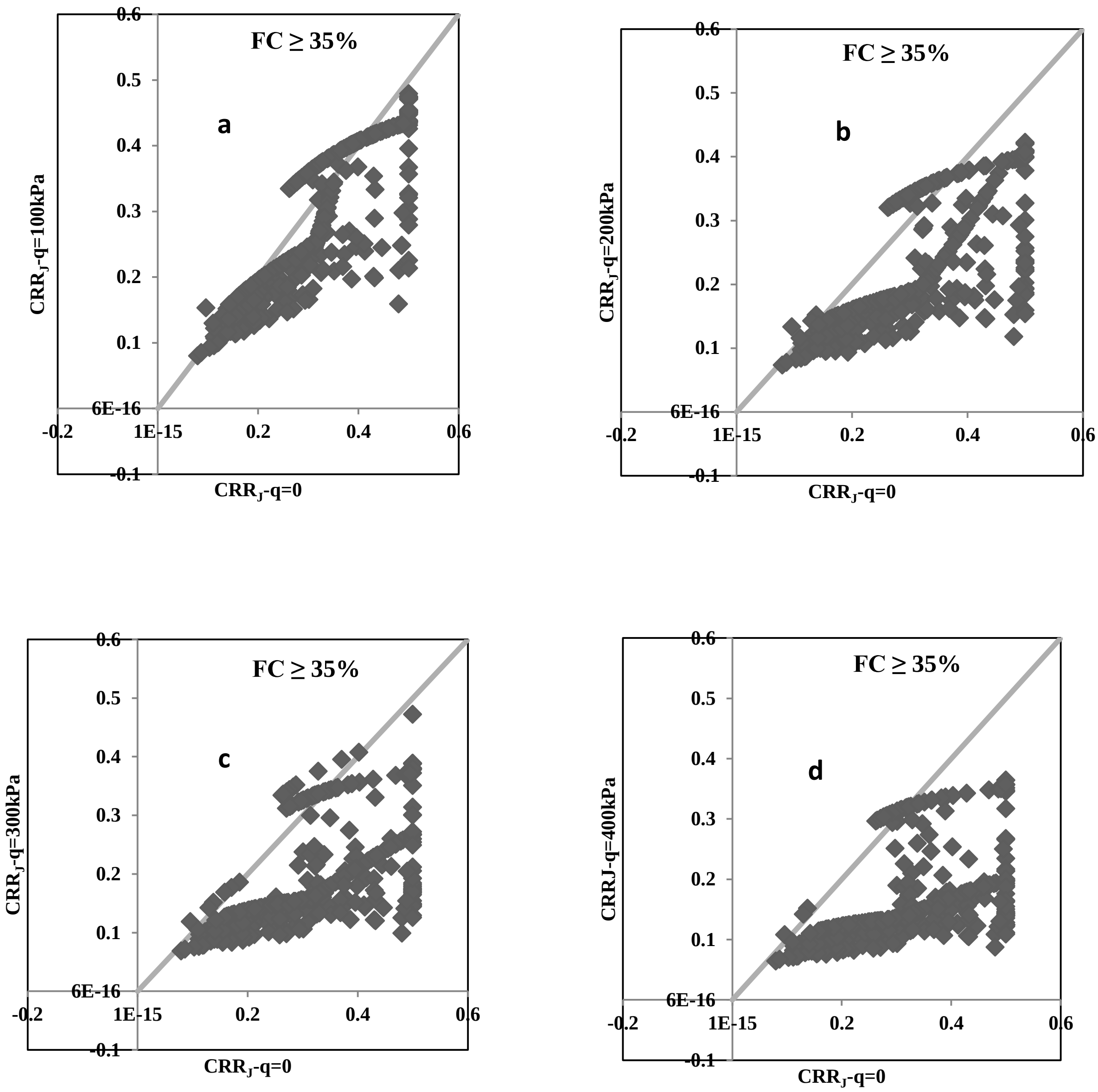


Figure 11. (a, b, c, and d). Effects of overburden on corrected cyclic resistance ratio (CRR$_J$) in soil layers (FC ≥ 35%): a-q=100kPa, b-q=200kPa, c-q=300kPa, d-q=400kPa

4.2. Effects of Overburden on FS

The analysis of data revealed that almost standard penetration test blow counts along Tabriz Metro Line 2 varied from 4 to 70. Safety factor (FS) values in saturate soil layers versus liquefaction-based SPT results calculated using Idriss and Boulanger's (2010) method with considering no overburden and overburden conditions are presented in Figure 12.As Figure 12 illustrates, in no overburden situation, about 30% and 40% of soil layers had safety factor less than one, whereas as overburden gradually increased from 100 to 400 KPa, more soil layers had safety factor less than one. According to Figure 12(e), when overburden corresponded to 400 KPa, liquefaction occurred in almost 80% of soil layers .These results can be verified considering CRRj values mentioned above.

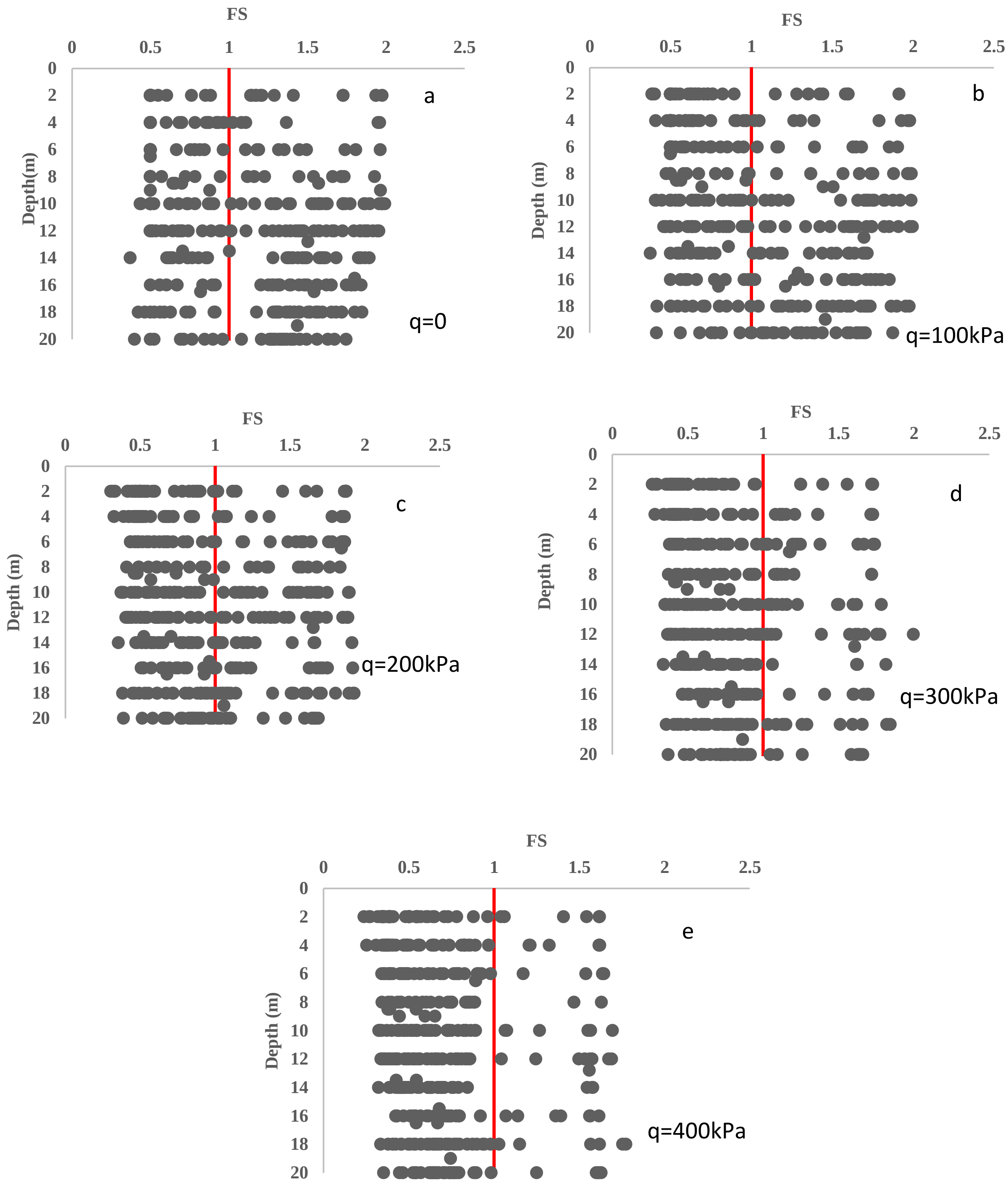
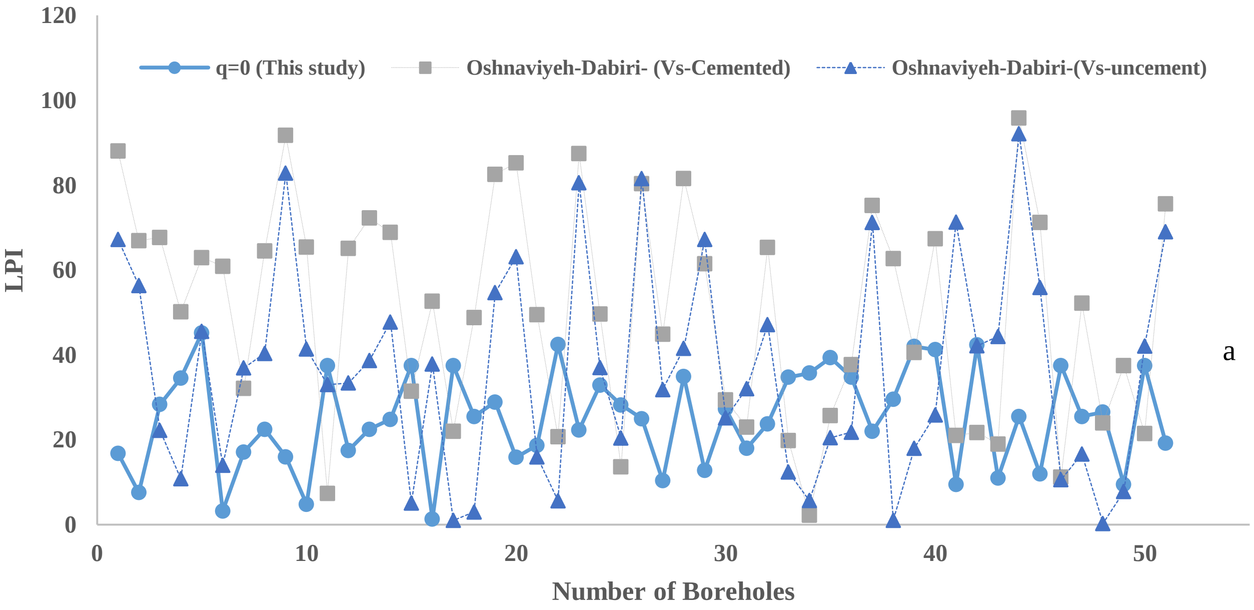


Figure 12. (a, b, c, d, and e). Effects of overburden on safety factor against liquefaction in soil layers: a-q=0, b-q=100kPa, c-q=200kPa, d- q= 300kPa, e-q=400kPa

4.3. Effects of Overburden on LPI

The impacts of overburden on liquefaction potential index (LPI) were evaluated in boreholes, and the findings were compared to those found in Oshnaviyeh and Dabiri's (2018) study. Oshnaviyeh and Dabiri (2018) determined liquefaction potential of soil layers in the study area using shear wave velocity in both cemented and uncemented conditions. As illustrated in

Figure 13, LPI has the highest values in liquefaction hazards' interpretations based on the shear wave velocity method. Additionally, there is no agreement between SPT and Vs methods. The results of the present study showed that with increasing the rate of overburden stress values, LPI elevated and almost matched shear wave velocity results in uncement condition. Moreover, the rate of growth in LPI due to overburden (i.e., 100, 200, 300, and 400 KPa) roughly equals to 47, 56, 85, and 92 percent, respectively. Thus, in high overburden values, the growth rate of LPI in soil layers is high.



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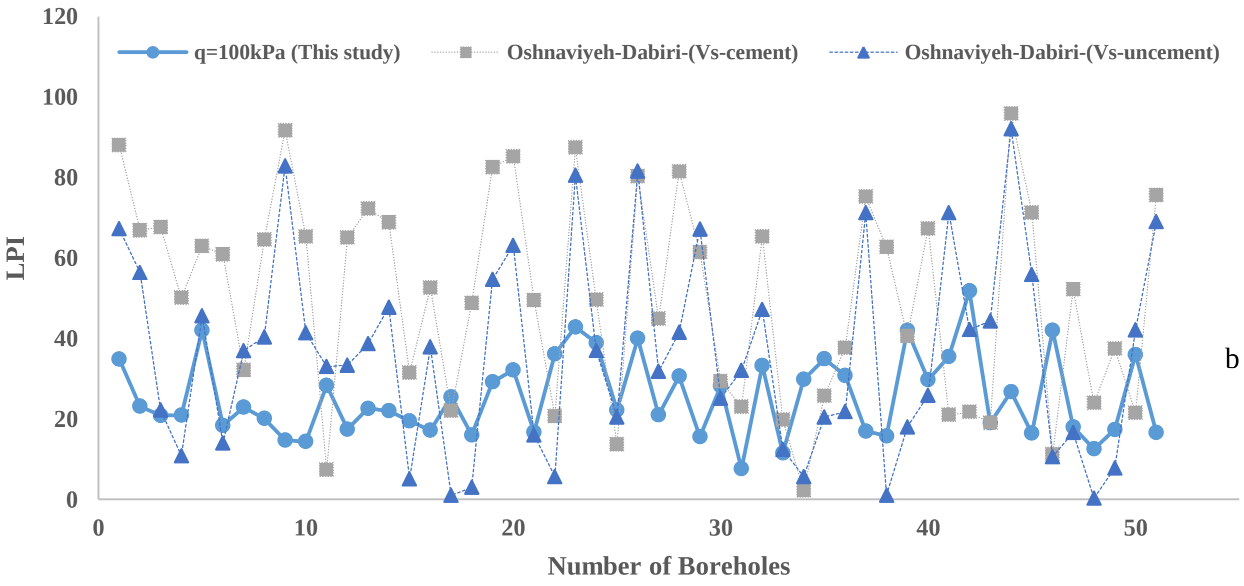

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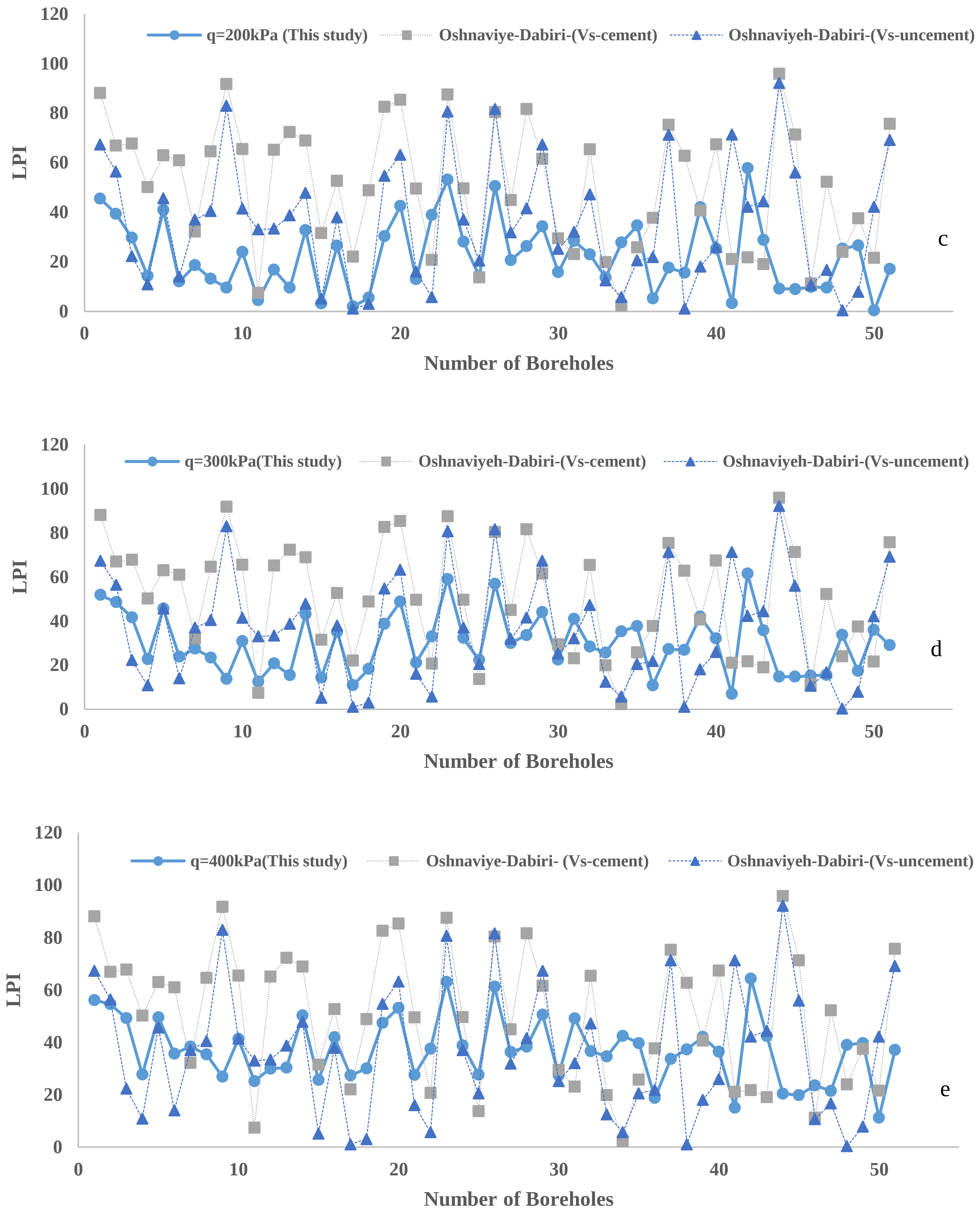

Figure 13. (a, b, c, d, and e). Effects of overburden on liquefaction potential index (LPI) along Tabriz Metro Line 2, a-q=0, b-q=100kPa, c-q=200kPa, d-q=300kPa, e-q=400kPa

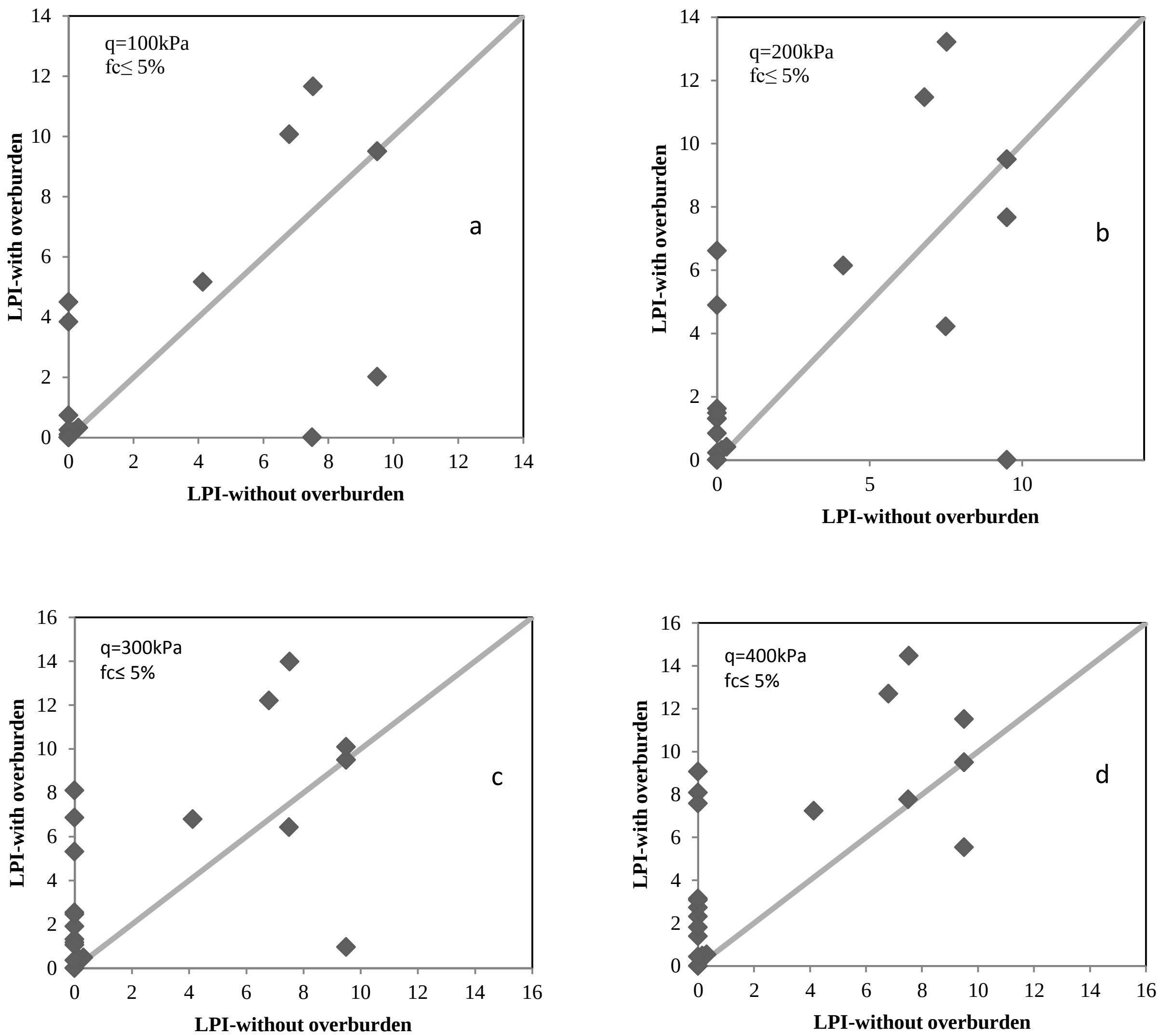

Figure 14. (a, b, c, d). Effects of overburden on liquefaction potential index (LPI) in soil layers (FC≤ 5%): a-q=100kPa, b-q=200kPa, c-q=300kPa, d-q=400kPa

In without overburden and overburden conditions, LPI of soil layers compared with LPI in q = 0 separately for fines content less than 5% was found to be equal to 15% and more than 35%, respectively, as shown in Figures 14, 15, and 16. According to Figure 14, with increasing overburden values, liquefaction hazards were observed in more boreholes, and approximately 80% of LPI values were placed above the middle line.

As shown in Figure 15, in low values of overburden (i.e., q=100kPa), almost 30% of LPI values were distributed on the middle line. Nonetheless, with growth of overburden, gradually LPI values increased, and nearly 80% of data moved above the middle line, indicating an increase in liquefaction potential in soil layers.

As illustrated in Figure 16, according to the above-mentioned reasons, liquefaction hazards in the study area elevated as overburden increased. However, the rate of growth in LPI was low, especially in high overburden values because of overburden in soil layers with fines content (more than 35%).This finding could be attributed to skeleton and structures of aggregates in mixed soils. Fines aggregates (silt in this study) are placed among grain particles resulting in the occurrence of liquefaction and absorption of effective stress due to overburden in soil layers. Also, in order to assess the rate of adaption, the results of liquefaction potential evaluation in soil layers between two conditions (i.e., with overburden and without overburden), were compared according to Table 3. The rate of matching means that the results of liquefaction potential analysis of soil layers in both conditions similarity explain safety factor less than one or not. In contrast, rate of non-adaption indicates that there was no agreement between results of analyses based on both conditions. According to Table 3, first, in soil layers (in all of fines content), as overburden increased, rate of adoption dropped. In contrast, rate of non-adoption increased. Second, in all of overburden values, soil layers with fines content less than 5% and more than 35% had the highest value of adoption rate, respectively.

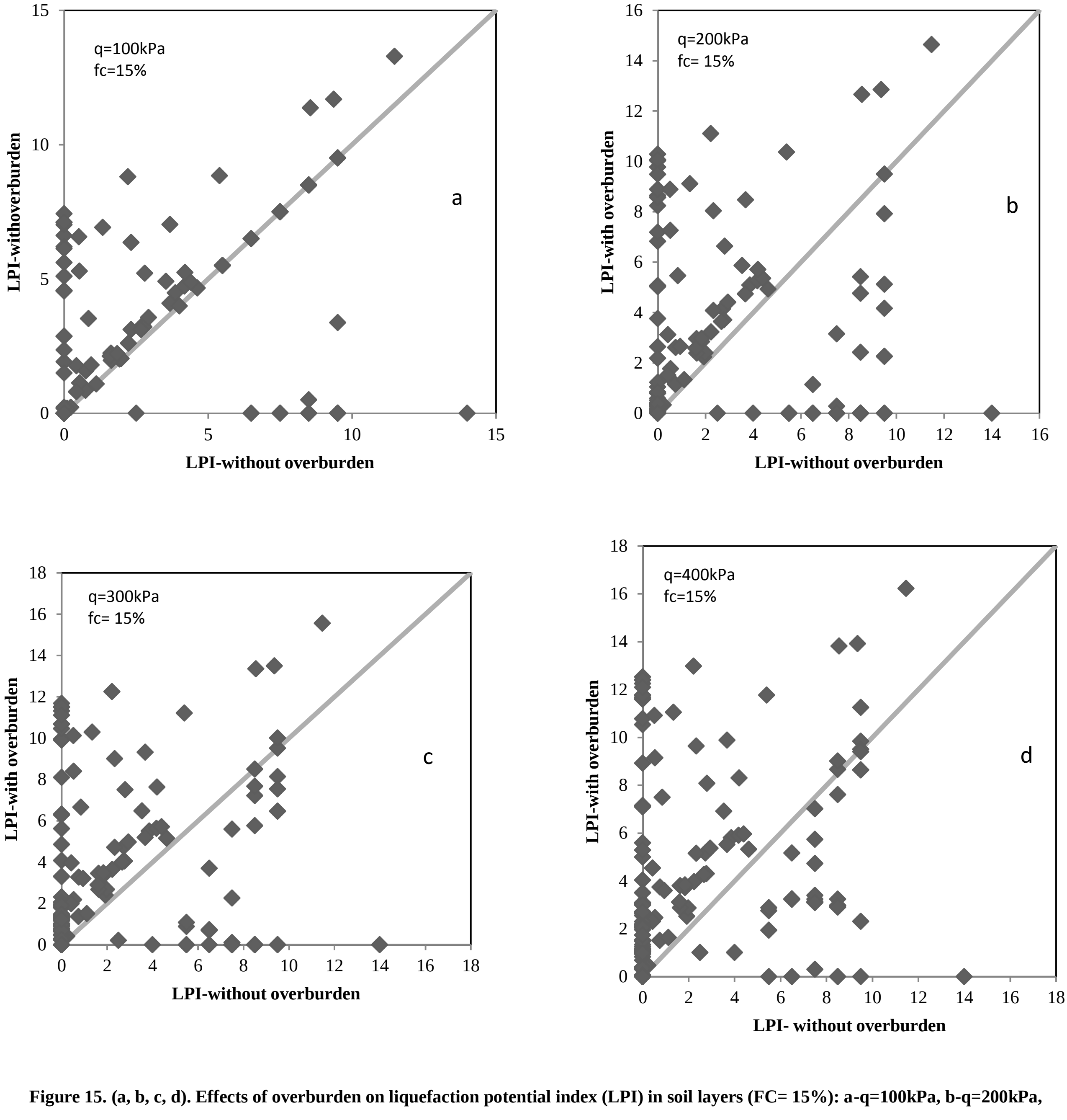

Figure 15. (a, b, c, d). Effects of overburden on liquefaction potential index (LPI) in soil layers (FC= 15%): a-q=100kPa, b-q=200kPa, c-q=300kPa, d-q=400kPa

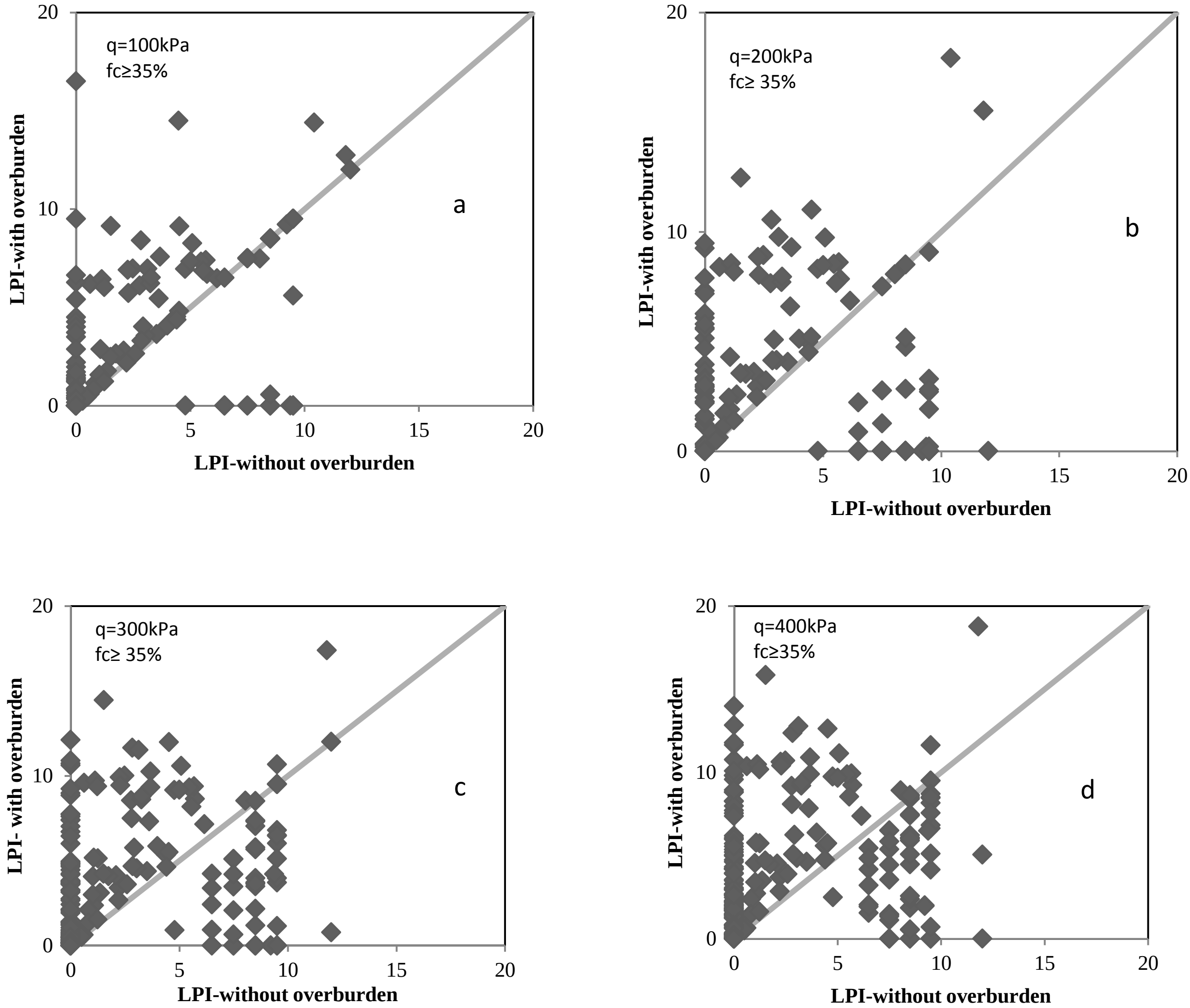

Figure 16. (a, b, c, d). Effects of overburden on liquefaction potential index (LPI) in soil layers (FC≥ 15%): a-q=100kPa, b-q=200kPa, c-q=300kPa, d-q=400kPa

Table 3. Rate of adaption between two conditions (i.e., with overburden and without overburden)

FC (%)	q=100kPa		q=200kPa		q=300kPa		q =400kPa	
5	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption
	80.65	19.35	67.75	32.25	61.3	38.7	51.3	48.7
15	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption
	77.39	22.61	53.77	46.23	48.75	51.25	50.26	49.74
35	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption	Rate of adaption	Rate of no adaption
	79.16	20.84	56.36	43.64	49.84	50.16	49.52	50.48

5. Discussion and Conclusion

As one of significant phenomena in earthquake geotechnical engineering, liquefaction can occur in loose saturate granular soils (clay soil layers in special conditions). Several factors are effective in the occurrence of liquefaction such as relative density, void ratio, fines content, over consolidated ratio (OCR), cementation, and vertical effective stress. A review on the literature revealed that overburdens resulting from building construction can affect severity of liquefaction hazards. This study mainly investigated the impacts of overburdens as a result of building constructions on liquefaction resistance of soil layers along Tabriz Metro Line 2 using SPT data. Results of this study can be mentioned as follows:

1. The analysis demonstrated that approximately 80% of soil layers had safety factor less than one, and generally with increasing overburden values, liquefaction resistance of soil layers dropped and liquefaction potential index (LPI) increased. The results of this study are in agreement with those found in Oshnaviyeh and Dabiri's study.
2. The rate of adaption between results soil layers liquefaction potential evaluation for two conditions (i.e., with overburden and without overburden) showed that in soil layers (in all of fines content), as overburden increased, rate of adoption dropped. Also, in all of overburden values, soil layers with fines content less than 5% and more than 35% had the highest value of adoption rate, respectively.
3. It can be concluded that vertical stress correction factor due to overburden ($K\sigma$) is effective in data analyses. $K\sigma$ is functions of relative density, vertical stress, and ground water table depth. Evaluations of data revealed that stress concentration and high effective vertical stress due to overburden in soil layers near ground surface are the factors increasing liquefaction potential resulting from building construction.
4. Accordingly, $K\sigma$ proposes a value less than 1 and CRRJ decreases. However, to exactly determine overburden effects on liquefaction potential of soils, the following points should be taken into account.

   a. Empirical relationship was used for evaluating effects of overburdens on liquefaction potential of soil layers. Considering soil types in the research site, the empirical data may be inappropriate for An accurate relationship needs to be evaluated using numerical and laboratory methods.

   b. Rate of effective vertical stress growth due to overburden in depth of soil layers should be determined and results should be compared with liquefaction potential of other soils.

   c. Generally, it is proposed that the exact horizontal distance of buildings in the study area be determined, overburden owing to construction be calculated, and finally, liquefaction potential of soil layers be evaluated.

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