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Determination of Liquefaction Potential of Tabriz City, Northwest of Iran

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Abstract

The city of Tabriz, located in Northwestern Iran, is one of the seismo-tectonically active regions of Iran. Historical earthquake sequences of this area show that the recurrence interval of earthquakes with M>6 can be estimated equal to 250 years (while some larger earthquakes with M>7 have been reported in the literature). Based on this knowledge, the occurrence of a large earthquake in the city of Tabriz is expected for upcoming decades. Therefore, evaluating the potential of liquefaction (as one of the significant hazards induced by earthquakes) and providing an appropriate hazard zonation map for this city is necessary for pre-crisis management. To this aim, different methods are applied to assess the potential of liquefaction in the study area and a comparison between their results is presented in this paper. Methods based on the standard penetration test and fully coupled finite element site response modeling are employed to investigate the potential of liquefaction. In this study, it has been shown that some populated areas of the studied city have been built in liquefiable regions and therefore necessary measures should be taken by city authorities for these regions.

Anahtar Kelimeler: Finite element, Liquefaction, Site response, Tabriz.

Tebriz Şehrinin Sıvılaşma Potansiyelinin Belirlenmesi, İran'ın Kuzeybatısı

Özet
İranın Kuzeybatısında bulunan Tebriz şehri, sismotektonik olarak İranın aktif bölgelerinden biridir. Bu bölgedeki tarihsel depremlere bakıldığında büyüklüğü 6 'ın üzerinde olan depremlerin tekrarlanma sıklığının 250 yıla eşit olarak tahmin edilebileceğini görülmektedir (literatürde büyüklüğü 7' den fazla olan bazı büyük depremler bildirilmiştir). Bu bilgilere ışığında, önümüzdeki yıllarda Tebriz şehrinde büyük bir depremin meydana gelmesi beklenmektedir. Bu nedenle, sıvılaşma potansiyelini (depremlerin neden olduğu önemli tehlikelerden biri olarak) değerlendirmek ve şehir için uygun bir tehlike haritası oluşturmak önem arz etmektedir. Bu amaçla bu makalede, çalışma alanındaki sıvılaşma potansiyelini değerlendirmek için literatürde yer alan farklı yöntemler uygulanmış ve elde edilen sonuçlar karşılaştırılmıştır. Sıvılaşma potansiyelini araştırmak için standart penetrasyon deneyi ve saha tepki analizlerine dayanan sonlu elemanlar yöntemi kullanılmıştır. Bu çalışmada, Tebriz'de nüfusun kalabalık olduğu bazı bölgelerin sıvılaşabilir olduğu gösterilmiştir. Bu veriler ışığında vakit kaybetmeden gerekli tedbirlerin alınması gerektiği sonucuna ulaşılmıştır.

Keywords: *Sonlu elemanlar, Sıvılaşma, Saha tepkisi, Tabriz.*

1. Introduction

Liquefactıon is a natural hazard that can occur during earthquakes. Saturated granular soils (and in some cases intermediate soils) are capable to liquefy during rapid vibrations. The tendency to contraction (in an undrained situation) results in developing positive pore water pressures and the reduction of effective stresses. By decreasing effective stresses, shear strength of the soil body will be decreased, therefore adjacent structures can be exposed to hazards. Liquefaction induced damages have been frequently reported in previous earthquakes from different areas of the world. For example, the Liquefaction-Induced Settlement of Single Story Structures in Roudboneh (a town in the north part of Iran) during the 1990 Manjil earthquake is shown in Fig. 1.

Figure 1. Liquefaction induced damages in Roudboneh, a town in the north part of Iran (Yegian et al., 1993).

In order to reduce the damage caused by earthquakes, determining the level of risk in urban areas (including the risk of liquefaction) is necessary not only for the proper design of future structures, but also for urban development plans, crisis management plans and land use plans. Extensive studies have been performed to determine the liquefaction potential of granular or non-plastic fine-grained soils previously. Experimental methods based on field experiments (Moss et al., 2006), laboratory tests (Monkul et al., 2015), experimental methods based on geomorphological and geological characteristics (Ganapathy and Rajawat (2012)), numerical methods (Jafarian et al., 2011) and methods based on artificial intelligence (Goh, 1994) are among the tools introduced for liquefaction hazard investigations. Yilmaz and Yavuzer (2005) presented liquefaction potential and susceptibility maps for the city of Yalova, Turkey. Yalcin et al. (2008) presented a liquefaction severity map for Aksaray city center (Central Anatolia, Turkey) by using SPT results and considering fine content effects. Tosun et al. (2011) used the SPT based methods to evaluate soil liquefaction potential in Eskisehir(a city in the north-west of Turkey). Sassa and Yamazaki (2016) presented a simplified approach to evaluate the potential of liquefaction using the concept of effective wave number. Kajihara et al. (2020) investigated liquefaction potential and road network subsidence relationship using the AIJ (2001) method. Bahari et al. (2020) estimated liquefaction potential using different approaches in Eco‑Delta City (Busan) with considering effects of fine contents. Cabalar et al. (2019) investigated soil liquefaction potential in Kahramanmaras (a city in Turkey) using the empirical methods (based on the standard penetration test results).

Iran is located in one of the most seismologically active regions of the earth and a large number of quakes (from negligible magnitudes to sever events) have been reported there every year. Because of such a hazardous geological situation, liquefaction hazard investigation (and hazard mapping) for different areas of this country is an essential step in pre-crisis management approaches. The city of Tabriz, located in Northwestern Iran, is one of the seismo-tectonically active regions of Iran. The location of Tabriz city, the general layout of the Tabriz metro network (as a main lifeline facility of the city) and geological map of this city are shown in Fig. 2.

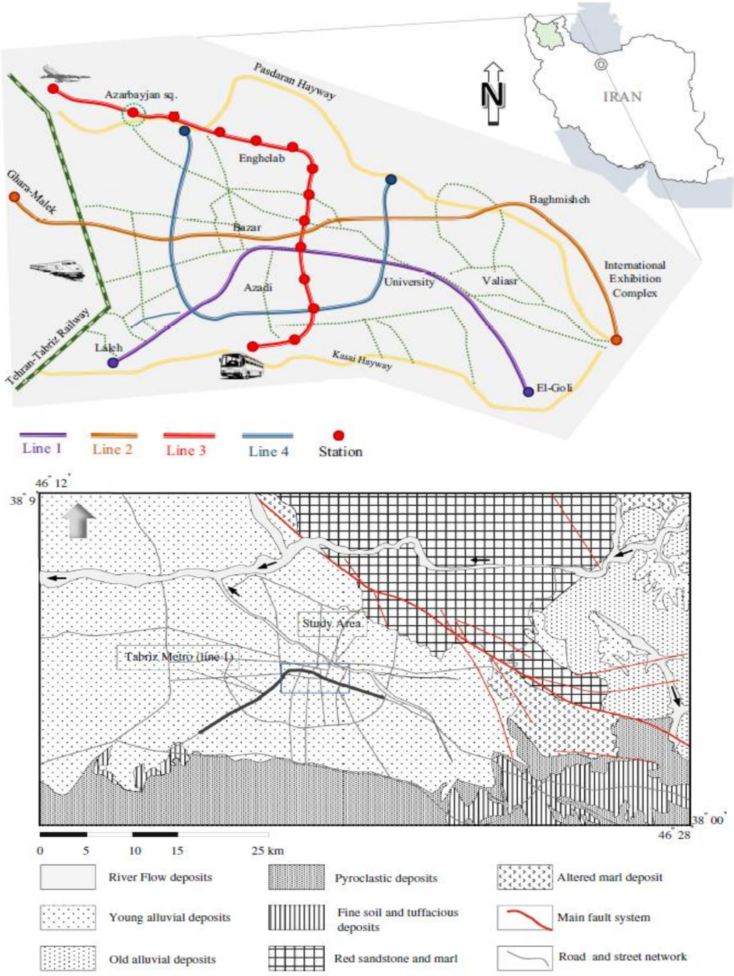


Figure 2. Location of Tabriz city, the general layout of the Tabriz metro network and geological map of this city (Barzegari and Zhao, Barzegari et al., 2018).

Historical earthquake sequences of this area show that the recurrence interval of earthquakes with M > 6 can be estimated equal to 250 years (while some larger earthquakes with M > 7 have been reported in the literature). Previously Recently done site investigations in this city show some evidence of historically liquefied deposits. For example, boiled sand layers were observed during excavations in the west part of the city. To investigate the potential of the liquefaction in Tabriz, seismic hazard analysis is applied in this paper. Seismicity parameters, design earthquake magnitude (for a 475-year duration), peak expected accelerations and distribution of these earthquake-induced peak accelerations are obtained. Then, different methods are applied to assess the potential of liquefaction in the study area and a comparison between their results is presented in this paper. Methods based on the standard penetration test and fully coupled finite element site response modeling are employed to investigate the potential of liquefaction.

2. Seismic Hazard Assessment of Tabriz City

Liquefaction potential of a site, directly related to received ground motion parameters. Therefore at the first step of any liquefaction hazard zonation, the main characteristics of the expected earthquake motion should be determined. Strong ground motion assessments can be done using seismological and geological data (JSSMF, 1993). In this paper, the probabilistic seismic hazard analysis (PSHA) is used for calculating the required parameters. To evaluate seismicity parameters, the Kijko method (Kijko and Öncel, 2000) is employed which is established upon doubly truncated Gutenberg-Richter relationship (Kijko, 2004) and the maximum likelihood estimation method. The Kijko method is an interesting approach especially for dealing with low accuracy data and different types of errors in seismicity data.

To obtain seismicity parameters, the used earthquake catalog is divided into three different groups. Historical earthquakes which contain magnitudes of earthquakes before the year 1900. For this group of earthquakes, the magnitude inaccuracy is considered equal to 0.5. The second group is consists of instrumentally recorded earthquakes between the years 1900 and 1964 with magnitude inaccuracy of 0.3 and the threshold magnitude of Ms = 4. The last group contains instrumentally recorded earthquakes from 1964 till now where the magnitude inaccuracy is selected equal to 0.1 and threshold magnitude of Ms = 4. Three seismicity parameters of the Kijko method (β: Seismicity Coefficient, λ: Annual Rate) are obtained by the method. The achieved results are presented in Table I. Annual rate of occurrence, λ, for different magnitudes is shown in Fig. 3.

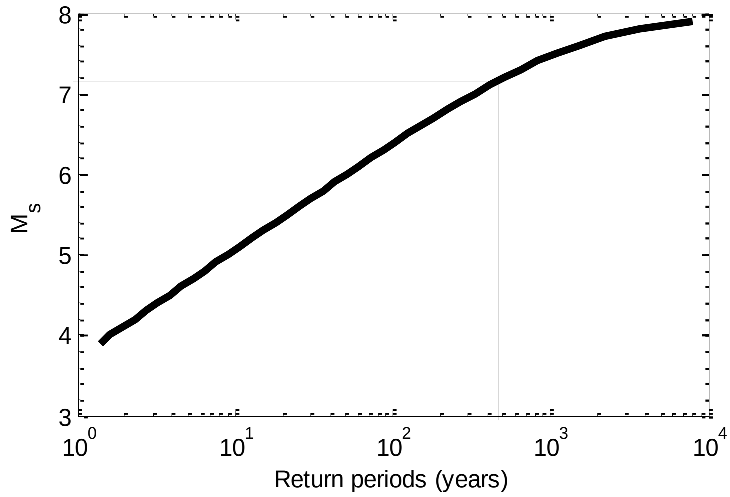


Figure 3. The relationship between the return period and the earthquake magnitude in 200 km radius around Tabriz.

Tablo 1. The Result Values of the Calculated Seismic Hazard Parameters by Kijko Method.

Parameters	**Value**
Beta	1.70
Lambda	0.73

To ensure the accuracy of the calculated seismicity parameters, the achieved results by Razaghi et al. (2016) are presented in Table II and Fig. 4. By neglecting effects of the selected threshold magnitude (4 in this research, 4.5 and 5 in the reference (Zare M. and Sabzali, 2006), it can be observed that both results are in a good agreement for strong quakes and the existent little differences may be arisen because of the occurred earthquakes between the two different research times (and different earthquake catalogs).

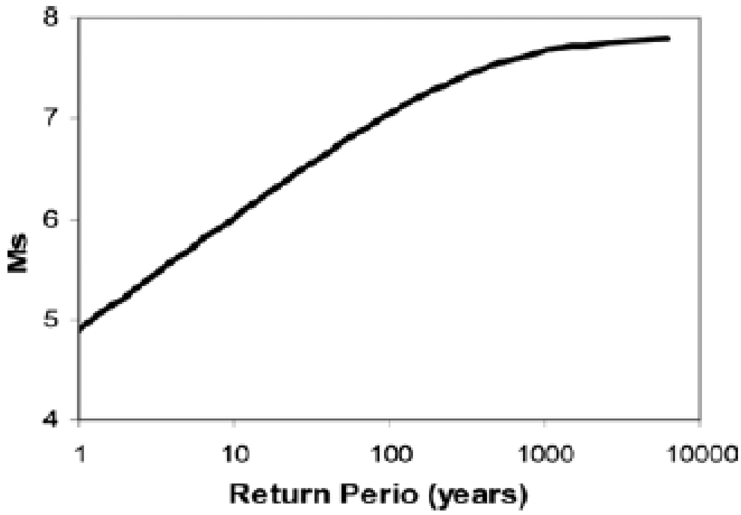
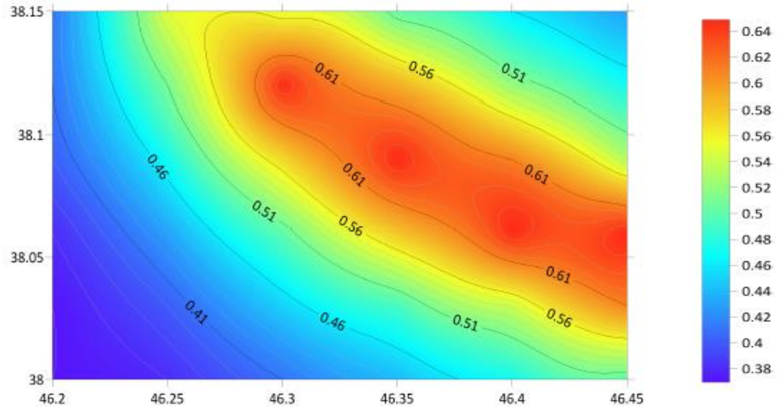


Figure 4. The achieved results for the relationship between the Return Period and the Earthquake Magnitude in 200 km Radius Around Tabriz by Razaghi et al., 2016.

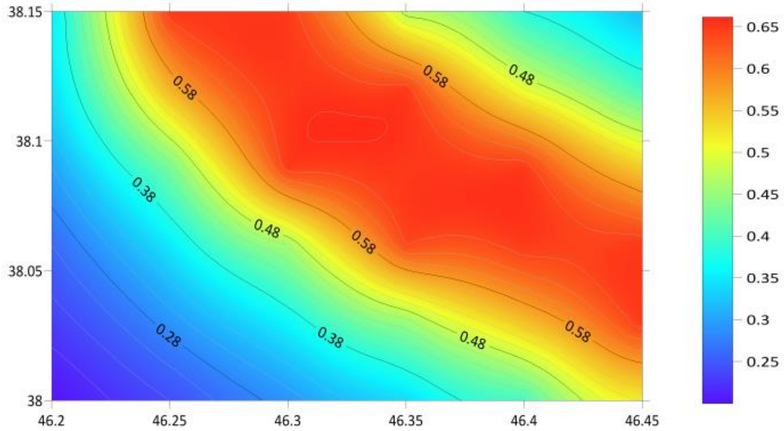
Tablo 2. The Result Values of the Calculated Seismic Hazard Parameters by Kijko Method, (Razeghi et al., 2016)

Threshold Magnitude=4.5		**Threshold Magnitude=5**	
Parameters	Value	Parameters	Value
Beta	2.03	Beta	1.90
Lambda	0.622	Lambda	0.70

To predict peak ground acceleration (PGA) during the design earthquake (Ms=7.2) two different attenuation relationships are employed. Results of the PGA by using the Zareh and Sabzali (Zare M. and Sabzali, 206) attenuation relationship is depicted in Fig. 5a. Fig. 5b shows the calculated PGAs using the attenuation relationship proposed by Campbell, 1997. Based on the achieved results amax=0.65 can be expected from the design earthquake of the Tabriz city.



(a)



(b)

Figure 5. Results of the PGA by using the Zareh and Sabzali attenuation relationship. (b) Calculated PGAs using the attenuation relationship proposed by Campbell (1997).

These results are in good agreement with the results of the seismic hazard zonation of Iran presented by Mousavi et al., 2014 (Fig. 6).

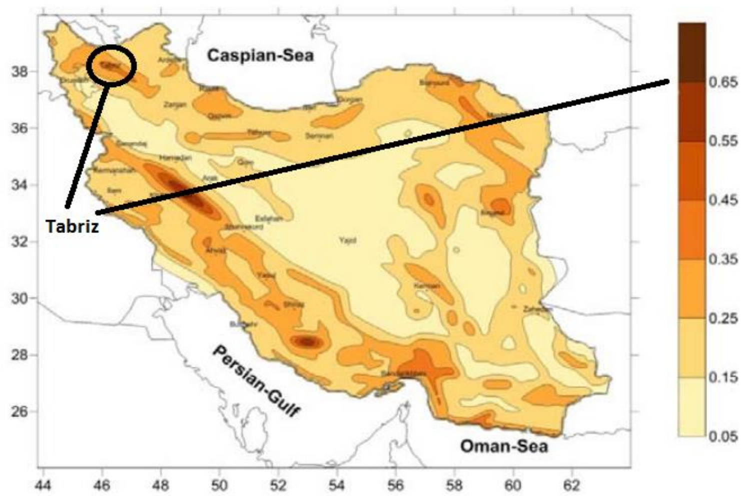


Figure 6. Seismic hazard zonation of Iran presented by Mousavi et al. 2014.

3. Hydrological and Geotechnical Properties Of Tabriz City

To assess necessary important geotechnical and hydrological features of Tabriz, a comprehensive database containing data of 350 sites are gathered and interpreted. Using this comprehensive database, the distribution of groundwater levels in the studied area is prepared. Fig. 7 shows the water level distribution (only areas with water level between the ground surface and -20m) on the interesting territory.

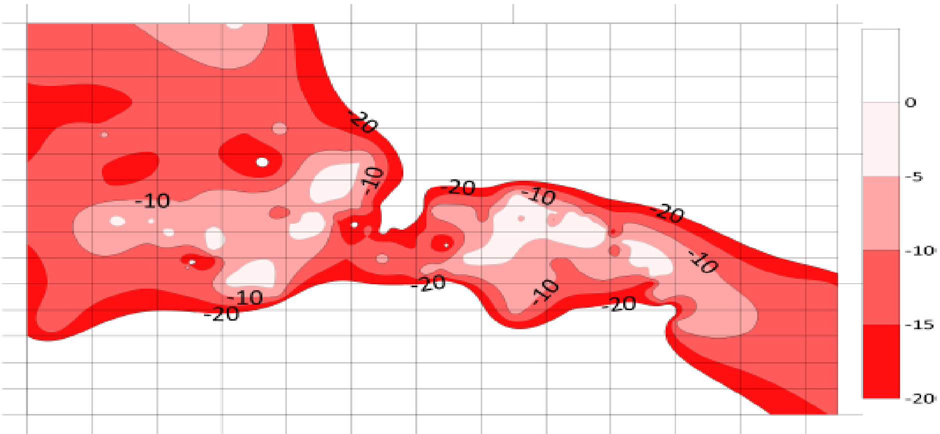


Figure 7. The water level distribution (only areas with water level between the ground surface and -20m) in the studied area.

To unify the justification criterion, geotechnical properties are evaluated by a modified standard penetration test number (SPT). The obtained results are depicted in Fig. 8. It should be mentioned that for the east north and west south of the study region, SPT numbers are sophistically considered (because of the lack of information at these areas). The considered SPT numbers for these areas (with mainly marl stones slopes) are selected based on the rarely available information and engineering judgment. As the northeast and southwest of Tabriz city has water level deeper than -20m and non-granular (liquefiable) soils, these considerations can not affect the accuracy of the results.

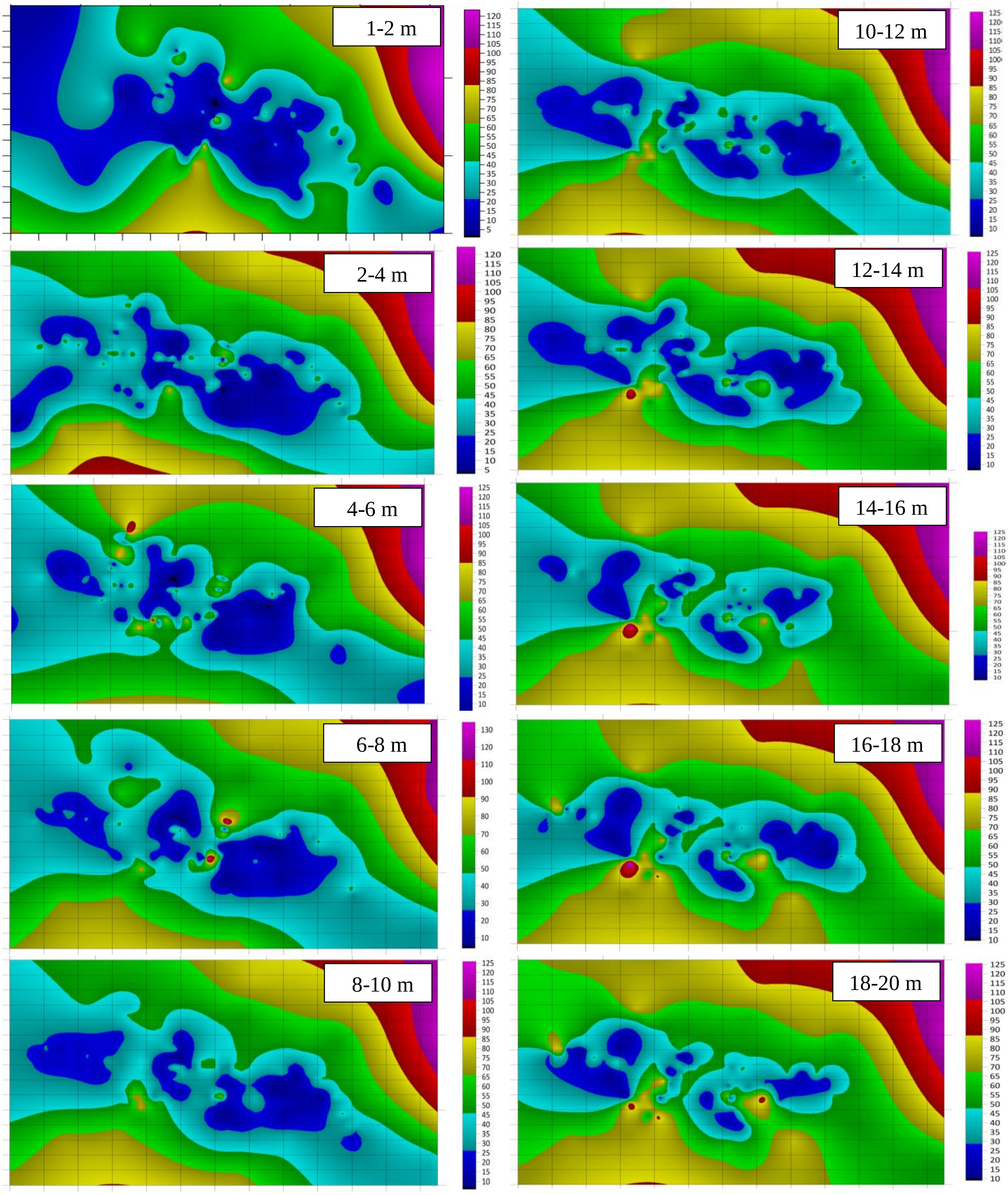


Figure 8. The Distribution of the modified SPT numbers around the studied area (Tabriz city).

After determining the SPT number distribution (where other geotechnical properties can be achieved by available correlation relationships) the next step is determining the soil types. To this aim, two main categories is used in this research. Type 1 is a soil media with mainly granular contents and types 2 is a soil media with mainly non-granular properties (cohesive, cemented, rock,…). It is obvious that liquefaction is a potential hazard in granular materials. Fig. 9 shows distribution soil types (with the mentioned two main categories) on the different depths of the Tabriz city.

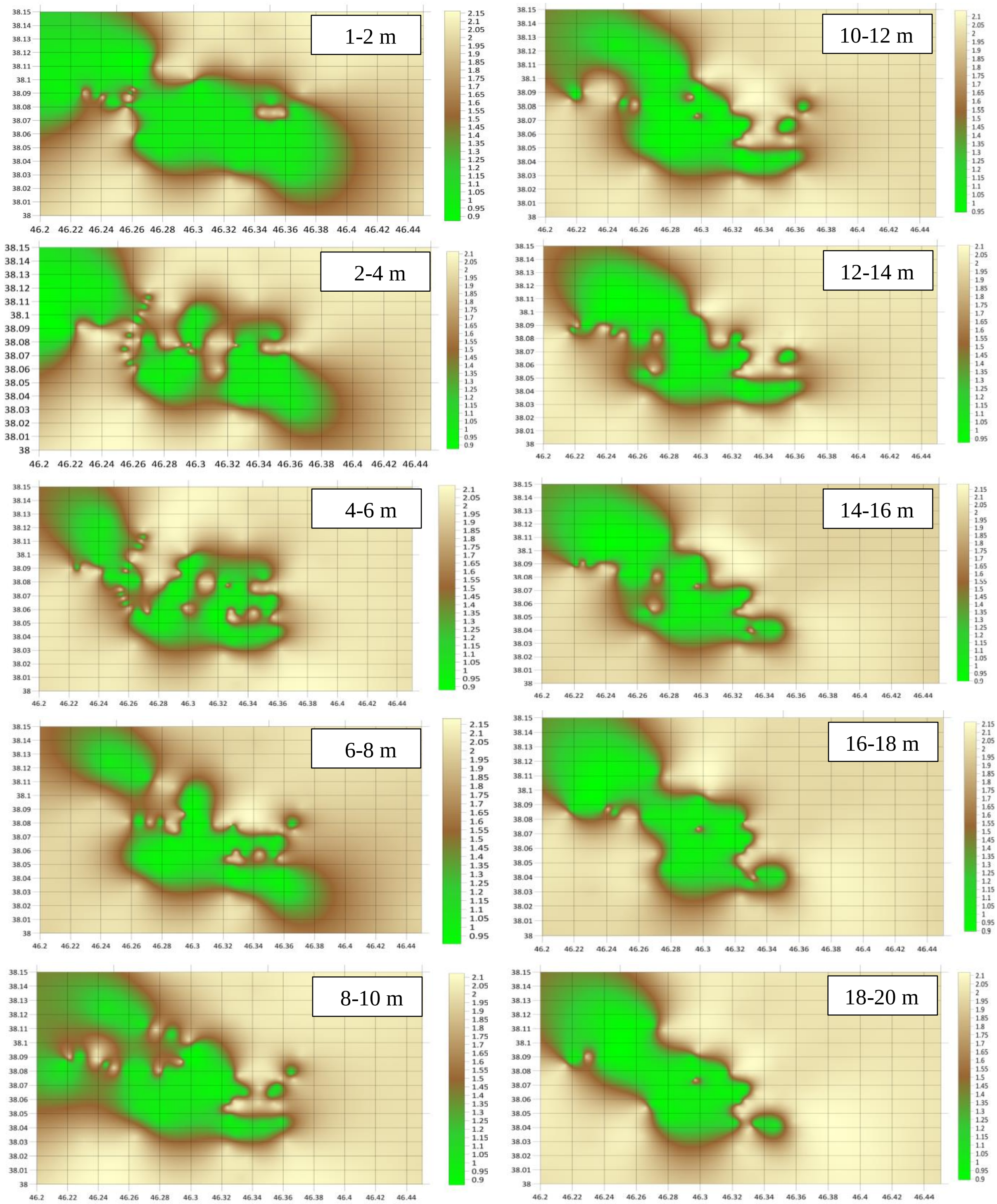


Figure 9. Distribution soil types on the different depths of the Tabriz city (green: granular, brown:non-granular).

4. Methods For Liquefaction Hazard Assessment

In this paper, two methods are employed to asses the factor of safety against seismically induced liquefaction. The method proposed by Seed and Idris (1971) which uses the SPT numbers in calculating cyclic resistance ratio (CRR-Fig. 10) and soil initial stress states (total and effective) with desired seismic motion properties (max or ag) for cyclic stress ratio (CSR-Eq.1) is selected to this aim.

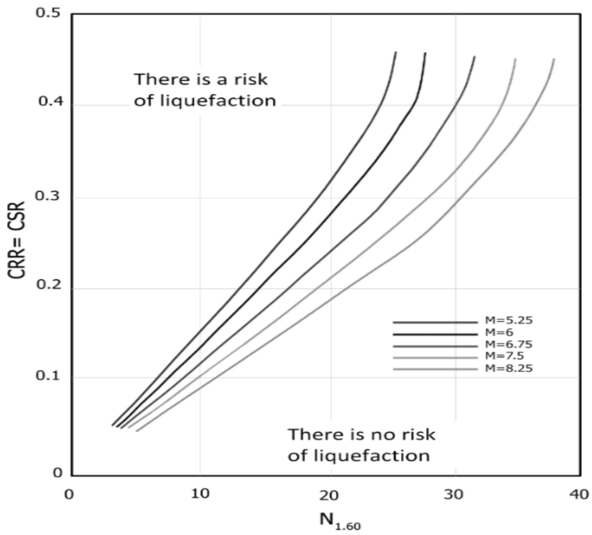


Fig 10. CRR against modified SPT number, $N_{1\text{-}60}$, (Seed Bolton, and I. M. Idriss, 1971)

$$CSR = 0.65\frac{a_g}{g}S\frac{\sigma_{v_0}}{\sigma'_{v_0}}\frac{r_d}{MSF} \tag{1}$$

In Eq.1 r_d is the depth reduction factor which can be determined using Eq. 2. MSF is the correction factor for earthquake magnitude. S is selected equal to 1 in the Seed-Idris approach.

$$r_d = 1 - 0.015z \tag{2}$$

Based on the applied investigation ag is selected equal to 0.65g for the studied area. In addition to the empirical approach proposed by Seed and Idris, a coupled finite element method with the Finn-Byrne, (1999) constitutive model is used for evaluating safety factor against liquefaction. The main interesting feature of this constitutive model is its simplicity and efficiency (low computational costs and high convergence rate). The Finn-Byrne constitutive model is a modified Mohr-Columb model where volumetric strains (in undrained situation it can be correlated with excess pore water pressure) are calculating by experimentally proposed relationships. In the FEM analysis, the only 1D motion of a soil column is considered (for example Fig. 11 shows a soil column with granular and non-granular layers). All required mechanical properties are achieved with correlation relationships of the SPT numbers.

For the FEM investigations, the QUAKE/W software is used. QUAKE/W is a software which is developed for 2D plane strain modeling based on the small displacement and small strain theory. Three main assumptions of the Finn-Byrne model which is employed in the QUAKE/W software are as follow:

• Volumetric strains during cyclic loading depend on the amplitude of the shear strains, not on the normal stresses.

• For an initial density and initial stress, the shear modulus increases with increasing number of cycles.

• As the relative density decreases, the volumetric strain increases and the shear modulus decreases.

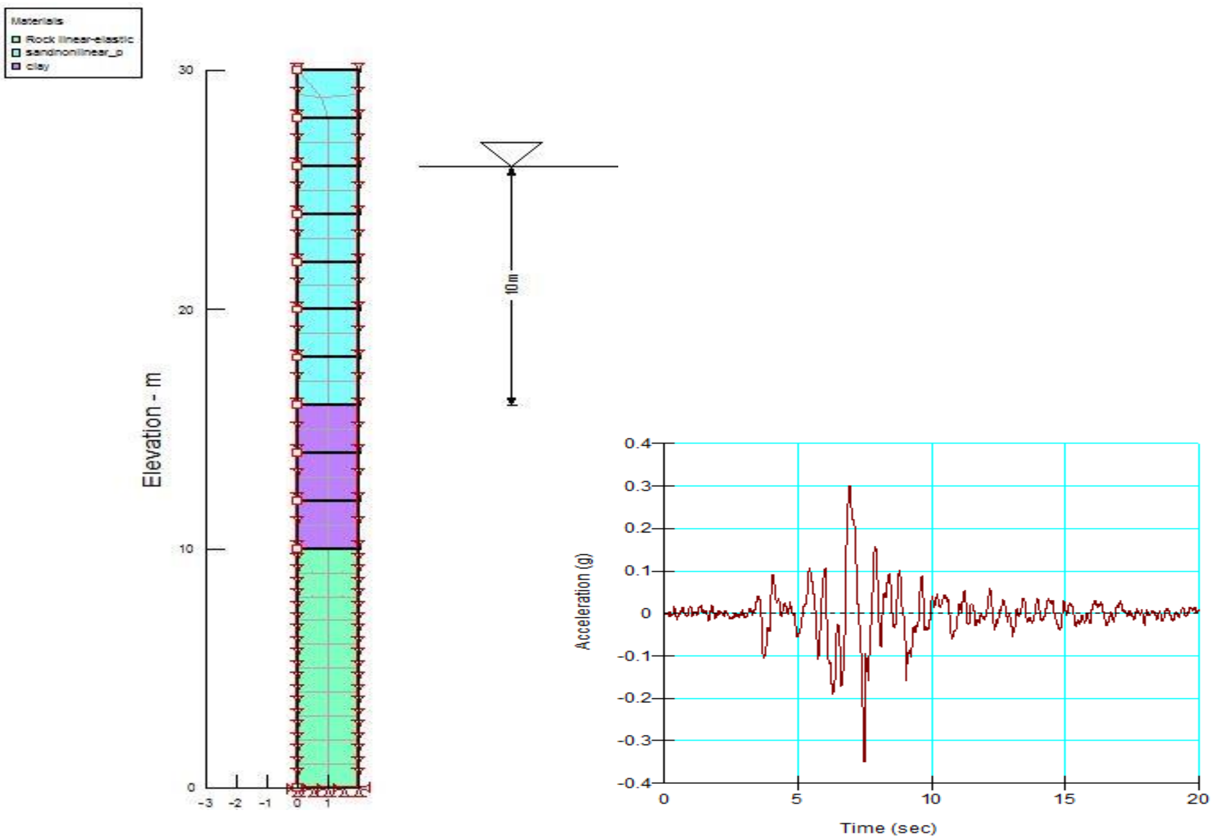


Fig 11. A soil column with granular and non-granular layers and the used acceleration time history (scaled for different sites).

5. Results

In this section results of the liquefaction hazard, zonation for Tabriz city is presented. A MATLAB code is written to evaluate the factor of safety against liquefaction using the Seed-Idris method. These hazard zonation maps are shown in Fig. 12 for depths between zero (ground surface) to -20m while red regions on these maps have the factor of safety less than 1.2. This figure shows that the west and central parts of the city (with a large number of population and lifeline facilities) are at high risk for depths between 4m to 10m. On the deeper layers, the risk of liquefaction mainly is high in the western part of the city.

As the second method, 1D coupled FEM analysis is undertaken to assess the factor of safety against liquefaction. The results of this analysis are presented in Fig. 13. By comparing achieved results, a good agreement between these two methods for depths between 0-14m can be seen. For deeper layers (14-20m) FEM shows larger hazardous areas. This overestimated hazard (in comparison with the used empirical approach) could be related to the depth reduction factor in the Seed-Idriss equations. However, both methods show that highly populated areas in western and central parts of the city may be at risk for a sever earthquake.

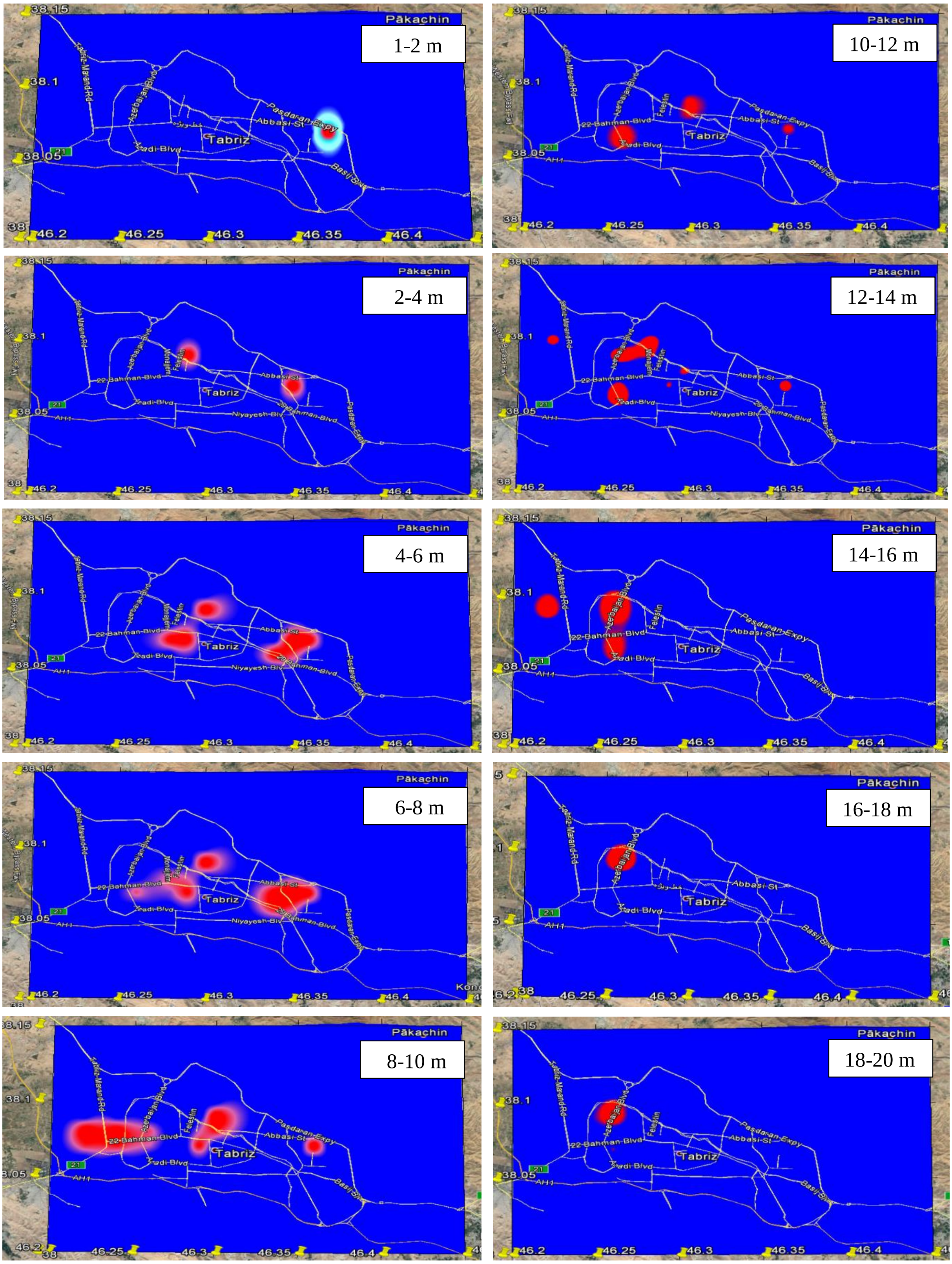


Figure 12. Liquefaction hazard zonation maps for different depths using the Seed-Idris method (based on the modified SPT number). Red regions have a factor of safety of less than 1.2.

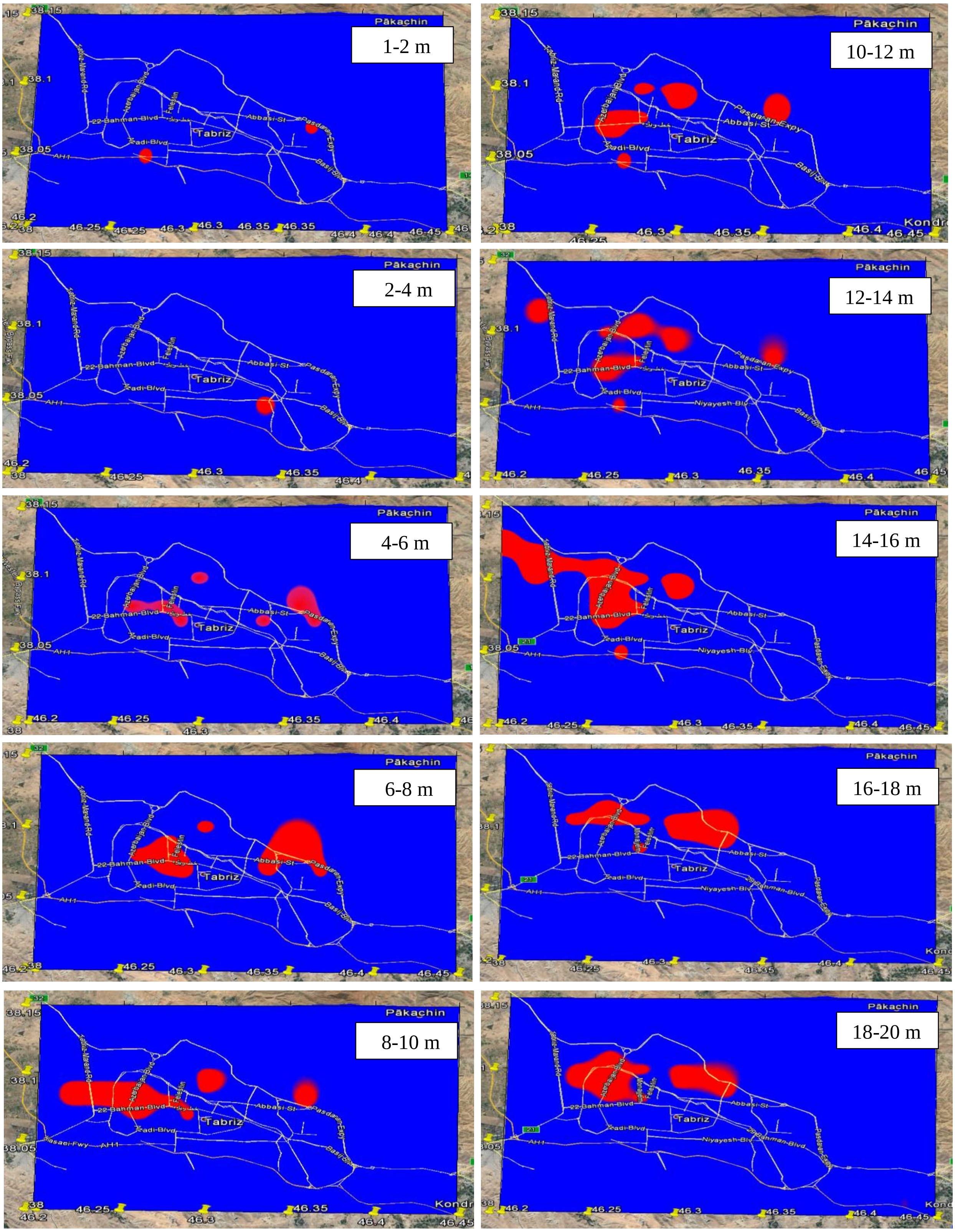


Figure 13. Liquefaction hazard zonation maps for different depths using the 1-D coupled FEM analysis (using the Finn-Byrne constitutive model). Red regions have a factor of safety of less than 1.2.

6. Conclusion

In this paper, probabilistic seismic hazard analysis is done to evaluate expected peak ground acceleration during the design earthquake. Comprehensive data of geological and hydrological conditions of the Tabriz city is gathered. Based on the applied PSHA and the interpreted data, two methods (empirical relationships and finite element nonlinear time-domain analysis) is undertaken to assess the potential of liquefaction in the studied area. it is shown that some highly populated areas such as western and central parts of the city can be at risk (for the design earthquake with M > 7) and every pre-crisis program should be noticed about this high-level hazard. In addition, comparision between the FEM and the emprical method shows a good agreement for depths 0-14m. However, for depths between 14-20m, the finite element approach leads to larger hazardous areas. This larger hazardous areas in the FE method can be interpretated by considering effects of the depth reduction factor in the Seed-Idriss equations.

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