

Development and Application of a Simplified Multi-Criteria Framework for Soil Liquefaction Assessment: A Case Study

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ABSTRACT

The liquefaction phenomenon has been one of the most important causes of damage to structures and vital lifelines during past earthquakes. The accurate assessment of liquefaction has always faced multiple challenges. Common methods based on field data such as Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Shear wave velocity (V_s) often provide different results, and relying on only one method can lead to errors in identifying liquefied layers, post-liquefaction settlement values, and the likelihood of surface manifestation. In this study, the evaluation of the safety factor was examined by four common methods. Moreover, three methods were employed to estimate the post-liquefaction settlement, and two methods were used to assess surface manifestation. The results indicate significant differences among the methods in determining the safety factor, the surface manifestation, and the settlement amount. Since none of the methods alone can fully capture the complexity of soil behavior, a four-step framework including multi-criteria assessment of liquefaction potential, settlement, and surface manifestation was introduced, and then the integration of results was presented. This approach, by reducing uncertainty and simultaneously considering three main components of liquefaction (occurrence potential, settlement, and surface manifestation), provides a potentially useful and more comprehensive engineering-oriented framework for assessing liquefaction-related hazards and can serve as a suitable basis for engineering studies and structural design in liquefaction-prone areas.

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Nomenclature & Abbreviations

Symbol	Description	Symbol	Description
D_r	Relative density	q_c	Cone tip resistance
D_{50}	Mean particle diameter	q_{c1}	Normalized cone tip resistance
FC	Fines content	Rf	CPT friction ratio
F_L	Liquefaction potential factor	S	Post-liquefaction settlement/displacement
H_1	Thickness of the non-liquefied surface layer	V_s	Shear-wave velocity
H_2	Thickness of the underlying liquefied layer	$W(z)$	Depth-dependent weighting function
$(N_1)_{60}$	Corrected SPT blow count	z	Depth of the considered soil layer
$(N_1)_{60cs}$	Fines-corrected SPT blow count for clean sand	γ	Soil unit weight
P_L	Liquefaction potential		

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Abbreviation	Description	Abbreviation	Description
AI	Artificial intelligence	K-NN	K-nearest neighbor
CPT	Cone penetration test	LSTM	Long short-term memory
CRR	Cyclic resistance ratio	PGA	Peak ground acceleration
CSR	Cyclic stress ratio	PLHA	Probabilistic liquefaction hazard analysis
FS	Factor of safety	SPT	Standard penetration test
GRU	Gated recurrent unit	SVM	Support vector machine

1. Introduction

The destruction of cities, casualties, and financial losses resulting from earthquakes are often due to settlement caused by liquefaction [1-3]. The liquefaction phenomenon has been observed in many earthquakes such as Niigata 1964, Alaska 1964, Manjil-Rudbar 1990, Kobe 1995, Chi-Chi 1999, Tohoku 2011, Christchurch 2011, Kumamoto 2016, Sulawesi 2018, Jishishan 2023, etc. [4-9]. The most important damaging effects of liquefaction include loss of bearing capacity, generation of buoyant forces, increased pore water pressure, sand boiling, lateral spreading, settlement, and heave [8]. For the first time, Casagrande [10] introduced the phenomenon of sand liquefaction and its effects. The term “spontaneous liquefaction” was used by Terzaghi and Peck [11] to describe the state change of loose sandy deposits and their flow like a viscous fluid due to slight disturbance. Studies show that numerous geotechnical parameters affect the occurrence of liquefaction, such as grain size distribution, initial relative density, drainage conditions, formation duration and dimensions of sand deposit, magnitude and nature of overburden, soil structure, prior deformation history, trapped air bubbles between particles, etc. [12-15]. Liquefaction has been a major cause of failure in soil structures, facilities, vital lifelines, and building foundations during past earthquakes [16-19]. Therefore, a complete understanding of liquefaction is essential for mitigation and improvement of structures and also for identifying liquefaction-susceptible zones.

The liquefaction potential depends on two factors: seismic load (intensity and duration) and the susceptibility of materials to liquefy. Various assessment methods have been proposed, including experimental-empirical and numerical methods. Experimental-empirical methods such as cyclic stress and cyclic strain approaches are popular due to their simplicity, acceptable accuracy, and computational speed [1, 8]. In the 1970s, significant advances in understanding the liquefaction phenomenon were made based on research by Seed and Idriss [20], focusing on defining the cyclic shear stress necessary for liquefaction, known as the cyclic stress method. Because many factors influence cyclic shear stresses, experimental evaluation of liquefaction resistance using cyclic stress alone is difficult. Hence, methods using cyclic strain instead of cyclic stress were suggested to define earthquake loading and liquefaction resistance. Since loading and resistance are determined based on strains instead of stresses, the cyclic strain method cannot provide a factor of safety (FS) against liquefaction. The advantage of the cyclic strain method is that it uses the strong relationship between pore pressure generation and cyclic strain amplitude. For a given soil, excess pore water pressure can be obtained more accurately from cyclic strain than cyclic stress. However, estimating cyclic strain is considerably more difficult than cyclic stress. Thus, cyclic strain has not become as common in seismic geotechnical engineering applications as cyclic stress [8].

Numerical methods have been developed to overcome weaknesses of experimental-empirical methods. New probabilistic methods such as probabilistic liquefaction hazard analysis (PLHA) use Monte Carlo simulations to consider statistical distributions of soil parameters and seismic accelerations, reducing uncertainty in liquefaction modeling. However, selection of an improper statistical distribution or seismic modeling assumptions can still cause error in risk prediction. Systematic reviews of PLHA reveal variability in models, logic tree construction, and seismic scenario selection lead to highly variable liquefaction hazard results. In other words, even among probabilistic models, differences in conceptual foundations, input data, and decision tree structure can limit the accuracy of liquefaction hazard prediction. Additionally, uncertainty in soil parameters and seismic models (particularly earthquake magnitude distribution and recurrence intervals) significantly affects liquefaction hazard maps, alongside numerical complexity and time consumption [7, 16, 21].

Recently, machine learning and deep learning methods have emerged to complement or replace empirical methods but face challenges. Artificial intelligence (AI) models such as support vector machine (SVM), k-nearest neighbor (K-NN), and deep networks such as long short-term memory (LSTM) and gated recurrent units (GRU) show high accuracy in predicting liquefaction sensitivity but depend heavily on the quality and preprocessing of experimental data. Prediction errors may arise due to overfitting or under-representation of uncertainty, particularly with limited training samples or unrepresentative data. Some studies have preferred to use interpretable models for predicting liquefaction because these models can help engineers understand which soil or seismic features play the most significant role in liquefaction hazard. However, this approach is limited by model assumptions and also it is sensitive to input data [16-22].

Evidence from reviews, case studies, and data-based research shows that no single method can perfectly predict liquefaction without error. A multi-method framework considering parameter, model, and input uncertainty is necessary for reliable prediction, improving confidence for engineering design and risk management. In routine engineering projects, the cyclic stress method is used to estimate liquefaction potential and provide safety factors at various depths, but this approach lacks accuracy and is subject to error. Most of the liquefaction assessment methods rely on field tests such as standard penetration test (SPT), cone penetration test (CPT), and Downhole of which uncertainties are now evident. Therefore, relying on one method that depends only on a single field test is not an appropriate approach. Furthermore, in the engineering projects, the evaluation only provides an FS regarding the occurrence or non-occurrence of liquefaction. In fact, two very important aspects-the surface manifestation of liquefaction and the

settlement caused by the liquefied layer-are not addressed in the current practice.

This study proposes a practical and simple approach to assess liquefaction potential in a borehole using various experimental-empirical methods, including those by Iwasaki et al. [23], Andrus and Stokoe [24], Moss et al. [25], and Boulanger and Idriss [26], based respectively on SPT, V_s , CPT, and SPT. These methods were chosen for their common use and acceptance. Besides, Tokimatsu and Seed [27], Ishihara and Yoshimine [28], and Wu [29] methods were utilized to assess seismic-induced settlement. Surface manifestation is evaluated using Iwasaki et al. [30] and Ishihara [31] methods. By comparing results, a simple multi-criteria practical framework is presented for liquefaction potential assessment in typical civil engineering projects.

It should be noted that while the authors have previously compared liquefaction assessment methods based on three field tests in a case study in Babol [1], the present study offers several novel contributions beyond that earlier work. First, the current study incorporates four liquefaction triggering methods instead of three, thereby providing a more comprehensive comparison. Second, unlike the previous study, which focused solely on the factor of safety, the present work systematically evaluates post-liquefaction settlement using three different field-test-based methods [27-29] and surface manifestation using two approaches [30, 31]. Third, and most importantly, this study introduces a practical four-step multi-criteria framework that integrates liquefaction triggering, settlement, and surface manifestation into a unified engineering classification. This framework represents a significant advancement over conventional single-method or single-criterion assessments and provides a structured basis for engineering decision-making in liquefaction-prone areas

2. Methods for evaluating liquefaction potential

Most experimental-empirical methods for assessment of liquefaction potential have been analyzed in Japan and the USA. Each of these methods is based on different assumptions and evaluates the liquefaction potential using various field test data. Below, the methods used in this study are briefly introduced. It is worth mentioning that this research employs methods that, first, are based on different field tests, and second, enjoy high acceptance within the engineering community.

2.1. Iwasaki et al. method

The process of evaluating liquefaction in this method is based on estimating the equivalent cyclic shear stress, which is likely to occur in the soil mass during an earthquake, as well as calculating the liquefaction resistance, and finally comparing them. It is also worth mentioning that this method is based on SPT results. The method proposed by Iwasaki et al. [23] was also adopted by the Japan Highway Bridge Association.

2.2. Andrus and Stokoe method

By measuring the shear-wave velocity (V_s) corresponding to small strains in the field, Andrus and Stokoe [24] introduced a new method for the determination of liquefaction resistance. The use of shear-wave velocity is based on the fact that both shear-wave velocity and the cyclic resistance ratio (CRR) are similarly affected by porosity ratio, effective confining stress, stress history, and geological age of the deposit. This method is applicable in soils that are difficult to sample, where penetration tests are unreliable, and at sites where deep drilling or probing is not feasible.

2.3. Moss et al. method

Moss et al. [25] method is based on detailed CPT results. Some advantages of this method include: collecting very extensive databases of case histories. Utilizing refined knowledge and experience regarding factors affecting CPT, site seismicity (directivity effects, site response, etc.), and cyclic stress ratio (CSR). Organizing case history data according to quality/uncertainty. Using higher-level probabilistic tools.

Moss et al. [25] method has not only significantly reduced uncertainty levels but also helped resolve several debated issues such as fines content correction and effective overburden stress correction. One key difference of this approach compared to others is calculating the stress reduction factor with much larger datasets.

2.4. Boulanger and Idriss method

Boulanger and Idriss [26] reviewed and updated semi-empirical methods for evaluating the liquefaction potential of saturated cohesionless soils during earthquakes for practical use. The updated items include the shear stress reduction factor, magnitude scaling factor, overburden correction factor for cyclic stress ratios, and overburden correction factor for in-situ tests. It is worth noting that this method is based on SPT results.

3. Methods for evaluating post-liquefaction settlement

In this section, the common methods used to evaluate post-liquefaction settlement will be introduced.

3.1. Tokimatsu and Seed method

Laboratory experiments have shown that volumetric strain varies with relative density and maximum shear strain. Tokimatsu and Seed [27] presented a relationship between the SPT number and CSR to estimate post-liquefaction strain for an earthquake with

a magnitude of 7.5 (Fig. 1). For earthquakes of different magnitudes, CSR can be determined by estimating CSR and adjusting it with a magnitude scaling factor.

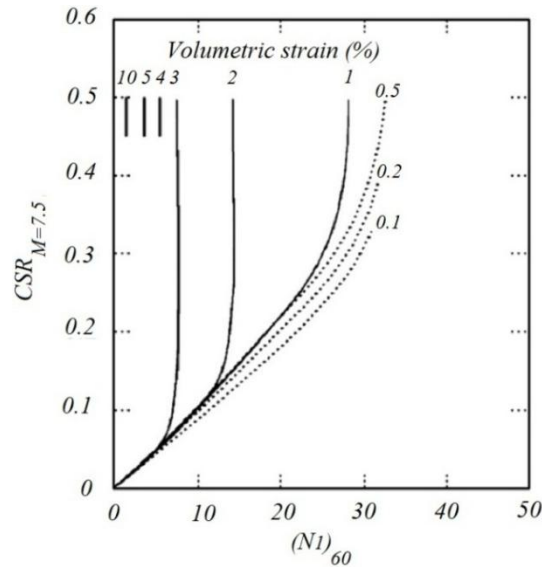


Fig. 1. The volumetric strain estimation based on the studies by Tokimatsu and Seed [27].

3.2. Ishihara and Yoshimine method

Ishihara and Yoshimine [28], continuing the efforts of Tokimatsu and Seed [27] and based on an extensive set of simple shear tests, proposed a method for predicting post-liquefaction settlements. This method expresses the volumetric strain as a function of relative density and also as a function of the FS against liquefaction (instead of CSR). It is worth noting that relative density can be estimated based on either of the two in-situ strength indices, namely the standardized SPT number or the cone tip resistance in CPT (Fig. 2).

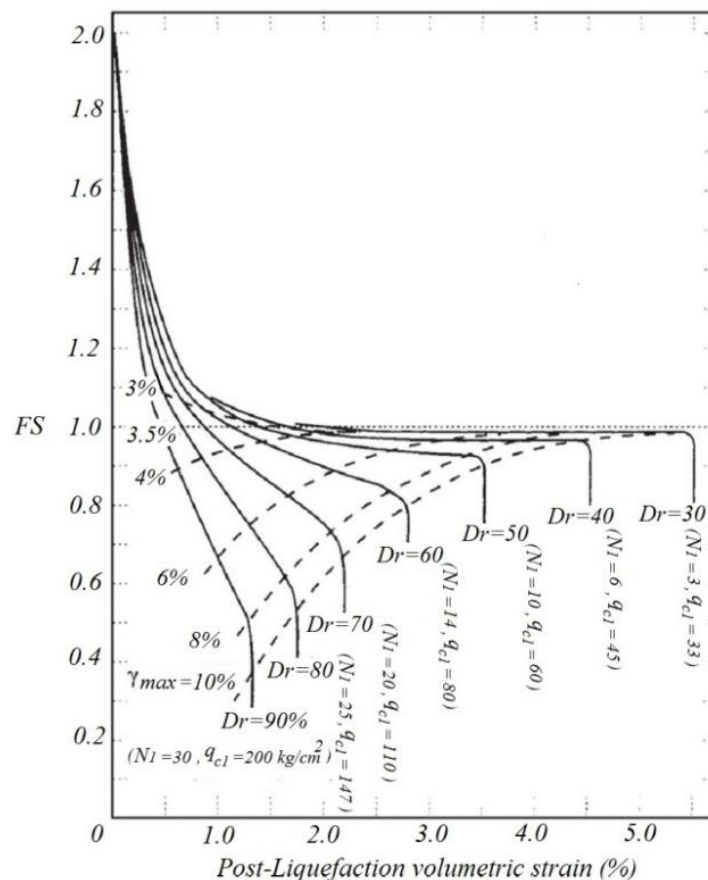


Fig. 2. The volumetric strain estimation based on the studies by Ishihara and Yoshimine [28].

3.3. Wu method

Wu [29] studied a collection of high-quality laboratory test databases and conducted a systematic test program to investigate the impact of relative density and effective stress on the generation of post-liquefaction shear and volumetric strains. He presented some curves, as a function of CSR and the corrected SPT number, to estimate post-liquefaction volumetric strain (Fig. 3).

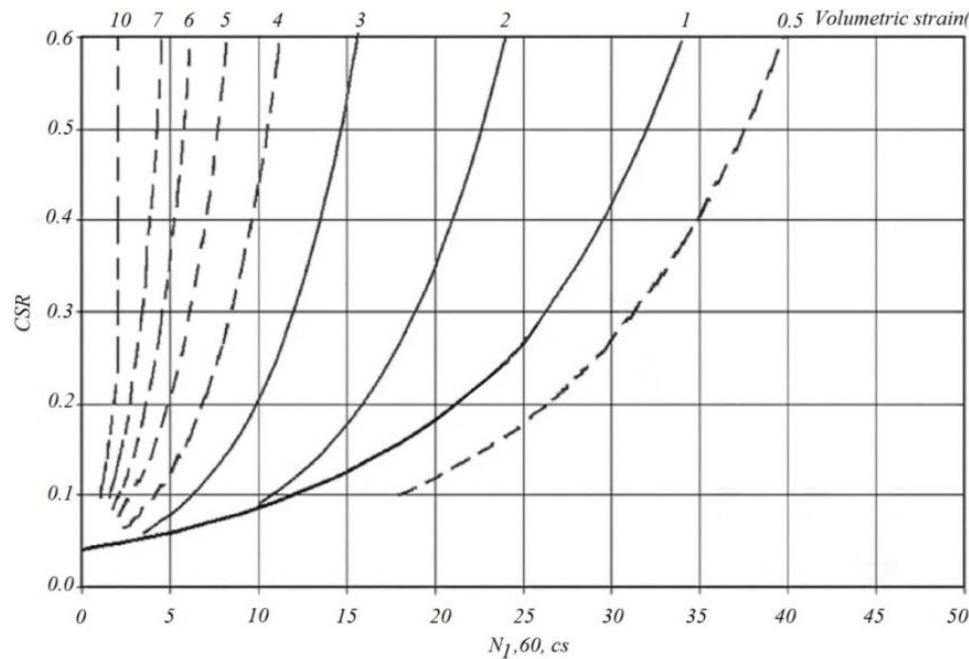


Fig. 3. The volumetric strain estimation based on the studies by Wu [29].

4. Methods for assessing the surface manifestation of liquefaction

The destructive effects of liquefaction on the ground and adjacent structures are of special importance. When the FS against liquefaction is less than one, the target soil layer will liquefy under the design earthquake conditions. However, it is necessary to mention that a low FS value in a soil layer does not necessarily mean the occurrence of overall failure at the ground surface. This is because a horizontal layer may liquefy during an earthquake without causing noticeable changes at the surface. Common analytical methods for determining the surface manifestation of liquefaction are presented as follows.

4.1. Iwasaki et al. method

Iwasaki et al. [30] expressed the severity of liquefaction occurrence at a site by introducing a parameter called the liquefaction potential index (P_L) as shown in Eq. 1:

$$P_L = \int_0^{20} F_L \cdot W(z) \cdot dz$$

(1)

where F_L is obtained based on the FS, as shown in Eq. 2:

$$F_L = \begin{cases} 1 - FS & FS \leq 1 \\ 0 & FS > 1 \end{cases}$$

(2)

$W(z)$ is a function of depth and is found by Eq. 3:

$$W(z) = \begin{cases} 10 - 0.5z & z \leq 20 \\ 0 & z > 20 \end{cases}$$

(3)

where z is the depth of the desired layer (m). Eq. 1 presents P_L values between 0 and 100. Based on this, Iwasaki et al. [30] provided Table 1 to relate P_L with the hazard level of each area.

Table 1. Relationship between PL and hazard level.

Liquefaction hazard and required measures	P_L
Very low-detailed research, studies, and measurements are not required.	$P_L = 0$
Low-detailed investigations are required for important structures.	$0 < P_L \leq 5$
High-detailed investigations and further research are required for structures.	$5 < P_L \leq 15$
Very high-research, detailed investigations, and executive measures are required.	$15 < P_L$

4.2. Ishihara method

Ishihara [31], based on the idea that the occurrence of liquefaction in the underlying soil layers alone does not necessarily cause damage to structures located on or near the ground surface, proposed a method to determine the surface manifestation of liquefaction. According to empirical observations from previous earthquakes, Ishihara [31] suggested that if the ratio of the thickness of the non-liquefied surface layer (H_1) to the thickness of the underlying liquefied layer (H_2) is greater than certain specified values, significant surface manifestation of liquefaction will not occur. This threshold value is a function of the peak ground acceleration (PGA), as seen in Fig. 4.

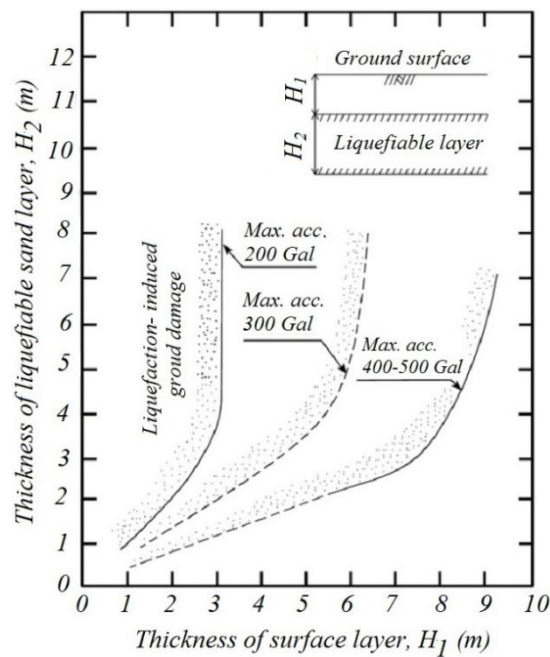


Fig. 4. Proposed boundary curves for determining the surface manifestation of liquefaction based on the studies of Ishihara [31].

5. Site and borehole characteristics

The geotechnical borehole used in this study is located in the southeastern region of Tehran, Iran, and was drilled to a depth of 20 m below the ground surface. Along with drilling the borehole, SPT, CPT, and Downhole tests were also conducted. The profile of the geotechnical borehole is shown in Fig. 5. The geotechnical properties of the layers are presented in Table 2, where γ , FC , D_{50} , D_r , $(N_1)_{60}$, V_s , q_c , and Rf are representative of the soil unit weight, percentage of fine particles, mean particle diameter, relative density, corrected SPT number, shear wave velocity, cone tip resistance, and friction ratio in CPT, respectively.

The geotechnical properties and field-test parameters presented in Table 2 were obtained directly from the in-situ and laboratory geotechnical investigations conducted at the study site. The dataset includes the results of SPT, CPT, and downhole testing, together with the relevant soil properties determined from laboratory testing. These measured and experimentally determined parameters were directly used as input data in the corresponding empirical liquefaction assessment methods.

For the liquefaction assessments presented in this study, a design earthquake scenario with moment magnitude $M_w = 7.5$ and peak ground acceleration $PGA = 0.35$ g was adopted. The magnitude $M_w = 7.5$ is used as the reference earthquake for the Tokimatsu and Seed [27] settlement estimation method, as well as for the magnitude scaling factor adjustments in the triggering methods. The $PGA = 0.35$ g corresponds to the design basis earthquake for the study area according to the Iranian seismic code and is used in the Ishihara [31] surface manifestation assessment. These parameters are consistently applied across all methods presented in Sections 6 through 8.

Depth (m)	Symbol	G.W. Level (m)	Description
1			Fill materials
2			SM
3			
4			
5			
6			Silty sand with gravel
7			ML
8			Silt with sand & gravel
9			SM
10			
11			
12			
13			ML
14			
15			
16			
17			
18			
19			
20			

Fig. 5. Geotechnical borehole.

Table 2. Geotechnical properties and field test results in the borehole.

Depth (m)	γ (kN/m ³)	FC (%)	D_{50} (mm)	D_r (%)	$(N_1)_{60}$	V_s (m/s)	q_c (MPa)	Rf (%)
2	17.2	41	0.13	42	16	193	4.8	1.90
4	17.3	43	0.15	45	17	200	5.6	3.30
6	17.4	48	0.08	50	20	220	7.8	3.60
8	18	51	0.8	50	18	208	6.2	3.00
10	17.6	15	1.5	38	12	180	5.4	2.50
12	18	20	1.4	48	19	202	7.2	2.80
14	17.8	60	0.07	51	20	215	7.9	3.20
16	17.1	90	0.003	53	21	217	7.1	3.30
18	17.4	85	0.003	55	23	223	9.2	3.10
20	18.8	78	0.02	57	24	233	10	3.20

6. Results of liquefaction potential assessment

Using the methods introduced in Section 2, the liquefaction potential in the borehole was evaluated. Fig. 6 illustrates the variations of CSR, CRR, and FS at different depths. It should be noted that the general nature of the Andrus and Stokoe [24] method differs from the other approaches, as previously stated, being based on shear wave velocity measurements. As shown in Fig. 6, within the first 8 m, due to the corrected shear wave velocity being greater than the threshold shear wave velocity, liquefaction will not occur. Since the velocities are smaller than this threshold, the FS cannot be calculated under these conditions, and only “non-occurrence of liquefaction” is reported. In fact, this situation highlights a weakness of the Andrus and Stokoe [24] method, because even when liquefaction is assumed not to occur, it is not possible to provide an FS at these depths. According to the previous investigations [30], even in the absence of liquefaction, if FS against liquefaction is less than 2, strength reduction exists and should be considered—something that cannot be evaluated using the Andrus and Stokoe [24] method.

The values obtained from different methods for calculating CRR are shown in Fig. 6a. The CRR values from Andrus and Stokoe [24] and Moss et al. [25] are smaller than the others. At depths of 8 to 14 m, the results of almost all methods are in good agreement with each other. Iwasaki et al. [23] method, particularly at greater depths, shows a significant difference compared to other methods. The reason for this difference is the presence of fine-grained particles at those depths (Table 2). By examining the CRR in Iwasaki et al. [23] method, the high importance of the percentage of fine particles and the mean particle size becomes evident, which justifies this discrepancy.

Fig. 6b shows the CSR results obtained from different methods of evaluating liquefaction potential. As seen, the methods of Boulanger and Idriss [26] and Andrus and Stokoe [24] display identical results due to similar relationships in determining CSR. Iwasaki et al. [23] method provides larger values for several reasons, such as not using the magnitude scaling factor and differences in the stress reduction coefficient relationships. Considering these points, it should be noted that the Iwasaki et al. [23] method is more conservative than other methods in measuring CSR. However, this conservatism applies only in this part. Considering the high CRR values, FS at some depths is much larger than in other methods. Another important point is that the CSR values obtained from Moss et al. [25] are smaller than those of other methods. The reason is the use of much more extensive field data (2153 case studies) compared to other approaches (a few hundred case studies) in determining the stress reduction coefficient relationship.

Fig. 6c compares the FS obtained from the mentioned methods. As evident, in terms of predicting liquefiable and non-liquefiable layers (regardless of the numerical value of the FS), not even two methods provide exactly the same results. This once again highlights the importance of more detailed and comprehensive evaluation of liquefaction potential and the inadequacy of existing engineering approaches.

The Iwasaki et al. [23] method indicates relatively similar results to other methods at depths of 7 to 13 m, but at other depths its results are generally different. The reason for this is the significant effect of considering the mean grain size in this method, which is ignored in other methods. This has caused the FS values in soils containing fine particles to increase sharply, which runs counter to conservatism. In fact, when the soil profile contains a large amount of fines, using this method is not very safe, as it may overestimate the FS compared to the actual value.

Since the Moss et al. [25] method results in smaller CSR values, it provides larger FS, such that at many depths, the FS is greater than that of other methods. The Boulanger and Idriss [26] method, although its results at many depths are reasonably similar to average values, still shows fundamental differences at some depths in terms of liquefaction occurrence or non-occurrence compared to the average results. At depths of 5 to 13 m, all methods, regardless of the numerical value of the FS, perform equally in predicting liquefiable and non-liquefiable layers. Another important point is that the average results of all methods from depths of 15 to 18 m are influenced by the very high FS values of the Iwasaki et al. [23] method, reporting FS greater than 1, while the results of other methods differ. Therefore, it can be stated that simply averaging the results of the methods and presenting a single number as the FS is not an accurate approach and may lead to misleading conclusions.

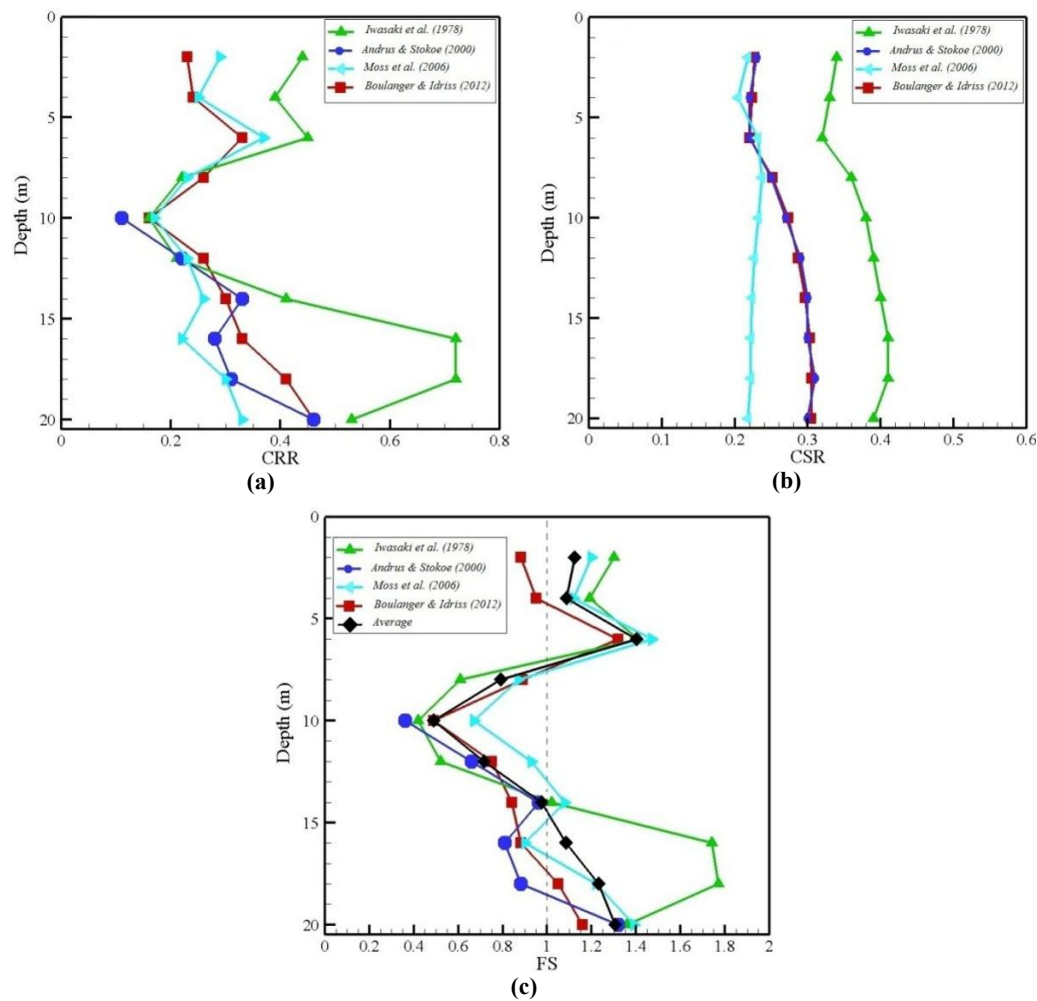


Fig. 6. Liquefaction potential assessment using different methods: (a) CRR; (b) CSR; and (c) FS.

7. Results of post-liquefaction settlement

In this section, the settlement caused by liquefaction (obtained from different methods of FS evaluation) is presented and compared using the three common approaches introduced in the previous sections.

7.1. Tokimatsu and Seed method

In order to estimate the post-liquefaction strain for an earthquake with a magnitude of 7.5, Tokimatsu and Seed [27] proposed a relationship between the SPT number and CSR. Therefore, the results of the methods by Andrus and Stokoe [24] and Moss et al. [25] cannot be evaluated using this approach, since the mentioned methods are respectively based on shear wave velocity and CPT. Fig. 1 has been used in this study to estimate the volumetric strain of the liquefied layer, and the results are presented in Table 3. It can be observed that the settlement values obtained from the two methods are approximately close to each other. However, the amount of settlement in the Iwasaki et al. [23] method is slightly greater than that of Boulanger and Idriss [26].

Table 3. The amount of soil settlement obtained from different methods based on the Tokimatsu and Seed [27] method.

Depth (m)	Layer thickness (m)	$(N_1)_{60}$	Iwasaki et al. [23]			Boulanger and Idriss [26]		
			CSR	Volumetric strain (%)	Settlement (cm)	CSR	Volumetric strain (%)	Settlement (cm)
2	2	16	0.34	1.8	3.6	0.23	1.6	3.2
4	2	17	0.33	1.6	3.2	0.22	1.5	3
6	2	21	0.32	1.3	2.6	0.22	1	2
8	2	18	0.36	1.5	3	0.25	1.5	3
10	2	12	0.38	1.9	3.8	0.27	2.1	4.2
12	2	19	0.39	1.6	3.2	0.29	1.4	2.8
14	2	20	0.40	1.4	2.8	0.30	1.5	3
16	2	21	0.41	1.3	2.6	0.30	1.4	2.8
18	2	23	0.40	1.2	2.4	0.30	1.2	2.4
20	2	24	0.38	1.2	2.4	0.30	1.1	2.2
Total settlement of the soil (cm)					29.6			28.6

7.2. Ishihara and Yoshimine method

In this section, post-liquefaction settlement of the soil layer is calculated using the Ishihara and Yoshimine [28] method. For this purpose, Fig. 2 was used to calculate settlement, and its results are presented in Table 4. Fig. 2 shows the curves estimating volumetric strain as a function of the normalized SPT number (N_1), normalized cone tip resistance (q_{c1}) and the FS against liquefaction (instead of CSR). It is observed that the settlement values from the methods of Moss et al. [25] and Boulanger and Idriss [26] are approximately close to each other. Since these two methods use the results of two different field tests to evaluate liquefaction, the similarity in settlement values calculated from these methods is significant. Furthermore, the Iwasaki et al. [23] method indicates quite different results from other methods and even from its own results calculated by Tokimatsu and Seed [27]. The reason for this is the application of the FS in the Ishihara and Yoshimine [28] method. It is worth mentioning that the Andrus and Stokoe [24] method cannot be evaluated using this approach due to the use of shear wave velocity.

Table 4. The amount of soil settlement obtained from different methods based on the Ishihara and Yoshimine [28] method.

Depth (m)	Layer thickness (m)	$(N_1)_{60}$	q_{c1} (kg/cm ²)	Iwasaki et al. [23]			Boulanger and Idriss [26]			Moss et al. [25]		
				FS	Volumetric strain (%)	Settlement (cm)	FS	Volumetric strain (%)	Settlement (cm)	FS	Volumetric strain (%)	Settlement (cm)
2	2	16	49	1.30	0.6	1.2	0.88	1.5	3	1.20	0.55	1.1
4	2	17	57	1.19	0.6	1.2	0.95	1.3	2.6	1.12	0.65	1.3
6	2	21	80	1.41	0.4	0.8	1.32	0.6	1.2	1.47	0.2	0.4
8	2	18	63	0.61	2.4	4.8	0.89	1.5	3	0.87	3.5	7
10	2	12	55	0.42	3.2	6.4	0.49	3.3	6.6	0.67	3.8	7.6
12	2	19	73	0.52	2.1	4.2	0.75	1.8	3.6	0.93	2.0	4.0
14	2	20	81	1.02	1.3	2.6	0.84	1.5	3	1.08	0.8	1.6
16	2	21	72	1.74	0.3	0.6	0.88	1.4	2.8	0.90	2.9	5.8
18	2	23	94	1.77	0.3	0.6	1.05	0.7	1.4	1.22	0.45	0.9
20	2	24	102	1.36	0.5	1	1.16	0.6	1.2	1.39	0.4	0.8
Total settlement of the soil (cm)						23.4	28.4			30.5		

7.3. Wu method

In this section, the settlement of the soil layer is once again calculated using the Wu [29] method. For this purpose, Fig. 3 has been used to calculate the settlement, and its results are presented in Table 5. As seen, the settlement values resulting from the two methods are approximately close to each other. The settlement value in the Iwasaki et al. [23] method is slightly higher than that in the Boulanger and Idriss [26] method. This result is similar to the Tokimatsu and Seed [27] method and opposite to the Ishihara and Yoshimine [28] method. Another point is that the Wu [29] method calculates settlement based on the modified SPT number for clean sand. Therefore, the Andrus and Stokoe [24] and Moss et al. [25] methods cannot be examined using this approach because these methods are based on shear wave velocity and CPT, respectively.

Table 5. The amount of soil settlement obtained from different methods based on the Wu [29] method.

Depth (m)	Layer thickness (m)	$(N_1)_{60cs}$	Iwasaki et al. [23]			Boulanger and Idriss [26]		
			CSR	Volumetric strain (%)	Settlement (cm)	CSR	Volumetric strain (%)	Settlement (cm)
2	2	21	0.34	2	4	0.23	1.6	3.2
4	2	22	0.33	1.8	3.6	0.22	1.4	2.8
6	2	26	0.32	1.2	2.4	0.22	0.7	1.4
8	2	23	0.36	1.6	3.2	0.25	1.2	2.4
10	2	15	0.38	2.8	5.6	0.27	2.6	5.2
12	2	23	0.39	1.6	3.2	0.29	1.5	3
14	2	25	0.40	1.5	3	0.30	1.2	2.4
16	2	26	0.41	1.4	2.8	0.30	1.1	2.2
18	2	28	0.40	1.1	2.2	0.30	0.8	1.6
20	2	29	0.38	1	2	0.30	0.8	1.6
Total settlement of the soil (cm)						32		
						27.8		

7.4. Comparison of the results of post-liquefaction settlement

To calculate the post-liquefaction settlement in this study, three methods were used: Tokimatsu and Seed [27], Ishihara and

Yoshimine [28], and Wu [29]. Examination of the results from these three methods illustrates that the calculated liquefaction-induced settlements are in reasonably good agreement with each other. As evident, despite the overall consistency, the amount of settlement differs slightly among the methods, and if the data are to be applied to specific engineering structures such as towers, nuclear reactors, etc., further scrutiny of the results is required. For example, the post-liquefaction settlement calculated using the Iwasaki et al. [23] method differs by up to 8.6 cm across various approaches, which is a considerable amount. Likewise, the post-liquefaction settlement calculated using the Iwasaki et al. [23] and Moss et al. [25] methods compared with Ishihara and Yoshimine [28] displays a difference of 7.1 cm, which again is a significant discrepancy.

The differences among the estimated post-liquefaction settlement can be attributed to differences in the input parameters, empirical formulations, calibration datasets, and underlying assumptions of the three methods. In addition, each method has been developed using specific experimental or field conditions and therefore may exhibit different sensitivity to soil density, cyclic stress level, and liquefaction severity. Consequently, the differences observed in the present study should not necessarily be interpreted as an indication that one method is universally superior to the others.

8. Results of surface manifestation

In this section, the surface manifestation is evaluated using the calculated FS obtained through different methods, with the aid of the approaches proposed by Iwasaki et al. [30] and Ishihara [31]. These evaluations are then compared with each other to provide a more comprehensive understanding of ground conditions after the occurrence of liquefaction.

8.1. Iwasaki et al. method

According to Eqs. 1 to 3 and Table 1, using the calculated FS values from each method, the P_L has been computed and presented in Table 6. As observed, the Iwasaki et al. [30] method evaluates surface manifestation qualitatively. However, it has an advantage over the Ishihara [31] method by considering the FS values. Based on the results presented in Table 6, the probability of failure according to the Iwasaki et al. [23] method is higher than that of other methods. The probability of failure using the Moss et al. [25] method is much lower than the other methods, though further detailed investigations are still required. It should be mentioned that since the database used to establish the Moss et al. [25] method was larger than that of the other methods, a higher FS has been reported. It is also worth noting that this method is based on CPT data, which provides continuous subsurface profiling and can offer advantages in identifying spatial variations in soil resistance compared with discrete SPT measurements.

Table 6. Evaluation of surface manifestation obtained from different methods based on the Iwasaki et al. [30] method.

Depth (m)	Iwasaki et al. [23]				Andrus and Stokoe [24]				Moss et al. [25]				Boulanger and Idriss [26]			
	FS	F_L	$W(z)$	$\frac{W(z)}{\times F_L}$	FS	F_L	$W(z)$	$\frac{W(z)}{\times F_L}$	FS	F_L	$W(z)$	$\frac{W(z)}{\times F_L}$	FS	F_L	$W(z)$	$\frac{W(z)}{\times F_L}$
2	1.3	0	9	0	-	-	-	-	1.20	0	9	0	0.88	0.12	9	1.08
4	1.18	0	8	0	-	-	-	-	1.12	0	8	0	0.95	0.05	8	0.4
6	1.41	0	7	0	-	-	-	-	1.47	0	7	0	1.32	0	7	0
8	0.61	0.39	6	2.34	-	-	-	-	0.87	0.13	6	0.78	0.89	0.11	6	0.66
10	0.42	0.58	5	2.9	0.36	0.64	5	3.2	0.67	0.33	5	1.65	0.49	0.51	5	2.55
12	0.52	0.48	4	1.92	0.66	0.34	4	1.36	0.93	0.07	4	0.28	0.75	0.25	4	1
14	1.02	0	3	0	0.96	0.04	3	0.12	1.08	0	3	0	0.84	0.16	3	0.48
16	1.74	0	2	0	0.81	0.19	2	0.38	0.90	0.10	2	0.2	0.88	0.12	2	0.24
18	1.77	0	1	0	0.88	0.12	1	0.12	1.22	0	1	0	1.05	0	1	0
20	1.36	0	0	0	1.32	0	0	0	1.39	0	0	0	1.16	0	0	0
P_L	7.16				5.18				2.91				6.41			
Description	High liquefaction risk (severe ground surface damage)				High liquefaction risk (severe ground surface damage)				Low liquefaction risk (requires detailed investigations)				High liquefaction risk (severe ground surface damage)			

8.2. Ishihara method

Upon examining the results obtained from various methods (Fig. 6c), it is observed that the thickness of liquefiable and non-liquefiable layers differs across all liquefaction assessment methods. The surface manifestation was evaluated according to Ishihara [31] method (Fig. 4), the values from Fig. 6c, and considering the $PGA = 0.35$ g (350 Gal). Table 7 presents the results of this evaluation. According to Ishihara [31], the Andrus and Stokoe [24] method shows no surface manifestation. In contrast, surface manifestation is observed in the Moss et al. [25] method. This issue does not align with the results of Iwasaki et al. [30], further emphasizing the importance of adopting a comprehensive approach to assess liquefaction effects in a region. It should also be noted that the Ishihara [31] method qualitatively examines surface manifestation, making direct comparisons between methods infeasible.

For instance, surface manifestation due to liquefaction is evident in the methods of Iwasaki et al. [23], Moss et al. [25], and Boulanger and Idriss [26], but it remains unclear which method indicates the greatest intensity of this phenomenon.

Table 7. Evaluation of surface manifestation obtained from different methods based on the Ishihara [31] method.

Method	Surface manifestation
Iwasaki et al. [23]	Yes
Andrus and Stokoe [24]	No
Moss et al. [25]	Yes
Boulanger and Idriss [26]	Yes

8.3. Comparison of surface manifestation results

In determining the extent of surface manifestation due to liquefaction, the methods of Iwasaki et al. [30] and Ishihara [31] were employed. As stated, Iwasaki et al. [30] method, similar to that of Ishihara [31] method, qualitatively evaluates surface manifestation; however, considering the inclusion of FS values, it has an advantage over Ishihara [31] method. Based on the approach proposed by Iwasaki et al. [30], surface manifestation resulting from liquefaction is observed in all methods except that of Moss et al. [25]. According to Ishihara [31] method, surface manifestation exists in all methods except Andrus and Stokoe [24]. This situation highlights the importance of employing multiple methods simultaneously to assess such a critical issue. According to the results of Iwasaki et al. [30], the damage estimated by Iwasaki et al. [23] is greater than that of other methods (larger P_L). However, Andrus and Stokoe [24], among the methods that assess the surface manifestation, has the least damage (smaller P_L), which is consistent with Ishihara [31] method.

9. Providing a strategy for evaluating liquefaction potential

Based on the results obtained from multiple evaluations conducted in this study, and the considerable discrepancies observed among different methods in determining liquefaction potential, post-liquefaction settlement, and surface manifestations, it is evident that the reliance on a single criterion or a single field test cannot provide an accurate assessment of soil behavior under seismic excitation. The findings indicate that methods based on SPT, CPT, and V_s each predict only a portion of soil behavior, and none alone is capable of presenting a comprehensive picture of the soil response. Furthermore, the mechanism of liquefaction is not a one-dimensional phenomenon, and merely the FS does not allow for reliable judgment regarding the severity of damage, post-liquefaction settlement, or the likelihood of failure propagation to the ground surface. Accordingly, in this section, a multi-stage framework is proposed with the aim of reducing the risk of relying on a single empirical procedure and providing a more comprehensive basis for engineering decision-making. This framework simultaneously considers the three principal components of liquefaction (potential occurrence, settlement, and surface manifestation) and utilizes the results of several different methods for final decision-making. Therefore, the framework consists of four essential stages as follows:

1. Assessment of liquefaction potential based on a multi-criteria approach
2. Calculation of post-liquefaction settlement
3. Evaluation of surface manifestation
4. Integration of results and final hazard classification

The novelty of the proposed framework does not lie in developing a new empirical equation for liquefaction triggering or post-liquefaction deformation. Rather, its main contribution is the systematic integration of three complementary aspects of liquefaction hazard, including triggering potential, post-liquefaction settlement, and surface manifestation, within a sequential engineering decision-making procedure. By combining different SPT-, CPT-, and V_s -based assessments with deformation and surface manifestation criteria, the framework provides an integrated interpretation of liquefaction consequences rather than relying solely on a single factor of safety.

9.1. Assessment of liquefaction potential based on a multi-criteria approach

Given the analyses performed, the necessity of using several different methods is felt. The analyses of this study showed that differences between methods arise from variations in the type of field test (SPT, CPT, and V_s), differences in theoretical assumptions in calculating CSR and CRR, differing sensitivities of methods to fines content, relative density, and stress history, the empirical nature of many relationships, and limitations of primary databases. Therefore, it is recommended that the initial assessment of liquefaction potential be performed using three different field-test-based methods (SPT, CPT, and V_s). Although these methods are not fully independent, as they are all influenced by common soil parameters such as density and effective stress, their combination can help reduce the influence of method-specific biases and uncertainties. This overlap of information compensates for weaknesses or errors of any one method by the other two.

It is also possible to use a separate decision-making system for each soil layer. For each depth layer, decisions can be made as follows: If two methods report $FS < 1$, the layer is considered liquefiable. The 'two out of three' criterion is adopted as a practical screening rule rather than a probabilistic threshold. It provides a compromise between the conservative interpretation of a single method (which may produce a false positive due to method-specific biases) and the potentially misleading requirement that all

methods must simultaneously indicate liquefaction (which may produce a false negative due to differing method sensitivities). This approach is analogous to the concept of 'consensus-based' decision-making in multi-model ensemble analyses, where the majority vote is considered more reliable than any single model output. If only one method reports $FS < 1$, the layer is considered suspect and requires further analysis. Finally, if all methods report $FS > 1$, the layer is stable. This approach is similar to multi-model probabilistic decision-making methods in seismic analyses and reduces uncertainty.

9.2. Calculation of post-liquefaction settlement

The research results indicate that the FS alone is insufficient for hazard assessment, as two layers may both have FS values near 1, yet exhibit vastly different settlement; one layer might liquefy but cause negligible settlement due to adequate density, while certain structures (e.g., pipelines, sensitive foundations, tanks) are more sensitive to settlement than to liquefaction itself.

To calculate settlement, some methods are applied based on diverse parameters such as cyclic stress, SPT number, FS, relative density, or large-scale laboratory data. The arithmetic mean of the settlement estimates obtained from the three methods is used as a practical engineering indicator of probable settlement (S), rather than as a statistically rigorous estimate of the true settlement. Since the three empirical methods are based on different assumptions, input parameters, and calibration datasets, their estimates cannot necessarily be considered statistically independent. The averaged value is therefore intended to provide a practical basis for the subsequent screening and classification within the proposed framework. Based on the settlement criteria and guidance provided in reputable foundation design codes and standards, including Eurocode 7 [32], BS 8004:2015+A1 [33], JGS 4001-2004 [34], and National Building Regulations of Iran, Topic 7 [35], settlement thresholds of 2 cm and 5 cm are adopted in this study as practical screening limits, leading to the following decision rule:

If $S < 2$ cm, liquefaction effects are negligible but should be added to total structural settlement and considered. If $2 \text{ cm} < S < 5$ cm, further review and numerical analyses for specific structures are required. If $S > 5$ cm, settlement is significant, necessitating soil improvement. Moreover, when the settlement estimates differ by more than 30%, the discrepancy should be regarded as an indication of increased uncertainty. The 30% discrepancy threshold is adopted based on common engineering practice and is intended to flag cases where the settlement estimates from different methods are sufficiently divergent to warrant additional scrutiny. In such cases, the CPT-based estimate or the estimate associated with the lower factor of safety may be given greater consideration, provided that the quality and applicability of the corresponding field data and empirical correlation are confirmed. These values are adopted as practical screening thresholds for the present framework and should not be interpreted as universal settlement limits for all types of structures. The acceptable level of liquefaction-induced settlement depends on structural characteristics, foundation type, serviceability requirements, and site-specific conditions. Therefore, the proposed limits are intended to identify cases requiring further engineering evaluation rather than to replace structure-specific settlement criteria.

It is worth noting that the approach used for settlement estimation (arithmetic averaging of three different estimates) differs from the approach used for FS evaluation (majority-rule decision-making). This distinction is intentional and reflects the different nature of the two assessments. For FS, the outcome is binary (liquefaction vs. non-liquefaction), and a single method with an FS slightly below 1 may be subject to method-specific biases; therefore, the majority-rule approach (two out of three) is more conservative and robust. For settlement, however, the outcome is a continuous variable (displacement in centimeters) and averaging multiple different estimates has been shown to reduce the influence of method-specific overestimation or underestimation, providing a more balanced engineering estimate.

9.3. Evaluation of surface manifestation of liquefaction

Even if $FS < 1$, liquefaction may occur at depth without producing any surface effects. The opposite may also happen, meaning FS slightly greater than 1, but due to the thinness of the surface layer, the ground may experience sand boiling and lateral spreading. Therefore, this stage complements the previous two stages and is critical for the safety of surface structures. Using reliable methods such as those presented in this study, surface manifestation should be evaluated, and decisions should be made according to the following rule:

1. If both methods indicate surface manifestation, a high likelihood of surface manifestation is inferred.
2. If only one method reports surface manifestation, the layer is suspicious and numerical analysis (FLAC, PLAXIS) or supplementary testing must be performed.
3. If both methods indicate no surface manifestation, surface manifestation is considered unlikely based on the adopted criteria, although site-specific uncertainties should still be considered.

9.4. Integration of results and final hazard classification

For the final decision, three main indicators should be integrated. In fact, the potential for liquefaction (FS), the severity of settlement (S), and the probability of surface manifestation (P_L and H_1/H_2) should be taken into account. Based on this, four levels of risk are defined, which are presented in Table 8. For the final classification, each of the three indicators is first evaluated independently: liquefaction triggering potential based on FS, liquefaction-induced settlement, and surface manifestation. The final hazard group is then governed by the most critical classification among these indicators. This conservative approach ensures that a potentially severe consequence is not masked by less critical values of the other indicators. The FS thresholds presented in Table 8 (0.8, 1.0, and 1.5) are adopted based on common engineering practice and recommendations in the literature. A threshold of FS =

1.0 represents the conventional boundary between liquefaction and non-liquefaction in deterministic analyses [20, 23, 26]. The upper threshold of $FS = 1.5$ is consistent with the recommendation by several codes and guidelines that require $FS \geq 1.2$ -1.5 for critical structures [4, 32-35]. The lower threshold of $FS = 0.8$ is adopted to identify layers where liquefaction is highly probable (i.e., seismic demand exceeds resistance by more than 25%) [4]. It should be emphasized that these thresholds are intended as practical screening criteria based on engineering judgment and current practice, and they may require adjustment for specific projects or regulatory requirements.

Table 8. Final classification of liquefaction hazard.

Criteria used for final liquefaction hazard classification	Group number			
	1	2	3	4
FS with multi-criteria approach	<1.5	1-1.5	0.8-1	0.8<
Settlement with multi-criteria approach (cm)	2<	2-5	5-10	<10
P_L	0	0-5	5-15	<15
Ratio of (H_1/H_2)	High	Medium	Low	Negligible
Risk level	Low	Medium	High	very high
Necessary actions	No specific action	Detailed investigation	Ground improvement	Definitive improvement/ design Rejection

The proposed approach provides several practical advantages, including the simultaneous consideration of SPT, CPT, and V_s information; integrated assessment of liquefaction triggering, post-liquefaction settlement and surface manifestation; and applicability to conventional engineering screening without requiring complex numerical analyses. The framework may also provide a basis for future extensions using probabilistic or data-driven approaches. Further validation using multiple case histories and geological settings is required before its use as a generalized assessment procedure or guideline framework.

9.5. Limitations and future applications

Despite the practical advantages of the proposed framework, several limitations should be acknowledged. First, the framework was demonstrated using a geotechnical borehole and therefore does not constitute a comprehensive validation under different geological and seismic conditions. Second, the input field measurements themselves are subject to inherent uncertainties. SPT blow counts can vary due to operator effects, energy transfer efficiency, and soil disturbance; CPT tip resistance and friction ratio are influenced by penetrometer type, rate of penetration, and soil fabric interpretation; and shear-wave velocity measurements obtained from downhole testing are affected by source-receiver coupling, signal processing, and layering assumptions. Third, the proposed settlement thresholds and decision rules are intended as practical screening criteria and should not replace structure-specific geotechnical and seismic analyses. Finally, liquefaction-related consequences such as lateral spreading, bearing capacity loss, and structure-specific differential settlement are not explicitly incorporated into the present framework.

10. Conclusions

The evaluation of liquefaction potential is considered as one of the most challenging aspects of geotechnical earthquake studies. The findings of this research indicate that the reliance on a single method of liquefaction potential assessment based on SPT, CPT, or V_s cannot provide a realistic and comprehensive picture of soil behavior during earthquakes. Significant discrepancies among methods in calculating CSR, CRR, and FS indicate that soil response under seismic loading is highly multifactorial and dependent on the specific characteristics of each layer, and single-criterion approaches cannot adequately meet engineering design requirements. Moreover, post-liquefaction settlement and surface manifestation are critical factors that unfortunately do not have a prominent role in current evaluation practices. In fact, situations may occur where the FS is greater than one, yet the structure experiences considerable settlement problems.

Data analysis further revealed that some methods behave conservatively at certain depths and non-conservatively at others, showing varying sensitivity to fines content, relative density, stress history, and analytical parameters. This highlights the potential value of adopting an integrated, multi-criteria framework as a practical basis for liquefaction assessment. The main findings of this study can be summarized as follows:

1. Performance differences among methods in determining liquefaction potential are striking. Methods based on SPT, CPT, and V_s did not provide consistent results, and discrepancies in FS were repeatedly observed. None of the methods even produced similar patterns in identifying liquefiable layers. This indicates that simple averaging of FS values obtained from different methods, without considering other geotechnical conditions, can be misleading.
2. Although the three methods of Tokimatsu and Seed [27], Ishihara and Yoshimine [28], and Wu [29] provided generally consistent and acceptable results in estimating post-liquefaction settlement, in some cases differences of up to 8 cm were observed. Such discrepancies are critical and unacceptable for sensitive structures. Moreover, the shear wave velocity-based method cannot be directly applied in this part, revealing another weakness of this method.
3. Differences in evaluating surface manifestation of liquefaction were observed. The Iwasaki et al. [30] method indicated high surface manifestation for most cases, except for the Moss et al. [25] method. Ishihara [31] confirmed that the Andrus and Stokoe [24] method showed no surface manifestation, while other methods considered it likely. This significant

discrepancy again demonstrated that surface manifestation cannot be determined by a single method. It is also important to employ an approach that provides not only qualitative but also quantitative estimates of surface manifestation due to liquefaction.

4. The findings demonstrate that liquefaction should be assessed simultaneously from three perspectives: triggering potential, settlement, and surface manifestation. The proposed four-step multi-criteria framework, integrating data from three field tests, three settlement estimation methods, and two surface manifestation evaluation methods, provides a more comprehensive engineering-oriented screening assessment than any single method alone.
5. The proposed framework demonstrates potential as a practical screening tool for liquefaction assessment in similar geotechnical conditions. It is expandable and can be used without the need for complex numerical analyses in preliminary engineering studies. However, it should be emphasized that the framework has been developed and demonstrated using a single borehole. Further validation using independent case histories, multiple boreholes, and sites with different geological and seismic characteristics is essential before the framework can be generalized as a standard assessment procedure. The approach represents a preliminary step toward reducing uncertainty in liquefaction evaluation, but its applicability to other regions and conditions requires additional verification.

Statements & declarations

Author contributions

Sadegh Rezaei: Conceptualization, Methodology, Validation, Formal analysis, Writing - Original Draft, Supervision.

Ali Hasanzadeh: Conceptualization, Methodology, Formal analysis, Writing - Review & Editing.

Majid Moradi: Methodology, Validation, Formal analysis, Writing - Review & Editing.

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Data availability

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to data ownership and usage restrictions.

Declarations

The authors declare no conflict of interest.

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