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SOIL SETTLEMENT RISK FROM LIQUEFACTION AT LAKE TOBA TOURISM INFRASTRUCTURE, NORTH SUMATERA, INDONESIA

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ABSTRACT: Lake Toba has emerged as a captivating tourist destination in Indonesia, and the government is currently dedicated to enhancing the tourism experience through extensive infrastructure development initiatives. As progress continues, the hazard map for the region notably emphasizes its susceptibility to liquefaction. Therefore, this study aims to evaluate risk of soil settlement arising from potential liquefaction within the Tourism infrastructure of Lake Toba. According to the data collected, it was evident that the prevailing soil layer was dominated by sand and shallow groundwater, rendering it prone to earthquakes, increasing liquefaction potential. Soil settlement was also found in Lake Toba, which further magnified the possibility of liquefaction incidents. The analysis of liquefaction potential was carried out following the empirical method by Idriss-Boulanger (2014) in determining Liquefaction Potential Index (LPI) values. Furthermore, the assessment focused on soil settlement that was observed during instances of liquefaction, by employing methods outlined in Tokimatsu and Seed (1984), Ishihara and Yoshimine (1992), and Cetin (2009). The results showed that the areas exhibited a high liquefaction potential, as evidenced by significantly elevated LPI values. This study centered on settlement reaching up to 1.5 meters during liquefaction events, underscoring the imperative need to implement targeted measures for effective mitigation of this potential hazard.

Keywords: Lake Toba, Liquefaction, Liquefaction Potential Index, Settlement, Tourism Infrastructure

1. INTRODUCTION

The relevance of Lake Toba is steadily growing as a top-tier tourist hotspot, drawing in visitors with its captivating attractions. Recognizing the potential for further tourism growth, the government is actively engaging in infrastructure development focused on pulling an increased number of tourists. The tragic incident as reported by Palu (2018) and characterized as liquefaction disaster causing structural damage and loss of life, serves as a poignant reminder of the serious consequences such events can bring about. Therefore, an assessment of infrastructure resilience against liquefaction is imperative, not only as a means of fostering growth but also as a fundamental step towards enhancing safety and safeguarding against future catastrophes. At the study site, apart from risk of liquefaction, there is also a possibility of the soil settlement. Existing market structures in proximity to Lake Toba have already borne witness to soil settlement, a phenomenon that raises concerns. These recently constructed new buildings have already begun to experience unsettling soil settlement. This serves as a poignant example of how liquefaction and the resulting soil settlement are interconnected, causing a ripple effect [1,2].

Several analyses are being carried out in relevant areas, encompassing both liquefaction [3-6] and soil settlement as well as their potential consequences [7]. However, a specific study of the geotechnical phenomena at Lake Toba has not been conducted.

This include factors that can induce liquefaction, namely soil layer characteristics [8], groundwater dynamics [9], seismic influences [10], fine particles distribution [11], and the degree of ground saturation [12]. The parameters drawn from the established hazard maps [13] suggest that the location occupies a zone of moderate susceptibility within a region prone to potential liquefaction. The results from soil investigation align with these indications, confirming the presence of liquefaction potential.

This study will be conducted through the use of the semi-empirical method proposed by Idriss-Boulanger [14]. Additionally, Liquefaction Potential Index (LPI) classification [15,16] will provide a comprehensive evaluation of liquefaction hazard. To delve deeper into these potential ramifications, Liquefaction Severity Index (LSI) analysis [17] will be performed, to determine the level of damage to occur in the event of liquefaction.

Following the evaluation of liquefaction potential, an assessment of the potential soil settlement that can arise during liquefaction event is performed through three methods, namely Tokimatsu and Seed (1984), Ishihara and Yoshimine (1992), and Cetin methods (2009).

2. RESEARCH SIGNIFICANCE

The analysis concerning soil settlement, attributed to liquefaction within the tourism infrastructure of Lake Toba holds significant importance in the assessment and mitigation of potential risk. This study centers on analyzing geotechnical characteristics and susceptibility to pinpoint high-risk zones and propose sustainable engineering remedies. By comprehending the elements that lead to soil settlement induced by liquefaction, this study contributes valuable insights for informed infrastructure planning and development. Ultimately, the results will enhance the safety and resilience of the tourism sector, thereby guaranteeing a sustainable and secure environment for both residents and tourists.

3. DATA COLLECTION

In conducting this evaluation, various data were required to substantiate the assessments, including field observation, soil investigation, and seismic conditions. The field observation indicated the presence of structures exhibiting conspicuous settlement within the surveyed area, as shown in Fig. 1. Considering this building was actively used for trading purposes, this scenario presented a potential danger.

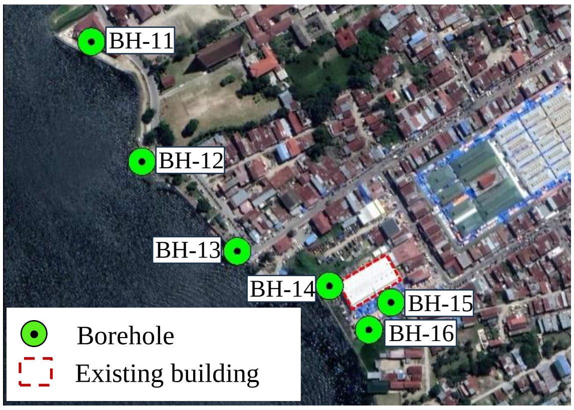

Fig.1 The study area and the borehole locations, modified from [18]

Soil investigations were conducted at the surveyed location, covering BH-11, 12, 13, 14, and 16. BH-15 was excluded due to its location within an embankment, resulting in distinct soil characteristics compared to the other boreholes.

The Standard Penetration Test (SPT) data retrieved from soil investigation were shown in Table 1. The data indicated that the SPT values remained below 10 up to a depth of 20 meters, indicating a low bearing capacity of the existing soil layers. This condition significantly escalated liquefaction risk [20], with relevant data for site class, groundwater level (GWL), and fine content (FC) parameters, as presented in Table 2.

The outcomes of soil investigation showed the presence of remarkably shallow groundwater. Additionally, it was evident that the site class was predominately classified as E, except for BH-13, falling under site class C. Site class E denoted a seismic design term for locations with deep, soft, or loose soil deposits, while category C referred to softer, more fractured, and weathered rock. These results from soil investigation collectively underscored the presence of liquefaction potential based on the triggering factors [10-14].

Table 1 SPT value

Depth (m)	SPT				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	2	2	41	-	2
-4	2	2	7	2	2
-6	2	2	8	2	2
-8	3	3	12	3	2
-10	5	4	15	4	3
-12	9	10	17	8	4
-14	10	17	16	2	7
-16	19	16	12	2	11
-18	21	22	10	5	21
-20	30	24	10	10	24
-22	35	38	20	18	33
-24	45	41	47	22	31
-26	60	-	60	26	39
-28	60	-	60	45	46

Table 2 Soil investigation data

Data	BH-11	BH-12	BH-13	BH-14	BH-16
GWL (m)	-3.0	-3.0	-2.0	-0.3	-1.0
Site Class	E	E	C	E	E
Fine Content (%)	8.54	6.75	7.49	13.46	6.49
Depth (m)	7.5	9.5	7.5	7.5	9.5

The seismic data necessary for analysis included the Peak Ground Acceleration (PGA) and earthquake information. The PGA value, extracted from the Ministry of Public Works and the website of Public Housing (http://rsa.ciptakarya.pu.go.id/2021/), was determined to be 0.5208 g at the site. For earthquake data, information was obtained from the United States Geological Survey website (https://earthquake.usgs.gov/), with the value being derived from the largest and closest seismic event to the location within the preceding 30 years. The seismic value used was 5.5 Mw, corresponding to an earthquake that occurred on 9 September 2005.

4. METHODS

The employed methods for assessing liquefaction potential and soil settlement were outlined as follows

4.1 Evaluation of Liquefaction Potential

4.1.1 Determining the Safety Factor (SF) against liquefaction

The analysis of liquefaction potential relied on the method proposed by Idriss-Boulanger, 2014 [14], which involved determining the safety factor through the comparison of Cyclic Stress Ratio (CSR) and Cyclic Resistance Ratio (CRR) values. A ratio below 1 signified the presence of liquefaction potential. Calculations for the CSR value were performed using Eq. (1-4).

$$rd = \exp\left[\alpha(z) + \beta(z)M\right] \quad (1)$$

$$\alpha(z) = -1.012 - 1.126\, sin\left(\frac{z}{11.73} + 5.133\right) \quad (2)$$

$$\beta(z) = 0.106 + 0.118\, sin\left(\frac{z}{11.28} + 5.142\right) \quad (3)$$

$$CSR = 0.65\ \frac{a_{max}}{g}\ \frac{\sigma}{\sigma'}\ rd \quad (4)$$

The calculation of CRR involved several steps, including the correction of the SPT value, determination of the Magnitude Scaling Factor (MSF), and computation of *Kσ*. CRR was computed using Eq. (5-15).

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \quad (5)$$

$$\Delta(N_1)_{60} = exp\left(1.63 + \frac{9.7}{FC+0.01} - \left(\frac{15.7}{FC+0.01}\right)^2\right) \quad (6)$$

$$(N_1)_{60} = (N)_{60}.C_N \quad (7)$$

$$C_N = \left(\frac{P_a}{\sigma'_{vc}}\right)^{0.784-0.0768\sqrt{(N_1)_{60cs}}} \leq 1.7 \quad (8)$$

$$(N)_{60} = N_m C_E C_B C_R C_S \quad (9)$$

$$CRR_{M=7.5;\sigma'vc=1} = exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right) \quad (10)$$

$$MSF = 1 + (MSF_{max})\left(8.64\, exp\left(\frac{-M}{4}\right) - 1.325\right) \quad (11)$$

$$MSF_{max} = 1.09 + \left(\frac{(N_1)_{60cs}}{31.5}\right) \leq 2.2 \quad (12)$$

$$K_\sigma = 1 - C_\sigma ln\left(\frac{\sigma'_{vc}}{P_a}\right) \leq 1.1 \quad (13)$$

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60cs}}} \leq 0.3 \quad (14)$$

$$CRR = CRR_{M=7.5;\sigma'vc=1}\ .\ MSF\ .\ K_\sigma \quad (15)$$

The safety factor for liquefaction potential was calculated using Eq. (16).

$$SF = \frac{CRR_{M=7.5;\sigma'vc=1}}{CSR} \quad (16)$$

4.1.2 Determining LPI

The LPI was computed by summing the weighted factors for each soil layer using Eq. (17).

$$LPI = \sum_{i=1}^{n} w_i F_L H_i \quad (17)$$

The LPI values were classified into distinct groups to assess the susceptibility to liquefaction [15,16].

4.1.3 Determining LSI

The LSI was determined by evaluating the integral of the product of *PL(z)* and *w(z)* within the range of 0 to 20 meters, employing the equation devised by Sonmez [17]. The calculation of LSI was performed using Eq. (18-19).

$$LSI = \int_0^{20} P_L(z) w(z) dz \quad (18)$$

$$P_L(z) = \frac{1}{1+\left(\frac{SF}{0.96}\right)^{4.5}} \text{ for } SF \leq 1.411 \quad (19)$$

$$P_L(z) = 0 \text{ for } SF > 1.411$$

The computed LSI values were categorized using the Sonmez framework to determine susceptibility levels to liquefaction, as proposed by Sonmez and Gokceoglu [17].

4.2 Analysis of Soil Settlement Potential Due to Liquefaction

The analysis of soil settlement potential resulting from liquefaction employed the Tokimatsu and Seed (1984), the Ishihara and Yoshimine (1992), and Cetin (2009) methods.

4.2.1 Tokimatsu and Seed Method (1984)

The process to compute the analysis of soil settlement potential resulting from liquefaction involved several steps [19]. Initially, the CSR was computed using Eq. (4), followed by the establishment of ϵv through the correlation between the *(N1)60* and CSR concerning Fig 2. Soil settlement value was derived using Eq. (20).

$$\Delta H = \sum_{i=1}^{n} H_1 \epsilon_{v1} \quad (20)$$

4.2.2 Method by Ishihara and Yoshimine (1992)

The procedure for calculating the analysis of soil settlement potential resulting from liquefaction [20], involved calculating the N_1 value and obtaining $(N_1)_{60}$ with Eq. (19) and (7) respectively. Subsequently, the volumetric strains were calculated by establishing the correlation between *SF* and N_1 values, regarding the graph in Fig. 3. Soil settlement was calculated finally using Eq. (19) and the volumetric strain value.

$$N_1 = 0.833(N_1)_{60} \quad (21)$$

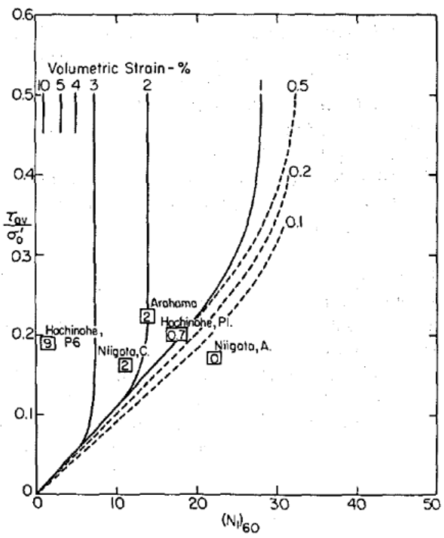

Fig.2 Relationship between Cyclic Stress Ratio, Volumetric Strain, and $(N_1)_{60}$ [19]

4.2.2 Method by Cetin (2009)

The procedure of calculating the analysis of soil settlement potential attributed to liquefaction [25] involved using Eq. (22-27) for calculation. Eq. (20) was subsequently used to compute settlement resulting from liquefaction after gaining the volumetric strains.

$$D_r = \sqrt{\frac{(N_1)_{60}}{46}} \quad (22)$$

$$K_{mc} = -3\ x\ 10^{-5}. D_r^2 + 0.0048 D_r + 0.7222 \quad (23)$$

$$CSR_{ss,20,1,D,1} = CSR \,.\, K_\sigma \,.\, K_{mc} \quad (24)$$

$$DF_i = 1 - \frac{d_i}{z_{cr}=18\ m} \quad (25)$$

$$\epsilon_{v0} = 1.879 \times \ln\left(\frac{780.416 \ln(CSR_{ss,20,1,D,1}) - (N_1)_{60cs} + 2442.465}{636.613 (N_1)_{60cs} + 306.732} + 5.583\right) \quad (26)$$

$$\epsilon_v = DF. \epsilon_{v0} \quad (27)$$

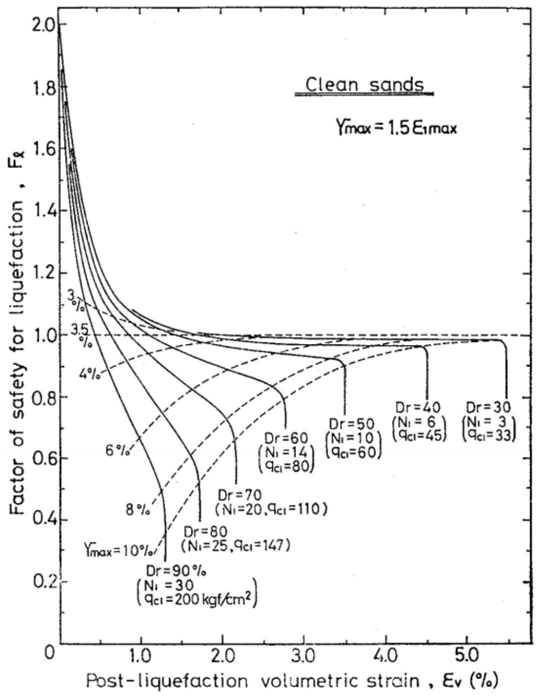

Fig.3 Relationship between *N1, Dr, SF* and volumetric strains [20]

5. RESULT AND DISCUSSION

Based on the results of soil investigation, it was observed that the groundwater table ranged from 0.3 to 3 meters below the ground surface. Fig. 4 showed soil stratigraphy based on the obtained soil investigation data. The dominant levels across all boreholes consisted of loose, medium, and dense sand layers. The loose sand with depths ranging from 15 to 20 meters, was underlain by the medium, which was followed by the dense layer. Rock formations were also present at the base of the existing structures. According to Ishihara [8], liquefaction occurred in fine to medium sand levels, and based on the observed stratigraphy, the location was indeed susceptible to liquefaction potential.

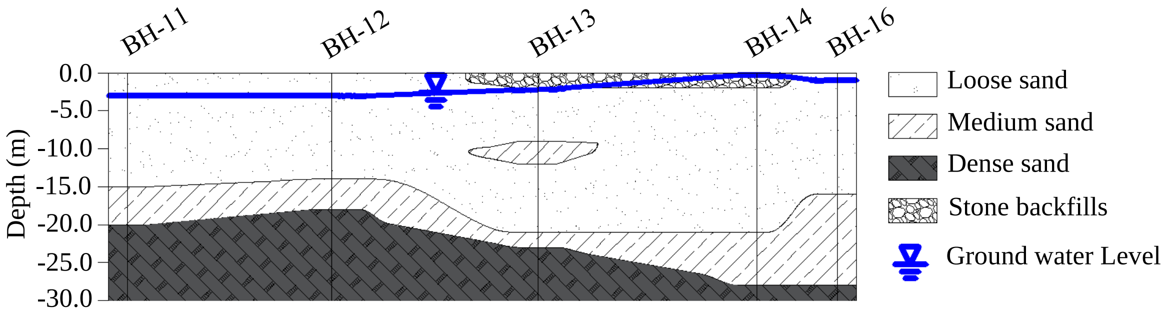

Fig.4 Site investigation stratigraphy and groundwater level

Based on the gathered data, an analysis of liquefaction potential was carried out employing the method introduced by Idriss-Boulanger (2014). In Table 3, the blue-colored columns indicated a safety factor below 1, signifying the presence of liquefaction potential within those layers. The data also showed that all boreholes in Lake Toba exhibited susceptibility to liquefaction. The depth of these potentially liquefiable layers extended up to 24 meters below the ground surface.

Table 3 Summary of liquefaction Safety Factors

Depth (m)	SF				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	-	-	-	-	0.341
-4	0.312	0.306	0.471	0.369	0.309
-6	0.310	0.303	0.458	0.365	0.305
-8	0.341	0.328	0.542	0.386	0.311
-10	0.387	0.356	0.606	0.419	0.340
-12	0.476	0.480	0.653	0.515	0.359
-14	0.510	0.648	0.633	0.426	0.426
-16	0.730	0.637	0.559	0.454	0.517
-18	0.798	0.802	0.540	0.531	0.757
-20	1.086	0.873	0.563	0.653	0.853
-22	1.292	1.401	0.800	0.859	1.147
-24	1.963	1.559	2.175	0.986	1.088
-26	8.998	-	8.519	1.116	1.393
-28	7.015	-	6.677	2.150	1.775

In BH-11 to BH-14, liquefaction potential was absent within the layer situated 2 meters below the ground surface. This was attributed to BH-11 and BH-12 having a groundwater level depth of 3 meters, effectively eliminating liquefaction-triggering factor. Similarly, in BH-13 and BH-14, the uppermost layer exhibited no liquefaction potential. This was observed in Fig. 4, where this layer was depicted as a stone backfill, making it resistant to risk of liquefaction.

Observing Fig. 5, it became evident that all layers exhibited liquefaction potential, with the red line denoting the boundary between the liquefiable and non-liquefiable layers. The layers resilient to liquefaction were located at depths exceeding 20 meters.

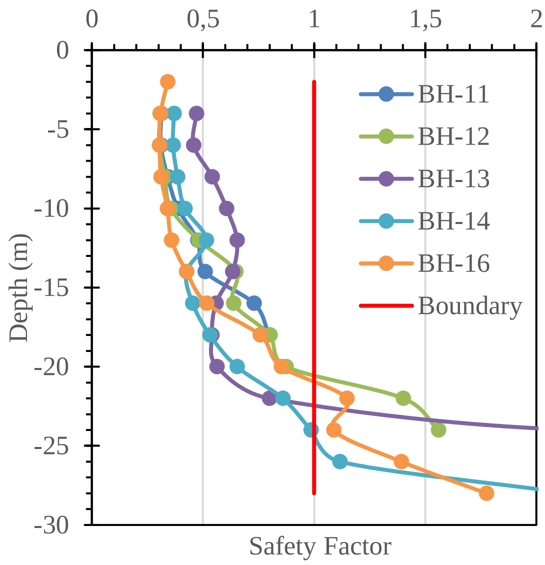

Fig.5 Summary of liquefaction Safety Factors

The results of soil investigation included an analysis of the LPI to denote the probability of liquefaction occurrences, which was presented in Table 4.

Based on Table 4, each borehole exhibited a high LPI index and according to Iwasaki [15], this result signified liquefaction potential within the area. Through this study, it was observed that Lake Toba was marked as susceptible to liquefaction. During the design process, detailed soil investigations emerged as an imperative solution to minimize the consequences of liquefaction.

This assessment also encompassed the LSI, gauging the impact of liquefaction occurrence. Table 5 showed that BH-14 and BH-16 exhibited moderate LSI values, while BH-11 to BH-13 indicated low LSI indices. This suggested that boreholes with lower LSI indices sustained relatively diminished potential damage compared to those with moderate destruction. The factors contributing to better LSI indices in BH-11 to BH-13 stemmed from marginally improved SPT values in these boreholes, subsequently impacting the bearing capacity of soil. This aligned with the notion that lower soil-bearing capacity indicated an increased susceptibility to liquefaction [20].

Table 4 Summary of LPI

Depth (m)	LPI				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	-	-	-	-	11.865
-4	11.003	11.099	8.466	10.090	11.050
-6	9.655	9.754	7.589	8.886	9.726
-8	7.910	8.064	5.499	7.371	8.262
-10	6.129	6.444	3.938	5.814	6.600
-12	4.194	4.156	2.773	3.880	5.129
-14	2.942	2.112	2.201	3.443	3.445
-16	1.081	1.452	1.766	2.186	1.931
-18	0.404	0.396	0.920	0.937	0.486
Total	43.318	43.477	33.151	42.609	58.495
LPI Index	Very High	Very High	Very High	Very High	Very High

Table 5 Summary of LSI

Depth (m)	LSI				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	-	-	-	-	8.916
-4	7.949	7.953	7.688	7.893	7.951
-6	6.957	6.961	6.758	6.911	6.960
-8	5.944	5.953	5.575	5.902	5.962
-10	4.917	4.943	4.439	4.883	4.954
-12	3.837	3.830	3.399	3.771	3.953
-14	2.836	2.563	2.600	2.924	2.925
-16	1.549	1.727	1.839	1.934	1.884
-18	0.697	0.692	0.930	0.935	0.744
Total	34.686	34.622	33.229	35.154	44.248
LSI Index	Low	Low	Low	Mode-rate	Mode-rate

The LPI value indicated the probability of liquefaction occurring, while the LSI portrayed the potential harm resulting from such an occurrence. These two measures did not consistently align, but there were situations where the probability was low and the ensuring impact was substantial, and vice versa.

Table 6 presented settlement that transpired in the event of liquefaction using the method outlined in [19]. Settlement values exhibited a range spanning from 0.627 meters to 1.505 meters. The area most susceptible to settlement was BH-14, with a theoretical potential for up to 1.505 meters. In contrast, the location least prone to settlement was BH-13, where the value stood at 0.627 meters. As the depth of soil layer increased, its density intensified, leading to a reduction in soil settlement. Even at a depth of 24 meters, settlement was still observed within BH-14.

Table 6 Soil settlement with Tokimatsu and Seed method

Depth (m)	Settlement (m)				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	-	-	-	-	0.104
-4	0.159	0.158	0.057	0.161	0.158
-6	0.183	0.182	0.059	0.183	0.182
-8	0.164	0.163	0.052	0.163	0.196
-10	0.120	0.149	0.049	0.147	0.177
-12	0.082	0.074	0.048	0.088	0.162
-14	0.081	0.051	0.053	0.200	0.101
-16	0.049	0.055	0.072	0.200	0.081
-18	0.048	0.046	0.090	0.162	0.048
-20	-	0.044	0.094	0.092	0.045
-22	-	-	0.053	0.056	-
-24	-	-	-	0.051	-
Total	0.886	0.922	0.627	1.505	1.251

Table 7 provided a summary of settlement arising as a consequence of liquefaction, with [20] serving as the point of reference. The observed settlement values spanned from 0.842 to 1.176 meters, with the area most susceptible to settlement occurring in BH-14 registering a value of 1.176. The least region prone to soil settlement was BH-13, with settlement of 0.842 meters. A notable trend observed was the decreasing settlement as depth increased, indicating denser soil layers. The deeper soil layer, the denser it became, leading to reduced soil settlement due to liquefaction but still occurring up to a depth of 28 meters in BH-16.

Settlement arising from liquefaction were presented in Table 8 [21] recording a value ranging from 0.178 to 0.403 meters. BH-16 showed the highest susceptibility, evidenced by a notable soil settlement of 0.403 meters, while BH-13 exhibited the least susceptibility, with a distance of 0.178. The trend indicated a decrease in settlement as depth increased, underscoring the presence of denser soil layers.

Table 7 Soil settlement with Ishihara and Yoshimine method

Depth (m)	Settlement (m)				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	-	-	-	-	0.108
-4	0.114	0.114	0.082	0.114	0.114
-6	0.114	0.114	0.088	0.114	0.114
-8	0.114	0.114	0.076	0.114	0.114
-10	0.112	0.114	0.072	0.114	0.114
-12	0.100	0.096	0.072	0.108	0.114
-14	0.100	0.080	0.074	0.114	0.104
-16	0.076	0.084	0.096	0.114	0.100
-18	0.070	0.070	0.102	0.114	0.072
-20	0.028	0.070	0.104	0.104	0.070
-22	0.024	0.010	0.076	0.082	0.018
-24	0.016	0.008	-	0.060	0.020
-26	-	-	-	0.024	0.016
-28	-	-	-	-	0.004
Total	0.868	0.874	0.842	1.176	1.082

Table 8 Soil settlement with Cetin method

Depth (m)	Settlement (m)				
	BH-11	BH-12	BH-13	BH-14	BH-16
-2	-	-	-	-	0.082
-4	0.077	0.080	0.049	0.063	0.081
-6	0.069	0.073	0.043	0.055	0.073
-8	0.054	0.057	0.030	0.044	0.063
-10	0.038	0.043	0.022	0.033	0.046
-12	0.023	0.022	0.015	0.020	0.033
-14	0.014	0.011	0.011	0.018	0.018
-16	0.005	0.006	0.007	0.009	0.007
Total	0.279	0.291	0.178	0.242	0.403

Based on these results, a summary was obtained in Table 9, and among the three methods, BH- 13 exhibited the least settlement. In the Tokimatsu & Seed and Ishihara & Yoshimine methods, BH-14 recorded the greatest settlement, while in the Cetin method, the highest soil settlement was observed in BH-16. This disparity stemmed from the distinct approaches employed in each technique, resulting in divergent outcomes.

Table 9 Summary of soil settlement due to liquefaction

Method	Settlement (m)				
	BH-11	BH-12	BH-13	BH-14	BH-16
Tokimatsu Seed	0.886	0.922	0.627	1.505	1.251
Ishihara Yoshimine	0.868	0.874	0.842	1.176	1.082
Cetin	0.279	0.291	0.178	0.242	0.403

6. CONCLUSION

In conclusion, Lake Toba featured prevalent sandy layers, a shallow groundwater level, and a history of frequent earthquakes, all contributing to an elevated risk of liquefaction.

Based on liquefaction analysis [19], the study observed that all boreholes had the potential for liquefaction up to a depth of 24 meters. The LPI values indicated a high potential for liquefaction across the entire region, meeting all triggering factors. Conversely, considering the LSI values, BH-11 to BH-13 displayed low LSI values, while BH-14 and BH-16 exhibited moderate figures. This implied that the potential impact of liquefaction was low for BH-11 and BH-13, and moderate for BH-14 and BH-16 based on [18]. The LPI and LSI values were not directly proportional due to their distinct representations. LPI indicated the probability of liquefaction occurrence and LSI represented the severity level. However, further investigation was necessary, as the LPI and LSI formulas limited the calculation to 20 meters deep, while liquefaction phenomena were observed at depths of up to 24 meters. Considering the dominant sandy soil, a more comprehensive examination was required.

Turning to settlement values, disparities emerged among the outcomes obtained from the three methods. BH-13 emerged as the location with the least potential ground settlement across the three methods. However, discrepancies were evident in the most substantial settlement values. Both the Tokimatsu & Seed as well as Ishihara & Yoshimine methods identified the highest settlement in BH-14, similar to the Cetin method in BH-16. The smaller settlement value in the Cetin method was attributed to the limited calculation depth of 18 meters. Considering liquefaction was observed up to a depth of 24 meters, it was advisable to employ the Tokimatsu and Seed or Yoshimine method for determining soil settlement due to liquefaction, specifically when the depth of liquefied soil exceeded 18 meters.

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