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GEOTECHNICAL ASSESSMENT OF SUBLAKE SLOPES AND LIQUEFACTION HAZARD IN LAKE TOBA, INDONESIA

Listia Ariani[1], *Fikri Faris[2] and Ahmad Rifa'i[3]

[1,2,3]Faculty of Engineering, Universitas Gadjah Mada, Indonesia

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ABSTRACT: Lake Toba, the largest lake in Sumatra Island, is a volcanic lake that holds great significance both geologically and culturally. It has a breathtaking natural wonder that captivates visitors from around the world. The fluctuation of surface levels in Lake Toba adds another layer of complexity to the stability of its sublake slopes during seismic activity. The key aim of this paper is to study the sublake slope stability, likelihood of liquefaction potential, and permanent deformation that subject to the fluctuation of Lake Toba surface levels. This research was conducted the numerical analysis of GeoStudio 2022.1 software by combining QUAKE/W, SLOPE/W, and SIGMA/W to evaluate the pre- and post-earthquake condition. The slope stability in the pre-earthquake condition was stable regardless of the reduced safety factor along with the declining lake surface level, but in the post-earthquake condition the safety factor was reduced nearly 60%, resulting in slope instability. An earthquake exhibits 0.25 g of acceleration within a period of 44.435 s, caused liquefaction up to 7.7 m layer of soil structure and high amplification of the ground surface approximately to 0.44 g. Massive permanent deformation occurred as the result were varying from 7 m to 12.1 m. As the surface level decreases, potential for liquefaction decreases as well but the safety factor value of slope stability increases, which can lead to a greater increase in the potential for permanent deformation. This indicates that the declining of the lake surface level influences slope failure during an earthquake.

Keywords: Lake Toba, Slope Stability, Water Level Fluctuation, Liquefaction, Deformation

1. INTRODUCTION

Lake Toba, located in North Sumatra, Indonesia, is not only the largest volcanic lake in the world but also highly significant due to its geological history. The lake is a result of a massive volcanic caldera, which formed around 74.000 years ago due to a catastrophic eruption of the Toba super volcano [1]. Due to complex geological and tectonic processes that have occurred over millions of years, the sublake slope in Lake Toba is formed. The formation of the sublake slope in Lake Toba is influenced by tectonic activity and the deposition of volcanic material. The supervolcanic eruption created a basin that was later filled with rainwater and river flow, forming Lake Toba. The sublake slope then formed along the deep bottom of the lake, following the sublake contours of the caldera. Considering the significant role of the lakefront in the surrounding ecosystem and its importance as a tourist destination, it is crucial to assess the stability of the sublake slope during seismic event is essential to ensure the safety and sustainability of the lakefront area [2].

Several studies have shown earthquakes can influence slope stability in the coastal area, such as lakefront, particularly in zones with specific regions linked to the lithological composition, geological structure, landform features, topographic variations, and human activities [3]. Lakefront in a high seismic activity can lead to certain effects, including slope failures, liquefaction, and soil mass deformation. These occurred as a result of slope instability [4,5]. The soil characteristics in coastal or lakefront areas are predominantly loose sandy soils, potentially enhancing the likelihood of liquefaction [6,7]. Liquefaction occurs when saturated cohesionless soil experiences a significant loss of strength, causing it to behave similar to liquid. This can lead to ground failure and substantial deformation in the affected area [8]. In past earthquakes such as Niigata and Kocaeli Earthquake, large ground deformation in alluvial sand deposits occurred in coastal areas [9-11], causing lasting changes to the ground formation because of both liquefaction and faulting, leading to substantial harm to superstructures and infrastructures.

In the context of sublake slope, lake surface level is one critical factor that contributes to the slope stability by increasing the pore water pressures within the soil or rock mass. During seismic events, these increased pore water pressures can reduce the effective stresses within the slope material, thereby decreasing its shear strength and potentially leading to slope failure and liquefaction. According to Irwandi et al [12], the varying surface levels of Lake Toba are influenced by multiple factors, including the inflow and outflow of water from various sub-watersheds that flow into the lake.

It is strongly associated with climate variability, climate change, and human activities. The fluctuation of surface levels in reservoirs and lakes is a significant factor influencing slope stability [13].

This study aimed to analyze sublake slope stability and liquefaction assessment induced by fluctuations in the surface level of Lake Toba during the earthquake event. The fluctuation of the Lake Toba surface level is different from tide conditions because it does not have a direct connection to the sea or water channels that allow the inflow of seawater or tidal movements, thus the effects of flow function and drawdown are not considered in this analysis. Analysis in this study was conducted finite element method utilizing GeoStudio 2022.1.

2. RESEARCH SIGNIFICANCE

This research explores the effect of surface level variation on the sublake slope stability of Lake Toba during an earthquake through numerical modeling. The finite element method was conducted to evaluate the stability of the slope for pre- and post-earthquake conditions, the likelihood of liquefaction during the earthquake, and the permanent deformation after the earthquake shaking. This study can provide valuable insights into the behavior and stability of the lakefront. Additionally, this research addresses a significant gap in existing literature. Existing literature has focused on the influence of ground water levels on slope stability, but little attention has been given to the specific effect of surface level variations in lakes such as Lake Toba. By investigating the role of fluctuation of lake surface level in landslide occurrence, this study contributes to a better understanding of the dynamics slope stability in lake environments during seismic events. The research findings from this study can be used by geotechnical engineers, urban planners, and policymakers to improve disaster preparedness and mitigate the risks associated with slope instability during earthquakes.

3. MATERIALS AND METHOD

3.1 Study Site

Samosir Island, situated in the middle of Lake Toba, surrounded by breathtaking natural beauty lakefront of Lake Toba. The research study is located in the western portion of Samosir Island, specifically in Pangururan District. The formation of Samosir Island is closely linked to the volcanic activity that created Lake Toba itself. According to Geological Map of The Sidikalang and (part of) Sinabang Quadrangles, Sumatra, this area has an alluvium rock formation (Qh) of the Holocene, which is an alluvial deposit consisting of layers of clay, sand, and gravel [14]. High ground water levels typically characterize coastal regions due to their proximity to the bodies of water. Saturated cohesionless soils of the Holocene have a higher liquefaction susceptibility compared to soil deposits of other older geological epochs, such as Pleistocene and Pre-Pleistocene [15].

The tectonic conditions that influenced the seismic activity of the research area are the Sumatra Subduction Zone and the Great Sumatran Fault. Several high-magnitude earthquakes have been recorded in the last few decades in North Sumatra. Based on the history of earthquakes in North Sumatra, Head of the Regional Disaster Management Agency (BPBD) of Samosir Regency stated that the 2005 Nias Earthquake which had a magnitude of 8.6 M_w significantly influenced the lakefront of Pangururan District [16]. The epicenter of the earthquake was located offshore about 78 km WSW (West-Southwest) of Singkil, at a depth of about 30 km within the oceanic slab of the Indo-Australian plate [17]. This area suffered severe damage, including the collapse of Public Junior High School 1 Pangururan and the subsidence of Jalan Danau Toba.

In this study, Jalan Danau Toba in Pangururan District within the coordinates 2.606N, 98.695E as shown in Fig. 1, was considered as the case study. In terms of geological condition, seismicity, and earthquake damage history, this area has a vulnerability to liquefaction that could potentially destabilize the slope. Therefore, assessing the stability of sublake slope in this study area was essential due to the soil liquefaction susceptibility under earthquake loading.

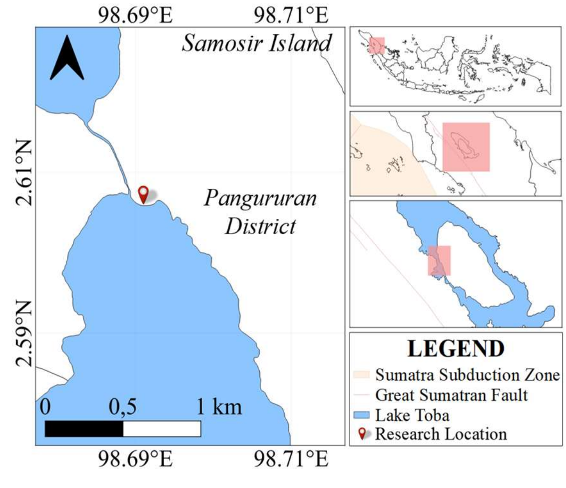


Fig. 1 The location of research study (modified from: [18,19])

3.2 Slope Stratigraphy

Slope stratigraphy, as shown in Fig. 3 adjusted to field conditions, is necessary to conduct the analysis. Required supporting data in developing soil stratigraphy included slope geometry and type soil layer. In order to define the slope geometry, planimetric and contour map of the study site were used. The soil type for each layer was determined based on the Standard Penetration Test (SPT) and sub-bottom profiler data as a validation.

According to the planimetric and contour map, the slope inclination was about 45° due to the geological history and formation process of the lake. Soil type and sediment interpretation data of SPT are consistent with sub-bottom profiler data. Based on SPT data as presented in Fig. 2, the entire slope layer profile of the study site was dominated by fine sand. First layer, at a depth of 0-12 m, the consistency of the Sand I layer was very loose. In the second layer of medium loose sand, Sand II, at a depth of 12-16 m. The third layer and fourth layer, Sand III at a depth of 16-22 m and Sand IV at a depth of 22-24 m were medium dense sand and dense sand, respectively. In accordance with the sub-bottom profiler data, lakebed sediment were loose sand deposits varying in thickness between 0.5-3 m. While the deeper sediment unit were identified as medium dense sand reaching greater than 10 m in thickness. Slope inclination and soil type may affect the slope stability. In addition, the steeper the slope, the greater the potential for slope instability. The potential for soil movement and slope failure will likely increase due to the significant gravitational force.

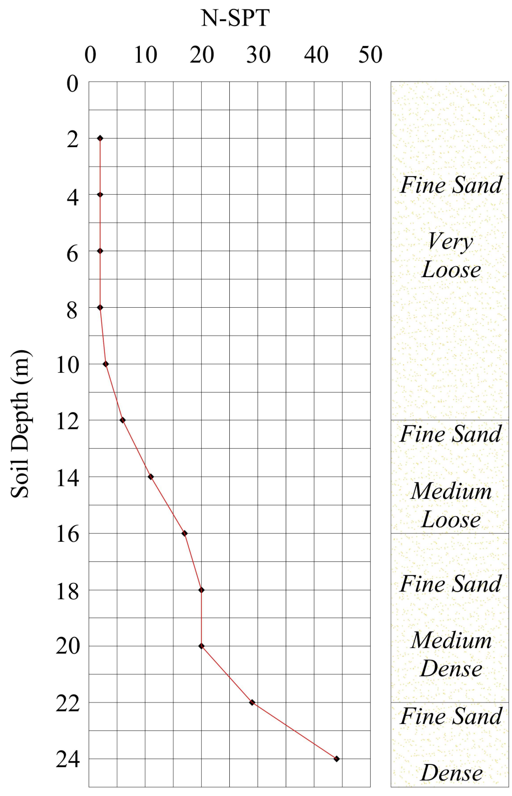


Fig. 2 Soil profile with SPT blow counts

3.3 Lake Toba Surface level

The fluctuation of Lake Toba surface level showed a significant downward trend from 1957 to 2016, with the highest and lowest level being 905.5 m and 902.8 m, respectively [20]. A significant decline in Lake Toba surface level occurred in 2016 according to Annual Report of PT Indonesia Asahan Aluminium, in comparison to the previous year, Lake Toba surface level decreased by 2 m [21]. Based on the Toba Asahan River Water Resources Management Policy, Lake Toba surface level must be maintained at 905.5 m (maximum) - 902.4 m (minimum), because within this surface level range, the operation of generators in both Siguragura and Tangga Hydroelectric Power Plants (HPP) can be operated effectively and efficiently.

The decline of Lake Toba surface level is likely to contribute to the stability of sublake slope. This factor should be considered in assessing slope stability. According to previously mentioned studies, Lake Toba surface level never exceeded the maximum or minimum threshold. Therefore, further analysis at four different lake surface levels was carried out to understand the effect of decreasing the surface level of Lake Toba. The Lake Toba surface level used in this analysis is 902.4 m, 903.4 m, 904.4 m, and 905.5 m.

3.4 Numerical Analysis

The software employed for this analysis was GeoStudio 2022.1 due to its advanced capabilities in conducting phased analyses using QUAKE/W, SLOPE/W, and SIGMA/W. QUAKE/W utilizes the finite element method to perform dynamic analysis and allows for the evaluation of liquefaction susceptibility by simulating the generation of excess pore water pressure during earthquake events. SLOPE/W quantify the safety factor for both pre- and post-earthquake conditions using a stress-based stability analysis. The slope is in stable condition if the safety factor value is satisfied more than 1.25 [22]. The deformation analysis in SIGMA/W was performed by modelling the stress redistribution to simulate the strength loss. In this study, the model will be analyzed by employing four circumstances according to the fluctuation of Lake Toba surface level under static and dynamic conditions.

3.4.1 Stability Factor

The stress-based stability analysis uses QUAKE/W static or dynamic stress to analyze the stability of slope. The stability factor equivalent to the safety factor (SF) is determined as the ratio of resisting forces (S_r) over the mobilized shear forces (S_m) as shown in Eq. (1). The summation of these forces over all columns in the given slip surfaces yields the total resisting shear force and total mobilized shear force.

$$SF = \frac{\sum S_r}{\sum S_m} \tag{1}$$

3.4.2 Liquefaction Analysis

The identification of excess pore water pressure is a critical point in predicting liquefaction. This is simply the fact that when a cyclic load applied to a sandy saturated soil, the excess pore water pressure tends to increase until it reaches the initial confining pressure, resulting in liquefaction. The equivalent linear model, which is extensively discussed in the geotechnical earthquake engineering literature, can be used to simulate excess pore water pressure development [23-25]. This method has provided findings that are comparable to field measurements and are commonly applied in engineering practice. The pore-pressure buildup in the equivalent linear soil model is based on cyclic stress ratios. The assumption is that a certain number of shear stress cycles at a certain shear amplitude will generate enough excess pore pressure to trigger the ground to liquefy. Seed et al. [26] found the pore pressure ratio function (r_u) can be used to measure the pore pressures established by the earthquake in Eq. (2). The cycle of stress (N), the cycle of stress necessary for liquefaction (N_L), and α is a relation of the soil properties and testing circumstances. The value of $\alpha = 0.7$ was used in this analysis because it gives the most appropriate value in relation to r_u.

$$r_u = \frac{1}{2} + \frac{1}{\pi} arc \sin\left[2\left(\frac{N}{N_L}\right)^{\frac{1}{\alpha}} - 1\right] \tag{2}$$

3.4.3 Deformation Analysis

The stress redistribution algorithm by SIGMA/W uses an elastic-plastic constitutive model to simulate the behavior of soil structures experiencing strength loss. In cases where a specific region of soil within a soil structure experiences an abrupt decrease in strength, the stress distribution and adjustment process will occur. The areas that have suffered this loss in strength will transfer their excess load to regions that have not been affected by the strength decline. This redistribution of stress continues until the entire structure achieves a state of equilibrium again. However, if the magnitude of this loss is significant enough to prevent the earth structure from re-establishing its balance, then it can lead to complete structural collapse and often result in disastrous consequences. Alternatively, if the structure manages to find a new point of equilibrium, the process of stress redistribution accompanies permanent deformations.

3.4.4 Seismic Motion

The seismic load for this analysis used a time history record that was applied at the lower boundary of the structure. The time history data can be adjusted to meet the conditions of a specific site or investigation. In determining the peak ground acceleration (PGA), regression of attenuation relation by Kanno [27] was used. The Kanno attenuation was determined by Eq. (3) for the focal depth ≤ 30 km. Pre is the predicted PGA (cm/s^2), M_w is the moment magnitude, and X is the source distance (km). According to the previous study, the PGA value from that attenuation relation was similar to the recorded PGA with the distance of epicenter up to 200 km [28]. Since earthquakes release wave energy that will spread in all directions, this study examined seismic data from the North Sumatra Province. The intensity of the earthquake will nevertheless have an impact on Samosir Island even though its epicenter is outside of the island.

$$\log pre = 0.56M_w + 0.0031X - \log(X + 0.0005\,.\,10^{0,5M_w}) + 0.26 + 0.37 \tag{3}$$

The PGA value of the earthquake used in this study was 0.25 g from the 2005 Nias Earthquake, based on the largest PGA of North Sumatra earthquake data from the United States Geological Survey (USGS) from 1970 to 2022. The moment magnitude, the focal depth, and the epicenter from the study site were 8.6, 30 km, and 185.6 km, respectively. Due to limitations in the observation stations at the site, the ground motion was used 2007 South Sumatra earthquake from the Sikuai Island Station with moment magnitude and focal depth were 8.7 and 34 km, respectively. Both earthquakes, in addition to having similar moment magnitude values and focal depths, also have similarities in the earthquake mechanism. A critical factor to consider in seismic analysis is the significant duration of ground motion. This parameter denotes the time interval during which 5% and 95% of the earthquake's total power intensity are reached. This duration is deemed significant because it captures a large portion, but not all, of the energy of the earthquake. The duration that will be used in this analysis is the significant duration of 2007 South Sumatra Earthquake, 44.935 s.

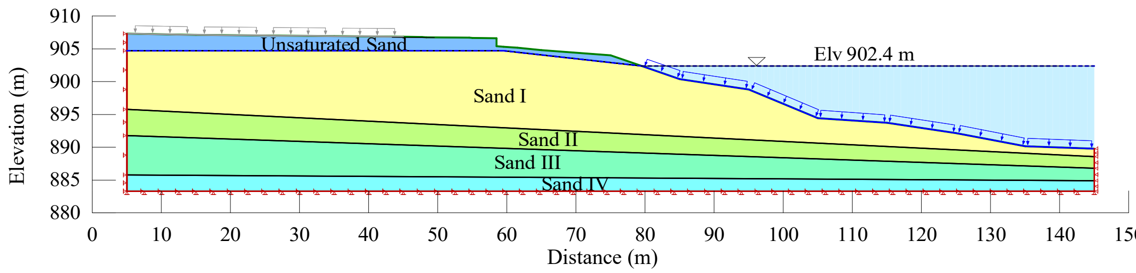


Fig. 3 The slope stratigraphy in the research study

3.4.5 Soil Material Properties

Soil properties data were obtained from laboratory soil investigation results and the correlation of soil parameters with soil type and N-SPT values. It was used as an input parameter in numerical analysis. An Equivalent Linear soil model was used for QUAKE/W analysis, whereas the Mohr-Coulomb soil model was used for SLOPE/W and SIGMA/W analysis. The soil properties from each layer can be seen in Table 1.

Table 1 Parameters of soil properties

Materials	γ_{sat} (kN/m^3)	v	G_{max} (kN/m^2)	c (kN/m^2)	φ (°)
Sand I	19.44	0.33	21253	0	20.22
Sand II	20.18	0.33	63383	0	28.14
Sand III	20.59	0.33	98371	0	37.19
Sand IV	21.27	0.33	137981	0	48.18

4. RESULTS AND DISCUSSION

4.1 Slope Stability

The static safety factor against slope failure was determined by using SLOPE/W under static and dynamic conditions. The static analysis was performed to determine slope stability before the earthquake occurred. As presented in Fig. 4, the slope stability in the critical slip surface, has safety factor value of 1.271 and 0.523 for the static and dynamic analysis, respectively. The result of the analysis shows that the slope stability decreased in the earthquake event.

The values of the safety factor during the earthquake shaking in dynamic analysis can be observed for each time step. As presented in Fig. 5, the smallest safety factor of the critical slip surface during the shaking process was 0.163 at about 20.14 seconds into the shaking, indicating failure would likely develop on a saturated slipping surface even during smaller earthquakes [29]. The result of slope stability in the pre-earthquake conditions for each scenario were in stable condition, while the post-earthquake conditions were unstable according to safety factor criteria as shown in Table 2, reducing approximately 60% of safety factor value. The safety factor of pre- and post-earthquake dramatically reduced as the lake surface level decreased, indicating that the hydrostatic pressure of the lake surface affects the stability of the slope, so the decline in lake surface level has an impact on the decrease in slope stability.

4.2 Soil Liquefaction

In the QUAKE/W analysis, liquefaction is expected to occur when the r_u value reaches 1.0. The cyclic stress ratio that affected the r_u value considerably depends on the specific characteristics of the sand type [30]. The pore water pressure escalated due to the entrapment of water, hindering its rapid drainage. Consequently, within the soil layer characterized by fine sand with its notable permeability, the moisture contained within the soil layer sought means of escape and attempted to regulate the pressure through percolation. As it appears in Fig. 6a, liquefaction was observed at layer thicknesses of approximately 7.7 m, at elevation 904.7 to 897 m in the coastal part of the lake and along the lakebed due to the earthquake shaking. At a time of 3.94 s, the process of liquefaction initially took place at an elevation of 904.7 m as it seen in Fig. 6b. This phenomenon can be attributed to the variation in hydraulic gradient between this particular layer and the one beneath it, specifically the former is positioned closer to the groundwater table. As a result, water tends to flow from regions with higher pore water pressure towards areas where such pressure is lower.

A decrease in liquefaction vulnerability occurred when the lake surface level declined as shown in Fig. 7. Liquefaction layers of greater thickness in close proximity to the ground surface, which provide direct support for buildings at ground level, can result in more significant instances of ground failure [31]. It is recalled that at the base value, which was the input earthquake record, has a peak of 0.25 g. The peak horizontal acceleration value at the crest of the slope reached a value 0.441 g, as is evident from Fig. 8. It was indicated that there was a significant amplification of the ground response during the earthquake. The peak horizontal acceleration values at the crest of the slope for each analyzed lake level presented in Table 3, suggest that there was no significant impact of lake level variation on the amplification.

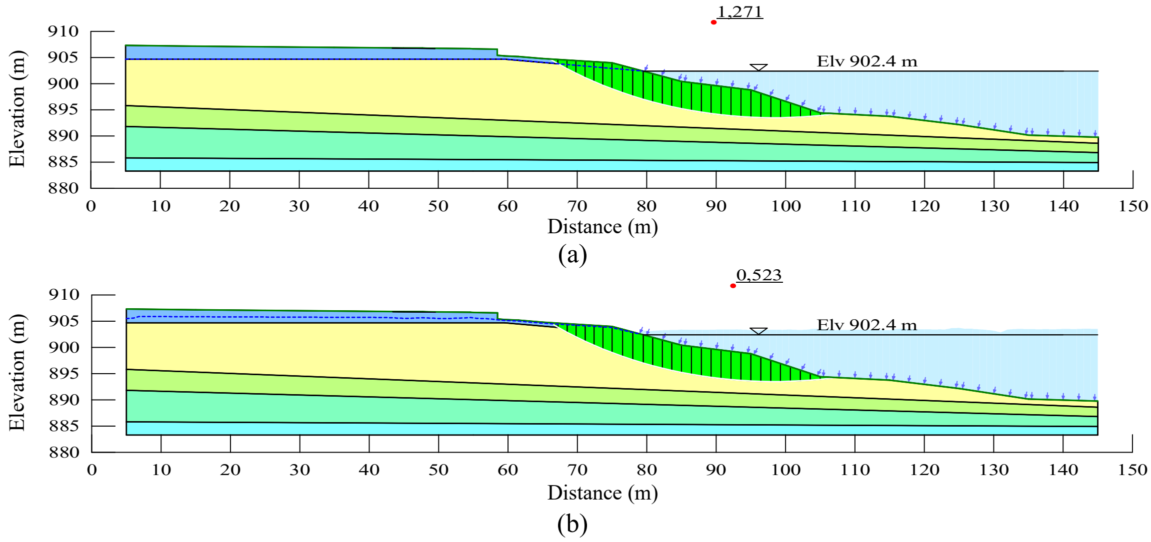


Fig. 4 The safety factor in the critical slip surface (a) static (b) dynamic analysis.

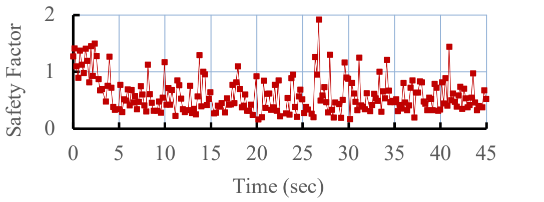


Fig. 5 Safety factor for critical surface during shaking

Table 2 The safety factor of the slope

Lake Surface Level (m)	Safet Factor (SF) Pre-Earthquake	Post-Earthquake
905.5	1.479	0.625
904.4	1.467	0.598
903.4	1.362	0.556
902.4	1.271	0.523

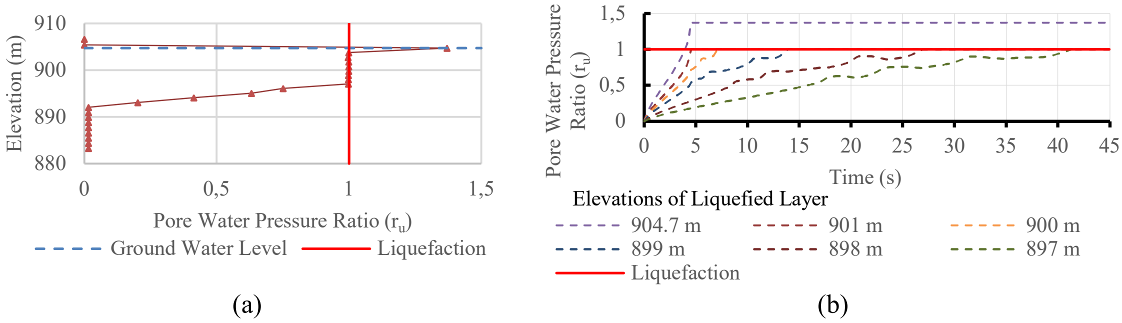
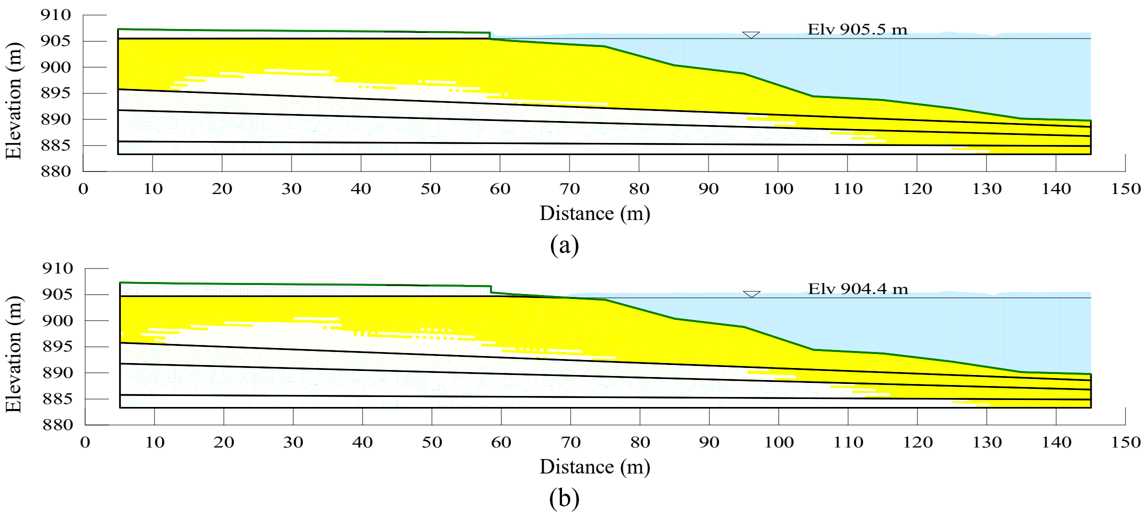


Fig. 6 Graph of pore water pressure ratio in liquefied soil layer within the lake coastal region (a) vs elevation at the end of the shaking (b) vs time



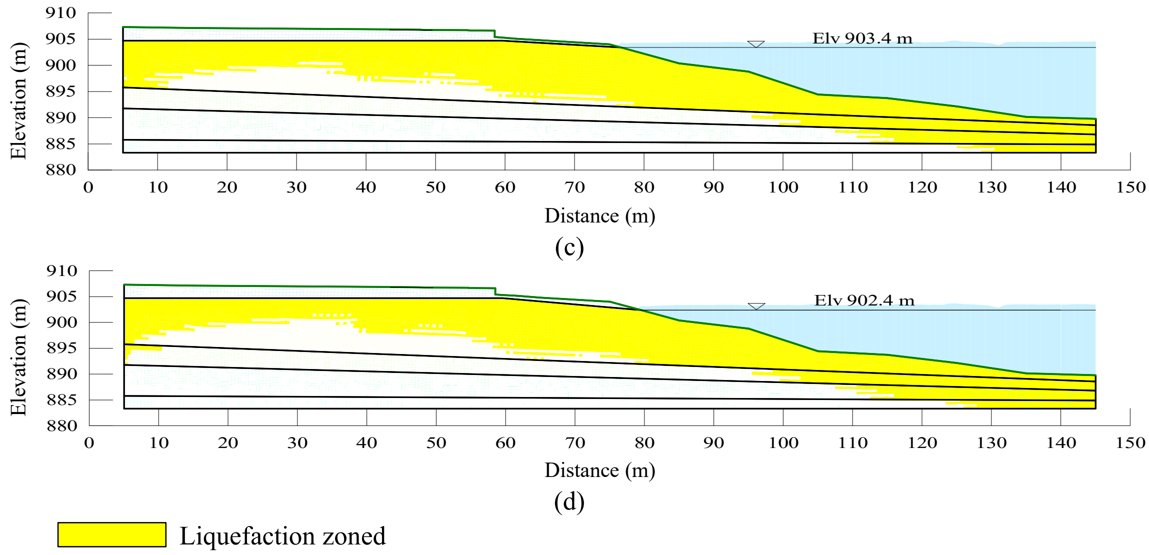


Fig. 7 Liquefaction Zoned (a) 905.5 m ;(b) 904.4 m; (c) 903.4 m; (d) 902.4 m

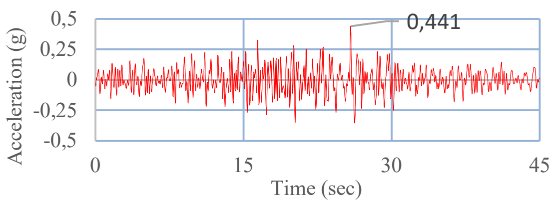


Fig. 8 Horizontal acceleration at the crest

Table 3 The peak horizontal acceleration at the crest of the slope

Lake Surface Level (m)	905.5	904.4	903.4	902.4
Acceleration (g)	0.444	0.443	0.442	0.441

4.3 Permanent Deformation

A massive deformation occurred as the results of SIGMA/W analysis for each variation of lake surface level as shown in Fig. 9, this may be associated with flow liquefaction. According to Fig. 10, the approximate direction of post-earthquake movement appears to be a reasonable representation of the initial movement that occurred. Along with the decrease in lake surface level, the permanent deformation value also increased, this suggests that the declining lake surface level severely reduced the slope stability after the earthquake shaking.

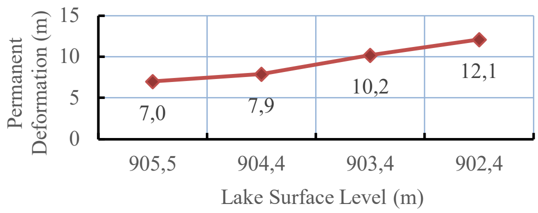
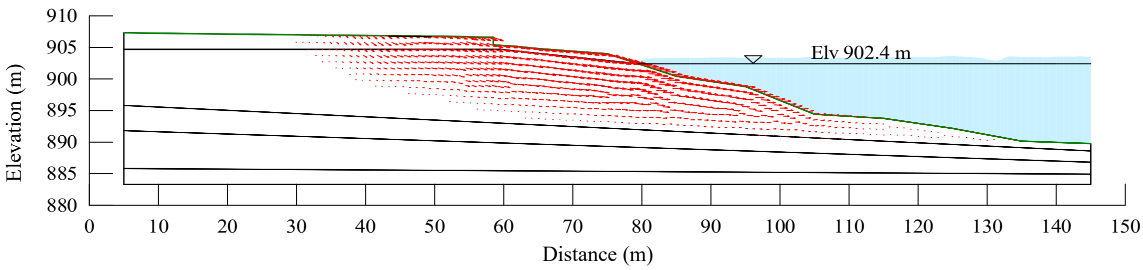
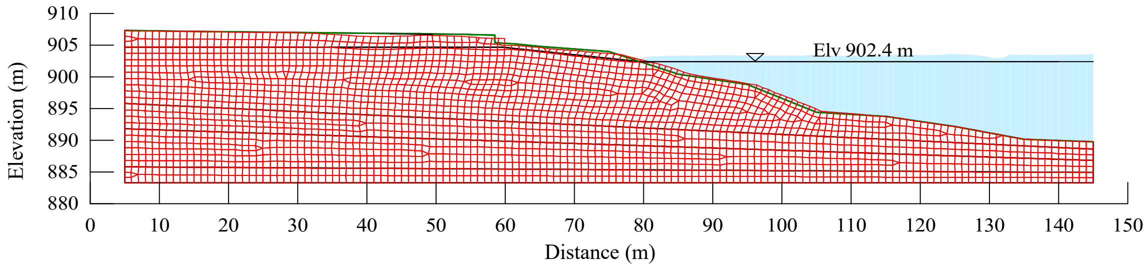


Fig. 9 Permanent deformation after the earthquake shaking

Massive permanent deformations may induce large displacements of soil masses that cause disturbances in the water, indicating the presence of a submerged landslide. The landslide moving pulls the water down, then the landslides move down the slope. As a result, the lake surface rushes forward to fill the space and water moving creates a swell, generating low-level tsunami. Low-level tsunami generated by sublake landslides may not be as destructive as large tsunami generated by undersea earthquakes, but still can cause localized damage and pose a threat to lakefront areas. However, this required further investigation in regard to the possibility of a submerged landslide due to slope instability influenced by liquefaction.



(a)



(b)

Fig. 10 The displacement vector from the post-earthquake condition (a) vector arrows (b) the deformed mesh

5. CONCLUSION

The numerical analysis based on finite element method was performed to evaluate the possibility of slope failure on the coastal area of Lake Toba by using GeoStudio software. The observation from the slope stability analysis in the static condition indicated that the slope was safe against slope failure. In this condition, the weakest safety factor value was 1.271 that occurred from the elevation of Lake Toba surface level was 902.4 m. This suggests that even in the minimum threshold of Lake Toba surface level, the slope was stable. The earthquake shaking reduced the slope stability by about 60%, indicating that the slope was in unstable condition when the earthquake occurred. The lowest safety factor from this analysis was 0.523 that occurred from the elevation of Lake Toba surface level was 902.4 m as well. Slope stability under either static or dynamic conditions reduced as the lake water level declined, indicating that the decline in lake surface level results in a decrease in hydrostatic pressure, which in turn affects slope stability.

The liquefied zone when the Lake Toba surface level at 905.5 m was more susceptible than at 902.4 m. This indicated that the increase of lake surface level resulted in saturated soil from the lake, enhancing likelihood of liquefaction. Along with the resulting from slope stability, the greatest permanent deformation was 12.1 m, occurred at 902.4 m. This may have occurred because the critical slip surface passes through the liquefied zones, increasing the slope failure susceptibility. As the surface level decreased, the likelihood of liquefaction decreased as well yet the slope stability factor and potential of permanent deformation increased. This indicates that the decline of the lake surface level influences slope failure during an earthquake. The findings of the discussed studies emphasize the importance of considering the variation of lake surface level factors when assessing slope stability and predicting the occurrence of liquefaction and flow failure. This is appropriate to provide considerable safety measures for the slope when the strong earthquake occurred.

6. ACKNOWLEDGMENTS

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