

Three-dimensional Slope Stability Evaluation Under Seismic Load: A Case Study in Balaroa, Central Sulawesi, Indonesia

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Abstract

The 2018 Mw 7.4 Palu earthquake was one of the largest natural disasters in Indonesia's history. This catastrophic event was followed by massive mass movements in the Balaroa area, leading to extensive damage to infrastructure and a huge loss of life. A three-dimensional slope stability analysis under seismic conditions emerged as one of the effective solutions for preventing and mitigating the impact of mass movement disasters triggered by earthquakes, particularly in large areas. The objective of this study is to evaluate the map results of the factor of safety (FoS) with the actual massive mass movement that occurred during the 2018 Mw 7.4 Palu earthquake. The research methodology is a three-dimensional stability analysis under non-seismic and seismic conditions with a seismic load coefficient (Kh) under the 2018 Mw 7.4 Palu earthquake using Plaxis 3D LE. The input variables used in this research are the study area 3D modelling, soil parameters, and the seismic load coefficient. The 3D slope stability analysis results show that the FoS map under non seismic condition with FoS values of 2.07 to 4.46, and the results under the 2018 Mw 7.4 Palu earthquake have FoS 0.66-0.90. This evaluation is based on the comparison between the analysis result with the actual massive mass movement under the 2018 Mw 7.4 Palu earthquake condition. This analysis results in an area relatively consistent with the actual mass movement in the study area. It can be interpreted that the massive landslide that occurred in the study area was significantly influenced by the Mw 7.4 Palu earthquake event on 28 September, 2018.

Keywords:

Slope stability, Factor of safety, Earthquake, Seismic load, Mass movement.

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1. Introduction

Historically, landslides triggered by earthquakes have been among the most prevalent natural disasters, particularly in high-magnitude earthquakes. Notable examples include the 6.7 Mw Northridge earthquake in California in 1994 (Havenith et al., 2016), the 8.0 Mw Wenchuan earthquake in China in 2008 (Chen et al., 2020), and the 7.3 Mw Chi-Chi earthquake in Taiwan in 1999 (Havenith et al., 2016). In Indonesia, earthquake-induced landslides have also been recorded, including the 5.6 Mw Cianjur earthquake in 2022 (Supendi et al., 2022) and the 7.4 Mw Palu earthquake in 2018, which resulted in landslides in areas such as Petobo, Sibalaya, Jono Oge, and Balaroa (PusGen, 2019).

The 2018 Palu earthquake, with a magnitude of 7.4, is a significant example of a large-scale natural disaster occurring in the study area. According to data from the National Disaster Management Agency of Indonesia, this seismic event resulted in 2,113 confirmed fatalities, 1,309 individuals reported missing, and 4,162 injuries. Additionally, approximately 223,000 people were displaced, and the earthquake inflicted significant damage on the infrastructure, affecting 68,451 buildings (PusGen, 2018). The event also triggered extensive landslides and liquefaction in areas such as Balaroa and Petobo, which were key contributors to the high casualty rate and considerable destruction of infrastructure in the affected region.

Slope stability analysis under seismic loading is typically performed using two-

dimensional cross-sectional models. This approach limits the effectiveness of mitigation strategies for broader or regional areas and requires a substantial amount of time for analysis. However, Plaxis 3D Limit Equilibrium (LE), a software developed by Bentley Systems Team, facilitates three-dimensional slope stability evaluations on a regional scale by employing the method of columns, which extends the traditional method of slices used in 2D analysis (Bentley Systems Team, 2021). Consequently, three-dimensional slope stability analysis emerges as an optimal approach for mitigation, management, and spatial planning, especially in regions vulnerable to earthquake-induced landslides.

To effectively reduce the risk and impact of earthquake-triggered landslides in the future, it is crucial to implement early and optimal mitigation strategies. One promising approach is to conduct additional research focused on the early detection of landslide risks associated with earthquakes, which will help identify regions vulnerable to such disasters. This research includes performing three-dimensional slope stability analyses under seismic loading across an extensive spatial range.

This research, “Three-Dimensional Slope Stability Evaluation Under Seismic Loading in Alluvial Formations”, uses a three-dimensional stability analysis approach to determine the distribution of the safety factor (SF) under earthquake influence. The analysis employs Plaxis 3D LE under non-seismic conditions and uses seismic coefficients from the 2018 earthquake.

2. Study Area

The geology of the Palu area consists of five formations: the Alluvium and Coastal Deposits, the Formation of the Celebes Molasse, the Formation of Granite and Granodiorite, the Metamorphic complex, and the Formation of Tinombo Ahlburg (Fig. 1) (Sukamto, 1973). The research area is regionally classified into Alluvium and Coastal Deposits formations, which are estimated to be of Holocene age. These formations comprise sand, silt, gravel, and cobbles of varying sizes, originating from river, delta, and shallow marine environments, and representing the region’s youngest sediments. These materials comprise the Palu Valley’s primary components (Sukamto, 1973).

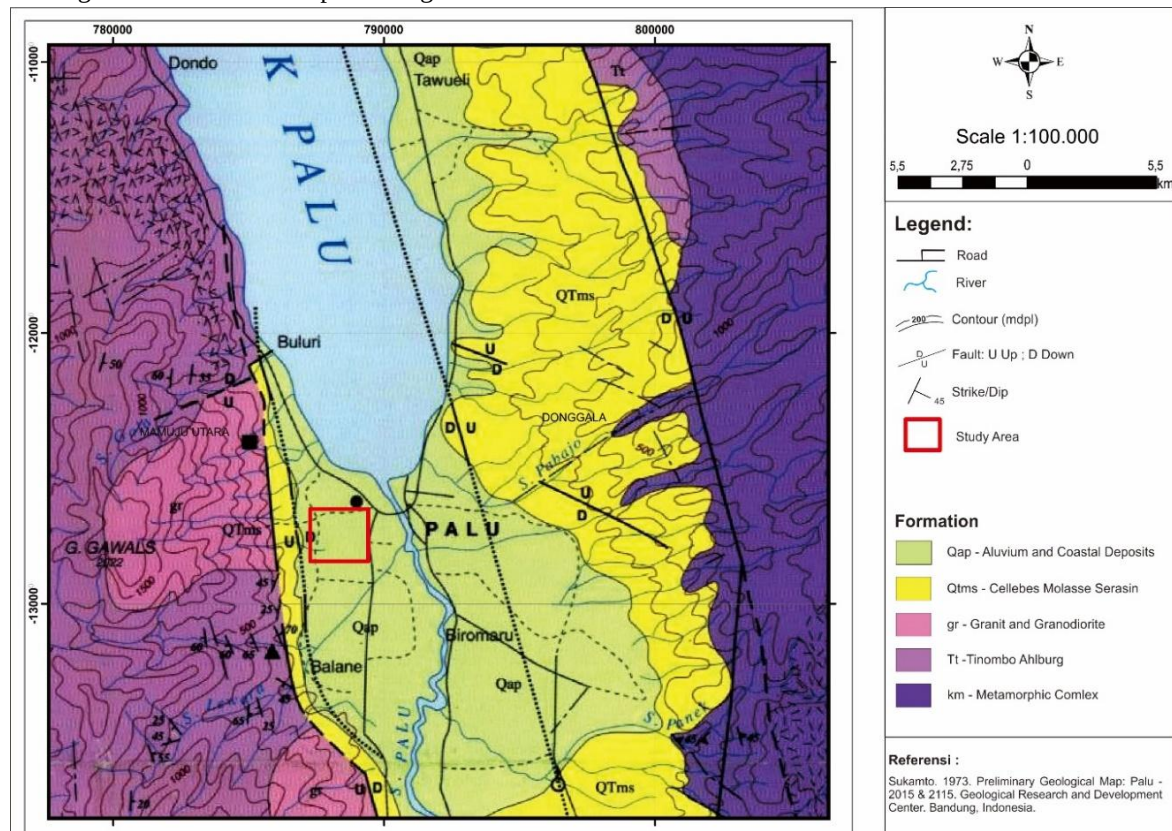


Fig. 1: Geological map of the study area (Sukamto, 1973).

The Palu-Koro Fault, an active fault, traverses the study area and extends over 300 km through Palu Bay, linking to the North Sulawesi subduction zone in the northern part of Sulawesi. This fault runs along the western boundary of the valley and research area with a dip ranging from 50 to 80 degrees toward the east (Socquet et al., 2006). Geomorphic features like streams and Quaternary alluvial fans provide evidence of left-lateral offset (Bellier et al., 2001). It is believed that the Palu-Koro Fault penetrates the thin lithosphere and is seismically locked at a depth of 12 km. GPS monitoring has revealed a high slip rate for the fault, with lateral displacement averaging around 39 mm per year, along with an extension rate of 11 to 14 mm per year (Socquet et al., 2006).

Seismicity in Sulawesi is primarily influenced by several geological features, including the subduction zone in northern Sulawesi, the Palu-Koro Fault, the Matano Fault, and the Molucca Sea Plate subduction zone to the east. The region's seismic activity is notably impacted by the Palu-Koro Fault, which runs directly through the area. Earthquakes generated

here are typically shallow strike-slip events (≤ 40 km) that occur predominantly around the Palu-Koro Fault, exhibiting seismic magnitudes of ≥ 4 Mw (PusGen, 2017).

The 28 September 2018 Palu earthquake had a magnitude of 7.4, followed and triggered by a large scale of mass movement in the Balaroa area. This natural disaster caused extensive damage to infrastructure and led to a significant loss of life. Balaroa is a sub-district within Palu City, located in Central Sulawesi Province. The region impacted by the earthquake-triggered mass movement covers approximately 40 hectares and stretches about 980 meters in length (PusGen, 2019) (Fig. 2). The United States Geological Survey (USGS) indicated that the epicenter of the earthquake was situated roughly 72 km north of the study area, occurring at a depth of 10 km. Geodetic evidence points to fault displacement extending up to 150 km. Fig. (3) shows the main shock, along with several foreshocks and aftershocks, highlighting their respective magnitudes (PusGen, 2018).

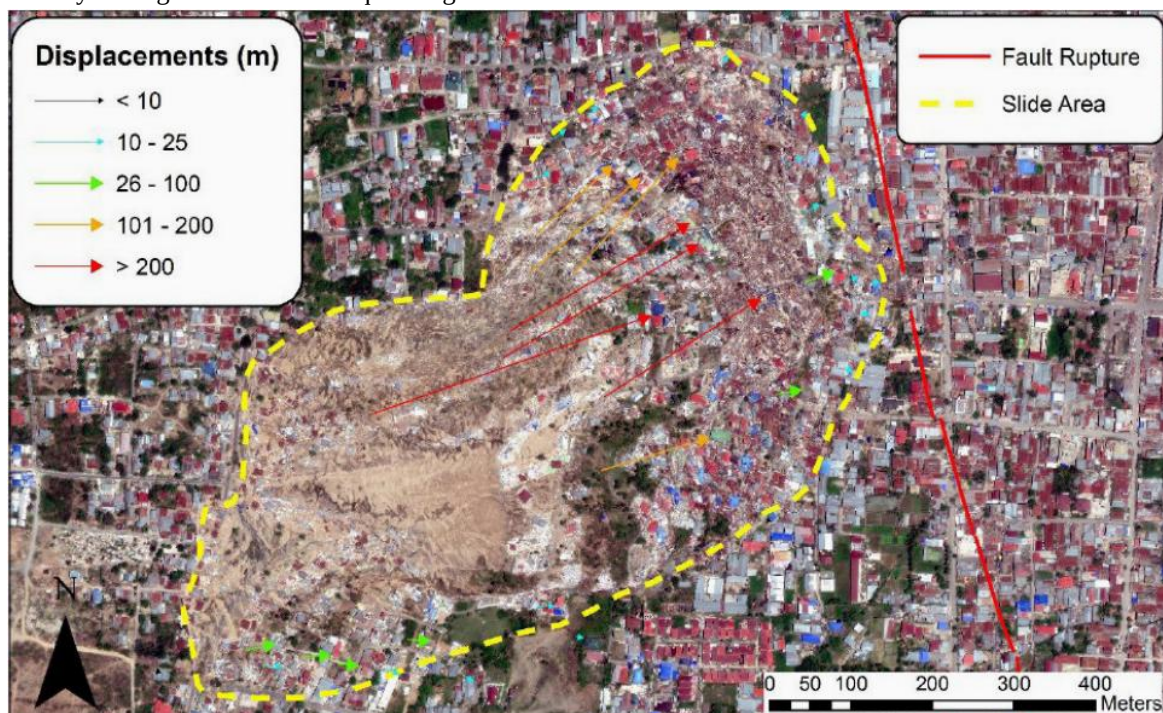


Fig. 2: Massive mass movement triggered by the 7.4 Mw Palu Earthquake on September 28, 2018 in the study area (Balaroa) (PusGen, 2019).

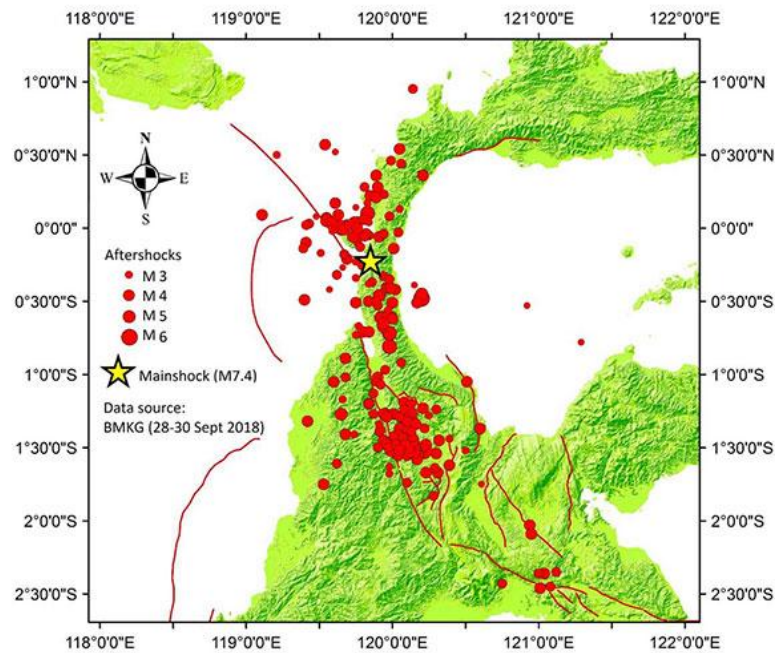


Fig. 3: Main shock and aftershock of the Palu Earthquake on September 28, 2018 (PusGen, 2018).

3. Materials and Methods

The slope stability analysis in this research involves simulations under two conditions: without the influence of an earthquake (non-

seismic analysis) and under the seismic conditions of the 2018 Mw 7.4 Palu earthquake. The input parameter values used in this study are presented in Table 1.

Table 1: Study Data Parameters.

Type of data	Data Source	Description
Soil property parameters (unit weight, cohesion, internal friction angle)	Soil sample (primary data)	Soil input parameters in the three-dimensional slope stability analysis using Plaxis 3D LE
Groundwater table	JICA, 2019	Groundwater input parameters in the three-dimensional slope stability analysis using Plaxis 3D LE
N-standard penetration test (SPT) value	JICA, 2019	Input data to determine seismic coefficient
Peak ground acceleration (PGA) of the Palu earthquake on September 28, 2018.	Sahadewa et al., 2019	Input data to determine the seismic coefficient
Digital Elevation Model (DEM)	Website: tanahair.go.id	Surface input parameters in the three-dimensional slope stability analysis using Plaxis 3D LE

The calculation of seismic load values in this study employs the pseudo-static method, which involves determining the seismic load coefficient. The seismic load coefficient used in this study is based on the conditions of the 7.4 Mw Palu earthquake on September 28, 2018. The seismic data used for the coefficient calculation are obtained from ground motion recordings by seismographs during the 2018 Palu earthquake (Fig. 4).

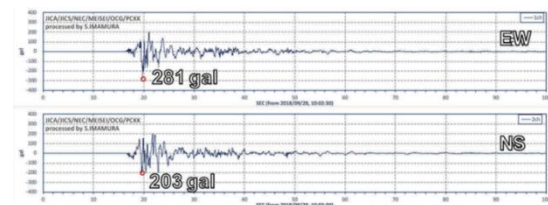


Fig. 4: Horizontal ground motion due to the 2018 Palu earthquake recorded by JICA-BMKG (Sahadewa et al., 2019).

This ground motion data allowed for the calculation of the Peak Ground Acceleration (PGA) used in the study, which is a maximum PGA of 281 gal. PGA is calculated by observing the specific site and considering the amplification factor, including the soil classification and the site

coefficient (F_{PGA}). The soil classification is determined based on the average value of N-SPT using the calculation procedure for calculation according to the Indonesian Standard (SNI 8560:2017, 2017). Based on JICA (2019), the soil classification of the study area has revealed a medium soil site (SD) class with an average N-SPT of 23.9. The soil classification was then used to determine the site coefficient (F_{PGA}), which was then processed to derive the seismic load coefficient (K_h) used in this study. The seismic coefficient (K_h) is expressed as (PUPR, 2004):

$$K_h = \frac{PGA_M}{g}$$

Where: K_h = seismic load coefficient representing the horizontal seismic load as a fraction of gravitational acceleration; PGA_M (modified peak ground acceleration) = adjusted peak ground acceleration considering the influence of site classification, expressed in gal (cm/s^2); g = gravitational acceleration constant equals 980 cm/s^2 .

The three-dimensional modelling of the study area is a preparatory stage before the stability analysis process. This stage involves creating a 3D surface model of the study area representing its condition before the 2018 Palu earthquake, as well as a 3D subsurface model based on the geological and geotechnical conditions of the study area.

The three-dimensional surface model in this study uses surface contour data of the Balaroa area based on National Digital Elevation Model (DEMNAS) data that shows the condition before the 7.4 Mw Palu earthquake disaster in September 2018, which is then exported into Plaxis Designer in the form of contours and converted into a mesh design (Fig. 5). The input soil parameters used in the analysis include soil unit weight (γ), cohesion (c), and internal friction angle (ϕ) (table 2), which were acquired through soil sampling in the study area and subsequently processed using laboratory soil mechanics testing.

Table 2: Input soil properties of the study area.

Material	γ_s (gr/cm^3)	γ_d (gr/cm^3)	c (kPa)	Φ^0 (degree)
Sand	1.66	1.40	3.6	29

The slope stability analysis method used is the limit equilibrium method under static earthquake conditions. The slope stability analysis is performed using the Plaxis 3D LE software. Plaxis 3D LE is software developed by the Bentley Systems Team for analyzing slope stability using

the method of columns, an extension or development of the 2D slope stability analysis (Bentley Systems Team, 2021). This is a three-dimensional analysis capable of assessing stability across a wide area. Using Plaxis 3D LE allows for modelling the combination of complex topographies with 3D parameter distribution, including subsurface properties, as well as incorporating additional parameters like seismic load coefficients. The calculation of the factor of safety (FoS) in this analysis method is performed using the formula shown in Equation 2 (Bentley Systems Team, 2021).

$$FoS = \frac{\sum(c' + (N - uA) \tan \phi) \cos \alpha_x}{\sum N \cos \gamma_x + \sum Wkh \pm \sum D_x \pm P} \quad (2)$$

Where: c' = Cohesion; N = force normal to the column surface; ϕ = Internal Friction Angle ($^\circ$); P = resultant force from external water pressure; α = angle between the column and x-axis ($^\circ$); u = Pore Water Pressure; D_x = total force acting horizontally on the column along the x-axis; γ_x = angle of the normal force acting at the base of the column; A = volume area of the column; kh = Seismic coefficient; W = weight.

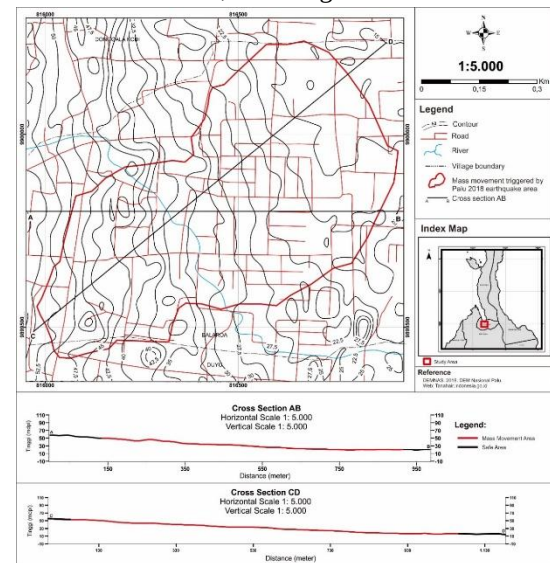


Fig. 5: Study area contour map and cross section.

The results of this analysis include the distribution of potential slip surfaces and the distribution of slope Factor of Safety (FoS) values for the study area in a 3D model. The analysis specifically focuses on the seismic conditions during the 2018 Palu earthquake.

4. Results and Discussion

The design of the three-dimensional model used in this study is based on the pre-7.4 Mw Palu earthquake condition on September 28, 2018. This condition also shows that the surface topography used was the condition before the mass movement triggered by the earthquake occurred in the study area. The subsurface model is based on the input data of the geological and geotechnical conditions of the study area.

The Three-dimensional slope stability analysis in this study is designed based on two simulation conditions: without seismic load (non-seismic analysis) and under the seismic conditions of the Palu earthquake on September 28, 2018. The slope stability analysis is performed using the Plaxis 3D LE software to calculate the factor of safety (FoS) value.

The base data for this modelling utilises DEMNAS data recorded in 2017, which is then exported into Plaxis Designer in the form of contours and converted into a mesh design. From this design, volume modelling is carried out, which serves as a reference for the 3D modelling used in the slope stability analysis (Fig. 6).

After the slope stability analysis results are obtained, validation is performed by comparing the factor of safety (FoS) from the map result of the 3D stability analysis with the minimum factor of safety ($FoS < 1$) as a reference for assessing potential landslide hazards. This validation is carried out for both scenarios: without the influence of seismic load and with the influence of the 2018 Mw 7.4 Palu earthquake.

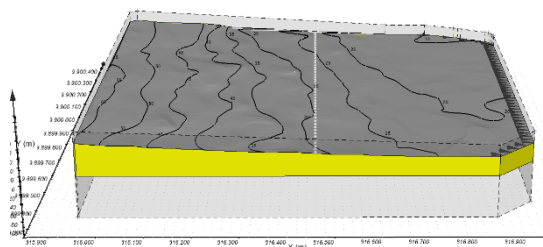


Fig. 6: 3D model design of the study area.

A. Three-dimensional Slope Stability Analysis Without Seismic Load (non-seismic Load)

This slope stability analysis simulation represents the original slope stability of the study area before the occurrence of the mass movement

triggered by the 7.4 Palu earthquake in the study area. The results of the slope stability analysis under non-seismic conditions show that the distribution of factor of safety (FoS) values in the study area ranges from 2.07 to 4.46, as shown in Figs. 7 and 8.

Based on the factor of safety (FoS) map result of the slope stability analysis under non-seismic conditions with spatial distribution, the slip surface areas in the study location are distributed in several zones, primarily in the steeper slope western part of the study area. In contrast, in the gentler eastern part of the study area, no slip surfaces are identified.

According to the validation of the factor of safety (FoS), the slip surfaces formed in this study analysis have a factor of safety (FoS) greater than the minimum factor of safety (FoS) (i.e., $FoS > 1$). Therefore, it can be interpreted that under the simulated slope stability analysis without seismic influence (non-seismic), the whole study area is in a stable state.

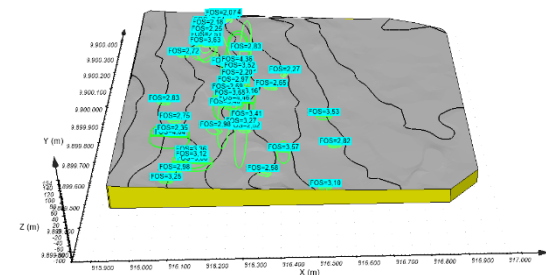


Fig. 7: 3D model of the slope stability analysis under the condition without seismic load showing a FoS range of 2.07 to 4.46.

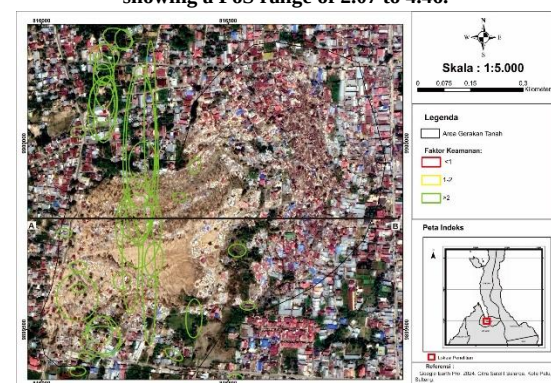


Fig. 8: Overlay map of the Balaroa landslide area and the results of slope stability analysis under non-seismic conditions with a Factor of Safety (FoS) ranging from 2.07 to 4.46.

B. Three-dimensional slope stability analysis under the 7.4 Palu Earthquake (seismic load)

The Three-dimensional slope stability analysis in this study is designed under seismic conditions. The seismic influence applied in this actual landslide.

Table 3: Input seismic load coefficient data

Under Condition	Seismic load coefficient (Kh)
7.4 Palu Earthquake 2018	0.35

The results of the slope stability analysis show that the distribution map of the Factor of Safety (FoS) in the study area ranges from 0.66 to 0.90, as shown in Figs. 9 and 10. Based on these results, the spatial distribution of slip surfaces extends across almost the entire study area, particularly in regions with steeper slopes, where the Factor of Safety (FoS) is less than 1.

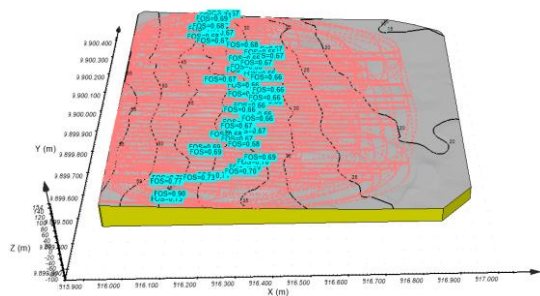


Fig. 9: 3D model of the slope stability analysis results for the Palu 2018 earthquake scenario with a Factor of Safety (FoS) ranging from 0.66 to 0.90.

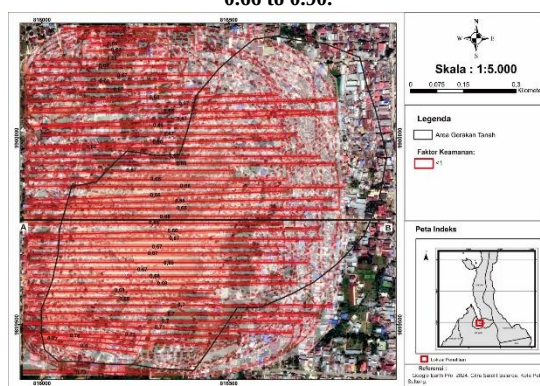


Fig. 10: Overlay map of the Balaroa landslide area and the results of slope stability analysis under the Palu 2018 earthquake scenario with a Factor of Safety (FoS) ranging from 0.66 to 0.90.

The map of the factor of safety result (FoS) in this analysis indicates that almost the whole study area was in an unstable state ($FoS < 1$). Compared with the map of the factor of safety

stability analysis is based on the seismic load coefficient values derived from seismographic records of the 2018 Palu earthquake event (Table 3). This simulation shows the current slope stability condition of the study area, which is indicated by the factor of safety (FoS) and compared with the result (FoS) under non-seismic conditions, it can be interpreted that the seismic event was the main factor in decreasing the factor of safety (FoS). This seismic event caused an increase in soil shear stress beyond its shear strength. The imbalance caused the driving forces for soil movement to exceed the resisting forces. This condition triggered instability of the slope, causing a landslide to occur.

Based on the comparison of the spatial distribution of potential slip surface results from the slope stability analysis and the area coverage of the actual massive mass movement triggered by the 2018 Mw 7.4 Palu Earthquake, as shown in Fig. (10), it is identified that the result of the analysis area has the same coverage area as the mass movement that occurred in Balaroa after the earthquake. This area analysis result is relatively consistent with the actual mass movement in the study area. It can be interpreted that the massive landslide that occurred in the study area was significantly influenced by the Mw 7.4 Palu earthquake event on 28 September, 2018.

5. Conclusion

The three-dimensional slope stability analysis results under non-seismic conditions showed a distribution of FoS from 1.36 to 4.98. This condition shows that the FoS values are greater than the minimum standard of FoS (i.e., $FoS > 1$). It can be interpreted that under the simulated slope stability analysis without seismic influence (non-seismic), the whole study area was in a stable state.

The three-dimensional slope stability analysis results under the 2018 Palu earthquake condition show that the map distribution of FoS in the study area ranges from 0.66 to 0.90, as shown in Figs. 9 and 10. According to these results, the spatial distribution of slip surfaces extends across almost the entire study area, particularly in regions with steeper slopes. Compared to the factor of safety (FoS) distribution under non-seismic conditions, it can be interpreted that the seismic event was the primary factor contributing to the

reduction in FoS. The earthquake induced an increase in soil shear stress, exceeding its shear strength. This imbalance caused the driving forces of soil movement to surpass the resisting forces, ultimately triggering slope instability and resulting in a landslide.

The evaluation of this study is based on the comparison between the three-dimensional slope stability analysis result with the actual massive mass movement coverage area that occurred in the study area during the 2018 Mw 7.4 Palu earthquake. The evaluation result shows that the analysis area has the same coverage area as the mass movement that occurred in Balaroa after the earthquake. This evaluation result is consistently the same as the actual mass movement in the study area. It can be concluded that the massive mass movement that occurred in the study area was significantly influenced by the Mw 7.4 Palu earthquake event on 28 September, 2018.

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7. Conflict of Interest

The authors declare that they have no conflict of interest.

8. Funding Statement

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تقييم ثلاثي الأبعاد لاستقرار المنحدرات تحت تأثير الأحمال الزلزالية: دراسة حالة في

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الملخص

كان زلزال بالو (7.4 Mw) سنة 2018 أحد أكبر الكوارث الطبيعية في تاريخ أندونيسيا. أعقب هذا الحدث الكارثي تحركات جماعية هائلة في منطقة الاروا مما أدى إلى أضرار جسيمة في البنية التحتية وخسارة فادحة في الأرواح. ظهر تحليل استقرار المنحدر ثلاثي الأبعاد في ظل الظروف الزلزالية كأحد الحلول الفعالة للوقاية من آثار كوارث الحركة الجماعية الناجمة عن الزلازل وتخفيفها، وخاصة في المناطق الواسعة. كان الهدف من هذه الدراسة هو تقييم نتيجة خريطة عامل الأمان (FoS) مع الحركة الجماعية الهائلة الفعلية التي حدثت خلال زلزال بالو 2018 Mw 7.4. كانت منهجية البحث هي تحليل الاستقرار ثلاثي الأبعاد في ظل الظروف غير الزلزالية والزلزالية مع معامل الحمل الزلزالي (Kh) تحت زلزال بالو 2018 Mw 7.4، باستخدام Plaxis 3D LE. كانت متغيرات الإدخال المستخدمة في هذا البحث هي النمذجة ثلاثية الأبعاد لمنطقة الدراسة ومعلومات التربة ومعامل الحمل الزلزالي. تُظهر نتائج تحليل استقرار المنحدر ثلاثي الأبعاد أن خريطة FoS في ظل ظروف غير زلزالية، حيث تراوحت FoS بين 2.07 و 4.46، ونتائج زلزال بالو الذي بلغت قوته 7.4 درجة على مقياس ريختر عام 2018، حيث تراوحت FoS بين 0.66 و 0.90. يستند هذا التقييم إلى مقارنة نتائج التحليل بحركة الكتلة الهائلة الفعلية في ظل زلزال بالو الذي بلغت قوته 7.4 درجة على مقياس ريختر عام 2018. وتتوافق نتائج هذا التحليل نسبيًا مع حركة الكتلة الفعلية في منطقة الدراسة. ويمكن تفسير ذلك بأن الانهيار الأرضي الهائل الذي حدث في منطقة الدراسة قد تأثر بشكل كبير بزلزال بالو الذي بلغت قوته 7.4 درجة على مقياس ريختر في 28 ايلول 2018.

الكلمات المفتاحية:

استقرار المنحدرات، عامل الأمان، زلزال، حمل زلزالي، تحرك جماعي.

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