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STATIC AND PSEUDO-STATIC SLOPE STABILITY ANALYSIS USING MORGENSTERN-PRICE METHOD (STUDY CASE EMBUNG UNPAD, JATINANGOR, WEST JAVA, INDONESIA)

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ABSTRACT

Infrastructure areas require preliminary geotechnical analysis, which includes slope design and periodical evaluation for assessing changes in geotechnical conditions due to the influence of earthquake loads, human activities, and environmental changes. Factors such as rainfall, groundwater level and earthquake vibrations play an important role in influencing slope stability, so slope stability analysis is an aspect that needs to be considered in geotechnical engineering, especially in areas prone to seismic activity. This research aims to evaluate slope stability using the Morgenstern-Price method, which combines static and pseudo-static conditions to assess the impact of seismic loads. This research focuses on analyzing slope stability in the Embung Unpad area, Jatinangor, which is located in a seismically active zone. The slope is characterized by volcanic soil derived from weathered young volcanic rocks, with slopes varying from moderate to steep. This research focuses on comparing 2D and 3D analysis approaches to determine their accuracy and reliability in capturing critical slope stability factors in seismic scenarios. In the analysis, the stability of the slope is calculated using the statistical-probabilistic method to determine the percentage of slope failure. The simulation results show that the stability analysis using the 3D approach produces a higher safety value than the 2D approach, namely FoS value of 0.955 in 3D analysis and FoS value of 0.913 in 2D analysis. 3D analysis is generally able to capture the complexity of slope geometry and parameters more thoroughly than 2D approach, one of which can evaluate the landslide mechanism in 3D characterized by the landslide volume that can occur. However, since the 3D model in this study is the result of 2D extrude model and consists of 1 material, the model in this study has lower complexity than if the constituent materials are heterogeneous. However, this study has the limitation that the 3D model is the result of extruded volume from 2D geometry with the result that the difference in FoS value is relatively similar between 3D and 2D models. This research highlights the importance of detailed analysis of slope safety risks in seismically active areas to ensure the sustainability and safety of surrounding infrastructure.

Keywords: Slope stability, seismic, Pseudo-static, 3D analysis, probabilistic analysis

ABSTRAK

Perancangan lereng pada kawasan infrastruktur memerlukan analisis geoteknik pendahuluan dan evaluasi berkala untuk menilai perubahan kondisi geoteknik akibat pengaruh beban gempa, aktivitas manusia, serta perubahan lingkungan. Faktor-faktor seperti curah hujan, tinggi muka air tanah, dan getaran gempa bumi memainkan peran penting dalam memengaruhi stabilitas lereng sehingga analisis stabilitas lereng merupakan aspek yang perlu diperhatikan dalam rekayasa geoteknik, terutama di daerah yang rawan aktivitas seismik. Penelitian ini bertujuan mengevaluasi stabilitas lereng dengan menggunakan metode Morgenstern-Price, yang menggabungkan kondisi statis dan pseudo-statik untuk menilai dampak beban seismik. Penelitian ini berfokus pada analisis stabilitas lereng di kawasan Embung Unpad, Jatinangor, yang berada di zona aktif seismik. Lereng di area Embung ini memiliki karakteristik tanah vulkanik yang berasal dari batuan vulkanik muda yang telah mengalami pelapukan, dengan kemiringan bervariasi dari sedang hingga curam. Penelitian ini berfokus pada perbandingan pendekatan analisis 2D dan 3D untuk menentukan keakuratan dan keandalannya dalam menilai faktor stabilitas lereng yang kritis dalam skenario seismik. Dalam analisisnya, kestabilan lereng dihitung menggunakan metode statistik-probabilistik *untuk mengetahui persentase kelongsoran dari lereng tersebut. Hasil simulasi menunjukkan bahwa analisis stabilitas dengan pendekatan 3D menghasilkan nilai keamanan yang lebih tinggi dibandingkan pendekatan 2D yaitu nilai FK sebesar 0.955 dalam analisis 3D dan nilai FK sebesar 0.913 pada analisis 2D. Analisis 3D umumnya mampu menangkap kompleksitas geometri dan parameter lereng secara lebih menyeluruh dibandingkan pendekatan 2D, salah satunya dapat mengevaluasi mekanisme longsor secara 3D ditandai dengan volume longsor yang dapat terjadi. Akan tetapi, karena model 3D pada penelitian ini merupakan hasil extrude model dari 2D dan terdiri dari 1 material sehingga model dalam penelitian ini memiliki kompleksitas yang lebih rendah dibandingkan jika material penyusunnya heterogeneous. Namun, penelitian ini memiliki keterbatasan model 3D yang merupakan hasil extruded volume dari geometri 2D dengan hasil perbedaan nilai FoS yang tidak terlalu jauh antara model 3D dan 2D. Penelitian ini menggarisbawahi pentingnya analisis mendetail terhadap risiko keamanan lereng di kawasan aktif seismik untuk memastikan keberlanjutan dan keselamatan infrastruktur di sekitarnya.*

Kata kunci: *Kestabilan lereng, seismik, pesudo-static, analisis 3D, analisis probabilistik*

INTRODUCTION

Slope design in infrastructure areas requires an initial geotechnical analysis and subsequent periodic evaluation. Initial geotechnical analysis of the slope seeks to identify the characteristics of the soil, mechanical properties of materials, seismic load and hydrological conditions that affect stability (Gol et al., 2016; Kusnadi, 2017; Mebrahtu et al., 2022; Olabode et al., 2022; Radityo et al., 2024; Rotaru et al., 2022). This periodic evaluation assesses changes in geotechnical conditions caused by the influence of seismic loads, human activities, and environmental changes, including those caused by rainfall, groundwater levels, and earthquake vibration (Jeanne et al., 2021; Marquez & Kamalzare, 2019; Vittecoq et al., 2020). Such methodology becomes important to mitigate the risks associated with possible slope failures, which could threaten the safety of nearby infrastructure and communities. This, therefore, gives reasons for including numerical, empirical, and experimental analytical techniques in the design to assure that it is safe, efficient, and sustainable.

Slope stability analyses using the 2D limit equilibrium method have been performed by many researchers. However, slope stability analysis using the 3D limit equilibrium method is still unfamiliar. In fact, the 3D approach has the potential to provide more realistic results because it is able to consider variations in slope geometry and force distribution in three dimensions (Ahmad Azizi et al., 2021; Aruan et al., 2024; Hu et al., 2022). The limitations to the use of 3D methods are mainly due to the complexity of the calculations, the requirement of more detailed data, and the relatively high computational costs. However, the modern computing technology makes it increasingly possible and relevant to apply 3D analysis to complex slope cases. Further study is expected to encourage the wider applications of the 3D method in research and practice of geotechnical engineering, regarding its benefits and limitations (Kumar et al., 2023). This paper compares the slope safety risk, using 2D and 3D approaches on the slope wall, around Embung Unpad Jatinangor in relation to the seismicity factor. This study is very relevant in the view of recent seismic activity occurring in the area of Sumedang City, which may influence slope stability in the area. Moreover, the existence of other potential active faults, such as the Lembang Fault and the Tanjungsari Fault, increases the urgency to study the impact of seismic activity on slope stability (Nugraha et al., 2019). It will involve an assessment incorporating earthquake-induced dynamic parameters such as peak ground acceleration (PGA) and dynamic response of soil, in an effort to fully understand the associated hazards. This research is therefore expected to contribute meaningfully to the field of geotechnical risk management, particularly for infrastructure located in areas of high seismic activity.

MATERIAL AND RESEARCH METHOD

Study Area

The study focuses on the slopes near Embung Unpad, Jatinangor, located in a seismically active zone, which is close to the Lembang fault (Daryono et al., 2019) and the Sumedang active fault that caused 2023 4.8 Mw earthquake. The area features volcanic soils derived from weathered tuffaceous young volcanics rock, with slope gradients ranging from moderate to steep. The embung (reservoir) infrastructure introduces additional loading conditions.

Figure 1. Study Area

Data Observation
The data were gathered through an elaborate field survey that meant to collect geological and geotechnical information from the designated study area. The collection of data included sampling of soil and rock, measurement of slope geometry, and a thorough documentation of findings. Undisturbed samples were collected at different sites from depths ranging from 0.5 to 2 meters (ASTM D1587, 2015). It was known in the research area that the upper part of the slope layer was a 40 cm thick top soil and the lower area was a completely weathered zone soil. Soil samples are from 4 samples directly collected in the field from UDS soil collection, and primary sample data before Embung Unpad was constructed in 2018. The soils were sampled for obtaining unit weight, cohesion and internal friction angle from the direct shear test in The Laboratory of Engineering Geology, FTG Unpad. These tests are helpful in defining the strength parameters of the soils, which become very vital in stability analysis.

Table 1. Material Properties Sample

Sample	Depth (m)	Material Properties		
		Unit Weight (kN/m$^{3)}$	Cohession (KPa)	Phi (°)
1	0.2 – 0.6	15.26	16.621	27.75
2	0.3	14.147	3.64	3.314
3	0.3	13.56	10.7	2.039
4	0.3	16.14	6.6	7.128

Slope Geometry
The slope geometry in the research area was obtained by primary data from direct measurements in the field including the height of the slope, the overall angle of the slope, the width of the bench, as well as the angle between benches until it reaches the Embung Unpad Jatinangor. The research slope has a height of 10 m with an overall slope angle of 21°. The slope is divided into three benches with angles of 40°and 29° from the actual condition in the field. The following is a 2D cross section of the research slope generated using Rocscience Slide2. The three-dimensional models is extruded from the two-dimensional measurement of the slopes in the field.

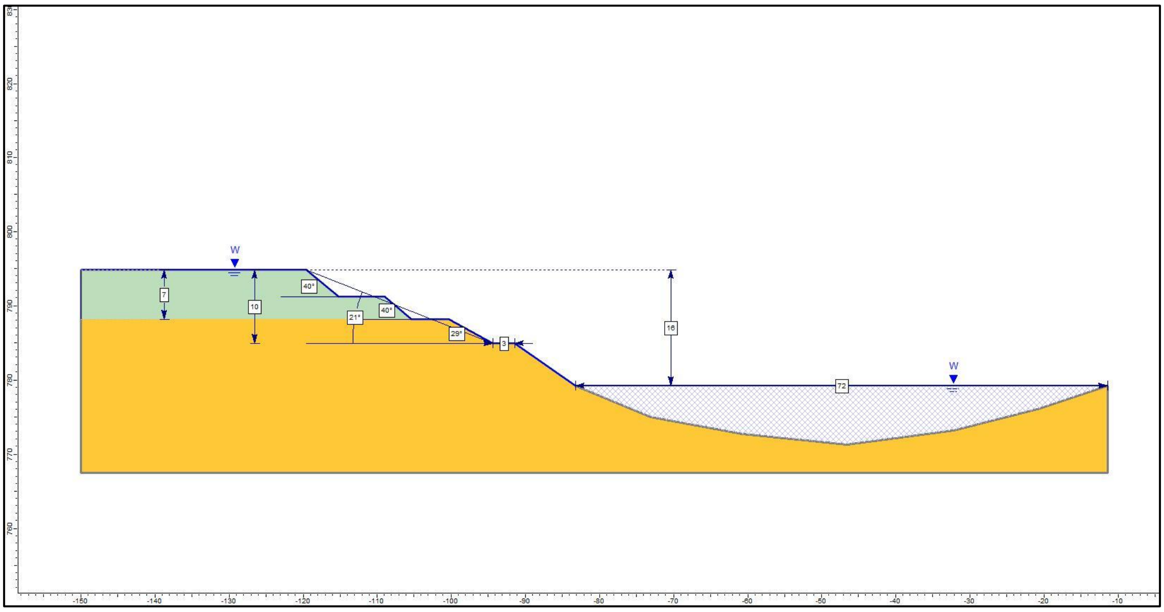


Figure 2. Slope Geometry

Laboratory Analysis

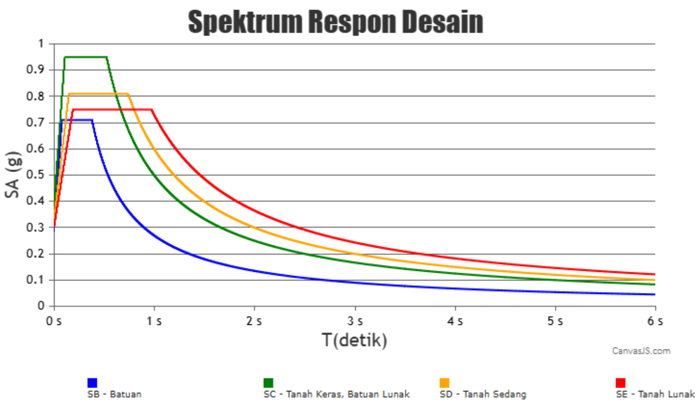
To obtain the soil's geotechnical characteristics, including its mechanical and physical characteristics, laboratory tests were carried out such as direct shear test to obtain the mechanical properties of the soil. The output of this test is to determine the soil's cohesion and internal friction angle, which are input parameters for the Mohr-coulomb strength type computation of slope stability. Tests were conducted on samples from the soil layer with undisturbed sample conditions. Each sample was tested twice with different normal loads. In addition, the field testing of rock mechanical properties was carried out with geological hammer and knife to determine the value of rock strength (Ren et al., 2019). GSI and Mi values are also determined because the rock calculation method uses Generalized Hoek-Brown. In addition to mechanical properties, physical properties were also tested by calculating the unit weight of the soil. The unit weight test is conducted to measure the weight of the soil content by comparing the total weight of the soil with the total volume of the soil. Soil content weight plays an important role in slope stability analysis, because it is directly related to the gravitational force that can cause soil movement.

Seismic Data

Seismic data is used to determine the effect of existing vibrations on the research area. Historical earthquake data for the region were obtained, focusing on peak ground acceleration (PGA) values. In the research area, there are various earthquake histories that affect the magnitude of the PGA value. Earthquake history is depicted with colored circles that show the depth of the earthquake that occurred. The larger the circle indicates the greater the magnitude of the earthquake in the area. On December 31, 2023, an earthquake with a magnitude of 4.8 Mw struck the Sumedang Regency in West Java (Jabar). The Geological Agency identified the source of the earthquake as the Cileunyi-Tanjungsari Active Fault, which has a northeast-southwest direction and is classified as a sinistral fault. Its distribution starts from the south of Tanjungsari Village, then towards the Cipeles River valley, west of Sumedang City. There is also the Lembang fault in the northwest part of the research area which is a thrust fault. The presence of these faults has a significant influence on the magnitude of the PGA value because faults are the main source of seismic energy release during earthquakes. The closer a location is to an active fault, the higher the perceived PGA value.

Figure 3. The History of Earthquake on Study Area

The value of PGA in the research area is based on the spectra response of the research area from Kementrian Pekerjaan Umum dan Perumahan Rakyat (PUPR) which is the dynamic response of the soil that makes up the research area to earthquakes. This spectra illustrates how a structure will respond based on the frequency and period of vibration, especially in the context of earthquakes recurrence with a probability of 5% in 50 years. In bed rock, the dynamic response to earthquakes is 0.4 g.



Results: Tabel dibawah ini merupakan Parameter untuk membuat Grafik Desain Spektra Indonesia:

Kelas	Semua	
Rentang T(s)	Value: 6	
PGA MCEG	0.5179	(g) bedrock
SS MCEr	1.1807	(g) bedrock
S1 MCEr	0.5011	(g) bedrock
TL	6	Detik

Kelas	T0(detik)	Ts(detik)	Sds(g)	Sd1(g)
SB	0.08	0.38	0.71	0.27
SC	0.11	0.53	0.95	0.50
SD	0.15	0.74	0.81	0.60
SE	0.19	0.97	0.75	0.73

Save

Figure 4. The Spectra dynamic response to earthquake near Embung Unpad

Research Methodology

The research method for conducting geotechnical evaluation is carried out into several stages starting from data collection, laboratory testing, and slope stability analysis. Data collection was carried out by direct observation in the field including measurement of slope geometry and undisturbed sampling. Soil testing was conducted in the laboratory on soil and rock samples to obtain geotechnical properties including cohesion value, internal friction angle, and uniaxial compressive strength. These tests help determine soil strength parameters, which are critical for stability analysis.

Slope Stability Analysis

In calculating the slope stability analysis, the Limit Equilibrium method (LEM) used for analysing the stability of slopes based on the principle of force equilibrium. This method assumes that the failure surface of the slope can be assumed either circular or non-circular (Deng et al., 2023). The type of LEM used in this research is the Morgenstern Price method formulated by Morgenstern (Morgenstern & Price, 1965). This method can be applied to all types of failure and satisfies all the conditions of equilibrium. The Morgenstern-Price method uses the same assumptions as the general limit equilibrium method, namely the relationship between the shear force between slices and the normal force between slices (Furuya, 2004). The equation based on the forces acting on a slice is as follows:

$$x = \lambda \cdot f(x) \cdot E' \text{ (eq. 1)}$$

Where x denotes the vertical shear force on the side of the slice, λ is a parameter, and $f(x)$ is the factor of inter-slice force.

From the equilibrium conditions acting on an infinitesimal slice (Fig. 5), we obtain :

$$E = \frac{1}{L+Kx}\left[E_i L + \frac{N_x^2}{2} + P_x\right] \text{ (eq. 2)}$$

$f = kx + m$, the function f is defined by equation (1) depends linearly on x.

E_0 equals zero at the beginning of the slip surface in the usual case. The value of E_n at the end of a slip surface is determined by integration across each slice. E_0 is usually zero from the boundary conditions. From the moment equilibrium about the midpoint of the infinitesimal slice, after simplifying and proceeding to the limit as dx -> 0, the following equation is derived:

$$X = \frac{d}{dx}(E^1 \cdot y_t') - y\frac{dE'}{dx} + \frac{d}{dx}(P_w \cdot h) - y\frac{dP_w}{dx}$$
(eq. 10)

By integrating equation (13), we obtain:

$$M = E(yt - y) = \int_{x^0}^{x} \left(x - E\frac{dy}{dx}\right) dx \text{ (eq. 11)}$$

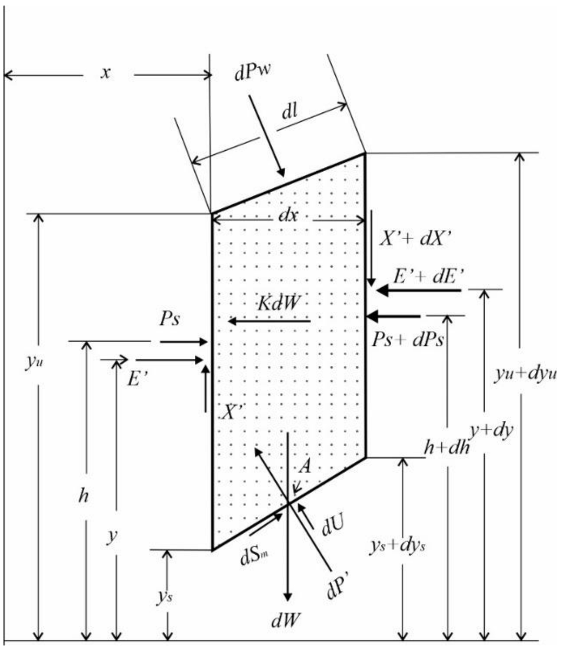


Figure 5. The forces on morgenstern-price slice (modified from *(Furuya, 2004)*)

In analyzing the stability of the slope, the research used the 2D method where then the section was processed by extruding the two-dimensional cross-section into a three-dimensional model to analyze the stability of the slope in three dimensions. In the 3D method, the mass along the slide plane is discretized into a vertical column with a square cross-section. The 2D wedge-based method satisfying force and/or moment equilibrium can be extended to the 3D column method where forces and moments are analyzed in two orthogonal directions. This 3D method was further developed by Cheng & Yip (2007) by developing equilibrium moments and forces in two orthogonal directions, the direction of the slip plane is specified rather than assumed, and the 3D system equations are statistically determined. The method of Cheng & Yip (2007) first considers the vertical equilibrium force (z-direction) as a single column of

$$\sum Fz = 0 \rightarrow N_i g_{3i} + S_i f_{3i} - (W_i + P_{vi}) = (Xx_{i+1} + Xx_i) + (Xy_{i+1} + Xy_i) \text{ (eq. 12)}$$

Then the normal and shear forces at the bottom can be determined through:

$$N_i = A_i + B_i S_i; \; S_i = \frac{C_i + (A_i - U_i) tan\Phi_i}{F[1-(\frac{B_i tan\Phi_i}{F})} \text{ (eq. 13)}$$

Where

$$A_i = \frac{W_i + P_i + \Delta Ex_i \lambda_x + \Delta Ey_i \lambda_y}{g_{3i}}; \quad B_i = \frac{f_{3i}}{g_{3i}} \text{ (eq. 14)}$$

Description:
A_i : Effective cohesion strength
B_i : Width of slice base
λ_x : stability coefficient

Pseudo-static Analysis

In assessment of the impact of the seismic vibration coefficient on slope stability, there is a need to establish the appropriate seismic coefficient which would be consistent with the amplitude magnitude of inertial forces imposed on the slope due to dynamic forces produced during an earthquake. The process of selecting coefficients for slope stability analysis is inherently subjective; thus, guidance is needed on the values of horizontal seismic coefficients. Melo and Sharma (2004) had summarize the utilization of the horizontal seismic coefficients in table 1.

Table 2. Recommended Horizontal Seismic Coefficients Modified *Melo and Sharma (2004)*

Horizontal Seismic Coefficient (Kh)	Description	
0.05 - 0.15	Used In the United States	
0.12 - 0.25	Used In Japan	
0.1	“severe” earthquakes	Sources from Terzaghi (1950)
0.2	“Violent, destructive” earthquakes	
0.5	“catastrophic” earthquakes	
0.1 - 0.2	FoS ≥ 1.15 (Seed, 1979)	
0.10	Major Earthquake, FoS > 1.0	Sources from Corps of Engineers (1982)
0.15	Great Earthquake, FoS > 1.0	
½ to 1/3 of PHA	FoS >1.0 (Marcuson, 1983)	
½ of PHA	FoS > 1.0 (Hynes-Griffin, 1984)	
FoS = Factor of Safety. PHA = Peak Horizontal Acceleration, in g’s		

As indicated in Table 1, there are no set procedures for selecting seismic coefficients appropriate for design. However, various selection criteria indicate that the seismic coefficient should be based on the predicted acceleration level inside the failure mass and correspond to a fraction of the expected peak acceleration.

The pseudo-static analysis is based on the method in which dynamic aspects of seismic activity are ignored, and the slope is considered to be under an additional static load (Day, 2007). The pseudo-static method includes a lateral force that acts at the shear centre of mass, acting outwards from the slope. The pseudo-static lateral force (Fh) is calculated using:

$$F_h = ma = \frac{Wa}{g} = \frac{Wa_{max}}{g} = k_h W \textit{ (eq. 14)}$$

Where:

- F_h = horizontal pseudo-static force acting through the shear center of mass (kN)
- m = total mass of displaced material (kg)
- W = total weight of displaced material (kN)
- a = maximum horizontal acceleration or acceleration at the ground surface caused by the earthquake (a=amax=m/s^2)
- amax = maximum horizontal acceleration at the ground surface caused by an earthquake (m/s^2)
- amax/g=K_h = seismic coefficient, also known as pseudo-static coefficient

In the wedge type slope stability analysis, the assumption is that the forces acting on the slope will act in a direction parallel to the planar sliding surface. Thus, the slope safety factor can be obtained by summing the forces parallel to the sliding surface to obtain the following results: Total stress pseudo-static analysis:

$$Fs = \frac{Resisting\ Force}{Driving\ Force} = \frac{cL + N\ tan\varphi}{W \sin\alpha + F_h\ Cos\alpha} = \frac{cL + (W cos\alpha - F_h\ sin\alpha)\ tan\,\varphi}{W \sin\alpha + F_h\ Cos\alpha} \textit{ (eq. 15)}$$

Probabilistic Analysis

The sampling method employed in this study is Monte Carlo because this method is a relatively simple probability method, the ability to model the correlation between variables, and is flexible when combining large varieties of probability distributions with few interpretations (Ceryan et al., 2018). In this analysis, there are variations in the material properties of the slope so that the

Monte Carlo sampling method is used by considering the uncertainty factor related to the stability of the slope at the time of analysis. The Monte Carlo simulation requires a threshold uses a safety factor based on the concept of boundary equilibrium calculation, meaning the slope is considered safe if FoS > 1, and will experience a landslide if FoS < 1. The probability of failure is determined from each test that meets these assumptions. It is important to note that the Monte Carlo simulation must run a certain number of tests to generate a normal distribution for its modelling (Gibson, 2011), (Adriansyah et al., 2021). The random distribution takes the same probability of every value in the specified range. The probability of slope stability is applied to calculate the Factor of Safety (FoS) Index that meets with all uncertainty for the parameters. We use Monte Carlo techniques for simulating FoS by combining distribution random input parameters.

RESULT AND DISCUSSION

Geotechnical Properties Embung Slope

The soil conditions were evaluated through direct field observations and supplementary sampling for a more detailed description. Soil type classification was performed using the Unified Soil Classification System (USCS) based on parameters like color, strength level, weathering degree, stratification structure, and moisture content. At the study site, the surface soil is 40 cm top soil that has a blackish brown color with a lot of overgrown vegetation on it. The bottom layer is soil that is classified as High Plasticity Clay (CH), which forms the topmost layer at slopes and surrounding areas. The soil has a reddish brown to blackish brown color with clay-sized particles and moderately plastic plasticity. It is also known for having a high moisture content that makes it cohesive in texture. The degree of weathering of this soil falls within the completely weathered zone. The soil of the studied area is supposed to be formed due to weathering processes of tuff, which is confirmed by identifying lithological outcrops representing the yellowish-brown tuff, weathered and with a coarse grain size. According to the classification of the International Society for Rock Mechanics (ISRM), 1978, this tuff has the strength classification from R0 to S6, which is described as weathered tuff capable of being compressed several inches under slight thumb pressure.

Figure 6. View of the research slope area from afar

Figure 7. Close-up of the research slope area indicates weathered tuff

From the laboratory tests that have been carried out, the data obtained will be used to calculate the stability of the slope on the research area. Before putting the laboratory test data into the research, statistical analysis was performed on the material properties of the research slope in order to acquire statistical data such as data distribution, average, maximum and minimum relative values needed as data validation in determining the probability of failure. The relative minimum value is obtained from the mean value subtracted by the lowest value, and the relative maximum value is obtained from the highest value subtracted by the mean value. The random variables used in this study are cohesion, Internal Friction Angle, and UCS values derived from the results of soil and rock mechanics tests on the samples. From the 4 data in monte carlo statistics, 1000 iterations of sampling were carried out and met the standards of probabilistic statistical analysis for slope stability analysis. Statistical analysis of material properties on slope is given in the following table.

Table 3. Statistical parameters of material properties

Soil			
Parameters	**Cohesion (KPa)**	**Internal Friction Angle (°)**	**Unit Weight (kN/m^3)**
Distribution	Log Normal	Log Normal	Log Normal
Mean	10.0585	9.39025	14.779
St Dev	11.9915	5.62287	1.14796
Minimum	2.039	3.64	13.56
Maximum	27.751	16.621	16.14
Skewness	1.8135	0.631654	0.267938
Kurtosis	3.30744	-0.526785	-2.34852
Relative Minimum	8.01885	5.75025	1.2116
Relative Maximum	17.6925	7.23075	1.3621
Tuff			
Parameters	**UCS (Kpa)**	**GSI**	**Mi**
Mean	2750	30	13
Minimum	500		
Maximum	5000		
Relative Minimum	2250		
Relative Maximum	2250		

Slope Stability Analysis

Slope stability analysis was conducted using the Morgenstern-Price method with 2-dimensional and 3-dimensional methods to determine the difference in the resulting FoS values using Rocscience Slide2 and Slide3. The following table 4 shows the results of the calculation of the FoS value and the probability of landslides in the calculation of the stability of the 2 dimensional and 3 dimensional slopes.

Table 4. Recapitulation of FoS value of 2D Slope at static and dynamic conditions

Condition	**Factor of Safety Value**		
	2D		
	FoS Mean	**FoS Deterministic**	**PoF (%)**
Static	1.303	1.463	40.44
Pseudo-static	0.822	0.913	73.4

A comparative analysis of slope stability under both static and pseudo-static conditions is shown in Table 4 based on 2D Factor of Safety (FoS) values. The slope under static conditions shows sufficient stability with a mean FoS value of 1.303 and deterministic FoS value of 1.463, resulting in a low Probability of Failure (PoF) of 40.44%. However, under pseudo-static conditions—conditions that simulate the effects of an earthquake—the stability drops to a mean FoS <1. This drastic reduction in FoS and increase in PoF under dynamic loading clearly highlights the vulnerability of the slope to seismic event. However, the slip surface failure potentially slips only in the soil material and does not penetrate the weathered tuff as the bedrock (figure 8 and 9). Each colored point represents a potential slip surface generated through probabilistic analysis matches the FoS color scale. The number points represent the 1000 iteration of slip surface potential. The orange to red color points represent the Factor of Safety below 1 and the gren to blue color point represent the Factor of Safety > 1.

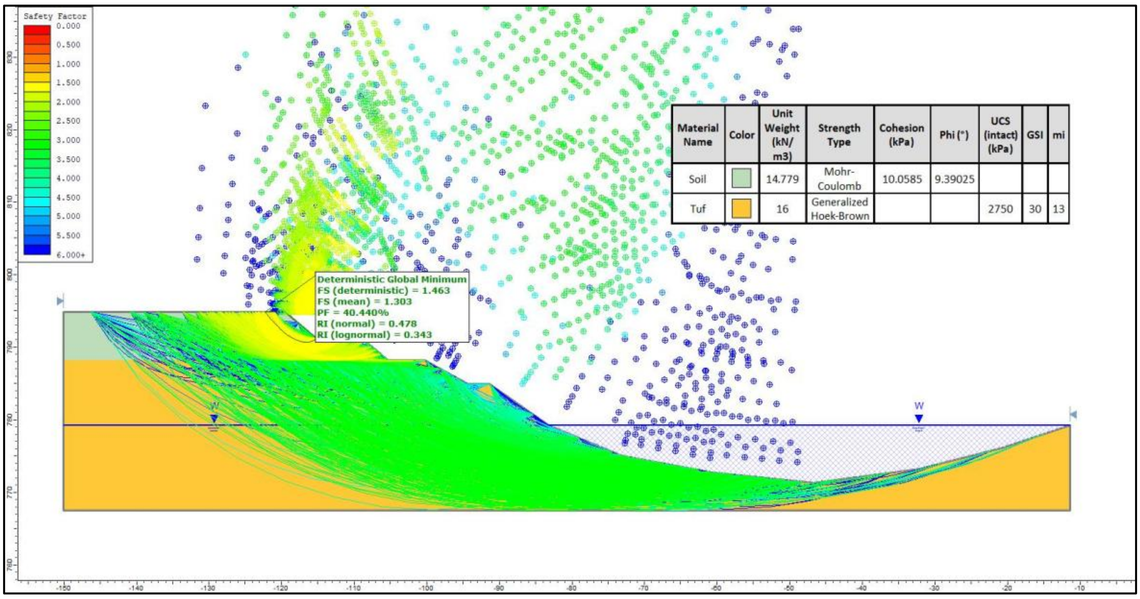


Figure 8. 2D slope simulation results under static conditions using Slide2 (FoS Value 1.463, PoF 40.44%)

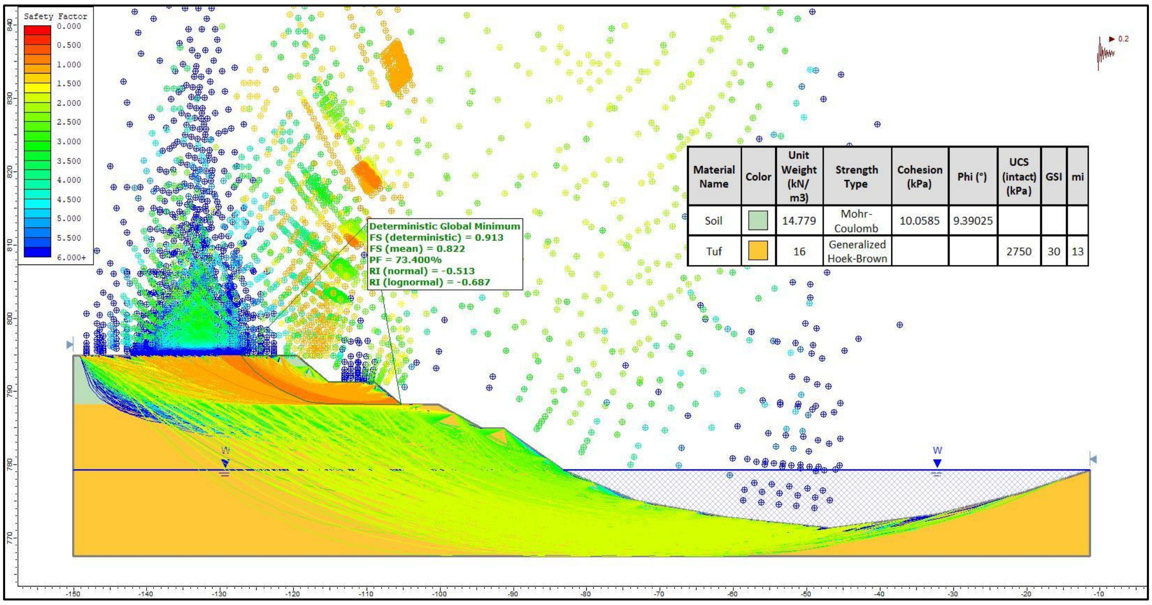


Figure 9. 2D slope simulation results under pseudo-static conditions using Slide2 (FoS Value 0.913, PoF 73.4%)

Table 5. Recapitulation of FoS value of 3D Slope extrude 50 m on pseudo-static condition

Condition	Factor of Safety Value 3D (Extruded Volume)	
	FoS Deterministic	PoF (%)
Static	1.497	40.7
Pseudo-static	0.955	70.8

Based on the table 4 provided, the FoS of a 3D slope extrude model of 50 m under pseudo-static conditions is calculated to 0.955, indicating unstable condition. The PoF is recorded at 70.8%, which suggests a high risk of slope instability due to seismic event.

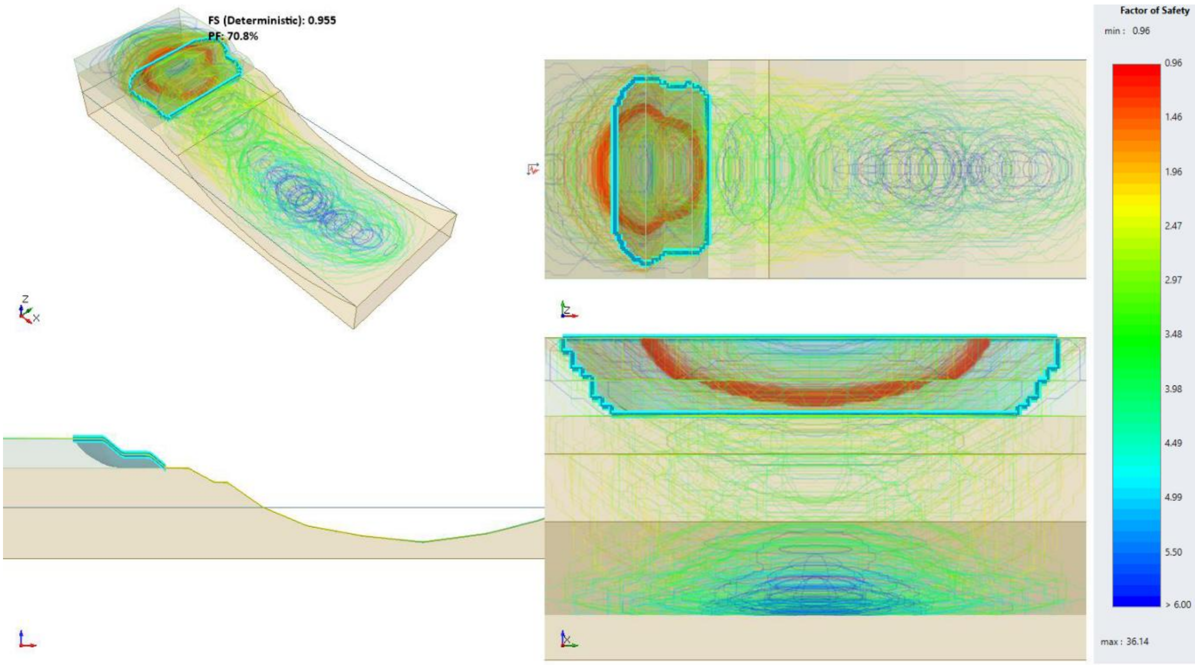


Figure 10. Figure 3D slope simulation results using Slide3 (FoS Value 0.955, PoF 70.8)

The results of the factor of safety values on slopes with 2 homogeneous materials in 2D and 3D analysis have a slightly different results. The factor of safety value in the 3D slope simulation has a greater value than the 2D slope simulation by 0.08368%. It is also known that sliding volumes in 3D analysis is smaller than those in 2D analysis so that the FoS value is greater (WU et al., 2024)**.** The 3-D approach for slope stability analysis is more in line with actual field conditions than the 2D approach (Read & Stacey, 2019).

There are several things that cause FoS values in 2D and 3D analysis to have different results, one of which is that 2D analyses are less complex than 3D analyses, which can require formulating intricate geometries and boundary conditions. Later McQuillan and Bar (McQuillan and Bar 2023) states that 3D models which are highly laterally constrained will produce a higher, unrealistic FoS than longer, laterally unconstrained 3D models. Thus, FoS values obtained from 3D analysis will be higher than with 2D analysis.

CONCLUSIONS

This research shows on the importance of detailed geotechnical analyses concerning slope stability in seismically active areas, especially around Embung Unpad, Jatinangor. The study, through the integration of field measurements, laboratory tests, and 2D and 3D stability analyses, represents the importance of evaluating slope safety risks under different seismic conditions. These findings of the study highlight the advantages of both 2D and 3D boundary equilibrium methods, even though they require more complicated data and computational effort. The pseudo-static approach combined with Monte Carlo simulations incorporates seismic loads and stochastic variations in geotechnical parameters into a rigorous worst-case risk assessment. These results underline the contribution of the local fault systems to seismic hazards and therefore slope stability assessments that need to be performed regionally. There is a decrease in FoS value during pseudo-static conditions in 2D and 3D simulations by 4.2%.

Another finding of the study lies in the difference between the slope safety factor values from 3D simulations compared to 2D simulations. The FoS in 3D Simulation shows slightly higher value than 2D simulation due to the complexity of subsurface models that are simplified through extruded volumes from 2D to 3D. Although in practice, the complexity of 3D analyses demands more parameters in order to make a better overall evaluation.

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