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Numerical and Field-Based Analysis of Soil Nailing for Slope Stability

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Abstract

Landslide occurrences in Indonesia are predominantly associated with soft soils and inadequate drainage conditions during periods of high-intensity rainfall. Nevertheless, the country's diverse geological settings pose significant challenges for implementing effective landslide mitigation strategies, particularly as most existing studies are concentrated on specific islands, each characterized by distinct geotechnical and geomorphological conditions. In certain areas of Flores Island, landslides have been observed at relatively shallow depths and steep slope angles, often occurring in remote locations. Additionally, the tectonic setting of Flores Island—surrounded by multiple active seismic sources—increases the susceptibility to both rockfalls and earthquake-induced landslides. Soil nailing has emerged as a promising stabilization technique in such conditions, particularly where subsurface materials exhibit high resistance to penetration (N-SPT > 60). Despite the steep terrain, the technique remains viable due to its adaptability and minimal disturbance to the existing slope geometry. Stability analyses conducted using both the FEM and LEM under static loading conditions indicate that soil nailing is effective in reinforcing the slope without inducing significant deformation. Furthermore, the reinforced slopes demonstrate sufficient stability under seismic loading, satisfying the design earthquake criteria stipulated by the Indonesian Standard.

Abstrak

Kejadian longsor di Indonesia umumnya berkaitan dengan kondisi tanah yang lunak dan sistem drainase yang tidak memadai selama periode curah hujan dengan intensitas tinggi. Namun demikian, keberagaman kondisi geologi menghadirkan tantangan dalam penerapan strategi mitigasi longsor yang efektif, terutama karena sebagian besar kasus yang ada masih terfokus pada pulau-pulau tertentu yang masing-masing memiliki karakteristik geoteknik dan geomorfologi yang berbeda. Di beberapa wilayah Pulau Flores, longsor yang terjadi pada kedalaman yang relatif dangkal dengan kemiringan lereng yang curam, dan sering kali terjadi di lokasi yang terpencil. Selain itu, kondisi tektonik Pulau Flores—yang dikelilingi oleh berbagai sumber gempa aktif—meningkatkan kerentanan terhadap jatuhan batu dan longsor yang dipicu oleh gempa bumi. *Soil nailing* muncul sebagai metode untuk mencapai stabilitas lereng pada kondisi yang curam dan batuan, terutama pada material lapisan yang relative keras (N-SPT > 60). Meskipun medan di wilayah tersebut curam, metode *soil nailing* sangat layak digunakan karena sifatnya yang adaptif dan minim gangguan terhadap geometrik lereng yang ada. Analisis stabilitas yang dilakukan dengan menggunakan Metode Elemen Hingga (FEM) dan metode Keseimbangan Batas (LEM) di bawah kondisi pembebanan statis menunjukkan bahwa *soil nailing* efektif memperkuat lereng tanpa menyebabkan deformasi yang signifikan. Selain itu, lereng yang diperkuat tersebut menunjukkan stabilitas yang memadai terhadap pembebanan seismik, dan memenuhi kriteria gempa rencana sebagaimana yang disyaratkan oleh Standar Nasional Indonesia (SNI).

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INTRODUCTION

Landslides on Indonesian national highways are common phenomena every year (Sari, Yusnidar, dan Hadinata 2021) in the rainy season (Istiqamah et al. 2025) as the cost becomes a major constraint for preserving slope with the 46,965 km total length of national roads in 2022. The network of national highways and landslides case in Flores Island is shown in Figure 1 and Table 1.

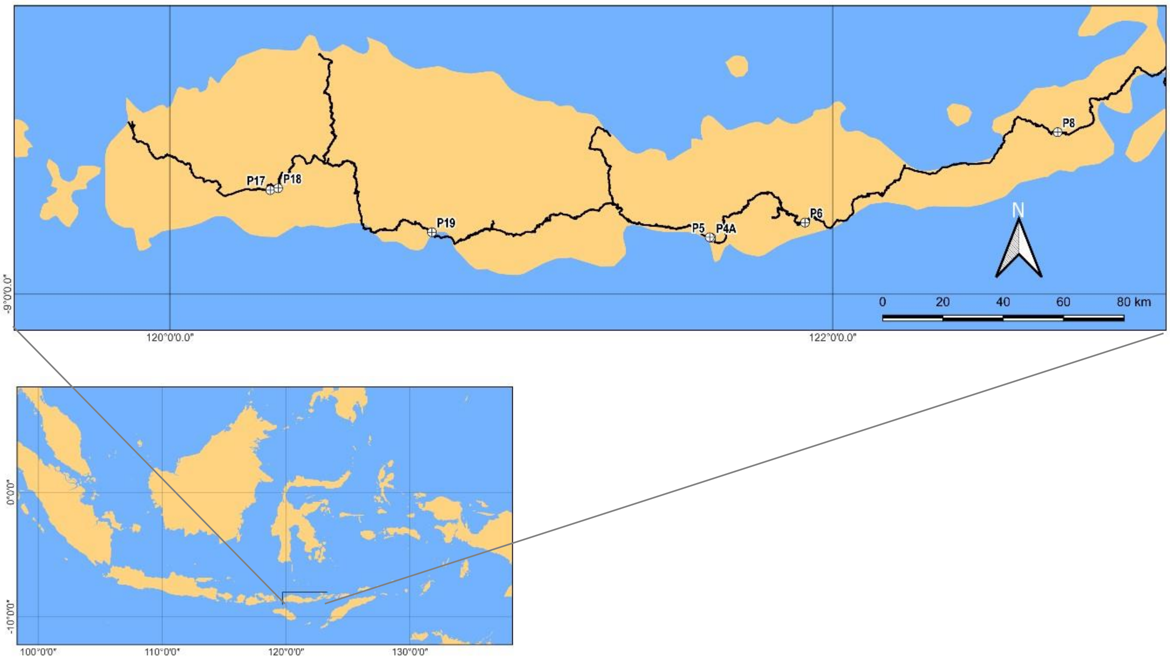

Figure 1. National Highway Network and Observed Landslides in Flores Island

Table 1. Location and Slope of Landslides Location

Location	Road Segment	Slope (%)
P4	Aegela – Ende City Border, STA. 002+100	45%
P5	Aegela – Ende City Border, STA. 002+500	120%
P6	Wolowaru – Maumere City Border, STA. 75+850	54%
P8	Waerunu – Larantuka, STA. 219+000	80%
P17	Malwatar – Ruteng City Border, STA. 40+000	51%
P18	Malwatar – Ruteng City Border, STA. 44+300	50%
P19	Aimere – Borong, STA. 167 +300	46%

Moreover, the challenge of diverse geological & geotechnical conditions and earthquakes also needs to be addressed (Yogaswara dan Herwina 2023). In the Flores Island case, the landslide occurred in a mountainous with a steep (25-45%) to very steep (>45%) slope and shallow depth of landslide that is characterized as a planar landslide. The slope of all of the locations based on DEMNAS (Geospatial Information Agency, 2018) is illustrated in Figure 2.

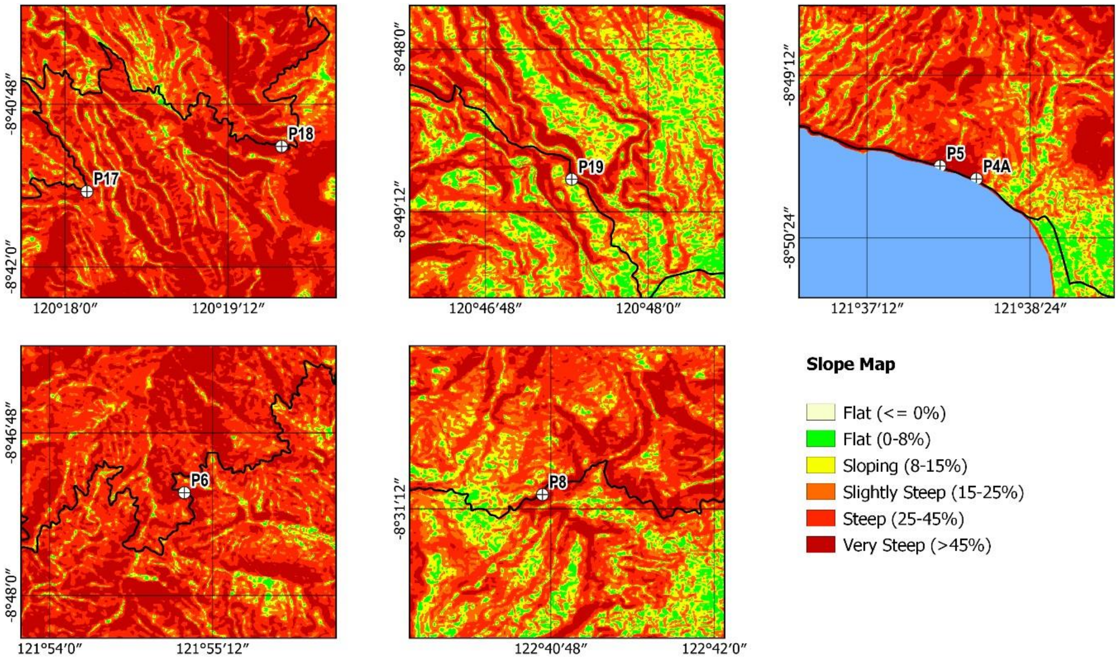

Figure 2. Slope Maps of Observed Landslide Locations

Study Site Geological and Geotechnical Condition

Several landslides that occurred on Flores Island are located in various geological conditions as illustrated in Table 2. In the P4 and P5 slopes, rockfall occurs every year due to rainfall and high waves in those slopes that easily induce rock collapse. Meanwhile, the rockfall in the P6 slope took place in an altered andesite that was characterized as very hard andesite. The rock slide developed as a cracked rock weakened by rainfall. In the P17 and P18 cases, the landslide occurred because of soft rock that was categorized as a lower cliff collapse. For P8 and P19 cases, the landslides are classified as rockfall. The P8 landslide is located in a protected forest with heterogeneous vegetation. P19 location collapses in hard volcanic sandstone.

Table 2. Geological Description of Observed Landslide Locations

Location	Formation	Description
P4A	Tanahhau Formation (Tmt)	Dalcitic Lava, breccia, tuff, rhyolitic lava, and glass tuff
P5, P8, P17, P18	Older Volcanic Products (Qtv)	Lava, breccia, agglomerate, and sandy tuff, interbedded with pumiceous tuff or breccia
P6	Granodiorit (Tmg)	Granite, granodiorite, and quartz diorite
P19	Coastal Terraces	Interbedded between conglomerate and coarse sandstone, slightly calcareous

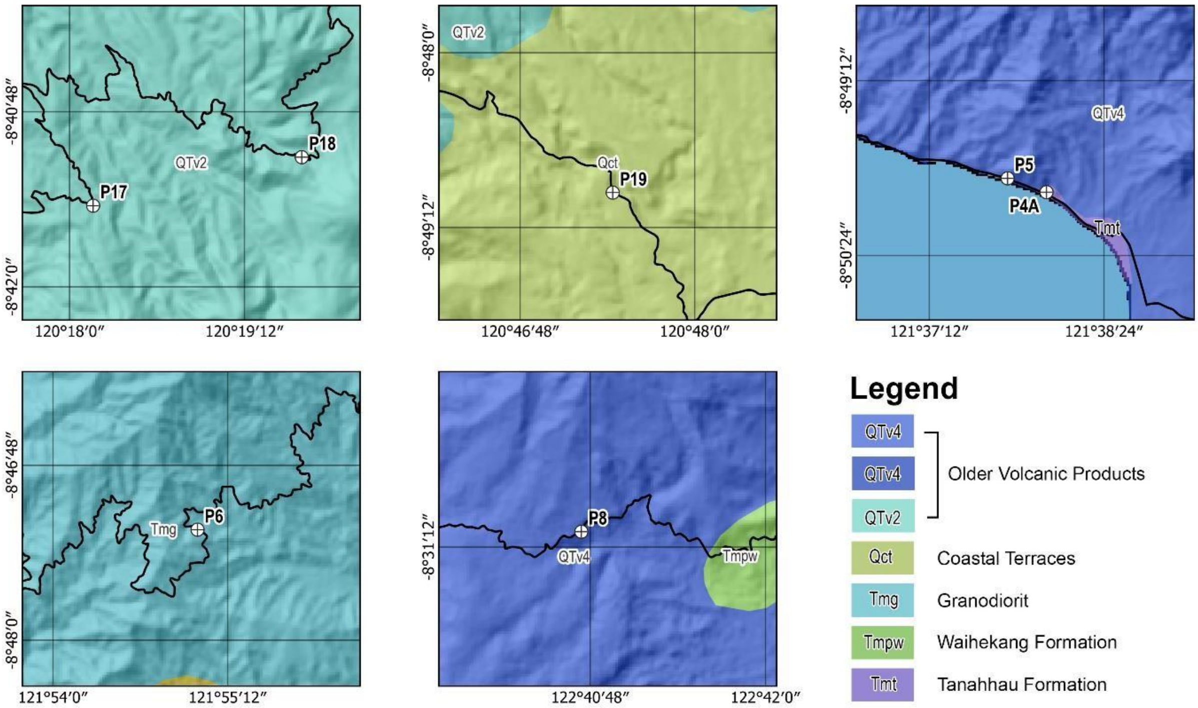

Figure 3. Geological Maps of Observed Landslide Locations (Pusat Survei Geologi, 2019)

The existing geological explains the geotechnical aspect of the site in which based on the standard penetration test (SPT), the locations are dominated by SPT > 60 in almost all depths. In terms of characteristics of the soil/rock, based on boring data, the soil/rock is characterized as the product of volcanic activity because the majority of soil consists of rock and sand.

Furthermore, the seismic activity also contributes to the increasing intensity of rockfall as approximately the observed locations are 70-80 km away from the seismic source as illustrated in Figure 4. Based on the Map of Indonesia Earthquake Sources and Hazard Map (Pustlitbang PUPR 2017), the nearest seismic sources are Flores Backarc Thrust (M_{max} = 7.5) and Sape Strikeslip (M_{max} = 6,7). In conventional bridges and road design, the Indonesian National Standard requires the earthquake load with a 1000-year return period, 75 years of design life, and a 7% exceedance probability. Thus, the earthquake peak ground acceleration (PGA) for design is obtained from LINI PUPR. The obtained PGAs of each location are tabulated in Table 3.

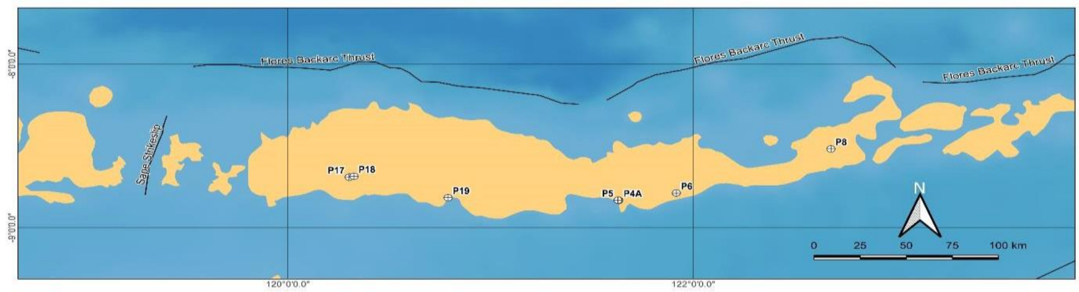

Figure 4. Seismic Sources of Observed Landslide Locations on Flores Island

Table 3. The PGA and horizontal coefficient of Earthquake in Observed Location

Observed Location	Latitude	Longitude	PGA	Fa	kh
P4	- 8.83277	121.633413	0.332	1.068	0.177
P5	-8.831189	121.628955	0.332	1.068	0.177
P6	-8.787364	121.91654	0.333	1.067	0.178
P8	-8.518135	122.678064	0.356	1.044	0.186
P17	-8.690741	120.30269	0.343	1.057	0.181
P18	-8.685199	120.326548	0.346	1.054	0.182
P19	-8.815211	120.791924	0.338	1.062	0.179

Finite Element Method (FEM) and the Limit Equilibrium Method (LEM)

Rock slopes exhibit complex characteristics: the presence of discontinuities (joints, fissures, bedding planes), heterogeneity, rock anisotropy, groundwater conditions, dynamic loading factors (e.g., earthquakes), and climatic influences (including intense rainfall) significantly affect the stability of rock slopes (Nata, Ren, Ge, Tanjung, et al. 2024), for rock slopes exhibiting such conditions, the Finite Element Method (FEM) and the Limit Equilibrium Method (LEM) are highly suitable analytical approaches (Pandey, Knoblauch, dan Zenz 2023; Valentino 2023).

"The Finite Element Method (FEM) is a numerical method used in slope stability analysis that incorporates the stress–strain relationship of materials. In contrast, the Limit Equilibrium Method (LEM) is an approach in which the slip surface can be assumed to have various geometries—such as planar, wedge, toppling, rotational (Azarafza et al. 2021), or other geometrical configurations depending on the failure mechanism being analyzed. This method ensures equilibrium of forces and moments, which may include horizontal and vertical force equilibrium, or moment equilibrium with respect to a reference point (Alok et al. 2024). The commonly used methods include Bishop's Simplified Method, Janbu's Simplified and Generalized Methods, the Morgenstern-Price Method, Spencer's Method, and the General Limit Equilibrium (GLE) Method.

REASEARCH METHODS

The methodology of this study begins with a literature review, followed by the collection of both primary and secondary data. Based on these data, numerical analyses were conducted using the Limit Equilibrium Method (LEM) and the Finite Element Method (FEM) to evaluate the slope safety factor. This study will employ a dual approach: numerical analysis and field-based observation/testing. The combination of these methods is expected to provide a more comprehensive understanding of soil nailing behavior in slope stability, validate the numerical model, and offer recommendations for design parameters. The complete workflow is illustrated in the flowchart Figure 5.

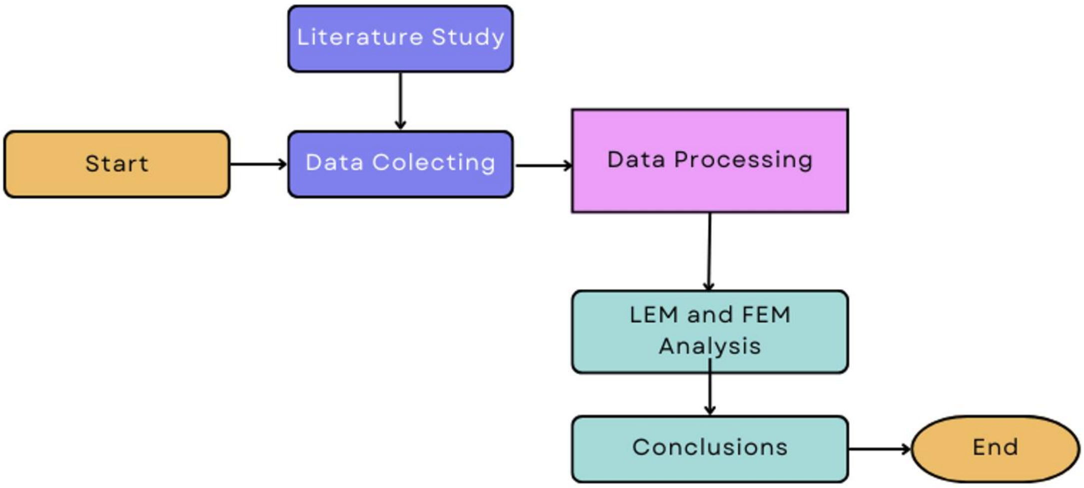

Figure 5. Research Flowchart

Numerical Analysis

The analysis is conducted using the finite element method, limit equibrilium method (Enkhbold et al. 2023). The constitutive model of the soil is Mohr-Coulomb in finite element method (FEM) and limit equibrillium method (LEM). Several studies have employed the finite element method (FEM) to analyze rock slope stability and assess the resulting stress distribution (Yogaswara dan Herwina 2023). In addition, other researchers have utilized numerical approaches, particularly the shear strength reduction (SSR) method, to evaluate the safety factor of slopes with inclinations exceeding 30 degrees (Chen, Chen, dan Wu 2021).

Moreover, the reinforced slope was designed using the soil nails with 15° inclinations. In the FEM analysis, the soil nail was modeled as embedded beam rows (EBR) meanwhile for LEM analysis, it was modeled as reinforcement load. The model of slope in FEM and LEM mode is illustrated in Figure 5 and Figure 6.

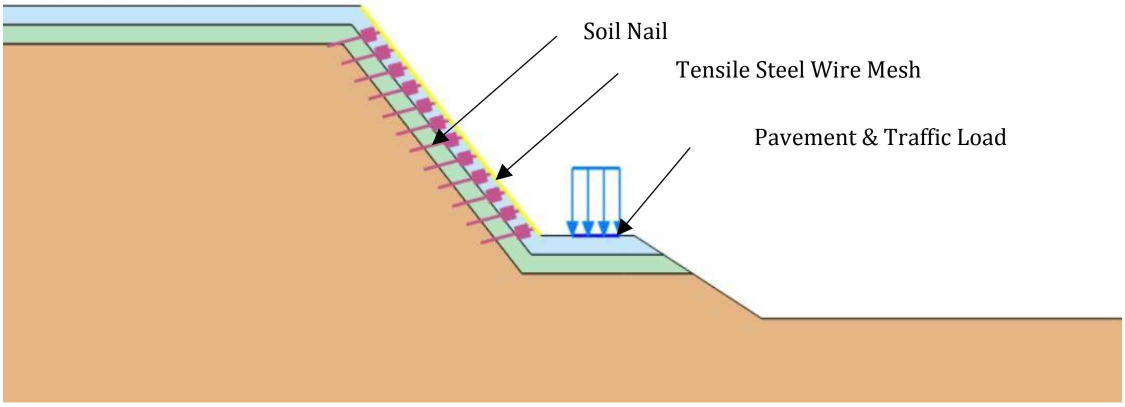

Figure 5. Finite Element Method Numerical Model

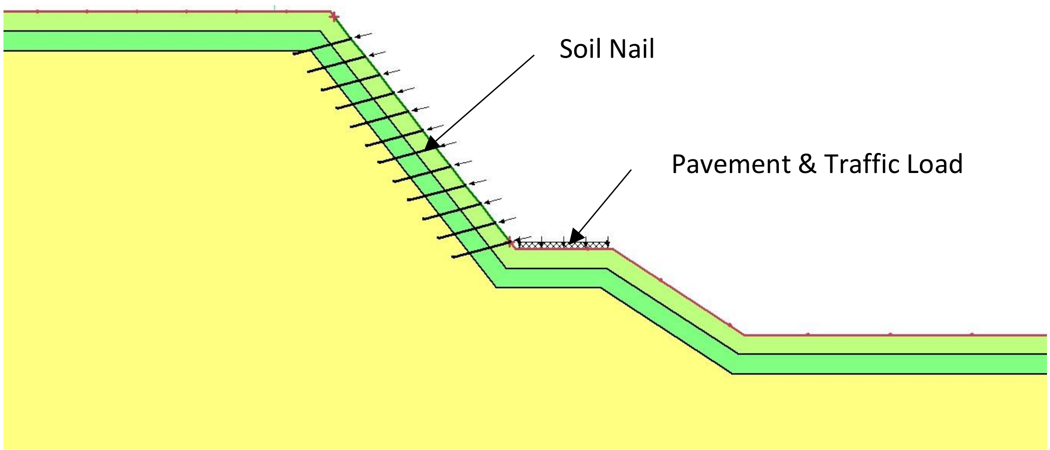

Figure 6. Limit Equibrilium Method Numerical Model

The analyzed soil parameters of each landslide location are shown in Table 4. The numerical models are analyzed under static and pseudostatic conditions (Sarkar dan Chakraborty 2020). In the case of pseudo-static, the cohesion of soil increases by 1.5 of the initial undrained cohesion as earthquakes cause rapid loading (Sultana 2014). The formula of C_u in dynamic conditions (W.F.Carroll 1963) is shown in Formula 1.

$$\frac{C_{u(dynamics)}}{C_{u(static)}} \approx 1.5 \tag{1}$$

Table 4. The Soil Properties for FEM and LEM Model

Observed Location	Depth (m)	NSPT	Soil Type	Elastic Modulus (MPa)	v	k m/day	γ_{unsat} kN/m^3	γ_{sat} kN/m^3	C_u (kPa)	ϕ (°)	C_u seismic (kPa)
P4	0,00-15,00	60	Sand	100.0	0.3	1.00E-03	17	20	15.3	50.00	22.95
P5	0,00-10,00	60	Sand	100.0	0.3	1.00E-03	17	20	32.0	50.00	48
P6	0,00-10,00	60	Sand	120.0	0.3	1.00E-03	17	20	35.0	50.00	52.5
P8	0,00-10,00	60	Sand	80.0	0.3	1.00E-03	17	20	46.4	37.81	69.6
P17	0,00-10,00	60	Sand	100.0	0.3	1.00E-03	17	20	35.0	50.00	52.5
P18	0,00-2,00	8	Clay	9.2	0.35	8.68E-08	16	18	40.0	5.00	60
	2,00-4,00	30	Sand	30.0	0.3	5.05E-02	17	20	5.0	40.00	7.5
	4,00-15,00	60	Sand	80.0	0.3	1.00E-03	17	20	35.0	50.00	52.5
P19	0,00-5,00	39	Sand	39.0	0.3	3.57E-02	17	20	20.0	42.25	30
	5,00-15,00	60	Sand	80.0	0.3	1.00E-03	17	20	32.0	50.00	48

The material properties of soil nails adopted for FEM and LEM analysis are shown in Table 5 and Table 6. For pavement and wire mesh are modelled as plate and geogrid in FEM analysis but they were not modeled in LEM analysis. The parameters for pavement and wire mesh are illustrated in Table 7.

Table 5. The Soil Nailing Parameters for FEM Analysis

Young Modulus, kN/m^2	E	25600.95
Diameter of Nail, mm	D	200
Unit Weight, kN/m^3	γ	25.4
Out-of-plane spacing, m	L_s	2.4
Axial Skin Resistance, kN/m	Tskin	Layer Dependent
Lateral Skin Resistance, kN/m	T_{lat}	Unlimited
Base Resistance, kN	Fmax	0

Table 6. The Soil Nailing Parameters for LEM Analysis

Pullout Resistance (qu), kPa	150
Nail Diameter, mm	32
Yield Strength (fy), MPa	490
Bond Diameter, mm	200
Tensile Capacity of Soil Nail, kN	394.08
Tensile Reduction factor	1.8

A similar approach has been adopted by (Bekele dan Meten 2023) (Nata, Ren, Ge, Fadhly, et al. 2024), who conducted slope stability analyses using the Limit Equilibrium Method (LEM) with the aid of Rocscience software. This method evaluates both force and moment equilibrium to determine the factor of safety (FoS) of the slope.

Table 7. The Parameter of Pavement and Wiremesh

Material	Model Type	(N_p) (kN/m)	Elongation at failure (%)	(EA) (kN/m)	(EI) ($kN.m^2/m$)	w (kN/m/m)	v
Pavement	Plate	-	-	10.4×10^6	2.16×10^5	3	0.15
Wiremesh	Geogrid	150	6	2500	-	-	-

RESULTS AND DISCUSSION

The result of modeling soil nailing using FEM and LEM have different outputs. In terms of FEM, it does not only give the global safety factor but also internal force distribution (Villalobos dan Villalobos 2021) ; (Derghoum dan Meksaouine 2021). For several cases in Flores, although the soil nailing does not increase the safety factor significantly it was also intended to prevent rockfall in those locations. The location also fails in the existing conditions in static and pseudo-static load but after soil nail installation.

Although several slopes have soils with a lower friction angle than the slope inclination, the slopes are stable. It is indicated that the slope soils are residual soils that have suction to resist sliding (Zhang et al. 2011). However, the rainfall event can deduct the suction to zero which initiates the landslide in the slope.

The result of slope stability safety factor before and after installation using FEM and LEM can deviate using although using similar properties. FEM in determining safety factors (ΣMSF) using the strength reduction method (SRM), which is deduct the cohesion (c) and friction angle (ϕ) of soil incrementally till the soil body collapse (Mebrahtu et al. 2022) using Formula 2. However, the study conducted by [(Nata, Ren, Ge, Tanjung, et al. 2024) reported that the factor of safety (FoS) obtained through finite element method (FEM) analysis is relatively low for rock layers that are highly susceptible to weathering.

$$\sum MSF = \frac{c}{c_{reduced}} = \frac{tan^{\theta}}{tan\theta_{reduced}} \tag{2}$$

Meanwhile, the LEM method uses the force equibrillium principle assuming that the LEM safety factor (SF) (Mouyeaux et al. 2023) is the ratio of shear strength (τ_f) against shear stress (τ), (Azarafza et al. 2021) as illustrated in Formula 3.

$$SF = \frac{\tau^{f}}{\tau} \tag{3}$$

The results of those methods are illustrated in Table 8

Table 8. Safety Factors Before and After Soil Nailing

Observed Location	FEM				LEM			
	Existing SF*	SF w/ Soil Nailing*	Existing SF Pseudostatic**	SF w/ Soil Nailing Pseudostatic**	Existing SF*	SF w/ Soil Nailing*	Existing SF Pseudostatic**	SF w/ Soil Nailing Pseudostatic**
P4	1.488	1.606	1.348	1.381	1.982	2.151	1.481	1.626
P5	1.422	1.508	1.353	1.4	1.505	1.591	1.146	1.232
P6	1.475	1.506	1.371	1.39	1.814	1.865	1.378	1.419
P8	1.619	1.621	1.418	1.419	1.699	1.699	1.259	1.259
P17	1.457	1.5	1.401	1.402	1.723	1.823	1.321	1.412
P18	Fail	1.546	Fail	1.408	1.163	1.587	0.88	1.277
P19	1.354	1.563	1.411	1.302	1.535	1.713	1.158	1.327

*Under static conditions the safety factor must exceed 1.5
** Under pseudo-static conditions the safety factor must exceed 1.1
*** In the LEM pseudo-static case, the C_u did not increase to $C_{u\ dynamics}$

As illustrated in Table 8, the safety factor either in existing and after soil nailing LEM produces a higher safety factor than FEM. After a series of analyses, the result also depicted some of the locations after using soil nailing have safety factor did not increase significantly but in Cases P18 and P19, the soil nails improved the slope stability safety factor to a satisfactory level as required by Indonesian National Standards (Safety factor of slope stability must exceed 1.5 in static case and 1.1 in earthquake case). The cases of P18 and P19 have shallow slip surfaces due to the existence of lower shear strength and friction angle soil layer. For locations where the slope stability does not increase soil nailing and meshing can mitigate the external force-induced rockfall.

CONCLUSIONS

The diverse geological conditions and multiple earthquake sources in East Nusa Tenggara become a challenge to slope protection of the national highway. In the cases of landslide/rock fall, it may be induced by external forces, such as rainfall, earthquakes, and high tide waves. The Flores cases shows that the landslide phenomena may occur in locations where the SPT value > 60. For those cases, soil nailing can be utilized for slope protection as the condition of soil/rock is located on steep slopes that are vulnerable to high disturbance. Moreover, it is important to model the slope in FEM/LEM alongside the check on individual mesh and nails to obtain the behavior of landslide. In some cases, soil nails are effective for slope stabilization, especially for steep slope and shallow slip areas. In the relatively rocky slope, although the soil nailing approach does not increase the safety factor of slope stability but it can withstand the potential rockfall due to rainfall or to other external forces.

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