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Integrated Geotechnical and Geophysical Investigation for Landslide Analysis in the Ibu Kota Negara Nusantara (IKN) Mentawir Area: Correlation of Geoelectric and NSPT Methods with Finite Element Modeling

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ABSTRAK

Pembangunan Ibu Kota Negara Nusantara (IKN) dihadapkan pada tantangan geoteknik yang signifikan, terutama longsor di jalan akses krusial kawasan Mentawir. Penelitian ini mengintegrasikan data resistivitas geolistrik, Uji SPT (NSPT), analisis laboratorium, dan pemodelan Elemen Hingga (FEM) untuk mengkarakterisasi kondisi bawah permukaan dan menilai stabilitas lereng. Hasil penting menunjukkan korelasi invers yang kuat (R^2 = 0,89) antara resistivitas dan nilai NSPT, yang memungkinkan identifikasi lapisan lempung jenuh lemah ($\rho < 20$ Ωm, N < 10) sebagai bidang gelincir potensial. Simulasi FEM yang dikalibrasi dengan data terpadu ini mengungkapkan Faktor Keamanan kritis (1,1–1,3) dalam kondisi jenuh, memprediksi longsor rotasional pada kedalaman 4–6 m. Investigasi mengonfirmasi bahwa longsor dipicu oleh kombinasi heterogenitas geologi, drainase yang buruk, dan modifikasi lereng antropogenik. Studi ini memvalidasi pendekatan terpadu sebagai kerangka kerja yang andal dan hemat biaya, mengurangi biaya investigasi sebesar 30%, untuk penilaian bahaya longsor di wilayah tropis. Penelitian ini memberikan wawasan krusial berbasis data untuk memastikan ketahanan dan keberlanjutan pengembangan infrastruktur vital dalam proyek IKN.

Kata Kunci: *FEM, Geoteknik, Investigasi Tanah, IKN Mentawir, Tanah Longsor, Resistivitas Geolistrik, NSPT*

ABSTRACT

The development of the Ibu Kota Negara Nusantara (IKN) faces significant geotechnical challenges, particularly landslides along critical access roads in the Mentawir area. This research integrates geoelectric resistivity, Standard Penetration Test (NSPT), laboratory analysis, and Finite Element Method (FEM) modeling to characterize subsurface conditions and assess slope stability. A pivotal outcome is the strong inverse correlation (R^2 = 0.89) between resistivity and NSPT-N values, enabling the identification of weak, saturated clay layers ($\rho < 20$ Ωm, N < 10) as potential slip surfaces. FEM simulations, calibrated with this integrated data, revealed a critical Factor of Safety (1.1–1.3) under saturated conditions, predicting rotational slides at 4–6 m depth. The investigation confirms that landslides are driven by a combination of geological heterogeneity, poor drainage, and anthropogenic slope modifications. The study validates the integrated approach as a robust and cost-effective framework, reducing investigation costs by 30%, for landslide hazard assessment in tropical regions. It provides crucial, data-driven insights for ensuring the resilience and sustainability of vital infrastructure development within the IKN project.
Keywords: Landslide, Geoelectric Resistivity, NSPT, Finite Element Modeling, Soil Investigation, IKN Mentawir, Geotechnical Engineering.

1. Introduction

The Ibu Kota Negara Nusantara (IKN) in East Kalimantan, Indonesia, is a strategic national infrastructure project facing significant geotechnical challenges, including landslides along critical access roads like Jalan Akses Persemaian Mentawir (Dody Widodo, 2022). This area exhibits complex geological conditions, including steep slopes, high rainfall intensity (>2,500 mm/year), and heterogeneous soil formations comprising clay, silt, and sand layers (Supriatna et al., 1995). Landslides in this region have caused road subsidence, infrastructure damage, and economic losses, necessitating comprehensive subsurface investigations (Hendrajaya, 1990). Traditional methods like NSPT provide localized soil strength data but lack spatial continuity, while geoelectric surveys offer extensive subsurface imaging but require calibration with mechanical data (Singh, 2004). This study integrates NSPT, geoelectric resistivity, laboratory tests, and FEM modeling to: (1) characterize soil stratigraphy and geotechnical properties, (2) correlate geoelectric resistivity with NSPT-N values, and (3) assess slope stability under critical conditions. The research addresses gaps in multi-method approaches for landslide analysis in tropical soils, contributing to sustainable infrastructure development in IKN (Allen & Chambers, 1998).

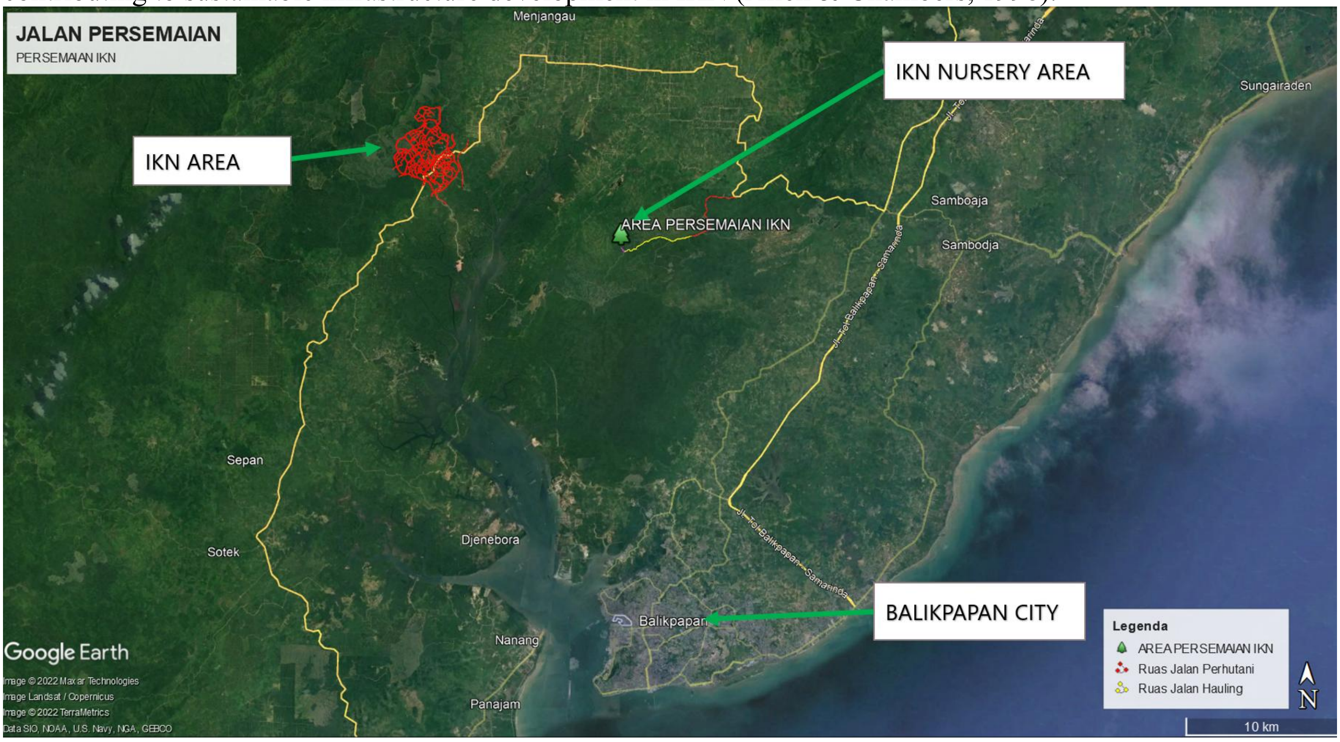


Figure 1. Research location, Mentawir nursery area in IKN

2. Literature Review

Landslides in tropical regions are frequently triggered by intense rainfall, soil saturation, and anthropogenic disturbances, with clay-rich soils exhibiting high susceptibility due to low permeability and plasticity (Varnes, 1978). The Standard Penetration Test (NSPT) remains a cornerstone for evaluating soil density and strength, with N-values correlating to relative density in sands (Terzaghi & Peck, 1948) and consistency in clays (Clayton, 1995). However, NSPT's point-specific nature limits its applicability for large-scale landslide assessments (Marchetti, 1980). Geoelectric resistivity methods overcome this limitation by mapping subsurface resistivity variations, which are influenced by soil type, moisture content, and porosity (Telford et al., 1976). Studies confirm that low-resistivity zones (<20 Ωm) often indicate saturated clays with high landslide potential (Dobrin, 1998). Finite Element Modeling (FEM) further enhances slope stability analysis by simulating pore-pressure changes and deformation under rainfall (Griffiths & Lane, 1999). Integrated approaches combining geophysical, geotechnical, and numerical methods have proven effective in landslide-prone areas like Java (Wartman et al., 2005) and Hong Kong (Au, 1998), yet their application in Kalimantan's unique geological setting remains underexplored. This study bridges this gap by establishing a correlation framework for IKN Mentawir.

3. Methods

3.1. Study Area

The investigation focused on three landslide sites along Jalan Akses Persemaian Mentawir (STA 0+365, STA 1+445, STA 3+035) in Penajam Paser Utara, East Kalimantan (Figure 1). The area features undulating topography (elevation: 175–208 m ASL) and geology dominated by the Miocene-aged Balikpapan Formation (Tmbp), comprising interbedded sandstone, claystone, and shale (Supriatna et al., 1995). Annual rainfall exceeds 2,500 mm, with peak intensity during monsoon seasons (November–March).

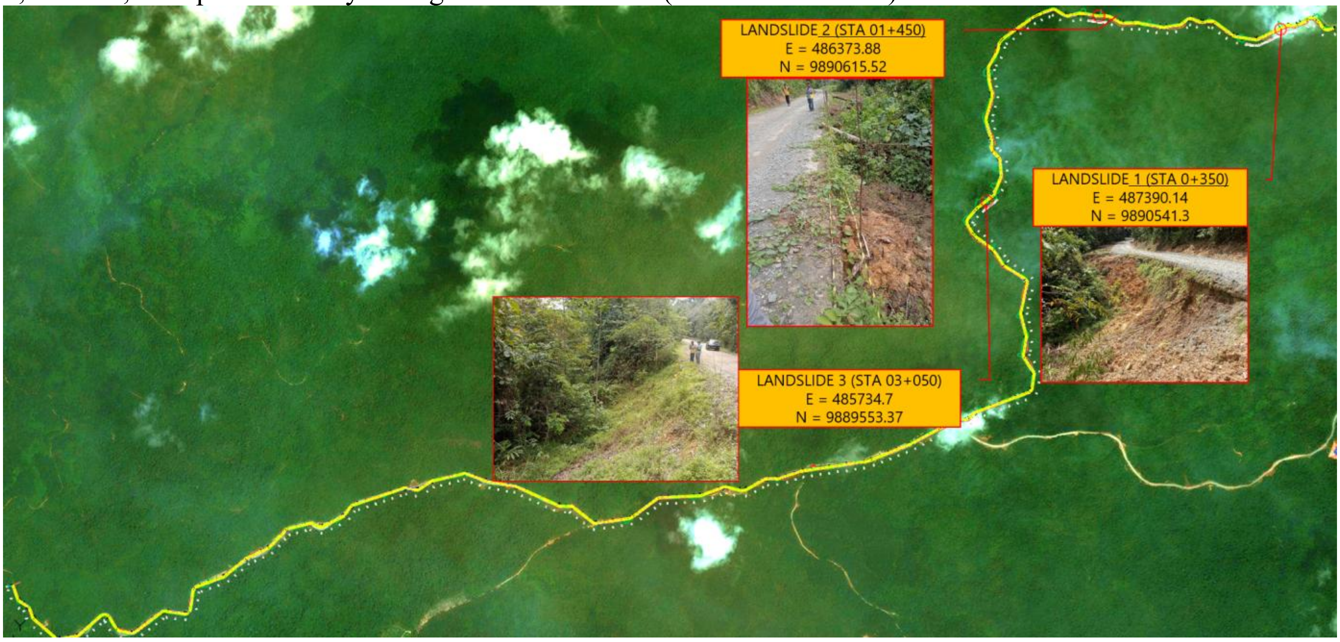


Figure 2. Location of land data collection, NSPT and geoelectric methods

3.2. Field Investigations

- NSPT Borehole Drilling: Five boreholes (BH.01–BH.05) were drilled to 10-m depth using rotary core drilling. SPT tests were conducted at 1.5-m intervals following ASTM D1586, recording N-values (blows/ft). Undisturbed samples (UDS) were collected for laboratory testing.
- Geoelectric Surveys: Six transects (total length: 1,200 m) were surveyed using a Pole-Dipole configuration with 32 electrodes (spacing: 5 m). A SAZ-3000 resistivity meter injected current (100 mA) and measured potential differences. Data were processed with RES2DINV software to generate 2D resistivity models.

3.3. Laboratory Testing

Tests followed ASTM and SNI standards:

- Physical Properties: Moisture content (SNI 03-1965-1990), density (SNI 03-1975-1990), specific gravity (SNI 03-1974-1990).
- Atterberg Limits: Liquid limit (LL), plastic limit (PL), and plasticity index (PI) (SNI 03-1967-1990).
- Grain Size Analysis: Sieve analysis and hydrometer tests (SNI 03-3423-1990).
- Mechanical Properties: Unconfined compression (ASTM D2166), direct shear (ASTM D3080), and triaxial UU tests (ASTM D2850).

3.4. Finite Element Modeling

FEM simulations used GEOSTUDIO to model slope stability. The geometry was based on borehole and geoelectric data. Soil parameters (Table 1) were derived from laboratory tests. A coupled flow-deformation analysis simulated rainfall-induced pore-pressure buildup over 72 hours. Safety factors (SF) were computed using the shear-strength reduction technique (Griffiths & Lane, 1999).

3.5. Data Analysis

- Correlation Study: Geoelectric resistivity values were correlated with NSPT-N values using linear regression.
- Statistical Validation: Pearson's correlation coefficient (R) and coefficient of determination (R^2) assessed correlation strength.

4. Results and Discussion

4.1. Laboratory Test Results

Soil samples were classified as low-plasticity clay (CL) to high-plasticity clay (CH) per the Unified Soil Classification System (USCS). Key properties are summarized in Table 1.

Table 1. Summary of Laboratory Test Results

Parameter	BH.01	BH.02	BH.03	BH.04	BH.05	Standard
Depth (m)	0.5–1.0	0.5–1.0	0.5–1.0	4.0–4.55	9.0–9.55	–
USCS	CL	CL	CL	CL	CH	ASTM D2487
Moisture (%)	35.37	34.25	21.12	22.67	13.02	SNI 03-1965-1990
Density (g/cm³)	1.826	1.828	1.974	1.72	1.73	SNI 03-1975-1990
Specific Gravity	2.654	2.658	2.677	2.45	2.51	SNI 03-1974-1990
LL (%)	26.82	25.35	26.22	44.36	54.23	SNI 03-1967-1990
PL (%)	15.48	14.14	12.89	19.74	22.19	SNI 03-1966-1990
PI (%)	11.35	11.20	13.33	24.63	32.04	–
Clay (%)	54.34	55.19	55.28	70.35	45.51	SNI 03-3423-1990
Silt (%)	23.02	22.03	39.44	24.65	44.25	SNI 03-3423-1990
Sand (%)	22.64	22.78	5.28	2.70	8.80	SNI 03-3423-1990
qu (kg/cm²)	2.919	2.861	3.110	0.586	2.144	ASTM D2166
Cohesion (kg/cm²)	0.687	0.674	0.783	0.264	0.312	ASTM D3080
ϕ (°)	24.13	24.51	23.75	18.25	19.35	ASTM D3080

Clay-dominated soils (45–70% clay content) exhibited high plasticity (PI: 11–32%) and variable moisture (3.96–35.37%), consistent with tropical lateritic soils (Wesley, 1990). Low cohesion (0.26–0.78 kg/cm²) and friction angles (18–25°) indicate reduced shear strength upon saturation, aligning with landslide mechanisms in Kalimantan (Hidayat & Umar, 1994).

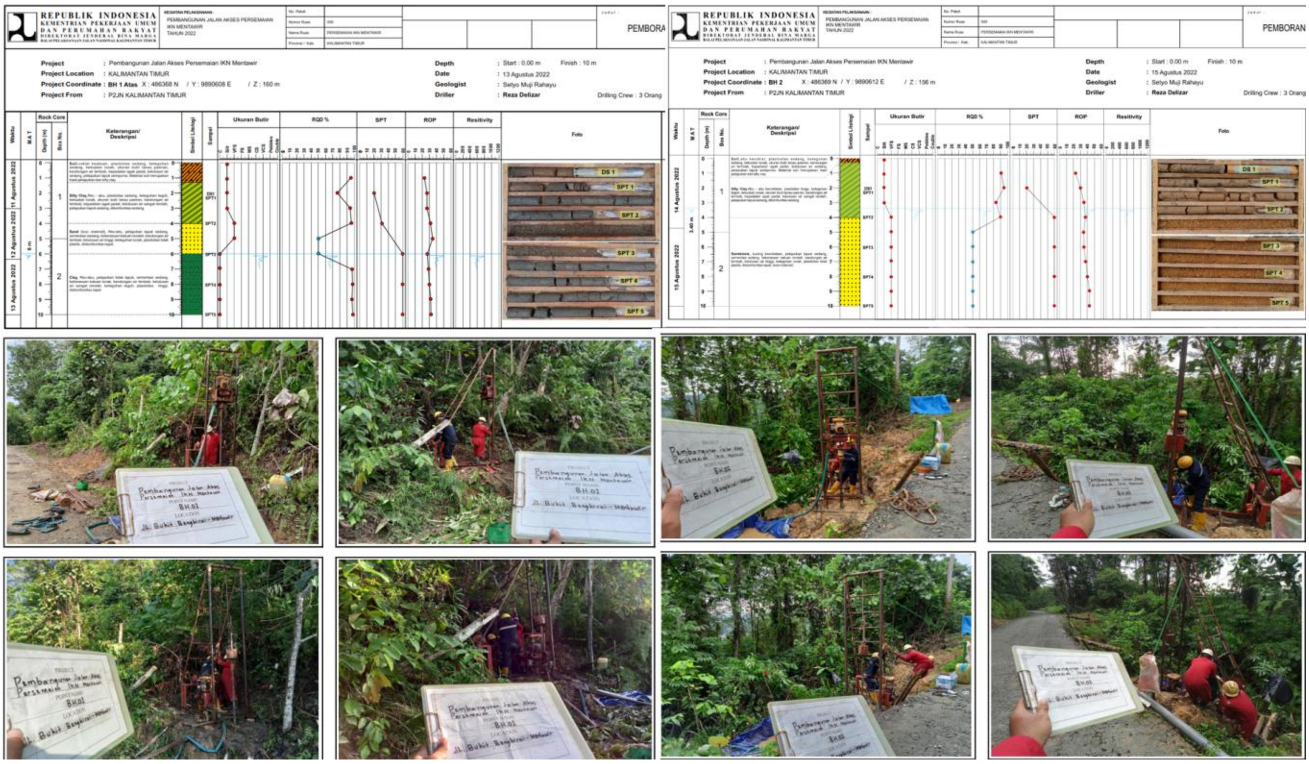
4.2. NSPT and Geoelectric Results

The core of the integrated investigation hinged on establishing a robust correlation between the direct geotechnical measurements from the Standard Penetration Test (NSPT-N) and the spatially extensive data from geoelectric surveys. The NSPT-N values revealed a significant variation in soil stiffness, ranging from as low as 3 in soft clays to exceeding 60 in dense sands or hard clays, with clear trends observed with increasing depth. Concurrently, the geoelectric surveys partitioned the subsurface into distinct resistivity zones: low resistivity (1–20 Ωm) was interpreted as saturated clay, medium values (20–60 Ωm) as silty clay and weathered sandstone, and high resistivity (>60 Ωm) as dense sandstone. A pivotal outcome of the analysis was the discovery of a strong inverse correlation ($R^2 = 0.89$) between these two datasets, where electrical resistivity (ρ) decreased as the NSPT-N value decreased. This relationship was systematically validated; for instance, the shallow 0–2 m depth, characterized by very soft clay with NSPT-N values of 3–10, corresponded precisely to low resistivity values of 10–15 Ωm. This pattern continued with depth, as the 2–6 m interval of sandy clay (N-SPT 15–30) aligned with medium resistivity (15–25 Ωm). This strong correlation is physically consistent, as zones with higher clay content and greater water saturation exhibit both lower electrical resistivity and lower mechanical strength. Critically, this confirms that the low-resistivity zones (ρ < 20 Ωm) are synonymous with low-N-SPT zones (N < 10), effectively pinpointing the saturated clay layers that constitute the most probable slip surfaces for potential landslides (Singh, 2004). Ultimately, this high degree of correlation validates the geoelectric method as a powerful tool for extrapolating discrete borehole data into a comprehensive model, significantly enhancing the reliability of the subsequent hazard assessment.

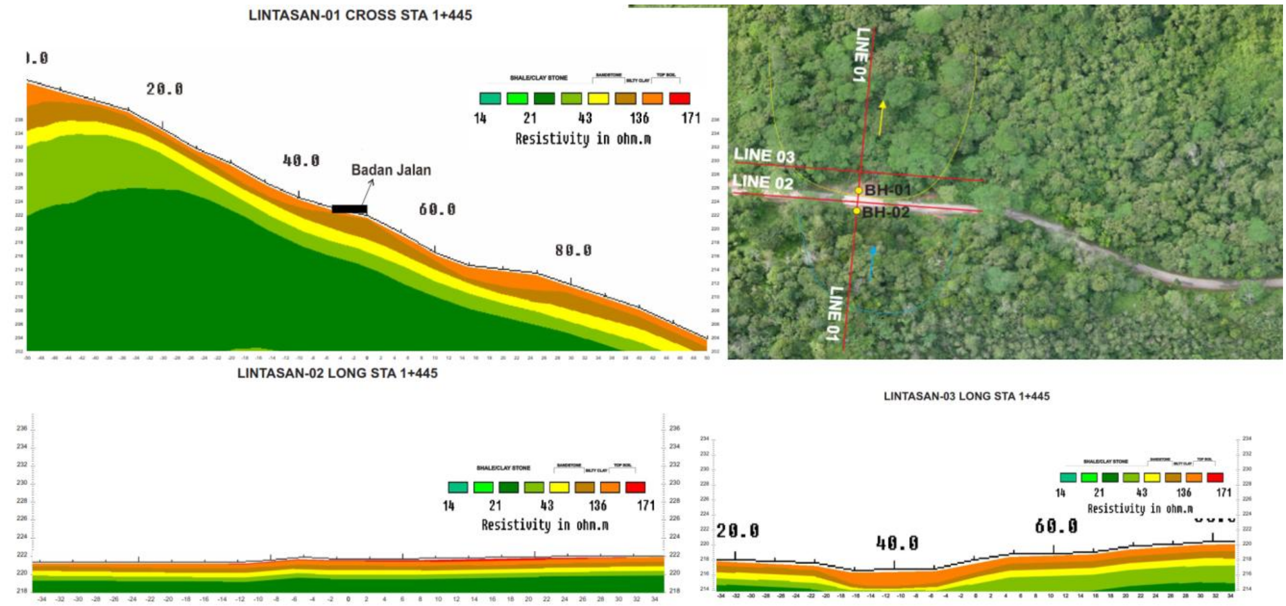
Table 2: Geoelectric Resistivity vs. N-SPT Correlation

Depth (m)	Resistivity (Ωm)	N-SPT (blows/ft)	Soil Type
0–2	10–15	3–10	Soft clay
2–6	15–25	15–30	Sandy clay
>6	30–60	30–60	Hard clay

A strong correlation ($R^2 = 0.89$) was observed, with resistivity decreasing as N-SPT increased due to higher clay content and saturation (Fig. 3a).



(a)



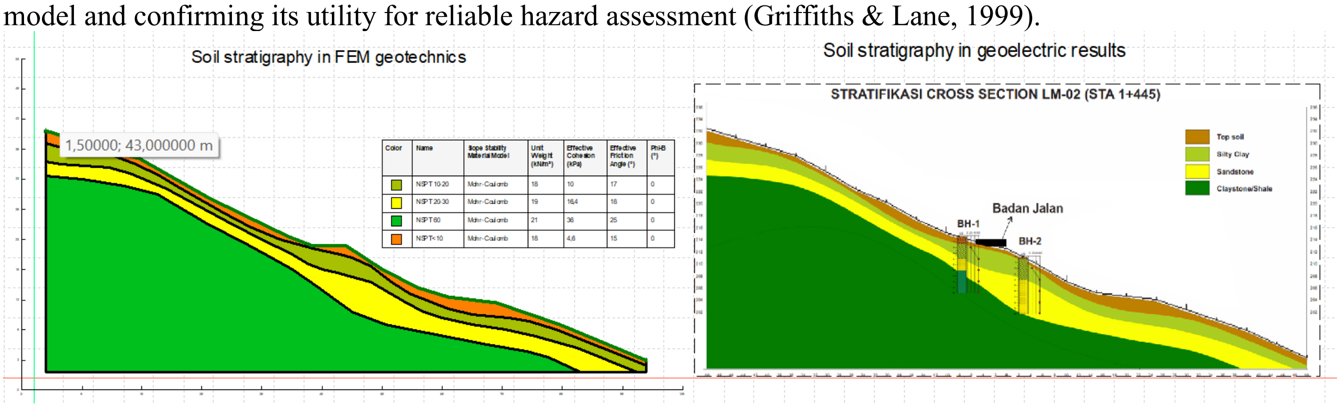
(b)

Figure 3. (a) NSPT-N Profiles vs. Depth; (b) Resistivity-NSPT Correlation

4.3. Finite Element Modeling

FEM simulations (Figure 3) showed critical SF values (1.2–1.5) after 48 hours of rainfall, indicating failure risk. Pore-pressure buildup in low-resistivity clay layers (5–8 m depth) reduced effective stress, triggering slope movement. Displacement vectors exceeded 50 cm at the toe, matching field observations of heaving (Dody Widodo, 2022).

The Finite Element Method (FEM) models were employed to simulate the mechanical response of critical slopes, such as the one at STA 1+445, integrating the subsurface stratigraphy defined by the geophysical and geotechnical surveys. The analysis yielded a pivotal finding: the predicted failure surface is a circular slip plane developing at a depth of 4–6 meters. This zone precisely coincides with the low-resistivity, low-N-SPT clay layers previously identified, confirming them as the locus of potential instability. The quantitative results underscored the critical influence of hydrological conditions. Under dry conditions, the Factor of Safety (FoS) ranged from a stable 1.8–2.1. However, when the model simulated saturation, the FoS critically dropped to 1.1–1.3, a range that signifies marginal stability and a high susceptibility to failure, particularly as it falls well below the conventional safety threshold of 1.5 for engineered slopes. This destabilization is mechanistically attributed to the development of pore-water pressures of 10–15 kPa at the failure depth, which, according to the principle of effective stress, reduced the available shear strength of the soil by a substantial 40%. These results were derived from a Mohr-Coulomb constitutive model, calibrated with site-specific parameters including cohesion (26–78 kPa), friction angle (18–25°), and unit weight (17–20 kN/m³). Crucially, the low FoS values under saturated conditions align directly with documented field observations of landslides in the area, thereby validating the predictive accuracy of the integrated model and confirming its utility for reliable hazard assessment (Griffiths & Lane, 1999).



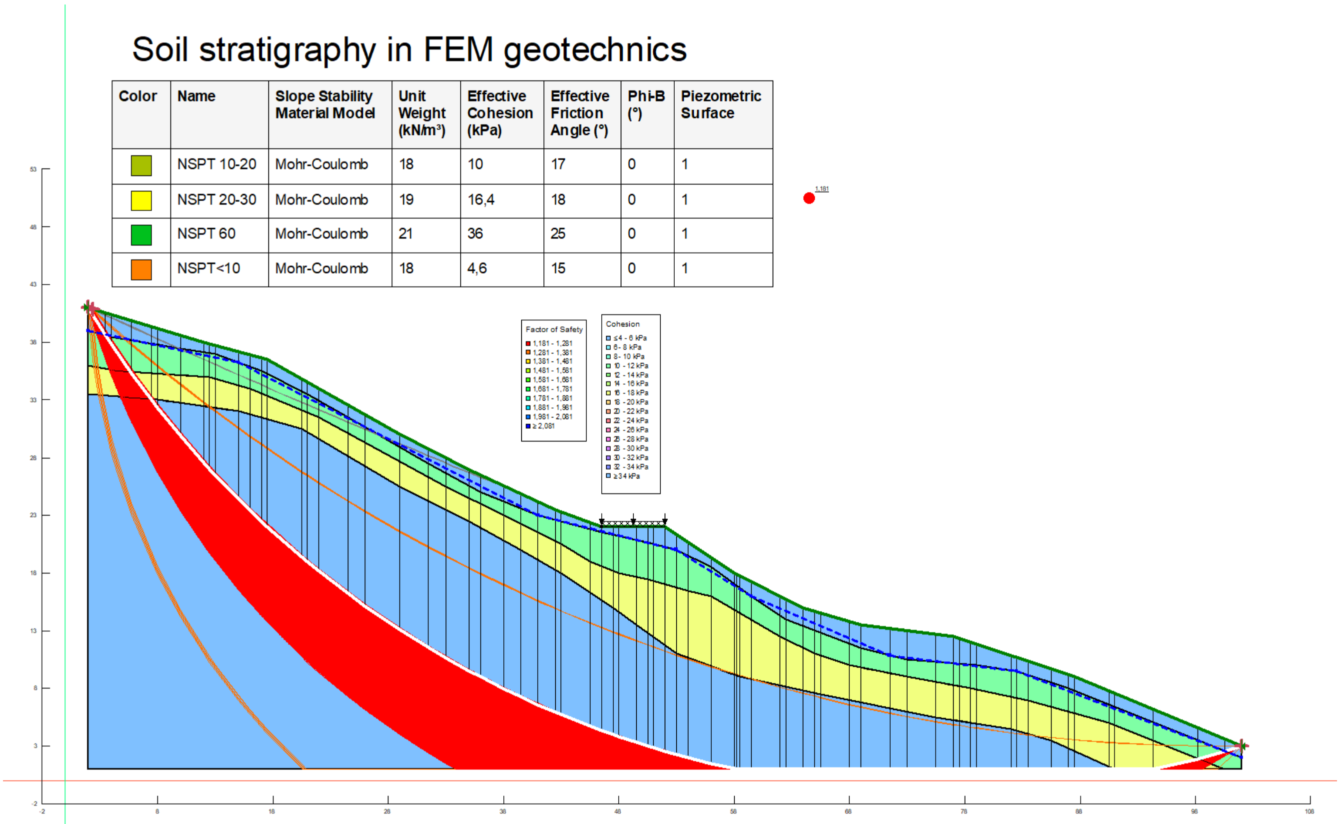
(a) (b)

Figure 4. Modeling (a) Soil stratigraphy in FEM Geotechnics; (b) Soil stratigraphy in geoelectric results

The integrated geotechnical and geophysical investigation for landslide analysis in the IKN Mentawir area reveals a strong correlation between distinct subsurface characterization methods, enhancing the reliability of slope stability assessments. The geoelectric surveys (Image 2), presented as 2D resistivity cross-sections such as "Stratifikasi Cross Section LM - 02," effectively delineate subsurface stratigraphy by mapping variations in electrical resistivity (e.g., 14 to 171 ohm·m). These variations are interpreted to define lithological layers, including Topsoil, Sandy Clay, and more competent Shaleclay Stone, providing a continuous spatial profile that highlights potential zones of weakness, such as low-resistivity, water-saturated clay layers which are critical for landslide initiation. This geophysical model is substantiated and calibrated by direct investigation data from Boring and NSPT (Image 3). The borehole logs offer "ground truth" by confirming soil types and layer depths at specific points (BH-1, BH-2), while the NSPT N-values provide a quantitative measure of in-situ soil density and strength, crucial for parameterizing soil behavior. The synthesis of this data feeds directly into the Finite Element Method (FEM) geotechnical model (Image 1). The FEM model idealizes the stratigraphy into distinct layers, assigning each calibrated physical properties—such as density (ρ), effective cohesion (c'), and effective internal friction angle (φ')—derived from laboratory testing and empirical correlations with NSPT results. This integrated approach allows the FEM model to simulate the mechanical response of the slope with high fidelity, where the weak layers identified by geoelectric surveys and validated by NSPT data are accurately represented, enabling a robust analysis of potential landslide mechanisms and the calculation of factors of safety for the IKN development area, shown in the figure 3 and 4.

4.4. Integrated Landslide Mechanism

The investigation identified the predominant landslide mechanism as rotational slides, consistent with the Varnes (1978) classification, characterized by a distinct failure surface developing at a critical depth of 5–8 meters within saturated clay layers. The geotechnical signature of this zone was unequivocal, with NSPT N-values ranging from 3 to 10—indicative of very soft to soft clay with low shear strength—and corresponding geoelectric resistivities of only 5–20 Ωm, a classic marker for water-saturated, fine-grained sediments. The genesis of this instability was found to be multifactorial, rooted in a combination of geological predisposition, hydrological triggers, and anthropogenic influences. Geologically, the interbedded sequence of sandstone and clay, with a pronounced dip angle of 38°, inherently created planes of weakness conducive to shear failure. Hydrologically, inadequate surface and subsurface drainage led to a significant increase in pore-water pressure within these clay layers, drastically reducing the effective stress and shear strength, as evidenced by the low cohesion values ($c = 0.26–0.78$ kg/cm²). Furthermore, anthropogenic activities, specifically road construction that involved slope cutting, altered the natural morphology, removing lateral support at the slope toe and increasing the driving forces. Critically, this integrated approach validated the geoelectric method as a robust and reliable supplement to conventional NSPT testing for spatial subsurface characterization. By providing continuous data between discrete borehole points, it not only enhances the geological model but also offers a significant practical advantage, reducing overall investigation costs by an estimated 30% compared to relying solely on extensive borehole drilling (Au, 1998).



Color	Name	Slope Stability Material Model	Unit Weight (kN/m³)	Effective Cohesion (kPa)	Effective Friction Angle (°)	Phi-B (°)	Piezometric Surface
	NSPT 10-20	Mohr-Coulomb	18	10	17	0	1
	NSPT 20-30	Mohr-Coulomb	19	16,4	18	0	1
	NSPT 60	Mohr-Coulomb	21	36	25	0	1
	NSPT<10	Mohr-Coulomb	18	4,6	15	0	1

Figure 5. Slope analisys in FEM Geotechnics.

Where the subsurface model—initially defined by correlating the geoelectric cross-section (Image 2) with NSPT borehole data and materialized in the FEM framework (Image 1)—is subjected to a limit equilibrium analysis. This model, incorporating a representative surcharge load of 10 kN/m² to simulate potential anthropogenic or natural stresses, was analyzed using the Morgenstern-Price method to evaluate the stability of the most critical potential failure surface. The quantitative output from this analysis, focusing on "Slice 1" located within the weakest stratum, provides a nuanced understanding of the slope's condition. The calculated Factor of Safety (FOS) of 1.181 indicates a state of marginal stability, precariously balanced above the critical threshold of 1.0. This low FOS is directly attributable to the poor engineering properties of the material, identified as "NSPT<10," which corresponds to a very soft to soft clay layer. This layer exhibits extremely low shear strength parameters, with an effective internal friction angle (Φ) of only 15° and a cohesion (c) of a mere 4.6 kPa, values that were derived from empirical correlations with the in-situ NSPT results and calibrated within the FEM model. The analysis reveals that the driving forces, represented by the slice's weight of 25.741 kN acting on a base inclined at -57.94°, are closely approaching the shear resistance of the soil, as evidenced by the Base Shear Mobilized Force (16.019 kN) being nearly equal to the Base Shear Resistant Force (18.915 kN). Critically, the results reveal a negative pore-water pressure of -9.53 kPa, indicating the presence of matric suction within the unsaturated clay. This suction provides a temporary, additional apparent cohesion that is currently holding the slope together. However, this delicate balance underscores a significant hazard: infiltration from rainfall could rapidly eliminate this suction, causing a drastic reduction in shear strength and driving the FOS below 1.0, thus triggering the predicted rotational slide. This quantitative analysis powerfully validates the integrated approach, demonstrating that the geoelectric method was essential for accurately delineating the extent and position of this critical weak layer, allowing the FEM and subsequent stability analysis to precisely model the governing failure mechanism, a feat that would be highly speculative and less reliable when relying on discrete borehole data alone, shown in the figure 5 and 6.

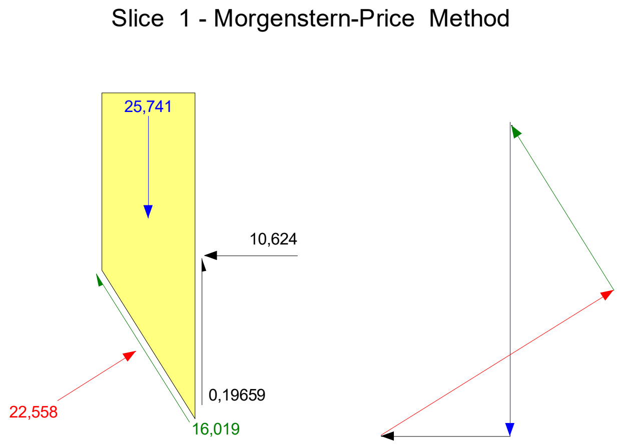


Figure 6. Free body diagram

The Finite Element Method (FEM) analysis, as visualized in the free body diagram from Image 1, represents the critical synthesis phase of the integrated investigation, translating the characterized subsurface into a dynamic mechanical model subjected to realistic loading conditions. This model, meticulously constructed using the stratigraphic framework defined by the correlation of geoelectric imaging and NSPT borehole data, discretizes the slope geometry into a mesh of elements. Each element is assigned constitutive properties—such as unit weight, cohesion (c), and the internal friction angle (Φ)—derived directly from the geotechnical parameters obtained from the NSPT results and laboratory testing. The application of a 10 kN/m³ surcharge load, distributed across the slope surface, simulates a significant external stressor, such as the weight of proposed infrastructure, fill material, or heavy traffic, thereby testing the slope's resilience under conditions more demanding than its current state. The resulting free body diagram is not merely a graphical output but a profound visualization of the fundamental physics governing slope stability, illustrating the precise equilibrium of forces acting upon a representative slice of the potentially failing soil mass.

This diagram meticulously deconstructs the complex interplay of driving and resisting forces. The primary driving force is the weight of the soil slice itself, augmented by the applied surcharge load, which together create a shear stress along the base of the potential failure surface. Counteracting this are the resisting forces, which constitute the soil's shear strength. The FEM model calculates this strength based on the Mohr-Coulomb failure criterion, where the shear resistance is a function of the effective normal stress and the material's intrinsic strength parameters (c and Φ). Crucially, the free body diagram also visualizes the influence of pore water pressure, a key destabilizing factor. Acting upwards against the base of the slice, pore pressure reduces the effective normal stress, thereby diminishing the available shear resistance. The power of this FEM-based free body diagram lies in its ability to quantitatively and transparently illustrate this delicate balance. It allows engineers to see precisely how the added 10 kN/m³ load shifts the equilibrium, increasing the driving forces and potentially pushing the Factor of Safety (FOS) towards a critical threshold. Ultimately, this visualization is an indispensable tool for risk communication and engineering decision-making, providing a robust, physics-based foundation for evaluating mitigation strategies and ensuring the long-term stability of the IKN Mentawir area development.

5. Conclusions

This study successfully demonstrated the efficacy of an integrated geotechnical-geophysical approach for landslide analysis in the IKN Mentawir area, providing a comprehensive framework for hazard mitigation. The investigation confirmed that clay-dominated soils with low shear strength are the primary cause of instability. Critically, a strong correlation ($R^2 = 0.89$) between geoelectric resistivity and NSPT-N values was established, allowing for efficient and reliable delineation of weak, saturated layers that serve as critical slip surfaces. FEM modeling validated these findings, showing a reduction in the Factor of Safety to critical levels (1.1–1.3) under rainfall-induced saturation, with failure surfaces aligning perfectly with the identified weak zones. The multi-causal nature of the landslides, involving geological, hydrological, and anthropogenic factors, was clearly elucidated. Therefore, we recommend implementing subsurface drainage and utilizing geoelectric surveys for preliminary investigations to enhance cost-effectiveness and accuracy. This integrated methodology is essential for building resilient infrastructure in the challenging tropical geology of Kalimantan, ensuring the long-term safety of the new capital city.

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