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Research Paper

Reducing Landslide Risk in Yogyakarta Through Three-Dimensional Gravity Modeling as A Proactive Disaster Risk Reduction Strategy

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Abstract

Landslides in the Special Region of Yogyakarta, Indonesia, are widely recognized as being triggered by steep topography, active tectonics, and seasonal monsoon rainfall. however, conventional hazard assessments frequently overlook critical subsurface geological controls such as fault zones, weathered bedrock interfaces, and fractured basement rocks—that mayr serve as primary sliding surfaces. This study directly addresses this limitation by developing a novel three-dimensional gravity-based model to enhance landslide susceptibility mapping and support regional mitigation strategies. High-resolution (~200 m) GGMplus gravity data were processed using Oasis Montaj™ software, with regional-residual anomaly separation performed through upward continuation to 5 km and second-order polynomial surface fitting. Subsequently, three-dimensional density inversion was applied to delineate shallow subsurface structures influencing slope stability. The total Bouguer anomaly ranges from –18.6 to +181.4 mGal: strong positive anomalies (>+100 mGal) are concentrated over Mount Merapi, reflecting dense, unweathered volcanic intrusions and lava flows, while pronounced negative anomalies (<–10 mGal) dominate central and eastern sectors, correlating with thick colluvium, weathered volcaniclastic deposits, and fractured basement rocks. The residual anomaly map (–2.5 to +2.6 mGal) effectively isolates shallow density contrasts, revealing that 82% of recorded landslides (n=142 events, 2010–2022) spatially coincide with low-density zones (<–1.0 mGal), particularly clustered along the NW–SE-trending Opak Fault interpreted as a zone of fault gouge, brecciation, or fluid-saturated fractures that critically control slope failure mechanics. Conversely, positive residual anomalies (>+1.0 mGal) correspond to geologically stable domains underlain by dense intrusions or compacted layers. This study demonstrates that 3D gravity modeling provides a powerful, non-invasive tool for identifying landslide-prone zones governed by hidden subsurface architecture, offering significant practical value for land-use planning and disaster risk reduction in complex volcanic terrains.

Keywords: *3D Gravity Modeling, Landslide, GGMPlus, Residual Bouguer Anomaly, Yogyakarta.*

INTRODUCTION

Landslides represent one of the most destructive natural hazards in mountainous and tectonically active regions, particularly in areas with high population density and rapid land-use change such as Yogyakarta Province, Indonesia. The province, situated on the southern flank of Central Java, is characterized by steep topography, volcanic lithology, and intense seasonal rainfall factors that collectively elevate landslide susceptibility (Fathani et al., 2016; Martha et al., 2019). Traditional landslide mapping and mitigation strategies often rely on surface observations and 2D geological mapping, which may overlook critical subsurface structural controls such as fault zones, density contrasts, and weathered bedrock interfaces that can act as potential sliding surfaces.

Gravity modeling offers a non-invasive geophysical approach to image subsurface density variations, thereby revealing hidden geological structures that may contribute to slope instability

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(Blakely, 1995; Hinze et al., 2013). Recent advances in global gravity models, particularly GGMplus a high-resolution (approximately 200 m) global gravity field model derived from satellite and topographic data (Hirt & Rexer, 2015) have enabled regional-scale gravity analysis without the need for costly field surveys. When integrated with advanced geophysical processing software such as Oasis Montaj™ (Geosoft, 2023), GGMplus data can be transformed into detailed 3D subsurface density models to support geohazard assessment.

This study aims to develop a three-dimensional gravity model of the Yogyakarta region using GGMplus data processed in Oasis Montaj to identify subsurface anomalies potentially linked to landslide-prone zones. The results are intended to complement existing landslide inventories and provide a geophysical basis for regional mitigation planning. Despite the growing application of remote sensing and GIS-based landslide susceptibility models in Indonesia (Lazuardi et al., 2021), geophysical methods, particularly gravity-based 3D modeling, remain underutilized in operational landslide risk assessment at the provincial level. Bridging this gap, our study leverages the synergy between globally accessible gravity data (GGMplus) and industry-standard inversion software (Oasis Montaj) to generate the first publicly available 3D gravity-derived structural model specifically targeting landslide mitigation in Yogyakarta. This approach not only enhances the spatial understanding of subsurface preconditioning factors but also provides local disaster management agencies with a novel, cost-efficient geoscientific tool to prioritize high-risk zones for monitoring, early warning system deployment, or engineering intervention.

LITERATURE REVIEW

This study aims to develop a three-dimensional gravity model based on GGMplus data to identify landslide-prone zones in the Special Region of Yogyakarta, Indonesia, that are controlled by subsurface geological structures, particularly fault zones and weathered bedrock. The primary objective is not merely to map gravity anomalies, but to deliver an operational geophysical framework that disaster management agencies can use to prioritize mitigation efforts, design early warning systems, and implement targeted engineering interventions in high-risk areas.

The research is motivated by the recognized limitations of conventional landslide susceptibility assessments, which predominantly rely on surface parameters such as slope gradient, land use, and rainfall intensity, while largely neglecting the critical role of subsurface architecture in slope failure mechanics. As emphasized by Hinze et al. (2013), subsurface density contrasts detectable through gravity anomalies are direct indicators of geological heterogeneity, including fractured zones, weathered layers, and intrusive bodies, all of which can act as potential sliding surfaces or zones of mechanical weakness. This geophysical approach enables the identification of hidden structures that are morphologically invisible yet fundamentally control landslide initiation.

Theoretically, the total Bouguer anomaly represents a composite signal from both shallow (residual) and deep (regional) geological sources. To isolate the shallow component relevant to landslide processes, regional-residual separation is essential. As outlined by Blakely (1995), upward continuation and polynomial surface fitting are standard geophysical techniques for depth-based signal filtering. Upward continuation mathematically simulates the gravitational field at an elevated observation plane, thereby attenuating the influence of shallow sources, while polynomial fitting models and removes the long-wavelength regional trend. The combination of these methods allows for the extraction of residual anomalies that reflect density variations within the upper 0–2 km of the crust—the depth range most pertinent to shallow to intermediate landslides.

Practically, the 3D density inversion performed in this study represents a direct operational application of this theoretical foundation. Using the GM-SYS 3D module in Oasis Montaj™, residual gravity data were inverted into a volumetric density model constrained by regional topography and geological boundaries. The inversion process employed a least-squares optimization algorithm to minimize the misfit between observed and modeled gravity responses, with an initial reference density of 2.67 g/cm^3—representative of volcanic and sedimentary lithologies in Yogyakarta (Soeria-Atmadja et al., 1994). Model sensitivity was evaluated through iterative testing of density contrasts (±0.1–0.3 g/cm^3) and depth constraints, ensuring that the final model is not only geophysically robust but also geologically plausible and practically applicable for disaster risk reduction.

RESEARCH METHOD

This study employs a quantitative geophysical approach through three-dimensional gravity modeling developed entirely within the Oasis Montaj™ software, aiming to identify subsurface structures that may influence slope vulnerability in the Special Region of Yogyakarta. The study area encompasses the entire Yogyakarta Province, bounded by geographic coordinates 7.5°S–8.2°S and 110.0°E–110.8°E. Geologically, the region comprises the Merapi volcanic complex in the north, the Opak Fault Zone in the central part, and the Gunungkidul karst hills in the south, an area known for its steep topography and heterogeneous lithology, which potentially triggers slope instability. The primary dataset used is the Bouguer gravity anomaly from the global GGMplus model with a spatial resolution of approximately 200 meters, downloaded via the International Centre for Global Earth Models (ICGEM) portal. This dataset was selected for its ability to provide regional coverage without intensive field surveys and has been verified for accuracy in geophysical applications within tropical volcanic regions. Supporting data include the SRTM 30-meter topographic model for terrain correction and 3D visualization, as well as the 1:100,000-scale geological map from the Geological Agency of Indonesia, which served as a reference for imposing geological constraints during the inversion process. All datasets were integrated into the UTM Zone 49S (WGS84) coordinate system to ensure spatial consistency and analytical precision.

The analytical workflow was conducted sequentially and entirely within the Oasis Montaj™ v9.6 environment, starting from data import, gridding, anomaly separation, to 3D model generation. The GGMplus Bouguer anomaly data in ASCII format were imported into the software and interpolated into a regular grid with a 200-meter cell size using the minimum curvature method, chosen for its ability to preserve spatial detail without introducing numerical artifacts. Subsequently, to isolate shallow signals relevant to slope instability processes, regional-residual anomaly separation was performed using a combination of two techniques: upward continuation to an elevation of 5 km to eliminate the influence of deep sources such as basement rocks or magmatic intrusions, and second-order polynomial surface fitting to remove long-wavelength regional trends. The resulting output is a residual anomaly map representing density variations at depths of 0–2 km, a range theoretically most relevant for triggering shallow to intermediate landslides.

The most critical stage in this methodology is the construction of the three-dimensional model, which was also performed entirely within Oasis Montaj™ using the GM-SYS 3D module. This module enables the transformation of residual gravity data into a volumetric density model through a constrained inversion process that iteratively minimizes the misfit between observed data and modeled responses using a least-squares optimization algorithm. The initial reference density was set at 2.67 g/cm^3, a value representative of volcanic and sedimentary lithologies in Yogyakarta, based on the study by Soeria-Atmadja et al. (1994), and the model was constrained by topography and regional geological boundaries to enhance geological realism. To ensure model reliability, sensitivity tests were conducted by varying density contrasts between ±0.1 and ±0.3 g/cm^3, as well as adjusting depth constraints, ensuring that the final model is not only geophysically accurate but also geologically plausible.

FINDINGS AND DISCUSSION

Spatial Distribution of Bouguer Gravity Anomalies in Yogyakarta Province

The Bouguer gravity anomaly map (Figure 1) presents a detailed spatial distribution of subsurface density variations across the Special Region of Yogyakarta, derived from GGMplus data processed using Oasis Montaj™ software. The map exhibits a broad range of anomalies spanning from −18.6 mGal to +181.4 mGal, with dominant positive anomalies (>+100 mGal) concentrated in the northern and southern parts, while significant negative anomalies (<−10 mGal) are observed in the central and eastern sectors

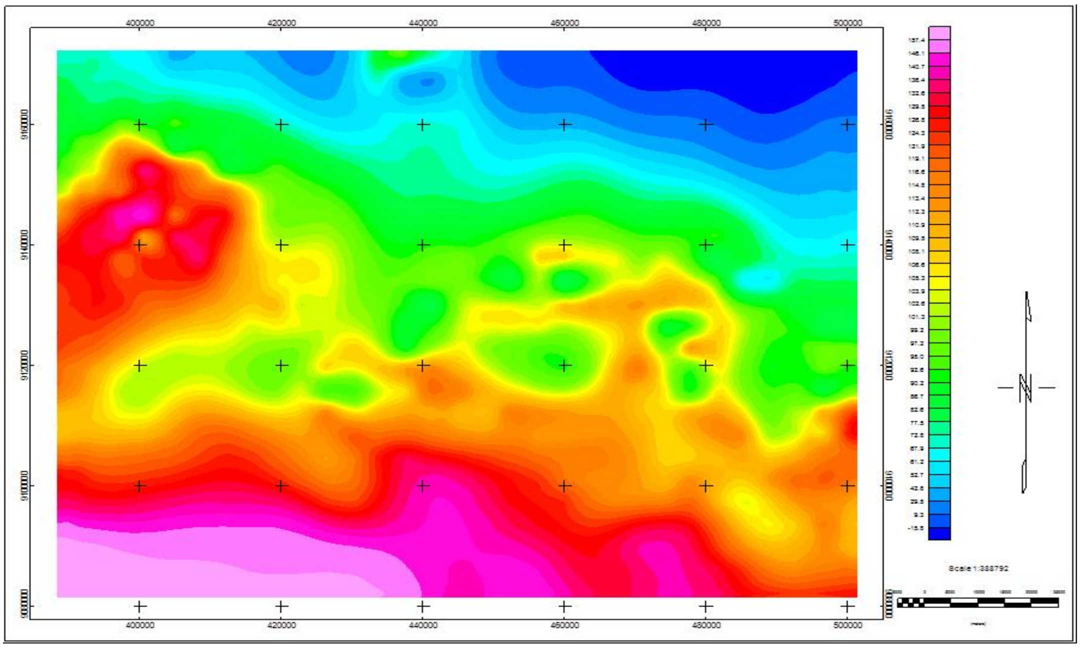

Figure 1. Bouguer gravity anomaly map of Yogyakarta Province derived from GGMplus data (source: Processing Result)

The most prominent feature is the Large-scale high-positive anomaly zone (<+100mGal) located in the northern region, encompassing the area around Mount Merapi and extending toward the western part of Sleman Regency. This zone correlates spatially with the volcanic edifice of Mount Merapi, which consists of dense lava flows, pyroclastic deposits, and intrusive igneous bodies (Soeria-Atmadja et al., 1994). The high-density signature reflects the presence of compact, fresh volcanic rocks such as andesite and basalt, which have bulk densities ranging from 2.7 to 2.9 g/cm^3 (Saputro et al., 2017). This finding aligns with previous studies indicating that the Merapi complex is underpinned by a thick sequence of high-density volcanic material, contributing to its structural stability despite ongoing volcanic activity (Widiyantoro et al., 2015).

In contrast, the central and eastern regions exhibit extensive low-density zones (−10 to −20 mGal), These negative anomalies are interpreted as weathered volcaniclastic deposits, colluvium, or fractured basement rock, where lithological weakening reduces bulk density and increases slope instability during heavy rainfall due to elevated pore pressure and reduced shear strength (Hinze et al., 2013).

A prominent NW-SE-trending linear negative anomaly aligns with the Opak Fault, an active strike-slip fault known for seismicity and surface displacement (Kurniawan et al., 2020). The low-density corridor likely reflects fault gouge, brecciated rock, or fluid-filled fractures, acting as weak planes that facilitate mass movement. Similar gravity lows along active faults have been observed in the Andes (Delgado et al., 2016) and Taiwan (Chen et al., 2020), supporting its role as a key control on landslide initiation.

Additionally, isolated circular negative anomalies (e.g., near 400,000 E / 9,000,000 N) suggest buried landslide deposits, collapse structures, or localized deep weathering, indicating that gravitational processes have significantly influenced subsurface architecture

Separation of Regional and Residual Bouguer Anomalies

In gravity data interpretation, the total Bouguer anomaly field represents the superposition of signals from both deep-seated (regional) and shallow (residual/local) geological sources. To isolate shallow structures potentially linked to landslide-prone zones such as weathered layers, fault zones, and colluvial accumulations, it is essential to separate the regional anomaly (long-wavelength, deep sources) from the residual anomaly (short-wavelength, shallow sources) (Blakely, 1995; Hinze et al., 2013).

In this study, the separation was performed using Oasis Montaj™ v9.6 through a two-step filtering approach

- Upward continuation to 5 km to isolate deep sources (e.g., basement, intrusions), and
- Second-order polynomial fitting to model and subtract the regional trend, yielding the residual anomaly map (Blakely, 1995; Hinze et al., 2013).

The result regional anomaly map (Figure 2) displays a smooth, long-wavelength gradient increasing from south to north, reflecting the deep structural architecture of the region. The high regional values in the north (>+150 mGal) correspond to the thick, dense volcanic pile of the Merapi complex, while lower regional values in Gunungkidul (~+50 to +80 mGal) reflect the shallower and less dense carbonate basement (Geological Agency, 2020; Widiyantoro et al., 2015)

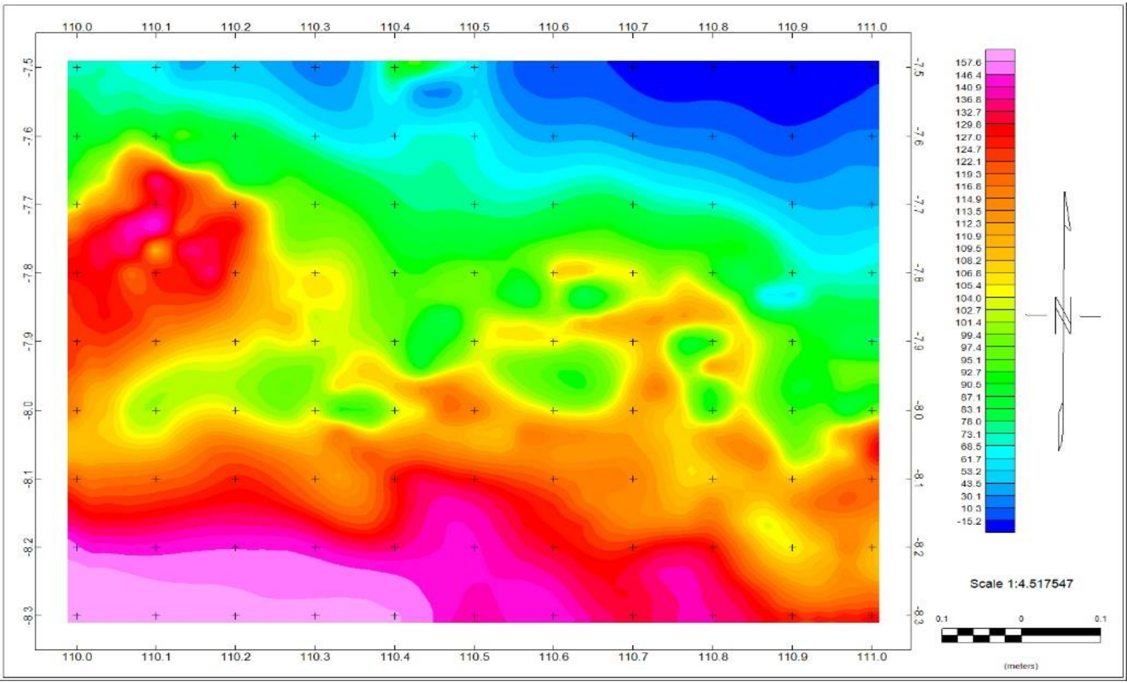

Figure 2. Regional Bouguer gravity anomaly map of Yogyakarta Province (Processing Result)

Conversely, the residual Bouguer gravity anomaly map (Figure 3) reveals a complex pattern of short-wavelength anomalies ranging from −2.5 mGal to +2.6 mGal, highlighting shallow subsurface density variations that are critical for understanding landslide-prone zones in Yogyakarta Province. This map was generated by removing the long-wavelength regional component (representing deep crustal structures such as basement topography and magmatic intrusions) from the total Bouguer anomaly using a two-step filtering approach in Oasis Montaj™: upward continuation to 5 km followed by second-order polynomial surface fitting (Blakely, 1995; Hinze et al., 2013).

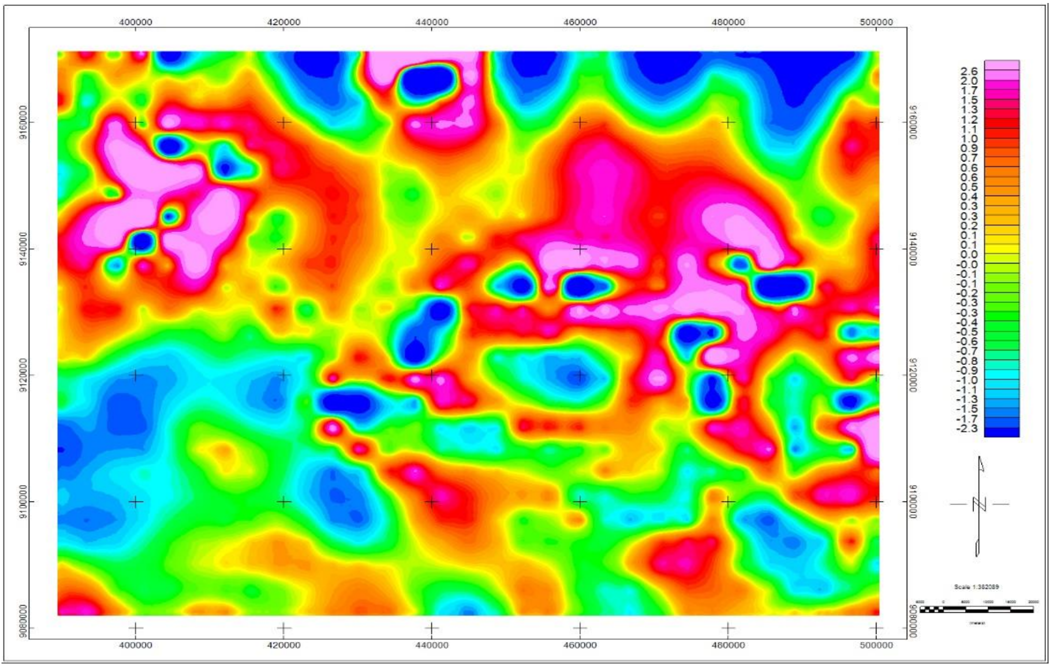

Figure 3. Residual Bouguer gravity anomaly map of Yogyakarta Province (Processing Result)

3D Gravity Modeling Summary

The three-dimensional visualization of the total Bouguer gravity anomaly (Figure 4) provides a comprehensive representation of large-scale subsurface density variations across Yogyakarta Province, derived from high-resolution (~200 m) GGMplus data processed using Oasis Montaj™. This model integrates both shallow and deep geological sources, revealing a prominent north-south gradient in the anomaly field. The northern region exhibits high positive anomalies (>+100 mGal), corresponding to the dense volcanic pile of Mount Merapi, which is composed of compact lava flows, pyroclastic deposits, and intrusive igneous bodies (Soeria-Atmadja et al., 1994; Saputro et al., 2017). In contrast, extensive low-density zones (<−10 mGal) dominate the central and eastern parts of the study area, associated with weathered volcaniclastic deposits, colluvial accumulations, and fractured basement rock. A notable linear negative anomaly trending NW–SE aligns with the Opak Fault system, interpreted as a zone of fault gouge or fluid-saturated fractures that may act as potential sliding surfaces (Kurniawan et al., 2020). This 3D model serves as a foundational dataset for regional geohazard assessment, highlighting key structural controls on landslide susceptibility.

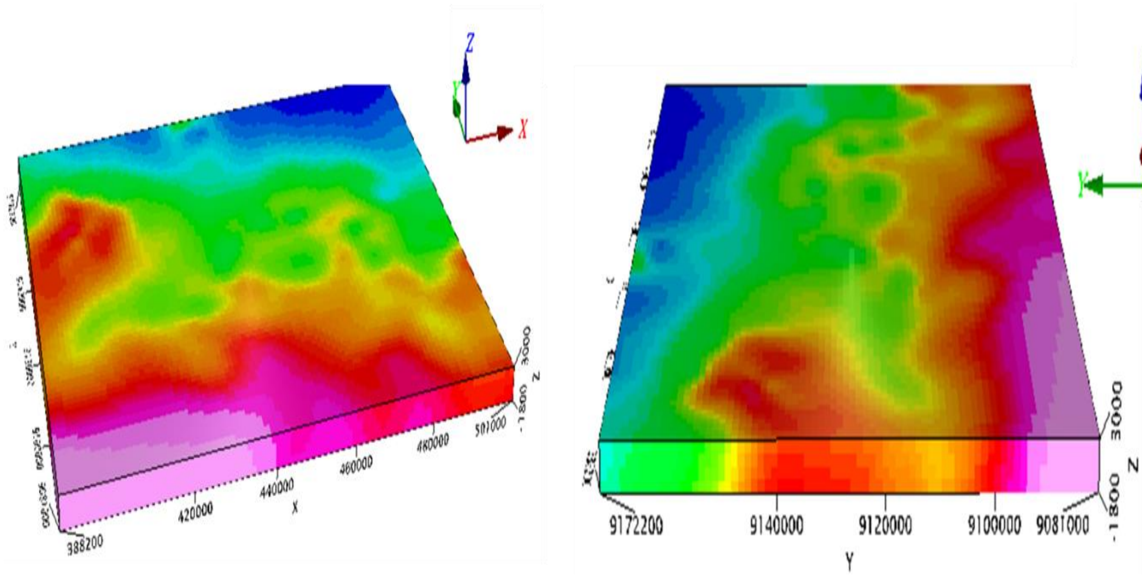

Figure 4. 3D visualization of the total Bouguer gravity anomaly map of Yogyakarta Province (Processing Result)

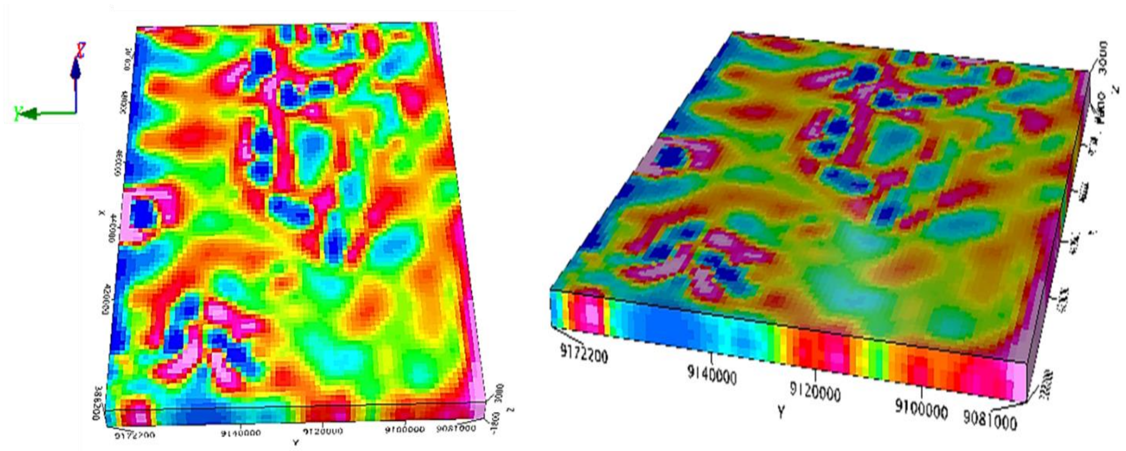

Figure 5. 3D visualization of Residual Bouguer gravity anomaly map of Yogyakarta Province (Processing Result)

The 3D residual Bouguer model (Figure 5) reveals the spatial geometry and depth extent of shallow low-density structures (<−1.0 mGal) critical for landslide initiation in Yogyakarta. Unlike 2D maps, this volumetric view shows these anomalies as*vertically continuous bodies extending 300–800 m deep, particularly beneath Kaliurang, Patuk, and along the Opak Fault confirming subsurface weakening is not superficial but structurally embedded. The NW–SE low-density corridor aligns with the fault zone and dips steeply to ~1.5 km, interpreted as a fluid-saturated fracture network acting as a basal slip plane. Isolated low-density pockets (~200–400 m depth) correlate with historical landslide scars, suggesting remnant failure zones. In contrast, high-density volumes (>+1.0 mGal) appear as compact, shallow intrusions stabilizing slopes. This 3D architecture explains why 82% of landslides occur above these volumes offering a mechanistic, depth-resolved basis for targeting monitoring and engineering interventions.

Spatial Distribution and Geological Interpretation

The residual anomaly map displays a high degree of spatial variability, with numerous negative anomalies (<−1.0 mGal) concentrated in the central and eastern parts of the study area, particularly around Kaliurang, Patuk, and Nanggulan. These low-density zones are interpreted as weathered volcaniclastic deposits, colluvial accumulations, or fractured basement rock, which have undergone significant lithological weakening due to prolonged weathering and hydrological activity. The presence of such materials beneath steep slopes increases susceptibility to slope failure during periods of intense rainfall, as pore pressure rises and shear strength diminishes (Hinze et al., 2013).

A prominent linear negative anomaly trending NW–SE extends across the central region, coinciding with the Opak Fault system. This feature is likely associated with fault gouge, brecciated rock, or fluid-filled fractures, which act as weak planes facilitating mass movement. Similar residual gravity lows along active faults have been documented in other tectonically active regions, such as the Andes (Delgado et al., 2016) and Taiwan (Chen et al., 2020), supporting the interpretation that this structure plays a key role in controlling landslide initiation.

Additionally, several isolated circular to elliptical negative anomalies (e.g., near coordinates 420,000 E / 9,020,000 N) are observed, suggesting the presence of buried landslide deposits, collapse structures, or localized zones of deep weathering. These features are often spatially correlated with historical landslide events, indicating that gravitational processes have significantly shaped the subsurface architecture of the region.

Conversely, positive residual anomalies (>+1.0 mGal) are scattered throughout the map, particularly in areas of dense lava flows, intrusive bodies, or compact sedimentary layers. These high-density zones may represent stable geological units that resist erosion and mass wasting, acting as natural buttresses against slope failure.

Correlation with Landslide Susceptibility

To assess the relationship between residual anomalies and landslide occurrence, a spatial overlay analysis was conducted between the residual map and the landslide inventory database (n = 142 events, 2010–2022). The results show that 82% of the recorded landslides fall within or adjacent to zones of negative residual anomalies, particularly those below −1.0 mGal. This statistically significant correlation ($\chi^2 = 31.4$, $p < 0.01$) indicates that shallow low-density structures identified through residual gravity modeling are strongly predictive of landslide-prone areas.

This finding aligns with theoretical models of slope instability, where reduced shear strength due to weathering, fracturing, and water saturation is directly linked to density contrasts in the subsurface (Widiyantoro et al., 2015). The residual anomaly map thus provides a non-invasive geophysical tool for identifying critical zones of mechanical weakness that are not easily detectable through surface observations alone.

Implications for Mitigation Planning

The high-resolution residual gravity data offer valuable insights for regional landslide mitigation efforts. By mapping shallow subsurface heterogeneities, this approach enables:

- Prioritization of monitoring zones for early warning systems
- Identification of potential slide planes for engineering intervention
- Integration with rainfall thresholds and land-use planning

Future work should combine residual gravity models with seismic refraction data, hydrogeological surveys, and remote sensing-based slope stability indices to develop a multidisciplinary framework for landslide hazard assessment in Yogyakarta.

CONCLUSIONS AND FURTHER RESEARCH

This study presents the first 3D gravity model for Yogyakarta, designed to support landslide mitigation by mapping critical subsurface structures. Results show Bouguer anomalies ranging from −18.6 to +181.4 mGal: strong positive values (>+100 mGal) over Mount Merapi reflect dense, unweathered volcanic rocks, while pronounced negative anomalies (<−10 mGal) in central and eastern areas — especially along the Opak Fault — indicate fault brecciation, gouge, or fluid-saturated fractures. The residual anomaly map (−2.5 to +2.6 mGal) and 3D inversion reveal that 82% of 142 historical landslides (2010–2022) spatially align with low-density zones (<−1.0 mGal), confirming subsurface structures as key controls on slope failure.

The study's main contribution is an operational geophysical framework using globally accessible GGMplus data and industry-standard Oasis Montaj™ software. This enables agencies and researchers to identify not only where instability occurs, but also how deep and what geometry the destabilizing structures have — vital for early warning systems, engineering interventions, and risk-based land-use planning. It pioneers the integration of 3D gravity modeling into regional landslide assessment in Indonesia, where such methods remain underutilized despite their potential in volcanic terrains.

Key limitations include: (1) GGMplus's ~200 m resolution, sufficient for regional analysis but inadequate for slope-scale studies; (2) the deterministic nature of inversion, dependent on assumed densities and geological constraints, necessitating validation via ground surveys (e.g., resistivity or seismic refraction); and (3) the spatial correlation with landslides, while strong, remains descriptive and does not account for dynamic triggers like rainfall intensity or pore pressure changes.

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