



Mapping of Liquefaction Potential in the Capital City of Sofifi, North Maluku Based on Groundwater Level Data as Disaster Mitigation

Armanto Arif^{1,2*}, Adi Susilo^{1,2}, Rahim Achmad³

¹ Department of Physics, University of Brawijaya, Malang, Indonesia.

² Department of Physics, Faculty of Mathematics and Natural Sciences, Brawijaya University, Malang, Indonesia.

³ Department of Mathematics and Natural Sciences Education, Faculty of Teacher Education and Physics, Khirun University, Ternate, Indonesia.

Received: September 28, 2025

Revised: April 03, 2026

Accepted: May 25, 2026

Published: May 31, 2026

Corresponding Author:

Armanto Arif

aryarmanto1110@gmail.com

DOI: [10.29303/jppipa.v12i5.9282](https://doi.org/10.29303/jppipa.v12i5.9282)

 Open Access

© 2026 The Authors. This article is distributed under a (CC-BY License)



Abstract: North Maluku Province, an eastern Indonesian region characterized by complex geological features, has its capital city, Sofifi, experiencing rapid development. However, Sofifi is a low-lying area with productive aquifers situated in an active seismic zone, rendering it highly susceptible to liquefaction. Liquefaction, defined as the loss of soil shear strength due to increased pore water pressure during an earthquake, frequently occurs in water-saturated sediments with fine to medium grain sizes. This study assesses liquefaction potential by correlating residual gravity anomalies, groundwater levels, and liquefaction vulnerability maps. Gravity data were sourced from GGMplus satellite imagery (200-meter resolution), and groundwater levels were directly measured at 367 well locations. Spatial analysis, conducted using ArcGIS 18.0 software, generated maps of gravity anomaly distribution and groundwater levels. These maps were subsequently validated against liquefaction susceptibility maps from BNPB (inaRISK). The results indicate a strong correlation between zones of low gravity anomalies (-1.7 to -0.1 mGal) and shallow groundwater levels (0–366 cm) in Sofifi City with high liquefaction vulnerability, particularly in the northwestern and central areas. The integration of geophysical and hydrogeological parameters proved effective in identifying liquefaction-prone zones. These findings are anticipated to serve as a crucial basis for spatial planning and disaster mitigation strategies in coastal urban areas like Sofifi.

Keywords: Disaster mitigation; GGMplus; Gravity anomaly; Groundwater level; Liquefaction; Sofifi

Introduction

Liquefaction is a natural phenomenon frequently observed in earthquake-prone areas, where saturated fine-grained soil loses its structural strength due to seismic activity or additional loads (Özener et al., 2020; Yakin et al., 2023). This phenomenon can lead to significant damage to infrastructure, especially in densely populated urban areas. Groundwater levels are a key factor influencing liquefaction potential (Baeruma et al., 2020; Anar et al., 2024). When an earthquake shakes water-saturated soil, pore water pressure increases, consequently decreasing soil shear strength

and ultimately triggering liquefaction (Nurbani et al., 2021; Setiawan et al., 2023).

Soil saturation levels are primarily controlled by the depth of the water table (Wasillah, 2017; Bleam et al., 2017). Consequently, areas with high water tables are generally more susceptible to liquefaction (Hidayah et al., 2024). The rate of pore water pressure increase during an earthquake is directly influenced by the groundwater level (Kamura et al., 2024). As a result, the propagation of seismic waves to the ground surface can trigger soil liquefaction, leading to a decrease in soil stiffness and stability (Beddu et al., 2022).

Effective disaster mitigation planning in earthquake-prone areas necessitates a comprehensive

How to Cite:

Arif, A., Susilo, A., & Achmad, R. (2026). Mapping of Liquefaction Potential in the Capital City of Sofifi, North Maluku Based on Groundwater Level Data as Disaster Mitigation. *Jurnal Penelitian Pendidikan IPA*, 12(5), 81–88. <https://doi.org/10.29303/jppipa.v12i5.9282>

understanding of the relationship between saturated loose sediments and liquefaction potential. Previous studies consistently show that low-lying and coastal regions frequently exhibit high levels of soil water saturation, which significantly elevates liquefaction risk (Syandi & Tampubolon, 2020; Babacan & Ceylan, 2021; Silalahi et al., 2023; Meng et al., 2023; Zhang et al., 2023; Fauzik et al., 2020; Darmawan, 2022). This research is particularly crucial for areas undergoing rapid infrastructure development and expansion.

Sofifi, the capital city of North Maluku Province, is one such earthquake-prone area due to its location within an active tectonic zone (Septiani et al., 2021; Saifuddin et al., 2021). Furthermore, Sofifi is characterized as a low-lying region possessing an unconfined aquifer (Bakri et al., 2016). The absence of an impermeable barrier in such aquifers allows groundwater to move freely between the aquifer and the atmosphere via soil pores. This condition critically influences groundwater table dynamics, which, in turn, plays a pivotal role in determining the region's liquefaction susceptibility.

This study aims to measure and map the groundwater table in Sofifi, the capital city, using direct measurements from several wells. The collected data will be utilized to generate a groundwater table map, facilitating the identification of areas susceptible to liquefaction (Hidayah et al., 2024). Additionally, gravity measurements were performed using GGMplus satellite imagery. Gravity anomaly values, particularly Bouguer anomalies, indirectly indicate liquefaction potential by depicting subsurface physical characteristics such as soil density, rock type, and geological structure. Specifically, negative anomalies suggest the presence of lightweight or low-density loose sediments that are prone to liquefaction, especially in water-saturated soils with fine to medium grain sizes, which are commonly found in alluvial plains, deltas, and coastal areas (Mandalika et al., 2023; Fauzik et al., 2020). Given the critical importance of disaster risk management in this region, a comprehensive study of water-saturated loose sediments and their correlation with liquefaction potential is urgently needed.

The main objective of this study is to analyze liquefaction potential in Sofifi City, North Maluku. This is achieved by correlating residual anomaly data, groundwater levels, and liquefaction vulnerability maps. Specifically, the research integrates gravity anomaly data to identify variations in rock density, analyzes groundwater levels to understand soil saturation, and investigates their relationship with existing liquefaction vulnerability maps. This study is expected to provide valuable insights, serving as a basis for infrastructure development planning and the

implementation of disaster risk mitigation strategies in Sofifi.

Method

This study was conducted in the capital city of Sofifi, North Maluku (Figure 1), employing the gravity method with GGMplus (Global Gravity Model Plus) satellite imagery. GGMplus offers a comprehensive representation of Earth's gravity, featuring global coverage and a 200m data resolution (Hirt et al., 2013). This method was utilized to measure gravity variations and identify subsurface density differences. High-resolution GGMplus data for the 5 x 5 km research area was accessed via <http://murray-lab.caltech.edu/GGMplus/index.html>.

GGMplus integrates satellite gravity data from GRACE (ITG2010), GOCE (TIM-4), and EGM2008, further enhanced by topographic gravity information. This model offers five key gravity field functions: gravitational acceleration, gravity disturbance, north-south and east-west vertical deflection, and quasigeoid height (Hirt et al., 2013). Input parameters for GGMplus include the maximum and minimum coordinates (latitude and longitude) of the study area. The outputs comprise coordinates (longitude and latitude), Free Air Anomaly (FAA) values, and topography, all essential for subsequent Bouguer anomaly analysis. Subsequently, a Moving Average operation is applied to the Bouguer anomaly to derive residual anomalies. These residual anomalies are crucial for interpreting rock density, understanding the underlying geological characteristics, and identifying potentially liquefaction-susceptible layers.

Groundwater level measurements were conducted through field surveys involving existing wells. At each resident's well, the water level was measured from the well water surface to the well flange (in cm), and the height of the well flange (in cm) was also recorded using a cylinder measuring device, following Formula 1 (Amri et al., 2021). The collected data was subsequently processed using ArcGIS 18.0 and Microsoft Excel.

$$GLD = \text{Water table to well} - \text{Height of well lip} \quad (1)$$

Coordinate points and groundwater level elevations from each well in the study area using GPS will be collected and plotted on a topographic map to form a groundwater level distribution map (GLD). The contouring of the groundwater table is done using the Tree Point method approach, which is based on the groundwater level information obtained from the analysis of groundwater depth information. By connecting locations with the same GLD value through a line, known as an equipotential line or contour line.



Figure 1. Research area design

Result and Discussion

Geologically, the study area within the capital city of Sofifi is dominated by Quaternary (Qa) deposits, specifically alluvial deposits composed of sand, gravel, and clay. These deposits lack discernible sedimentary rock structures. The presence of sand and gravel as alluvial components is characteristic of coastal and riverine environments (Abdul et al., 2020). Seismic activity in North Maluku Province, based on data visualization, recorded 852 earthquake epicenters with 11 distribution points in 2021, decreasing to 498 epicenters with the same distribution in 2022 (Saleh et al., 2023). Primary (P) and secondary (S) seismic waves generated by earthquakes induce ground vibrations. These vibrations elevate pore pressure within the soil, particularly in water-saturated strata such as loose sand or alluvial soil. Hydrologically, the Sofifi region is also characterized by the presence of moderately productive aquifers (Rahman et al., 2022). Collectively, these geological and hydrological attributes indicate a notable potential for liquefaction within the capital city of Sofifi.

The community in the capital city of Sofifi still heavily relies on groundwater wells. A field survey within the study area identified 367 active community wells (Figure 1). This dependency suggests that when productive aquifers are close to the ground surface, the saturation level of the overlying soil can increase. Consequently, this elevates the potential for liquefaction if the soil contains fine-grained components (e.g., fine sand) and is triggered by an earthquake event (Hidayah et al., 2024).

This study compares the groundwater level, residual anomaly, and liquefaction vulnerability maps. For reference, we utilized liquefaction vulnerability map data published by BNPB via the inaRISK website. The liquefaction vulnerability data obtained from inaRISK was subsequently mapped using ArcGIS 18.0 software.

Complete Bouguer Anomaly (CBA)

The Complete Bouguer Anomaly (CBA) represents a gravity anomaly value that has been fully corrected for gravitational effects attributed to the Earth's shape, elevation, and the density of materials above a reference surface. Variations in subsurface density directly reflect differences in the underlying geological layers or materials (De Ritis et al., 2023).

In the Sofifi capital region, CBA values range from -169.0 to 191.6 mGal, as depicted by color variations from dark blue to purple (Figure 2). Notably, significant differences in CBA distribution are observed between the northwestern and eastern portions of the study area.

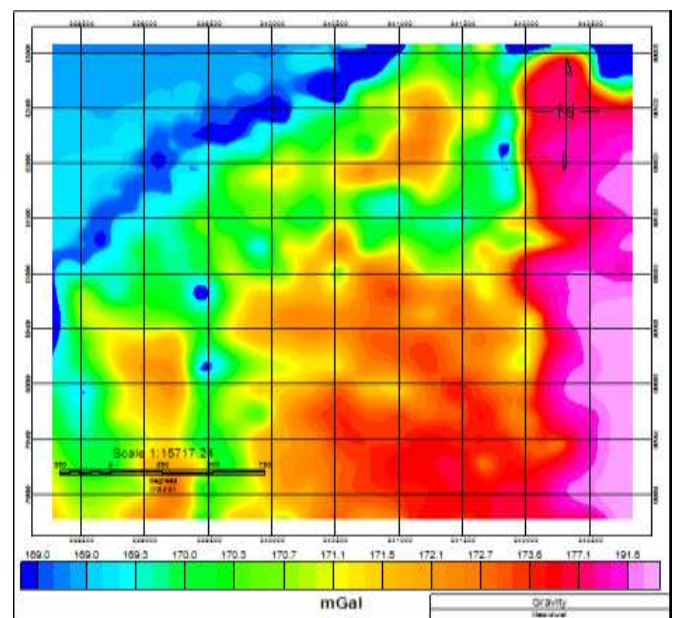


Figure 2. Complete bouguer anomaly (CBA)

Low gravity anomalies, ranging from -169.0 mGal to -170.7 mGal (indicated by blue to dark blue colors), were observed along the northwest coastline, encompassing both marine and coastal areas. These relatively low anomaly values suggest the presence of looser, water-saturated sediment layers, attributed to the dominance of alluvial formations and fluvial sediment elements in this region (Rustam, 2012; Bakri, 2016).

Conversely, high gravity anomalies, ranging from 171.1 mGal to 191.6 mGal (indicated by yellow to orange colors), were identified in the eastern and southeastern parts of the study area. Specifically, in the eastern portion extending from north to south, anomaly values reached 173.6 mGal to 191.6 mGal (depicted with color variations from red to purple). These elevated anomaly values signify the presence of denser and more compact rocks, potentially indicating igneous intrusions or other solid rock formations. This distinct contrast highlights significant geological differences between the solid rock zone and the sedimentary deposit areas. To acquire

more accurate and in-depth geological data and to comprehend the various elements influencing subsurface density distribution, the Complete Bouguer Anomaly (CBA) was subjected to separation using an upward continuation filter within Oasis Montaj software (Kurniawan et al., 2021). This separation process specifically aims to delineate regional and residual anomalies from the raw CBA data.

Regional Anomaly

Similarities observed between the regional anomaly results and the Complete Bouguer Anomaly (CBA) can arise from several factors, particularly in study areas characterized by homogeneous geology. It is plausible that deep geological structures, which primarily influence regional anomalies, exhibit resemblances to the shallower structures affecting residual anomalies, thus yielding relatively similar anomaly maps. Furthermore, the overall homogeneous geological conditions within the region can also contribute to the observed similarity in these results (Ayala et al., 2016; Bezák et al., 2023).

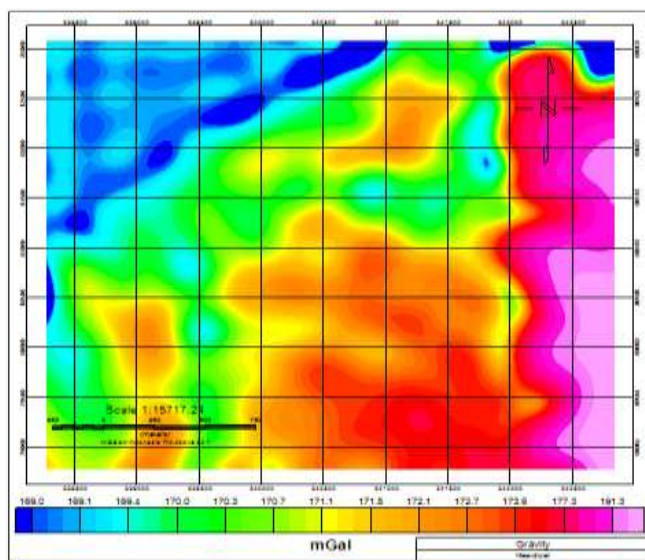


Figure 3. Regional anomaly

Sharp changes in anomaly values (high gradients) typically indicate a geological contact between rocks of differing densities, such as the boundary between igneous rocks and sedimentary deposits. Higher regional gravity anomaly values, ranging from 173.6 mGal to 191.3 mGal (indicated by color variations from red to purple), signify the presence of denser geological structures in the area.

Conversely, areas exhibiting low anomaly values (shown in shades of blue to green) point to lower densities, suggesting the presence of sedimentary basins, weathering zones, or aquifers. This aligns with the potential formation of extensive sedimentary basins

resulting from depositional processes within alluvial areas. Geologically, this study area is indeed dominated by Quaternary alluvial sediment deposits (Qa) (Rustam, 2012; Bakri, 2016). These low anomalies are likely associated with alluvial deposits in coastal zones or basins formed by crustal deformation processes. Furthermore, the presence of the large Kali Oba river in the region potentially contributes significantly to the local sedimentation process.

Residual Anomaly

Residual anomalies reflect variations in subsurface mass density at shallow to medium depths. This analysis is highly beneficial for identifying local geological features relevant to secondary structures.

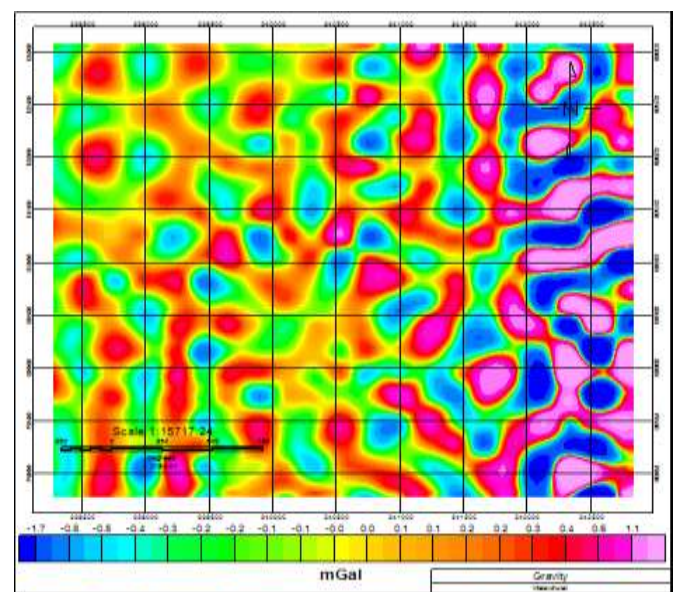


Figure 4. Residual anomaly

The positive anomaly zone, ranging from 0.0 mGal to 1.1 mGal (represented by yellow, red, and purple colors), indicates the presence of high-density masses. Geological interpretations for this zone include intrusions of igneous rock, uplifted tectonic structures (horsts), or dense and hard rock layers (Abiyudo et al., 2021). Conversely, the negative anomaly zone, ranging from -1.7 mGal to -0.1 mGal (shown in blue to green), reflects the presence of lower-density masses. This low anomaly zone may indicate shallow basins filled with sedimentary material, which is highly consistent with the alluvial geological characteristics surrounding the study area. Furthermore, these basins may also signify the potential for aquifers (Mickus et al., 2022).

Correlation between Residual Gravity Anomaly Data, Groundwater Level, and Liquefaction Susceptibility Map

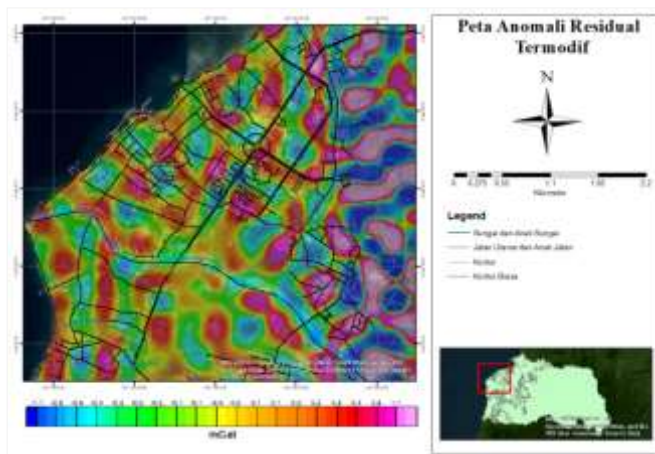


Figure 5. Residual anomaly map

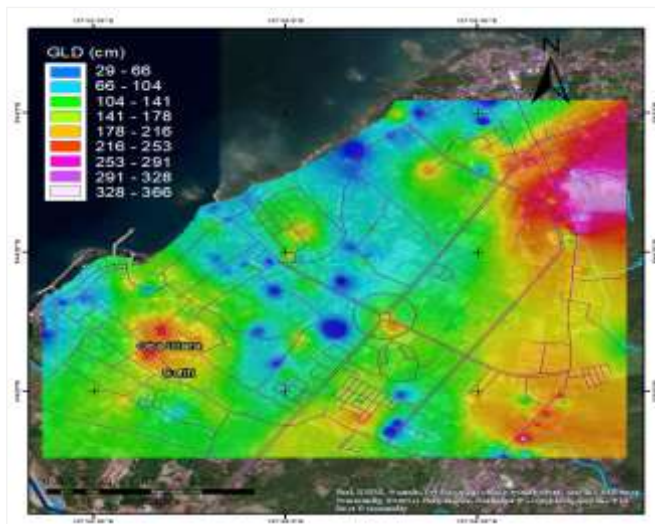


Figure 6. Groundwater Distribution Map (GLD)

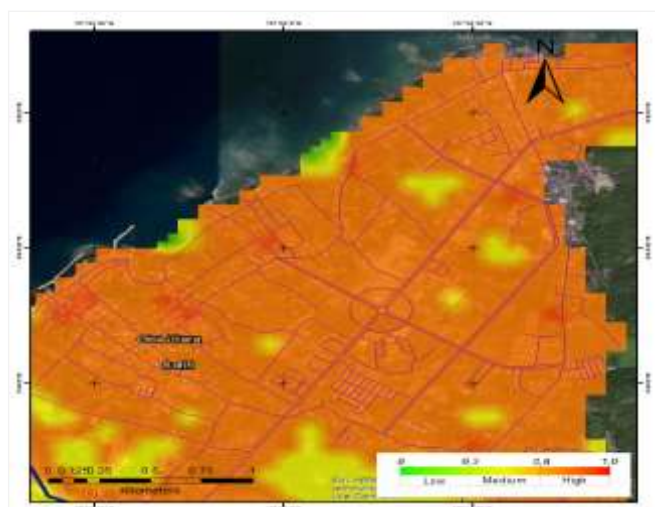


Figure 7. Liquefaction vulnerability map based on inaRISK Data, BNPB

Residual Anomaly Map

Analysis of the residual gravity anomaly map shows anomalies ranging from -1.7 to 1.1 mGal overlaid

on a thematic map of the study area. This map specifically illustrates subsurface density variations in densely populated and developed areas of the study area, using color gradients to show the distribution of gravity anomalies in specific locations (Figure 5).

The central and southwestern regions, represented by yellow, red, and purple colors (positive gravity anomalies, 0.0 mGal to 1.1 mGal), reflect the presence of dense materials, such as bedrock or denser sediments (Sutasoma et al., 2022). Conversely, concentrations of lower-density material are located in the northeast and southwest, indicated by blue and green zones with negative anomalies (negative gravity anomalies, -1.7 to -0.1 mGal). This condition may indicate the presence of water-saturated material or loose sediment deposits (Mickus et al., 2022). Given the higher water saturation in low-density, looser soils at depth, this zone requires monitoring for potential liquefaction. The presence of river and stream networks in this area also correlates with the distribution of loose sediments that influence anomalies in the study area, as shown by the groundwater table map (Figure 5).

Groundwater Distribution Map (GLD)

Groundwater level (GWL) mapping in Sofifi City reveals variations ranging from 29 to 366 cm. This data was derived from well point measurements, processed using Microsoft Excel, and subsequently visualized with ArcGIS 18.0 software to generate a groundwater level distribution map (Figure 6). Specifically, shallow groundwater levels, ranging from 29 to 104 cm, are indicated by the blue to green zones. These areas are predominantly distributed in the northwestern part of Sofifi and at several specific locations within residential zones. Conversely, the eastern and southeastern regions are characterized by deeper groundwater levels, spanning 216 to 366 cm, depicted by pink to red areas. Based on this distribution, a significant portion of the Sofifi area exhibits a high potential for water saturation, particularly in regions adjacent to rivers and the sea.

Shallow groundwater depths, especially when situated above fine-grained alluvial soil, can considerably increase the potential for liquefaction (Zeffitni et al., 2023). The groundwater level in Sofifi's capital city remains relatively shallow, which is a critical factor for liquefaction susceptibility, considering that groundwater depths prone to liquefaction typically range from 0 to 4 meters (Baeruma et al., 2020; Beddu et al., 2022; Zeffitni et al., 2023).

Liquefaction Vulnerability Map

The capital city of Sofifi exhibits varying levels of liquefaction vulnerability, categorized into low, moderate, and high, as depicted in the liquefaction vulnerability map (Figure 7). High liquefaction

vulnerability zones are indicated in orange to red, encompassing most of Sofifi City and several coastal districts. These zones are predominantly composed of alluvial sedimentary material, specifically mud and fine sand (Febriandri, 2014). Conversely, the northwestern and southern parts of Sofifi show low vulnerability zones, represented by green colors. This can be attributed to the denser soil conditions or the presence of coarser soil particles in these areas, which consequently reduces the likelihood of liquefaction.

Zones exhibiting high liquefaction vulnerability (marked in red on the liquefaction vulnerability map, Figure 7) show a clear correlation with areas possessing shallow groundwater depths (0–366 cm), which are still categorized as shallow for liquefaction potential (Figure 6). An overlay analysis comparing the groundwater table map, residual anomaly map, and liquefaction susceptibility map indicates that the high-potential liquefaction zones, particularly prevalent in Sofifi City, demonstrate a significant likelihood of liquefaction (Figure 7).

The Sofifi capital city area is paradoxically classified as a safe groundwater conservation zone. This is attributed to its status as a groundwater recharge zone, characterized by high aquifer productivity (>3 l/s) and a shallow groundwater depth (0–5 m), with dominant rock types being sand and gravel derived from the Oba River and coastal deposits (Febriandri, 2014). Nevertheless, the prevalence of alluvial soil sediments with high water content renders locations within the Sofifi capital region significantly vulnerable to liquefaction.

Conversely, zones with low to moderate liquefaction vulnerability (Figure 7) are generally found in areas where groundwater levels range from 216–366 cm (Figure 6). This observation strongly suggests that the level of liquefaction vulnerability in Sofifi is profoundly influenced by groundwater saturation and the presence of water-saturated sediments. Furthermore, areas with shallow groundwater levels, among other contributing factors, provide a direct indication of liquefaction potential (Musa Sjahrain et al., 2021; Hidayah et al., 2024).

Conclusion

This study consistently demonstrates that the Sofifi area possesses significant liquefaction potential, substantiated by the integrated analysis of gravity anomalies, groundwater levels, and liquefaction vulnerability maps. Low gravity anomaly values indicate the presence of loose soil, a condition exacerbated by shallow groundwater levels, thereby increasing pore water pressure during seismic events. Liquefaction vulnerability maps further corroborate

these high-risk zones around Sofifi and North Oba. Overlay results and spatial analysis affirm the strong correlation between hydrogeological and geophysical parameters and liquefaction potential. Overall, the western and central regions of Sofifi, including parts of Oba Utara District, are identified as priority mitigation zones. These areas collectively meet all three primary indicators of liquefaction risk: low groundwater table depth, negative gravity anomaly values, and a high vulnerability classification, a finding further reinforced by the presence of rivers and floodplains that facilitate the accumulation of loose sediments and groundwater saturation.

Acknowledgements

The authors are grateful to all parties involved in this research. The authors would like to thank Mr. Adi Susilo and Mr. Rahim Achmad for conducting the research. Brawijaya University Malang and inaRISK, BNPB for providing liquefaction vulnerability data and facilitating the author in conducting the research.

Author Contributions

Author contributions include Adi Susilo and Mr. Rahim Achmad: focusing on methodology, reviewing, etc.; Armanto Arif: collecting data, processing data, analyzing data, and writing the original manuscript.

Funding

No external funding.

Conflicts of Interest

No conflict interest.

References

- Abiyudo, R., Daud, Y., & Satya, D. Y. (2021). Subsurface Structure Identification from Gravity Modelling of Silangkitang Geothermal Field for Future Injection Well Targeting. *The 2nd Digital Indonesia International Geothermal Convention (DIIGC), September*. Retrieved from https://earthjay.com/earthquakes/20220225_sumatra/abiyudo_et_al_2021_Subsurface_Structure_Gravity_Modelling_Silangkitang_sumatra.pdf
- Amri, M. A. (2021). Pengaruh Air Permukaan terhadap Air Tanah berdasarkan Data Muka Air Tanah Dangkal Daerah Danau Sunter dan Sekitarnya. *PETRO: Jurnal Ilmiah Teknik Perminyakan*, 10(3), 176–179. <https://doi.org/10.25105/petro.v10i3.10828>
- Anar, H., Rifa'i, A., & Faris, F. (2024). Groundwater level influence on liquefaction potential at Pombewe housing site, Sigi regency, Central Sulawesi. *E3S Web of Conferences*, 476. https://doi.org/10.1051/e3sconf/202447601048?urlappend=%3Futm_source%3Dresearchgate.net

- %26utm_medium%3Darticle
- Ayala, C., Bohoyo, F., Maestro, A., Reguera, M. I., Torne, M., Rubio, F., Fernández, M., & García-Lobón, J. L. (2016). Updated Bouguer anomalies of the Iberian Peninsula: a new perspective to interpret the regional geology. *Journal of Maps*, 12(5), 1089–1092. <https://doi.org/10.1080/17445647.2015.1126538>
- Babacan, A. E., & Ceylan, S. (2021). Evaluation of soil liquefaction potential with a holistic approach: A case study from araklı (trabzon, Turkey). *Bulletin of Geophysics and Oceanography*, 62(1), 173–198. <https://doi.org/10.4430/bgta0332>
- Baeruma, M. M., Manoppo, F. J., & Mandagi, A. T. (2020). Analisis Perkuatan Embankment Pada Tanah Berpotensi Likuefaksi Akibat Gempa Dengan Menggunakan Ijuk. *Jurnal Sipil*, 8(3), 327–336. Retrieved from <https://ejournal.unsrat.ac.id/v2/index.php/jss/article/view/28751>
- Bakri, H. (2016). Pendugaan Ketebalan Aquifer Air Tanah Untuk Pengembangan Kawasan Sofifi Maluku Utara. *Jurnal Geomine*, 4(1). <https://doi.org/10.33536/jg.v4i1.37>
- Beddu, A., Rahainun, R., Fadliah, I., Rahayu, A., & Setiawan, H. (2022). Pengaruh Tinggi Muka Air Terhadap Deformasi Tanah Terlikuefaksi. *Rekonstruksi Tadulako: Civil Engineering Journal on Research and Development*, 9–14. <https://doi.org/10.22487/renstra.v3i2.457>
- Bezák, V., Bielik, M., Marko, F., Zahorec, P., Pašteka, R., Vozár, J., & Papčo, J. (2023). Geological and tectonic interpretation of the new Bouguer gravity anomaly map of Slovakia. *Geologica Carpathica*, 74(2), 109–122. <https://doi.org/10.31577/GeolCarp.2023.08>
- Bleam, W. (2017). Chemical Hydrology. In *Soil and Environmental Chemistry*. <https://doi.org/10.1016/b978-0-12-804178-9.00002-1>
- De Ritis, R., Cocchi, L., Passaro, S., Campagne, T., & Gabriellini, G. (2023). Bouguer Anomaly Reduction and Interpretative Remarks of the Phlegraean Fields Caldera Structures (Southern Italy). *Remote Sensing*, 15(1). <https://doi.org/10.3390/rs15010209>
- Febriandri, D. (2014). *Evaluasi Geologi Untuk Pengembangan Daerah Sofifi Dan Sekitarnya, Kecamatan Oba Utara, Kabupaten Tidore Kepulauan, Propinsi Maluku Utara*. Universitas Gadjah Mada.
- Fauzik, D., Haris, A., Martha, A. A., & Riyanto, A. (2020). Liquefaction potential identification in the Central Sulawesi using gravity inversion model. *IOP Conference Series: Earth and Environmental Science*, 538(1). <https://doi.org/10.1088/1755-1315/538/1/012035>
- Hirt, C., Claessens, S., Fecher, T., Kuhn, M., Pail, R., & Rexer, M. (2013). New ultrahigh-resolution picture of Earth's gravity field. *Geophysical Research Letters*, 40(16), 4279–4283. <https://doi.org/10.1002/grl.50838>
- Hidayah, R. N., Suhendra, S., Halauddin, H., Irkhos, I., & Syaputri, T. D. (2024). Identification of liquefaction potential in Kampung Melayu Bengkulu based on water level depth (watertable). *Journal of Aceh Physics Society*, 13(2), 1–8. <https://doi.org/10.24815/jacps.v13i2.37089>
- Kamura, A., Kikumoto, M., Unno, T., Matsumaru, T., & Yoshida, S. (2024). Monitoring Excess Pore Water Pressure During Seismic Events to Assess Liquefaction Potential in Reclaimed Land. *Japanese Geotechnical Society Special Publication*, 10(16), 546–551. <https://doi.org/10.3208/jgssp.v10.os-5-09>
- Lumintang, V. G., Pasau, G., & Tongkukul, S. J. (2015). Analisis Tingkat Seismisitas Dan Tingkat Kerapuhan Batuan Di Maluku Utara. *Jurnal Ilmiah Sains*, 17(1), 94. <https://doi.org/10.35799/jis.15.2.2015.9224>
- Meng, Q., Li, Y., Wang, W., Chen, Y., & Wang, S. (2023). A Case Study Assessing the Liquefaction Hazards of Silt Sediments Based on the Horizontal-to-Vertical Spectral Ratio Method. *Journal of Marine Science and Engineering*, 11(1). <https://doi.org/10.3390/jmse11010104>
- Mickus, K., Frifita, N., Ben Zaid, M., & Ouassar, M. (2022). Gravity and electrical resistivity analysis of deep and shallow structures related to aquifers within the Jeffara Plain, southeast Tunisia. *Journal of African Earth Sciences*, 196(December). <https://doi.org/10.1016/j.jafrearsci.2022.104685>
- Musa Sjahrain, U., Rondonuwu, S. G., & Riogilang, H. (2021). Analisis Potensi Likuefaksi dengan Menggunakan Parameter Kuat Geser Tanah Lempung. *Jurnal Ilmiah Media Engineering*, 11(3), 2087–9334. Retrieved from <https://ejournal.unsrat.ac.id/index.php/jjme/article/view/40916>
- Nurbani, G., & Yakin, Y. A. (2021). Analisis Potensi Likuefaksi pada Tanah Pasir Akibat Gempa (Studi Kasus Mataram, Nusa Tenggara Barat). *RekaRacana: Jurnal Teknil Sipil*, 6(3), 166. <https://doi.org/10.26760/rekaracana.v6i3.166>
- Özener, P. T., Greenfield, M. W., Sideras, S. S., & Kramer, S. L. (2020). Identification of time of liquefaction triggering. *Soil Dynamics and Earthquake Engineering*, 128(October), 105895. <https://doi.org/10.1016/j.soildyn.2019.105895>
- Rustam, M. (2012). *Penelitian Air Tanah di Kota Sofifi Halmahera Maluku Utara Menggunakan Metode Geolistrik Kombinasi Resistivity Dipole-Dipole, Wenner Dan Induced Polarization*. Universitas Gadjah Mada.

- Rahman, S., & Miradj, A. (2022). Analisis Debit Banjir Rancangan Pada Saluran Drainase Kawasan Perumahan Asn Sofifi. *Dintek*, 15(1). Retrieved from <http://jurnal.umm.ac.id/index.php/dintek/article/download/1170/799>
- Saifuddin, A., & Pertiwi, E. I. (2021). Pemetaan Zona Resiko Gempabumi Berdasarkan Peak Ground Acceleration Terhadap Energi Dan Sumberdaya Mineral Di Provinsi Maluku Utara. *Seminar Nasional Geomatika*, April, 171. <https://doi.org/10.24895/sng.2020.0-0.1132>
- Saleh, I., Mandar, G., & Noh, J. (2023). Analisis Data Gempa Di Maluku Utara Menggunakan Algoritma K-Means Dan Linear Regression. *Dintek*, 16(2), 12-19. Retrieved from <https://jurnal.umm.ac.id/index.php/dintek/article/view/1718>
- Septiani, I., & Pujiastuti, D. (2021). Analisis Seismisitas Wilayah Kepulauan Maluku Periode 1970-2019 dengan Menggunakan Metode Likelihood. *Jurnal Fisika Unand*, 10(4), 461-466. <https://doi.org/10.25077/jfu.10.4.461-466.2021>
- Setiawan, A., Sholeha, D. Z., Kausari, A., & Hadi, A. I. Analysis of Liquefaction Potential Based on Seismic Wave Velocity in Bengkulu City. *Jurnal Fisika Flux: Jurnal Ilmiah Fisika FMIPA Universitas Lambung Mangkurat*, 20(1), 80-93. <https://dx.doi.org/10.20527/flux.v20i1.15243>
- Silalahi, M. T., Dahrin, D., Abdurrahman, D., & Tohari, A. (2023). Identification Of Liquefaction-Potential Zones Using The Gravity Method In Lolu Village, Central Sulawesi. *Jurnal Penelitian Pendidikan IPA*, 9(8), 6206-6212. <https://doi.org/10.29303/jppipa.v9i8.4830>
- Sutasoma, M., Susilo, A., Sunaryo, Suryo, E. A., & Minardi, S. (2022). Analysis of the Rock Layer Contact Using the Gravity Data of Satellite Imagery and Resistivity Method. *International Journal of GEOMATE*, 23(96), 69-76. <https://doi.org/10.21660/2022.96.3306>
- Syandi, R., & Tampubolon, T. (2020). Application of Geoelectrical Measurements for Identify the Liquefaction Potential Area in Lobu Tua Village. *Journal of Physics: Conference Series*, 1428(1). <https://doi.org/10.1088/1742-6596/1428/1/012047>
- Yakin, Y. uki A., Pratiwi, D. S., & Jaelani, F. T. (2023). Pengaruh Magnitude Moment Terhadap Potensi Likuefaksi Tanah Loose Sand Jenuh Air Menggunakan Model UBC3D-PLM. *Jurnal Serambi*, 8(2), 5565-5576. Retrieved from <https://ojs.serambimekkah.ac.id/jse/article/view/6009%0Ahttps://ojs.serambimekkah.ac.id/jse/article/download/6009/4367>
- Zeffitni, Rusdin, A., Napitupulu, M., Basir-Cyio, M., & Juniah, R. (2023). Hydromorphological and Hydrogeological Assessment of Liquefaction Vulnerability in Central Sulawesi, Indonesia. *International Journal of Design and Nature and Ecodynamics*, 18(4), 923-929. <https://doi.org/10.18280/ijdne.180419>
- Zhang, H., Lu, Y., Liu, X., Li, X., Wang, Z., Ji, C., Zhang, C., Wang, Z., Jing, S., & Jia, Y. (2023). Morphology and origin of liquefaction-related sediment failures on the Yellow River subaqueous delta. *Marine and Petroleum Geology*, 153(February), 106262. <https://doi.org/10.1016/j.marpetgeo.2023.106262>