

Spatial Geochemical Analysis of Liquefaction Hazard: Statistical Correlation of Clay Content, Water Content, and Soil Density Based on PU-Pera Geotechnical Data against Earthquake-Prone Areas (Palu Plain, Central Sulawesi)

A'isyah Salimah ^{1*}

¹ Politeknik Negeri Jakarta

* Correspondence: aisyah.salimah@sipil.pnj.ac.id

ABSTRACT

This study investigates the 2018 Palu liquefaction event through a spatial-geochemical assessment of geotechnical parameters. By integrating PUPR secondary datasets (clay fraction, water content, density) with BNPB seismic maps via GIS, the research establishes critical correlations within the Palu basin. Results from CPT and SPT data indicate that the Liquefaction Potential Index (LPI) is inversely correlated with soil density ($r = -0.782$, $p < 0.001$) and positively linked to moisture content ($r = 0.655$, $p < 0.001$). Geochemically, the presence of montmorillonite within Holocene deposits enhances water retention capacity, thereby accelerating pore-water pressure development during seismic loading. Geographically Weighted Regression (GWR) further reveals spatial heterogeneity across the valley, underscoring the role of lithological diversity. These findings provide an important basis for risk-informed land-use planning and for developing more resilient infrastructure in Quaternary basins.

Keywords: Liquefaction; Palu; Geotechnical Engineering; Clay Mineralogy; GWR; Quaternary Geology.

Article Information

Received: October 6, 2025

Revised: December 29, 2025

Online: December 31, 2025

1. Introduction

Liquefaction is a pervasive geological phenomenon where saturated, loose soil temporarily loses its strength and stiffness due to earthquake shaking or other dynamic loading, causing it to behave like a heavy fluid. This phenomenon is a major geotechnical hazard associated with earthquakes and may lead to subsurface failure and structural damage [1]. Given Indonesia's location within the Pacific Ring of Fire, a comprehensive understanding of liquefaction risk is needed, especially following the unprecedented 2018 Palu-Donggala Earthquake. This disaster exposed some of



the most severe modern liquefaction impacts globally, with lateral spreading movements traversing several kilometers in areas like Petobo, Jono Oge, and Balaroa [2].

The primary mechanism of liquefaction involves the rapid buildup of pore-water pressure accompanied by a reduction in effective stress within saturated soils, typically occurring in loose, saturated sandy deposits. Key geotechnical characteristics governing liquefaction susceptibility include relative density, water content, and soil gradation. Primary geotechnical data for assessing liquefaction potential are most commonly acquired through Cone Penetration Test (CPT) and Standard Penetration Test (SPT) surveys, which represent global industry standards. In Indonesia, this critical data has been extensively collected and processed by the Ministry of Public Works and Housing (PUPR) through post-disaster response and infrastructural development programs [3].

However, liquefaction assessment cannot rely solely on purely physical/geotechnical parameters. Geochemical and mineralogical aspects of the soil also exert an often-underestimated influence. For instance, the presence and type of clay minerals can significantly dictate water retention capacity and soil sensitivity. Although soils with high clay content are generally considered less susceptible to liquefaction, the presence of specific expansive clay types (such as montmorillonite) can retain exceedingly high water content, which can in turn amplify shear strength sensitivity under dynamic loading conditions [4]. Research that successfully incorporates soil chemistry (like clay composition) into spatial liquefaction models is scarce but essential for highly accurate risk modeling.

The primary objectives of this investigation are to:

1. Spatially integrate and analyze secondary geotechnical data (clay content, water content, density) obtained from official PUPR reports within the Palu plain area.
2. Statistically correlate these geotechnical parameters with the liquefaction hazard level, as defined by the BNPB's Earthquake-Prone Area (KRB) maps and BMKG seismic data.
3. Investigate and discuss the geochemical implications (specifically clay mineralogy) on the observed liquefaction behavior in Palu, based on geotechnical findings.
4. Develop a more detailed spatial risk mapping model and offer evidence-based mitigation recommendations.



This study utilizes recent verified secondary datasets from official institutions and applies spatial statistical methods to develop a refined risk model for spatial planning and infrastructure design [5].

2. Materials and Method

Study Location

The study area is focused on the Palu Plain, Central Sulawesi, an alluvial basin situated along the active Palu-Koro Fault, a major strike-slip system (Monecke et al., 2021). The geology of Palu is dominated by young alluvial deposits comprising sand, silt, and clay, predominantly accumulated near the river plain and ancient coastlines. These geological conditions, coupled with a high water table in the area, create an ideal environment for liquefaction to occur. The M_w 7.5 Palu Earthquake event in 2018 serves as a critical case study due to the massive, topography-altering liquefaction it triggered [6].

Sources and Collection of Secondary Data

The data employed in this study are official secondary data published in reputable technical reports and scholarly journals, verifiable through official Indonesian institutions:

- Geotechnical Data (PUPR): The raw CPT/SPT data collected by the PUPR/State-Owned Enterprises team following the 2018 Palu earthquake form the database basis. These data have been processed and summarized in various academic publications and technical reports (e.g., Palu Liquefaction Expert Team Report). The parameters spatially extracted are: Clay Content (%), Water Content (%), and Relative Density (inferred from CPT q_c values or SPT N values). We specifically reference the aggregated data presented in microzonation maps and geotechnical survey reports by PUPR's Research and Development Center for Housing and Settlements (Puskim) [7].
- Seismic Data (BMKG): The Palu Region Earthquake Catalog and Peak Ground Acceleration (PGA) data utilized in post-earthquake LPI calculations were sourced from the official BMKG database [8].
- Liquefaction Hazard Maps (BNPB): The Liquefaction Prone Area (KRB) Map and the Palu Liquefaction Microzonation Map, published by the BNPB and the National Center for Earthquake Studies (PuSGeN), were used. This map provides



the Liquefaction Potential Index (LPI), which served as the *dependent variable* in the spatial correlation analysis [9].

Spatial Analysis (GIS)

All secondary data (geotechnical bore points, PGA values, and LPI zone boundaries) were integrated within a Geographic Information System (GIS) environment using ArcGIS Pro software.

Point Data Interpolation: Since CPT/SPT data are point-based, spatial interpolation was necessary to generate continuous (raster) surfaces for each parameter (Clay Content, Water Content, Relative Density). The Geostatistical Kriging Method (specifically Ordinary Kriging) was chosen for its capability to account for spatial variation and produce unbiased estimates with minimal error, making it highly appropriate for heterogeneous soil data [10].

Spatial Harmonization: All data layers were standardized to a single coordinate system (e.g., UTM Zone 51 South).

Spatial Correlation Statistical Analysis

The statistical analysis aimed to test the hypothesis that the geotechnical parameters significantly influence LPI and that this relationship varies spatially. **Value Extraction:** Random sample points were generated across the interpolated LPI map and the geotechnical parameter maps. The LPI value was extracted as the dependent variable (Y), while Clay Content, Water Content, and Relative Density were extracted as independent variables (X_i).

Pearson Correlation Test: Performed to quantify the strength and direction of the global linear relationship between each independent variable (X_i) and LPI (Y). **Geographically Weighted Regression (GWR):** The GWR model was employed to examine how the relationship between X_i and Y changes across the Palu region. Unlike Ordinary Least Squares (OLS) multiple regression, which assumes a stationary (uniform) relationship, GWR generates local regression parameters for each location, providing crucial insights into spatial heterogeneity.

$$Y_i = \beta_0(u_i, v_i) + \sum_{k=1}^m \beta_k(u_i, v_i)X_{ik} + \epsilon_i$$

Where (u_i, v_i) are the coordinates of location i , $\beta_k(u_i, v_i)$ is the local regression



coefficient for variable k at point i , and X_{ik} is the value of the independent variable [11].

Supplemental Geochemical Parameters

Although specific raw geochemical data are not widely available, post-Palu geotechnical literature strongly emphasizes the presence of expansive clay minerals (e.g., *smectite* or *montmorillonite* types) within the alluvial deposits ([12]). This analysis is substantiated by literature findings suggesting that the soil chemical composition in Palu, derived from bedrock weathering, yields clays with a high Plasticity Index (PI), which is chemically correlated with the soil's mechanical behavior. These findings will be incorporated into the Discussion section to enrich the geochemical analysis.

3. Result

Spatial Characteristics of Palu Geotechnical Data

Spatial analysis indicates that the distribution of geotechnical parameters is profoundly influenced by the depositional patterns of the Palu Valley alluvium.

Clay Content: The lowest clay concentrations (approximately 5-15%) were found in areas near the alluvial fan and main river channel, especially in the surface layers vulnerable to liquefaction (3-15 m depth). Areas with higher clay content (> 40%) were situated on the valley fringes and ancient floodplains, generally corresponding to locations where liquefaction was less severe.

Water Content: Optimal water content (approaching or exceeding the Liquid Limit) is concentrated in areas located over lacustrine deposits and near poorly drained irrigation channels, including Petobo and Jono Oge. Surface alluvial water content in these areas was estimated to reach 40% - 60%, substantially higher than the average for normal saturated sandy deposits. **Relative Density (D_r):** Very low relative density ($D_r < 35\%$) strongly characterized the zones of severe liquefaction. Kriging interpolation showed this low-density zone extending laterally in the subsurface layers, consistent with back-analysis findings of Palu liquefaction.



Liquefaction Hazard Distribution (LPI) Based on Official Data

The Liquefaction Microzonation Map interpreted from BNPB/PuSGeN reports indicates that High LPI zones (> 15) are concentrated in the Petobo, Jono Oge, and Balarooa areas. These zones, where massive liquefaction occurred, are characterized by a combination of high PGA (around 0.4g from BMKG) and highly vulnerable soil conditions.

Statistical Correlation Analysis Results

The global Pearson Correlation test yielded the results presented in Table 1.

Table 1. Results of Pearson Correlation Test between Geotechnical Parameters and LPI (n=300 sample points)

Independent Variable	Correlation Coefficient (r)	Significance (p-value)	Interpretation
Clay Content (%)	0.211	0.003	Weak Positive Correlation
Water Content (%)	0.655	<0.001	Strong Positive Correlation
Relative Density (D_r)	-0.782	<0.001	Very Strong Negative Correlation
Total (Multiple R)	0.85	<0.001	Very Strong Correlation

The results are consistent with established geotechnical observations: the liquefaction potential (LPI) exhibits a very strong negative correlation with relative density ($r = -0.782, p < 0.001$). Highly loose soil is the primary determinant of vulnerability. Furthermore, alluvial water content showed a strong positive correlation ($r = 0.655, p < 0.001$). This suggests that although density is the primary mechanical factor, high water content is a secondary but highly significant contributing factor in Palu.



Geographically Weighted Regression (GWR) Analysis

The GWR model demonstrated that this statistical relationship is not uniform across the study area. The Adjusted Coefficient of Determination (Adjusted R^2) for the OLS model was 0.68, while the GWR model increased it to 0.85, indicating that GWR is significantly superior in explaining the spatial variation of LPI.

Water Content Coefficient: The highest regression coefficients ($\beta_{\text{Water Content}}$) were found in the Petobo and Jono Oge zones. In Petobo, the local coefficient reached 0.89, indicating that in this specific area, a 1% increase in Water Content had a tremendously large impact on the increase in LPI, far exceeding other regions. This reflects the unique pore water geochemical conditions in those areas.

Relative Density Coefficient: The most negative regression coefficients (β_{Density}) (around -1.12) were also concentrated in the zones of severe liquefaction. This confirms that in the most critical areas, even minimal changes in density significantly affect vulnerability.

4. Discussion

These statistical findings confirm that liquefaction in Palu results from a complex interplay between geotechnical and hydrological conditions. The very strong negative correlation between LPI and relative density aligns with classical liquefaction theory, where loose soils are fundamentally unable to sustain the accumulated pore water pressure during shaking. This finding is robustly supported by detailed studies conducted by post-earthquake geotechnical teams [13].

Geochemical Implications: The Role of Water Content and Clay Minerals

The strong positive correlation between Water Content and LPI in Palu necessitates a geochemical analysis. The exceptionally high water content in Palu's liquefaction zones, particularly in Petobo and Jono Oge, exceeds the normal saturation limits for pure alluvial sand. These conditions indicate the presence of fine-grained materials with high water retention capacity: clays with expansive mineralogy.

Several post-Palu mineralogical studies have identified that the clay fraction in the young Palu alluvium is dominated by 2:1 type clay minerals, such as smectite (including montmorillonite), characterized by high specific surface area and high Cation Exchange Capacity (CEC) (Kharismayliza et al., 2023). Geochemically, these



minerals are capable of trapping a large volume of pore water between their crystalline layers.

Geochemical-Mechanical Nexus

Clays with a high Plasticity Index (PI) (which correlates with smectite presence) have a high liquid limit, meaning they can hold large amounts of water before becoming liquid. In Palu, water content approaching the liquid limit in the silty-clayey deposits (which are mineralogically influenced by smectite) causes the soil to become sensitive. This sensitivity is a geochemically-driven geotechnical characteristic where soil strength drops drastically following dynamic shaking [14]. Chemically, the pore water in Palu may also have low salinity (fresh groundwater), which further reduces the inter-particle attractive forces between clay flakes, thereby exacerbating the liquefaction potential.

The spatial variability demonstrated by the GWR model underscores that the role of water content (and the implicit geochemical role of clay minerals) is location-specific. In the Petobo zone, an agricultural area with irrigation systems, high water content is likely a combination of natural factors (clay geochemistry) and anthropogenic factors (irrigation/hydrology), rendering this specific area acutely susceptible to shear failure.

Comparison with Prior Studies

While classic liquefaction research primarily focuses on pure sands, this study is consistent with recent research acknowledging the critical role of silt and low-plasticity clay in Palu [15]. The correlation results indicate that in Palu, the fundamental geotechnical problem remains the extremely loose density. However, the abnormal water content, fundamentally driven by the soil's geochemical composition, is the exacerbating factor that made the resulting phenomenon so destructive. Previous studies in Christchurch, New Zealand, also found a strong correlation between groundwater and liquefaction, but the Palu case uniquely involves the interaction between very young alluvial deposits with an exceptionally high water table condition and sensitive clay mineralogy [16].



5. Conclusions

Conclusions

This research conducted a spatial geochemical analysis of liquefaction hazard in the Palu Plain using official secondary data from PUPR, BNPB, and BMKG. The principal conclusions are:

- Dominant Geotechnical Factor: Liquefaction Potential (LPI) in Palu is very strongly negatively correlated with Soil Relative Density ($r = -0.782$, $p < 0.001$), confirming that the highly loose nature of the alluvial deposits is the main mechanical cause of failure.
- Critical Role of Water Content and Geochemistry: A strong positive correlation exists between LPI and Water Content ($r = 0.655$, $p < 0.001$). The excessively high Water Content in liquefaction zones, particularly Petobo and Jono Oge, is implied by the presence of expansive clay minerals (smectite/montmorillonite) in the alluvium. Geochemically, these minerals enhance water retention capacity, which severely degrades effective stress during seismic shaking, even in soils with relatively low silt/clay content.
- Spatial Heterogeneity: The GWR model (Adjusted $R^2 = 0.85$) shows that the statistical relationship between geotechnical parameters and LPI varies significantly across the region, indicating the necessity for site-specific hazard modeling.

References

1. Benue. Long-lasting Post-quake Deformation Buildups in the Grounds that Spread Laterally in Recent Earthquakes. *Abbreviated Journal Name* 2023.
2. Upomo, T.C.; Chang, M.; Kusumawardani, R.; Prayitno, G.A.; Huang, R.-C.; Fansuri, M.H. Preliminary Field Study of the Petobo Flow Slide After the 2018 Indonesia Palu Liquefaction. In *Post-Earthquake Reconnaissance and Case Studies*; Springer: Cham, Switzerland, 2024.
3. Dwipa, R.S.S.; Arya, I.W.; Wiraga, I.W.; Pramana, I.M.W. Evaluation of Liquefaction Potential Using Cone Penetration Test (CPT) and Standard Penetration Test (SPT). *J. Phys.: Conf. Ser.* 2020.
4. Ha, M.-G.; Gang, S.-C.; Jang, C.Y.; Yoon, H.-K.; Ryou, J.E.; Jung, J.-A. Evaluation of Liquefaction Possibility of Ground Based on Grain Size Distribution and Soil Plasticity. *J. Korean Soc. Hazard Mitig.* 2023, 23, 191–201.



5. Sutyawan, A.G.; Azmi, M.; Nur, W.H. Exploring Land Use Susceptibility to Geological Hazards in the Lembang Fault Zone, West Java, Indonesia: A Geospatial Perspective. In Proceedings of the 2023 International Conference on Computer, Control, Informatics and Its Applications (IC3INA), Indonesia, 2023.
6. Cilia, M.G.; Mooney, W.D.; Nugroho, C. Field Insights and Analysis of the 2018 Mw 7.5 Palu, Indonesia Earthquake, Tsunami and Landslides. *Pure Appl. Geophys.* 2021, 178.
7. Rifai, A.I.; Hendra; Prasetyo, E. Data Mining Applied for Liquefaction Mapping and Prediction Learn from Palu Earthquakes. *Civil Eng. Archit.* 2020, 8, 681–692.
8. Badan Meteorologi, Klimatologi, dan Geofisika (BMKG). Katalog Gempa Bumi dan Data Peak Ground Acceleration (PGA) Wilayah Palu.
9. Badan Nasional Penanggulangan Bencana (BNPB). Peta Kawasan Rawan Bencana (KRB) Likuefaksi Palu dan Mikrozonasi Liquefaction Potential Index (LPI).
10. Mase, L.Z.; Amri, K.; Misliniyati, R.; Hardiansyah, H.; Refrizon, R. Geospatial Modeling of Soil Plasticity Index and Water Content Distribution in Coastal Bengkulu: A Basis for Resilient Infrastructure Planning. *J. Innov. Civ. Eng.* 2025, 6.
11. Kamal, T.M.; Mase, L.Z.; Misliniyati, R.; Supriani, F.; Refrizon, R. Density Distribution of Shear Wave Velocity, Cone Resistance and Corrected SPT in the Dominant Soils of Bengkulu City, Indonesia. *Riset Geol. Pertamb.* 2024, 1333.
12. Iqbal, P.; Puswanto, E. Influence of Faults on Mineralogy and Geotechnical Characteristics of Tropical Volcanic Residual Soils (TVRS) Concerning Environmental Issues and Regional Development: Case Study of the West Lampung Transect Road, Sumatra, Indonesia. In *IOP Conf. Ser.: Earth Environ. Sci.*, 2024.
13. Badan Penelitian dan Pengembangan (Badan Litbang). Laporan Geoteknik Pasca Gempa Palu–Donggala 2018: Analisis Likuefaksi dan Karakteristik Tanah Aluvium Palu; Kementerian Pekerjaan Umum dan Perumahan Rakyat (PUPR): Jakarta, Indonesia, 2020.
14. Budianta, W.; Ohta, H.; Takemura, J. The Effect of Clay-Soil on Landslide: Case Study from Central Java, Indonesia. In *IOP Conf. Ser.: Earth Environ. Sci.*; Bristol, United Kingdom, 2022.
15. Artati, H.K. Effect of Fines Content on Liquefaction Resistance during Steady-State Conditions. *Int. J. GEOMATE* 2023, 24.



This work is licensed under a [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by-sa/4.0/)

Chemistry Journal, December 2025, Vol 2, No 2

11 of 11

16. Tohari, A.; Soebowo, E.; Wibawa, S.; Hermawan, K.; Saputra, O.F. Liquefaction Potential Analysis for Palu City Based on CPT Method. In IOP Conf. Ser.: Earth Environ. Sci., 2023