INTEGRATED MICROTREMOR AND GEOSPATIAL ANALYSIS FOR LIQUEFACTION POTENTIAL EVALUATION IN KAPANEWON PUNDONG

Mujianto[1,2*], Yohana Noradika Maharani[2], Arif Riyanto Budi Nugroho[2], Eko Teguh Paripurno[2], Suharsono[2]

[1] *Sleman Geophysical Station, Jl. Wates Km. 8, Balecatur, Gamping, Sleman, Yogyakarta, Indonesia 55294*

[2] *Disaster Management Master Study Program, UPN Veteran Yogyakarta, Jl. Babarsari 2 Yogyakarta, Indonesia 55281*

email: muds.bmkg@gmail.com

ABSTRACT

Kapanewon Pundong is in an active tectonic zone and has experienced significant seismic events, including the 2006 Bantul earthquake (Mw 6.3), which caused extensive damage. Liquefaction was a key contributor to infrastructure failure during the event. This study aims to evaluate liquefaction potential in Kapanewon Pundong through integrated microtremor and geospatial analysis. The Horizontal-to-Vertical Spectral Ratio (HVSR) method assessed local site effects that influence ground shaking. Liquefaction probability was estimated using the model by Zhu et al. (2017), considering parameters such as V_{s30}, PGV, water table depth (WTD), distance to water bodies (DW), and average annual precipitation. The research findings include V_{s30} values that range from 221 to 893 m/s, PGV values from 16 to 29 cm/s. Panjangrejo and Srihardono villages exhibit the highest liquefaction probabilities, up to 30%. The estimated Liquefaction Spatial Extent (LSE) in these areas reaches 5.1%. These findings identify high-risk zones for earthquake-induced liquefaction and provide a quantitative foundation for spatial planning and disaster mitigation strategies in the region.

Keywords: *Geospatial Analysis; HVSR method; Kapanewon Pundong; microtremor; liquefaction potential*

INTRODUCTION

Special Region of Yogyakarta (DIY) is part of the Sunda Arc, where the Indo-Australian Plate subducts orthogonally beneath the Eurasian Plate. The convergence rate is estimated to be around ~5.6 cm/year in the western part of Java and increases to about ~6.5 cm/year in the eastern part (Koulali et al., 2017). In addition to the subduction zone, several active faults control seismicity around Yogyakarta (Muttaqy et al., 2022). This makes Yogyakarta and its surroundings one of the earthquake-prone areas due to both subduction and inland fault activity (Partono et al., 2023). Throughout its history, Java has experienced many earthquakes that have resulted in damage and loss of life. One was the Yogyakarta earthquake on May 27, 2006 (Daryono et al., 2023; Librian et al., 2024). The earthquake, with a depth of 10 km and centered in Pundong, approximately 25 km southeast of Yogyakarta City, had a magnitude of 6.3 Mw and caused 5,716 fatalities, along with economic losses amounting to billions of dollars (Librian et al., 2024). One of the factors contributing to building damage during the 2006 Yogyakarta earthquake was liquefaction. This is based on the correlation between building damage distribution and the liquefaction potential (Buana et al., 2016).

Liquefaction is a phenomenon that occurs due to earthquake vibrations, which trigger an increase in pore water pressure, causing loose sand layers to lose their strength (Tohari et al., 2015). Water can rise to the surface through the pores of the rock due to earthquake vibrations, making it appear as if the soil layer is liquefying. The devastating earthquake on May 27, 2006, resulted in widespread liquefaction (Figure 1), including in Kapanewon Pundong, Special Region of Yogyakarta.

Geologically, Kapanewon Pundong is characterized by three main rock formations: the Wonosari Formation, the Nglanggran Formation, and deposits from Mount Merapi. Given the geological and seismic conditions in Pundong, which favor the occurrence of liquefaction, there is a potential for such disasters to recur. Therefore, it is essential to conduct a study to evaluate the potential for liquefaction in Kapanewon Pundong, Special Region of Yogyakarta.

(a) (b)

Figure 1. Liquefaction phenomena observed during the 2006 Yogyakarta earthquake: (a) sand boils, (b) lateral spreading (Maze, 2017)

Liquefaction potential studies due to earthquakes can be conducted through various methods, including geotechnical (Cetin et al., 2018), geological, geophysical, and empirical and numerical analyses. Liquefaction potential studies also cover various scales, from global (Zhu et al., 2017), continental (Meisina et al., 2022), regional, to local (Brankman & Baise, 2008). Additionally, geospatial approaches have evolved as an effective method for mapping and predicting liquefaction potential by considering various spatial parameters.

Geospatial methods allow for rapid predictions of liquefaction coverage post-earthquake using available datasets, and support mitigation planning and quick response (Zhu et al., 2017). This approach integrates data on liquefaction vulnerability, soil amplification, hydrology, geology, and topography to produce more accurate models. Geospatial liquefaction models can provide quick estimates of liquefaction distribution following major earthquakes (M > 6) based on shaking intensity and other geospatial parameters (Zhu et al., 2017), thus serving as a tool for disaster risk analysis and decision-making.

Several studies on liquefaction potential have been conducted using SPT and CPT methods (Kundu et al., 2024; Seo et al., 2024). Similar studies have also been conducted in Indonesia (Hendro & Prakoso, 2023; Kusmanto et al., 2024). In Bantul, research indicates that earthquakes with high acceleration can cause liquefaction around the Opak Fault (Zakariya et al., 2023). Studies on liquefaction in Yogyakarta using shear wave velocity and Ground Shear Strain (GSS) approaches have also been conducted. The results showed the potential for liquefaction at several depths below the surface (Hartantyo et al., 2015). An approach using Geographic Information Systems (GIS) has also been applied to investigate liquefaction potential in Bantul Regency. The findings indicate that the Liquefaction Potential Index is a quantitative parameter for evaluating subsurface zones impacted by liquefaction, reaching depths of up to 20 meters (Haifani et al., 2023).

Although numerous studies on liquefaction potential have been conducted using SPT and CPT methods, and several studies have applied shear wave velocity (Vs) and GIS-based approaches, there are still limitations in utilizing liquefaction prediction models that integrate various geospatial parameters and microtremor data. Most previous studies have focused more on soil bearing capacity analysis, without considering the geophysical aspects contributing to the local soil response to earthquake shaking.

This study aims to evaluate the liquefaction potential in Kapanewon Pundong, Special Region of Yogyakarta, through an integrated microtremor and geospatial analysis for liquefaction prediction. The study introduces a novel approach by applying the geospatial liquefaction model (Zhu et al., 2017), which combines parameters such as average annual precipitation, closest Distance to Water bodies, shear wave velocity up to 30 meters (V_{S30}), Peak Ground Velocity (PGV), and Water Table Depth. The local site effects are also characterized using the Horizontal to Vertical Spectral Ratio (HVSR) method, derived from microtremor data. This method has not been widely applied in liquefaction studies in the Yogyakarta region, particularly in Kapanewon Pundong. The results of this study are expected to offer new insights into liquefaction risk assessment and enhance spatial planning and disaster mitigation strategies, with a more substantial reliance on geospatial and geophysical data.

METHOD

Data and Equipment

This study applies the algorithm by Zhu et al. (2017) to determine the likelihood of liquefaction occurrence. Primary data were obtained from 65 measurement points to characterize the local site effect and determine the V_{S30} values in Kapanewon Pundong. The locations of the microtremor measurement data are shown in Figure 2. The primary data also includes ground shaking data in the form of *PGV*. Meanwhile, the secondary data used and their sources are listed in Table 1. Microtremor data acquisition was carried out using several pieces of equipment, including Portable Seismograph, Digitizer, compass, GPS, and laptop.

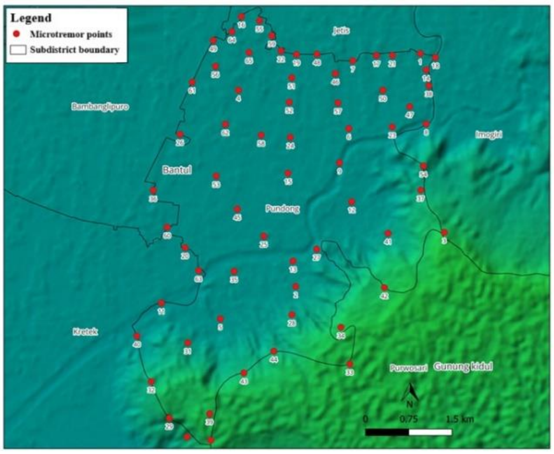

Figure 2. Microtremor measurement points in Kapanewon Pundong

Table 1. Data sources used in this study

No	Data Type	Source of Data
1	Precipitation (*precip*)	https://worldclim.org/
2	Water Table Depth (*WTD*)	http://thredds-gfnl.usc.es/thredds/ncss/grid/GLOBALWTDFTP/annualmeans/OCEANIA_WTD_annualmean.nc/dataset.html
3	Distance to the nearest Water body (*DW*)	https://www.hydrosheds.org/

Data Processing

The local site effect, which is influenced by local geological features, is another factor affecting ground shaking at the surface and the distance from the earthquake epicenter (Sesma et al., 2002). This effect can be characterized using the *HVSR* method based on microtremor data, which refers to background seismic noise used to assess subsurface mechanical properties, particularly seismic wave velocity. The primary sources of microtremor include low-frequency natural phenomena such as earthquakes and wind, and high-frequency anthropogenic activities such as vehicle traffic and industrial machinery (Molnar et al., 2018). Microtremor data were recorded for 30–60 minutes at each measurement location to ensure signal stability and spectral reliability. Before HVSR processing, the raw signals were preprocessed using a bandpass filter of 0.2–20 Hz to remove noise, and only stationary segments were retained using window selection in Geopsy software. The HVSR curves were then computed by applying Equation (1) to determine the spectral ratio of horizontal to vertical seismic waves to indicate local soil characteristics.

$$HVSR(\omega) = \sqrt{H_{NS}^2(\omega) + H_{EW}^2(\omega)}\,/V(\omega) \quad (1)$$

H_{NS}, H_{EW}, and V represent the north-south, east-west, and vertical components, recorded at the desired location. Several important parameters, including the dominant frequency, amplification factor, seismic vulnerability index, and ground shear strain, can be derived from the *HVSR* approach (Nakamura, 2000). These parameters play a role in determining the soil's response to seismic waves and the potential for damage due to earthquakes.

The shear wave velocity (V_S) profile can be obtained through the *HVSR* inversion process, which identifies subsurface structures based on shear wave characteristics. In this study, HVSR inversion was performed using Dinver software. The inversion process required the initial model with parameters including compression-wave velocity (V_P), shear-wave velocity (V_S), Poisson's ratio, and density. These parameters were assigned based on the regional lithological characteristics and were iteratively adjusted during the inversion to match the observed HVSR curves. To evaluate the seismic condition of the soil at a specific depth, the V_{S30} value was estimated using Equation (2), by the standards established in SNI 1726:2019 (BSN, 2019).

$$V_{S30} = \frac{30}{\sum_i^n \frac{h_i}{Vs_i}} \quad (2)$$

where *n* is the number of layers within the 30-meter depth range, *hi* is the thickness of each sediment layer (in meters), and Vs_i is the shear wave velocity (in meters per second). V_{S30} is one of the key parameters used to estimate ground shaking caused by earthquakes. By understanding V_{S30}, we can better assess the seismic hazard in a given area (Ghione et al., 2023).

Ground shaking at the surface due to earthquakes can be quantified using Peak Ground Velocity (*PGV*) values. *PGV* is one of the key parameters in seismic analysis and is closely related to liquefaction potential. It represents the maximum velocity of ground movement caused by an earthquake and is often used to indicate structural damage levels and soil response to seismic vibrations. Several studies (e.g., Chiou & Youngs, 2014; Afsari et al., 2022) have demonstrated that PGV correlates better with structural damage than PGA, and is widely recognized in seismic risk assessments for evaluating the dynamic response of ground and structures. High PGV values can increase the likelihood of liquefaction, especially in water-saturated sandy soils with low density.

This study determined *PGV* values using the Deterministic Seismic Hazard Analysis (DSHA) method. DSHA was selected over Probabilistic Seismic Hazard Analysis (PSHA) in this study because it provides a conservative estimate suitable for worst-case scenario planning. Considering the region's historical earthquakes and proximity to the Opak Fault, this approach aligns with national building code requirements for maximum considered earthquake hazard. DSHA evaluates the maximum earthquake hazard at a site based on the controlling seismic source. The steps include identifying potential earthquake sources, determining the maximum magnitude, and selecting an attenuation model such as the Ground Motion Prediction Equation (GMPE) CY-14 NGA (Chiou & Youngs, 2014). DSHA is a site-specific hazard assessment approach that considers the maximum hazard from the controlling source that affects the location (Afsari et al., 2022). The results of these calculations are used to determine the maximum seismic hazard level at the study site. DSHA is considered conservative because it assumes the worst-case earthquake scenario, making it widely used in earthquake-resistant structural design and seismic risk mitigation planning.

Precipitation data processing was conducted by calculating the average annual precipitation using WorldClim data from 1970 to the most recent year available within the study area. After obtaining the mean annual precipitation values, the data were further processed using GIS software. Subsequently, Distance to Water body (*DW*) data from the HydroSHEDS database were processed using ArcMap 10.8 software to calculate the nearest distance from each microtremor measurement point to the closest water body. In addition, Water Table Depth (*WTD*) data were processed using data from the THREDDS Data Server and ArcMap 10.8 software to estimate water table depth at each microtremor measurement location.

Liquefaction potential, in the form of liquefaction susceptibility (*Z*) and liquefaction probability (P_l), in Kapanewon Pundong can be estimated using the geospatial liquefaction prediction model developed by Zhu et al. (2017). The liquefaction susceptibility (*Z*) is formulated in Equation (3).

$$Z = 8.801 + 0.334[ln\,(PGV)] - 1.918\,[ln\,(V_{S30})] + 5.408\,x\,10 - 4\,(precip) - 0.2054(DW) - 0.0333(WTD) \quad (3)$$

Where *precip* is the average annual precipitation (mm), *DW* is the Distance to Water body (km), *WTD* is the Water table Depth (m), *PGV* is the Peak Ground Velocity (cm/s), and V_{s30} is the average shear wave velocity down to 30 meters depth (m/s). The liquefaction probability is formulated using Equation (4), where P_l is the liquefaction probability value is represented by *Z*, which is the liquefaction susceptibility.

$$P_l = \frac{1}{1+e^{-z}} \quad (4)$$

The mapped liquefaction probability can be used to estimate the spatial extent of liquefaction. This spatial estimation is called the Liquefaction Spatial Extent *LSE* (Zhu et al., 2017). The *LSE* equation can be written as Equation (5).

$$LSE = \frac{49.15}{(1+42.4*exp(-9.165*Z))^2} \quad (5)$$

RESULT AND DISCUSSION

Utilizing the geospatial liquefaction prediction model implemented in this study, a comprehensive analysis was performed to evaluate the susceptibility and probability of liquefaction occurrence in Kapanewon Pundong. The assessment was carried out by integrating various geospatial parameters influencing liquefaction potential, including *PGV*, V_{s30}, *precip*, *DW*, and *WTD*. The model generates liquefaction susceptibility values (*Z*), which are then converted into liquefaction probability values (P_l) at each measurement point. These probabilities were subsequently mapped using spline interpolation to visualize the spatial distribution of areas with high, moderate, and low liquefaction potential. The same interpolation method was also applied to generate spatial distribution maps for other parameters. The results of this study are expected to provide a more accurate representation of liquefaction vulnerability levels in the area, serving as a foundation for more effective disaster mitigation planning and spatial management.

HVSR and Inversion Analysis

The microtremor measurements in Kapanewon Pundong show significant variation in the dominant frequency and seismic wave amplification factor at various locations tested. The data obtained indicate differences in soil characteristics that influence the seismic vulnerability potential in the area. The dominant frequency analysis ranges from 0.59 to 14.12 Hz, suggesting that the soil in certain areas has a high amplification potential at specific frequencies.

The *HVSR* curve from the microtremor measurements was inverted to obtain a 1D shear wave velocity (V_s) profile with depth. This process provides in-depth insight into the study area's subsurface structure and soil characteristics. Figure 3 shows the results of the microtremor processing and *HVSR* inversion at point 15, which illustrates the distribution of V_s with depth at that location. This analysis helps to understand the dynamic response of the soil to seismic shaking, which is crucial for disaster risk evaluation and spatial planning.

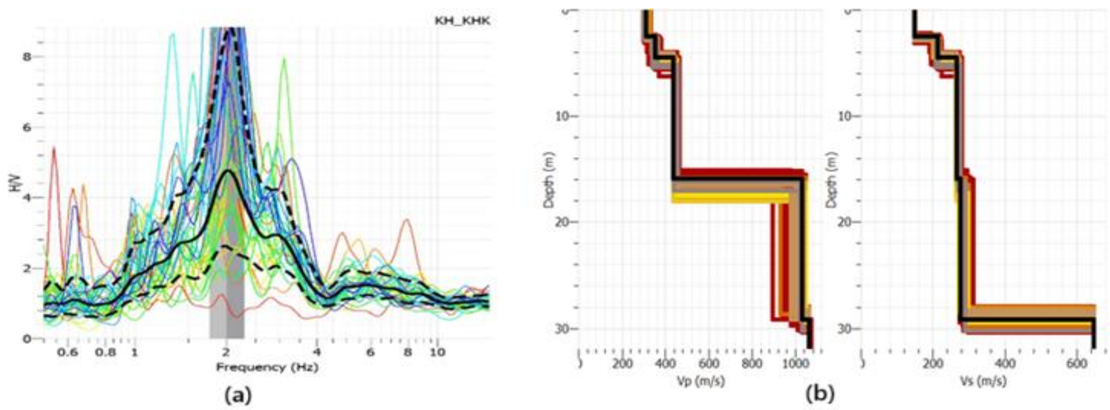

Figure 3. HVSR curve (a), and shear wave velocity (V_s) profile (b) at measurement Point 15

Dominant frequency information derived from *HVSR* analysis is crucial in identifying areas more susceptible to seismic ground shaking, making it a key parameter in seismic risk assessment. Additionally, the V_s profile obtained through *HVSR* inversion offers valuable insights into the subsurface soil layer structure. This information is essential for analyzing liquefaction potential, evaluating the dynamic response of structures, and improving earthquake ground motion modeling. By integrating microtremor data and *HVSR* inversion techniques, a more accurate predictive framework can be developed to support earthquake risk mitigation efforts in Kapanewon Pundong. A comprehensive understanding of local soil characteristics and their seismic response is fundamental for implementing effective disaster mitigation and land-use planning strategies.

V_{S30} Analysis

The *HVSR* inversion produces a V_s profile with depth. The V_{S30} value is calculated from the V_s profile obtained through the *HVSR* inversion. In the study area, the V_{S30} Values range from 221 to 893 m/s, reflecting variations in soil conditions in Kapanewon Pundong. Figure 4 shows the distribution of V_{S30} values in the study area. Areas with relatively lower V_{S30} values include Kalurahan Panjangrejo and Srihardono, while higher values are found in Kalurahan Seloharjo. The significant variation in V_{S30} values indicates the subsurface geological heterogeneity in Kapanewon Pundong.

Based on the classification from SNI 1726:2019 (BSN, 2019), the research area generally falls into category D soil (stiff soil), with V_{S30} values ranging between 175–350 m/s, and category C soil (hard soil), with V_{S30} Values ranging between 350 and 750 m/s. Stiff soil is predominantly found in Kalurahan Panjangrejo and Srihardono. Stiff soil layers at the surface, which likely consist of alluvial deposits and clay, indicate a higher seismic amplification potential in this area. Areas with lower V_{S30} values tend to experience higher seismic wave amplification, thus increasing the risk of building damage during an earthquake. Meanwhile, hard soil is more dominant in Kalurahan Seloharjo. The results of *HVSR* inversion are consistent with geological data and previous research (Maharani et al., 2023).

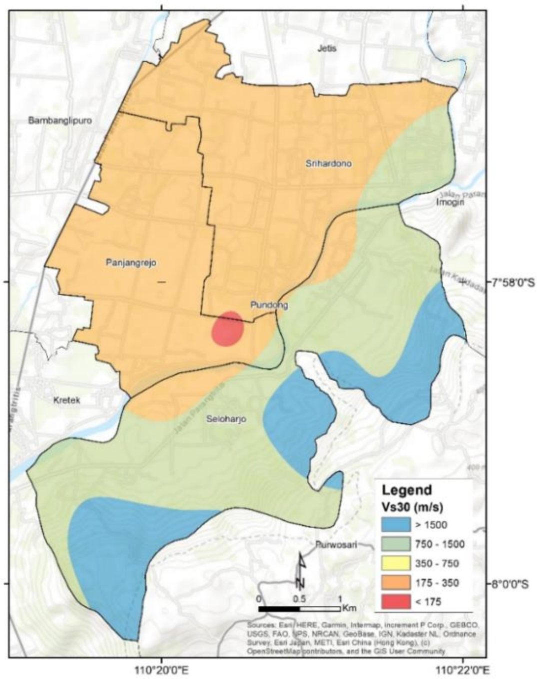

Figure 4. Distribution of V_{s30} values in Kapanewon Pundong

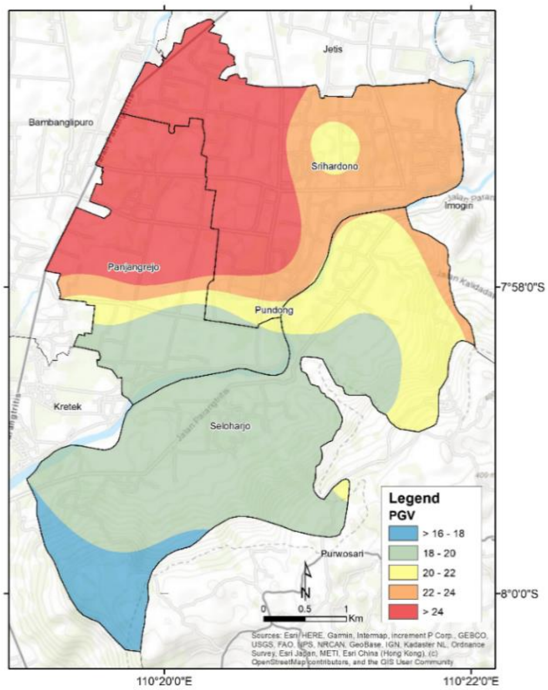

Figure 5. Distribution of *PGV* values in Kapanewon Pundong

Peak Ground Velocity (*PGV*)

PGV measures the maximum ground velocity during an earthquake. This value is critical because it directly relates to structural and infrastructure damage. Several studies have shown that PGV correlates better with structural damage than other parameters such as Peak Ground Acceleration (*PGA*), making *PGV* a commonly used metric in damage prediction models and seismic risk assessments. Based on the worst-case earthquake scenario from the Opak Fault with a magnitude of 6.6, *PGV* values in the study area range from 16 to 29 cm/s, as shown in Figure 5. *PGV* values below 10 cm/s typically cause minor damage; *PGV* between 10 and 30 cm/s can cause moderate to severe damage to buildings not designed to withstand earthquakes; and *PGV* values above 30 cm/s tend to result in severe damage or collapse of structures not engineered explicitly for seismic resistance.

The distribution of *PGV* values in Kapanewon Pundong shows relatively high values in Kalurahan Panjangrejo and Srihardono, while lower values are found in Kalurahan Seloharjo. This indicates that Kalurahan Panjangrejo and Srihardono have a higher potential for structural damage than Kalurahan Seloharjo. The *PGV* distribution provides valuable information for disaster mitigation and regional spatial planning. Buildings and infrastructure in areas with high *PGV* values require stronger design and construction to minimize the risk of damage.

Liquefaction Susceptibility

Liquefaction susceptibility in the geospatial liquefaction prediction model developed by Zhu et al. (2017) refers to assessing an area's potential to experience liquefaction during an earthquake. This model uses a geospatial approach to identify and map regions vulnerable to liquefaction based on various geological and seismic parameters. Liquefaction susceptibility is a parameter that indicates the degree of soil vulnerability to the liquefaction phenomenon.

The results of this study show that liquefaction susceptibility values in the study area range from -4.6 to -0.84. Based on this method, the distribution of liquefaction susceptibility in Kapanewon Pundong was classified into five categories: very low, low, moderate, high, and very high, using threshold values adapted from Zhu et al. (2017), as shown in Figure 6. The resulting liquefaction susceptibility map indicates that areas with very high and high susceptibility include Kalurahan Panjangrejo and Srihardono. In contrast, areas with moderate, low, and very low susceptibility are in Kalurahan Seloharjo. To validate the model outputs, the liquefaction susceptibility maps were compared with phenomena observed during the 2006 Yogyakarta earthquake, including sand boils and lateral spreading. The high-risk zones identified in the maps correspond well with these observations, supporting the reliability of the model predictions.

 ISSN: 2502-2016

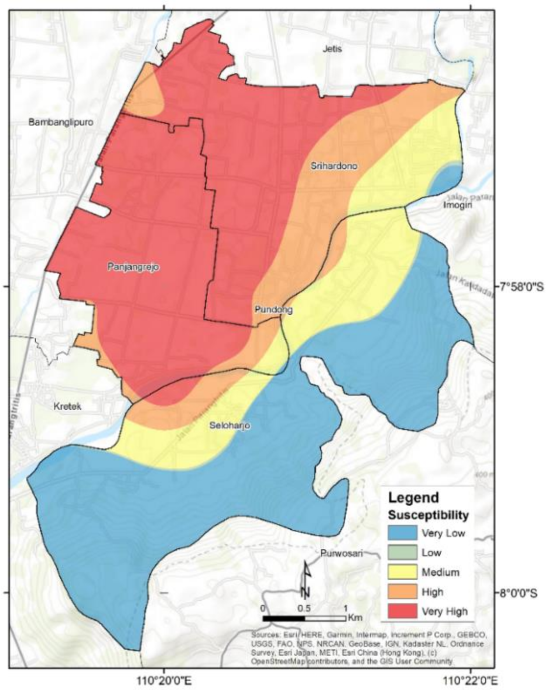

Figure 6. Distribution of liquefaction susceptibility in Kapanewon Pundong

Liquefaction susceptibility is crucial for disaster planning and mitigation. Kalurahan Panjangrejo and Srihardono, with high liquefaction susceptibility values, indicate that the soil conditions in these areas are more prone to liquefaction. Factors such as lithology, groundwater conditions, and soil density contribute to this high vulnerability. On the other hand, Kalurahan Seloharjo, with lower susceptibility values, shows more stable soil conditions and is less prone to liquefaction. This study classified liquefaction susceptibility into five categories: very low, low, medium, high, and very high. These categories are derived from a susceptibility index, in which higher values indicate greater vulnerability to liquefaction. The medium category represents areas with a moderate level of potential, meaning they are neither exceptionally stable nor highly susceptible. In such areas, liquefaction may occur under specific triggering conditions, such as intense earthquake ground shaking or elevated groundwater levels. This classification system provides a more refined understanding of the spatial distribution of liquefaction risk and enhances the interpretability of the susceptibility map by clearly delineating varying hazard levels.

This study also emphasizes the importance of local understanding of geological and seismic characteristics in developing accurate liquefaction prediction models. The V_{S30} data, reflecting the seismic wave velocity in the soil layers, is a key indicator for determining liquefaction susceptibility. Areas with lower V_{S30} values typically have less dense, water-saturated soils, increasing the risk of liquefaction. The liquefaction susceptibility map also serves as a guide for spatial planning and infrastructure development. Areas with high liquefaction susceptibility require specific mitigation measures, such as stronger foundations or even restrictions on construction in highly vulnerable regions. This research is valuable for reducing the risks and impacts of liquefaction in identified areas.

Liquefaction Probability

Liquefaction probability is the likelihood of a particular area experiencing liquefaction during a specific earthquake. The results of the liquefaction probability calculation in Kapanewon Pundong, Special Region of Yogyakarta, range from 1% to 30%. Figure 7 shows the spatial distribution of liquefaction probability across the study area.

Relatively low liquefaction probabilities are represented by green to blue colors, with values less than 10%, and are primarily located in Kalurahan Seloharjo. Meanwhile, higher liquefaction probabilities, represented by yellow to red colors, with values greater than 10%, are predominantly found in Kalurahan Panjangrejo and Srihardono.

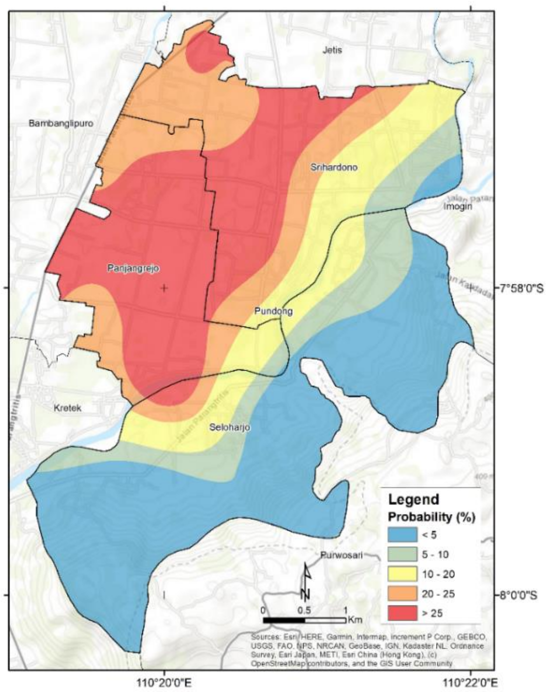

Figure 7. Distribution of liquefaction probability in Kapanewon Pundong

The liquefaction probability analysis mapped in Kapanewon Pundong correlates with the distribution of V_{S30} values. Liquefaction events are not only triggered by seismic vibrations during an earthquake but are also influenced by factors such as lithology and the presence of water bodies. One of the prerequisites for liquefaction is the presence of soils that are typically loose and have high porosity. The V_{S30} value represents the shear wave velocity in the subsurface layers, allowing for identifying rock layer types. Areas with lower V_{S30} values generally exhibit higher liquefaction probabilities. In this study, Kalurahan Panjangrejo and Srihardono have lower V_{S30} values and higher liquefaction probabilities than Kalurahan Seloharjo.

The findings also align with the geological data of Kapanewon Pundong, where Kalurahan Panjangrejo and Srihardono lie on the Young Volcano Deposit of Merapi, which typically consists of tuff, ash, breccia, agglomerate, and lava flows that are inseparable. Liquefaction events are often associated with Quaternary sediment deposits characterized by fine-grained materials. The Young Merapi Volcano Deposit Formation is a zone with a high potential for liquefaction events. The liquefaction probabilities derived in this study positively correlate with the findings of Buana et al. (2016), which indicate that Kapanewon Pundong, located in the Young Merapi Volcano Deposit area, has a liquefaction potential. Furthermore, the model's reliability was confirmed by comparing the liquefaction susceptibility and probability maps with phenomena observed during the 2006 Yogyakarta earthquake, such as sand boils and lateral spreading. The high-risk zones identified in the model matched these observations, indicating strong consistency with actual events.

Liquefaction Spatial Extent

Research on liquefaction potential in a given area is further conducted by analyzing the Liquefaction Spatial Extent (*LSE*) value. The percentage value indicated by *LSE* represents the spatial extent of areas potentially affected by liquefaction. This analysis is crucial for understanding the distribution and risk level of liquefaction in various regions, enabling more informed decision-making in disaster mitigation and spatial planning. The *LSE* values calculated in the study area range from 0.04% to 5.1%, as illustrated in Figure 8.

The Liquefaction Spatial Extent (LSE) distribution shows relatively high values in Kalurahan Panjangrejo and Srihardono, while Kalurahan Seloharjo exhibits relatively low values. This finding is consistent with the liquefaction probability results, which indicate that Kalurahan Panjangrejo and Srihardono are more susceptible to liquefaction impacts than Kalurahan Seloharjo. Factors such as geological conditions, soil type, and groundwater saturation levels in these areas contribute to these differences. For example, the looser and water-saturated soils in Kalurahan Panjangrejo and Srihardono make these areas more vulnerable to liquefaction than the denser and drier soils found in Kalurahan Seloharjo. Understanding the spatial distribution of LSE can help identify critical infrastructure and settlements at risk and design more effective mitigation strategies for potential liquefaction hazards.

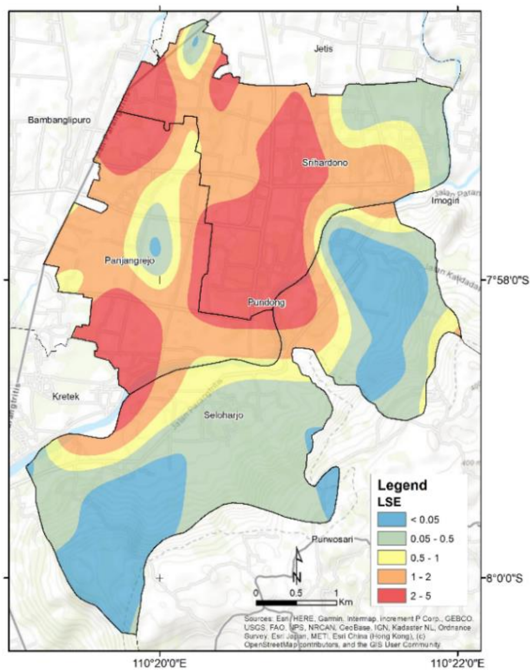

Figure 8. Distribution of *LSE* in Kapanewon Pundong

CONCLUSION

This study applies a geospatial liquefaction prediction model integrated with microtremor analysis to evaluate the liquefaction probability in Kapanewon Pundong, Bantul Regency, Special Region of Yogyakarta. The model effectively estimates both liquefaction susceptibility and probability values by combining key geospatial parameters such as *PGV*, V_{S30}, precipitation, Distance to Water body (*DW*), and Water Table Depth (*WTD*).

The results indicate that Kalurahan Panjangrejo and Srihardono exhibit the highest liquefaction probabilities, reaching up to 30%, highlighting their higher susceptibility than other areas. In contrast, Kalurahan Seloharjo generally demonstrates lower liquefaction vulnerability. The *HVSR* analysis provides insights into the local soils' dominant frequency and amplification characteristics. At the same time, inversion results generate 1D shear wave velocity (V_s) profiles that reflect subsurface structural variations. V_{s30} values range from 221 to 893 m/s, classifying the soils C and D according to SNI 1726:2019. Areas with lower V_{s30} values tend to have softer soils and higher amplification potential, increasing their susceptibility to liquefaction and seismic damage. The PGV analysis based on a worst-case scenario from the Opak Fault reveals values between 16 and 29 cm/s, with the highest *PGV* concentrations also occurring in Kalurahan Panjangrejo and Srihardono. These areas are thus more likely to experience significant structural damage in an earthquake. Liquefaction susceptibility and probability values derived from the model align with the area's geological setting, particularly loose, water-saturated volcanic deposits from the Young Merapi Formation. This is further supported by Liquefaction Spatial Extent (LSE) analysis, which shows that up to 5.1% of the area in Kalurahan Panjangrejo and Srihardono could be affected during a liquefaction event.

This study demonstrates that integrating microtremor HVSR analysis with geospatial liquefaction modeling offers a comprehensive and accurate framework for assessing liquefaction potential. The findings are essential for seismic risk mitigation strategies, such as enforcing stricter building codes, guiding land-use planning, and prioritizing infrastructure reinforcement in highly susceptible zones. This research contributes to a better scientific understanding of local seismic vulnerability and provides practical recommendations for reducing the impact of future earthquakes in Kapanewon Pundong.

ACKNOWLEDGMENT

I would like to express my sincere gratitude to all individuals and organizations who have contributed to the completion of this article. Special thanks to my research colleagues and mentors for their invaluable guidance, insights, and support throughout the research process.

REFERENCES

Afsari, N., Abdipour, M.S. & Taghizadeh-Farahmand, F. (2022). Seismic Hazard Analysis from Deterministic Method Using Fuzzy Logic in Anzali Port. *Earth Sci Inform*, 15(1): 563–572.

BSN-Badan Standarisasi Nasional. (2019). *SNI 1726:2019 Tata Cara Perencanaan Ketahanan Gempa Untuk Struktur Bangunan Gedung dan Nongedung*. www.bsn.go.id.

Brankman, C.M. & Baise, L.G. (2008). Liquefaction Susceptibility Mapping in Boston, Massachusetts. *Environmental & Engineering Geoscience*, 14 (1): 1–16.

Buana, T. W., Wafid. M., Sadisunuana, I. A. (2016). Hubungan Potensi Likuifaksi Pada Endapan Gunungapi Merapi Muda Dengan Kerusakan Bangunan Di Kabupaten Bantul Pada Kasus Gempabumi 27 Mei 2006. *Jurnal Lingkungan dan Bencana Geologi*, 7(2): 103–111.

Cetin, K. O., Seed, R. B., Moss, R. E. S., Kammerer, A. M., Wu, J., Pestana, J. M., & Riemer, M. F. (2018). SPT-Based Probabilistic and Deterministic Assessment of Seismic Soil Liquefaction Triggering Hazard. *Soil Dynamics and Earthquake Engineering*, 115: 698–709.

Chiou, B.S.J. & Youngs, R.R. (2014). Update Of the Chiou and Young's NGA Model for The Average Horizontal Component of Peak Ground Motion and Response Spectra. *Earthquake Spectra*, 30(3): 1117–1153.

Daryono, M.R., Pamumpuni, A., Wardhana, D.D. & Natawidjaja, D.H. (2023). Mataram Fault - New Active Fault Crosses East-West in the Centre of Yogyakarta City. *IOP Conference Series: Earth and Environmental Science*.

Ghione, F., Köhler, A., Dichiarante, A.M., Aarnes, I. & Oye, V. (2023). V_{S30} Moreover, Depth to Bedrock Estimates from Integrating HVSR Measurements and Geology-Slope Approach in The Oslo Area, Norway. *Front. Earth Sci., Sec. Geohazards and Georisks,* Vol. 11.

Haifani, A.M., Nirwansyah, A. W., Suntoko, H., Alimah, S. (2023). The Distribution of Spatial Liquefaction with Different Interpolation Methods Using GIS: A case in Bantul Region, Indonesia. *Research Square*, doi.org/10.21203/rs.3.rs-3356256/v1

Hartantyo, E., Brotopuspito, K.S., Sismanto & Waluyo. (2015). Predicting The Liquefaction Phenomena from Shear Velocity Profiling: Empirical Approach To 6.3 Mw, May 2006 Yogyakarta Earthquake. *AIP Conference Proceedings*.

Hendro, B. & Prakoso, W.A. (2023). Model Indeks Likuifaksi Berbasis Standard Penetration Test Menggunakan Multi-Gene Genetic

Programming. *Jurnal Rab Contruction Research*, 8 (1), 34-44.

Koulali, A., McClusky, S., Susilo, S., Leonard, Y., Cummins, P.R., Tregoning, P., Meilano, I., Efendi, J., & Wijanarto, A.B. (2017). The Kinematics of Crustal Deformation in Java from GPS Observations: Implications for Fault Slip Partitioning. *Earth and Planetary Science Letters*, 458, 69–79.

Kundu, P., Pain, A. & Das, J. (2024). Earthquake-Induced Liquefaction Potential and Risk Assessment of The World's Largest Mobile Manufacturing Plant, Noida, Uttar Pradesh. *Environ Earth Sci*, 83(7).

Kusmanto, Ismanti, S. & Setiawan, F. (2024). Assessment Of Liquefaction Risk with Unidentified Seismic Parameters for Newly-Discovered Faults: Numerical Analysis. *International Journal of GEOMATE*, 26(114): 50–59.

Librian, V., Ramdhan, M., Nugraha, A. D., Mukti, M. M., Syuhada, Lühr f, B. G., Widiyantoro, S., Mursitantyo, A., Anggraini, A., Zulfakriza, Muttaqy, F., Husni, Y. M. (2024). Detailed Seismic Structure Beneath the Earthquake Zone of Yogyakarta 2006 (Mw ~6.4), Indonesia, From Local Earthquake Tomography. *Physics of the Earth and Planetary Interiors*, Vol. 351 107170.

Maharani, Y.N., Sunardi, B. & Algary, T.A. (2023). Potensi Likuifaksi Di Kabupaten Bantul Provinsi D.I. Yogyakarta. *Jurnal Mineral, Energi, dan Lingkungan*, 7(1): 8–14.

Mase, L.Z. (2017). Experimental Liquefaction Study of Southern Yogyakarta Using Shaking Table. *Jurnal Teknik Sipil*, 24(1).

Meisina, C., Bonì, R., Bozzoni, F., Conca, D., Perotti, C., Persichillo, P., Lai, C. G. (2022). Mapping Soil Liquefaction Susceptibility Across Europe Using the Analytic Hierarchy Process. *Bulletin of Earthquake Engineering*, 20(11), 5601 - 5632.

Molnar, S., Cassidy, J. F., Castellaro, S., Cornou, C., Crow, H., Hunter, J. A., Matsushima, S., Sánchez-Sesma, Yong, A. (2018). Application of Microtremor Horizontal-to-Vertical Spectral Ratio (MHVSR) Analysis for Site Characterization: State of the Art., *Surv Geophys*, 39, 613–631.

Muttaqy, F., Nugraha, A.D., Mori, J., Puspito, N.T., Supendi, P. & Rohadi, S. (2022). Seismic Imaging of Lithospheric Structure Beneath Central-East Java Region, Indonesia: Relation to Recent Earthquakes. *Front. Earth Sci., Sec. Solid Earth Geophysics*, Vol. 10.

Nakamura, Y. (2000). Clear Identification of Fundamental Idea of Nakamura's Technique and Its Applications. *Proceedings 12th World Conference on Earthquake Engineering*, Selandia Baru.

Partono, W., Nazir, R., Kistiani, F., Sari, U.C. (2023). Seismic Microzonation of Yogyakarta Province Based on 2019 Risk-Targeted Maximum Considered Earthquake. *Proceedings of the 5th International Conference on Rehabilitation and Maintenance in Civil Engineering. ICRMCE 2021*, Vol. 225. Springer, Singapore.

Sanchez-Sesma, F.J., Palencia, A. & Luzon, F. (2002). Estimation Of Local Site Effect During Earthquake: An Overview. *ISET Journal of Earthquake Technology*, 39(3): 167–193.

Seo, H., Kim, H.S., Baise, L.G. & Kim, B. (2024). Geospatial Liquefaction Probability Models Based on Sand Boils Occurred During the 2017 M5.5 Pohang, South Korea, earthquake. *Engineering Geology*, Vol. 329, 107407.

Tohari, A., Sugianti, K., Syahbana, A.J. & Soebowo, E. (2015). Kerentanan Likuifaksi Wilayah Kota Banda Aceh Berdasarkan Metode Uji Penetrasi Konus. *Jurnal RISET Geologi dan Pertambangan*, 25(2): 99.

Zakariya, A., Rifa'i, A. & Ismanti, S. (2023). Ground Motion and Liquefaction Study at Opak River Estuary Bantul. *IOP OP Conference Series: Earth and Environmental Science,* Volume 1244.

Zhu, J., Baise, L.G. & Thompson, E.M. (2017). An updated geospatial liquefaction model for global application. *Bulletin of the Seismological Society of America*, 107(3): 1365–1385.