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ALLUVIAL SOIL PHYSICAL PROPERTIES IN A POST-EARTHQUAKE LIQUEFACTION ZONE IN YOGYAKARTA

SIFAT FISIK TANAH ALUVIAL PADA ZONA LIKUIFAKSI PASCA GEMPA BUMI YOGYAKARTA

Rauf Karim[1], Mohammad Nurcholis[1*]

[1] Department of Soil Science, Faculty of Agriculture, Universitas Pembangunan Nasional "Veteran" Yogyakarta

*) Corresponding author: nurcholis@upnyk.ac.id

ABSTRACT

Liquefaction is a secondary impact of earthquakes that can cause severe land degradation, including damage to agricultural areas. Bantul Regency experienced liquefaction during the 2006 earthquake, making it prone to further liquefaction, especially in the Jetis subdistrict. This study investigates the physical characteristics of soils prone to liquefaction and examines the correlation between the soil maturity index and liquefaction potential. Sampling points were determined using purposive sampling. The liquefaction potential index value was calculated using qualitative geological techniques at depths of 0–300 cm, yielding values of 28.40 and 18.01 for perennial tree and seasonal crop areas, respectively. Soil samples were collected, and laboratory analyses, including soil particle size, texture, organic matter, maximum moisture content, electrical conductivity (EC), permeability, redox potential (Eh), and plasticity index, were conducted. The results show key characteristics supporting liquefaction potential, including a dominant sand fraction (79.15%), maximum moisture content (88.94%), moderately fast permeability, high EC (0.416 mS/cm), and Eh values indicating aerobic tendency. All soil samples were categorized as physically immature based on the soil maturity index, reflecting weak interparticle bonding and high dispersion when saturated. Regression analysis between the soil maturity index and median grain size (D_{50}) revealed insignificant correlations, with R = -0.56 (R^2 = 0.3161) and 0.38 (R^2 = 0.145) for perennial and seasonal crop areas, respectively. Visually, quadratic regression yielded R^2 values of 0.4109 and 0.4226, suggesting a potential nonlinear pattern. These findings indicate that soil maturity index influences liquefaction propensity. Further research is necessary to understand other controlling variables.

Keywords: *Liquefaction, Soil physical properties, Soil maturity index, Liquefaction potential*

ABSTRAK

Likuifaksi merupakan dampak sekunder gempa bumi yang dapat menyebabkan degradasi lahan, termasuk kerusakan pada lahan pertanian. Kabupaten Bantul mengalami likuifaksi pada gempa bumi tahun 2006, sehingga rentan terhadap likuifaksi lebih lanjut, terutama di Kecamatan Jetis. Penelitian ini menyelidiki karakteristik fisik tanah yang rentan terhadap likuifaksi serta mengkaji korelasi antara indeks kematangan tanah dan potensi likuifaksi. Titik pengambilan sampel ditentukan secara *purposive sampling*. Nilai indeks potensi likuifaksi dihitung dengan teknik geologi kualitatif pada kedalaman 0–300 cm dan diperoleh 28.40 dan 18.01, masing-masing untuk area tanaman tahunan dan musiman. Sampel tanah diambil dan dilakukan analisis laboratorium yang meliputi ukuran partikel tanah, tekstur, bahan organik, kadar air maksimum, konduktivitas listrik (EC), permeabilitas, potensial redoks (Eh), dan indeks plastisitas. Hasilnya menunjukkan karakteristik utama yang mendukung potensi likuifaksi, termasuk fraksi pasir dominan (79.15%), kadar air maksimum (88.94%), permeabilitas cukup cepat, EC tertinggi (0.416 mS/cm), dan nilai Eh yang menunjukkan kecenderungan aerobik. Semua sampel tanah dikategorikan sebagai belum matang secara fisik berdasarkan indeks kematangan tanah, yang mencerminkan ikatan antar partikel yang lemah dan dispersi yang tinggi saat jenuh. Analisis regresi antara indeks kematangan tanah dan ukuran butir median (D_{50}) mengungkapkan korelasi yang tidak signifikan, dengan R = -0.56 (R^2 = 0.3161) dan 0.38 (R^2 = 0.145), masing-masing untuk area tanaman tahunan dan musiman. Secara visual, regresi kuadrat menunjukkan nilai R^2 sebesar 0.4109 dan 0.4226, yang menunjukkan pola nonlinier potensial. Temuan ini menunjukkan bahwa indeks kematangan tanah memengaruhi kecenderungan likuifaksi. Penelitian lebih lanjut diperlukan untuk memahami variabel pengendali lainnya.

Kata kunci: Likuifaksi, Sifat fisik tanah, Indeks kematangan tanah, Potensi likuifaksi

INTRODUCTION

Liquefaction is a secondary effect of earthquakes that can damage soil, buildings, infrastructure, and agricultural land. In geotechnical engineering, this phenomenon is understood as the loss of soil strength due to the increase of pore water pressure and decrease of effective stress, causing the soil to behave like a fluid and be unable to bear loads (Ghani et al, 2024). Liquefaction is likely to occur in water-saturated soil. Some types of water-saturated soil include soil in swampy areas, alluvial soil formed from deposits of sand, gravel, and clay accumulated by water flow, and muddy soil (Tijow et al., 2018). There are three main factors causing liquefaction: coarse-grained soil, particularly sand with loose consistency and structure; groundwater levels close to the surface or relatively shallow, causing the soil to be water-saturated; and dynamic loads in the form of earthquake shaking (Masrurah et al., 2023).

Yogyakarta is one of the regions in Indonesia that has experienced several major earthquakes, resulting in liquefaction. The National Disaster Management Agency (BNPB) recorded that Bantul Regency, Yogyakarta, experienced a major earthquake in 2006 with a magnitude of 5.9 and an epicenter at a depth of less than 10 km, causing liquefaction at several locations. An area that has experienced liquefaction is at risk of experiencing it again. This is also due to geological environmental conditions such as alluvial deposits, shallow groundwater levels, the active Opak fault zone, and the Bantul Graben. A study by Soebowo et al. in 2009 showed that liquefaction occurred in Kapanewon Jetis, Bantul Regency. Thus, this area was selected as the study site.

A better understanding of the liquefaction potential is crucial, given the environmental impacts of liquefaction, including soil damage, particularly in agricultural lands. Specifically, the study site consists of perennial trees and seasonal crop fields. If liquefaction occurs in this area, it will result in soil damage, including damage to agricultural lands. Given this situation, a more in-depth analysis of soil physical conditions and soil maturity indices is necessary to reduce the liquefaction potential.

This study aims to identify several physical characteristics of soil prone to liquefaction and to determine the correlation between soil maturity indices and the potential for liquefaction in the soil. It is hoped that this research will provide information on areas prone to liquefaction through the soil maturity index approach and other factors based on soil physical properties as a mitigation strategy for liquefaction potential and for proper regional spatial planning.

MATERIALS AND METHODS

This study was conducted in Trimulyo Village (Sample point 1, S1) and Sumberagung Village (Sample point 2, S2), Jetis Subdistrict, Bantul Regency, from January to March 2025 (Figure 1). The sampling locations were selected due to the variation in liquefaction potential shown on the 2006 liquefaction history map of the area (Sudarsono and Sugiyanto, 2007). Verification of the locations was carried out through field surveys to ensure consistency with actual conditions, considering differences in land use and similar alluvial soil characteristics. The land uses in the sampling locations are perennial trees and seasonal crops fields for S1 and S2, respectively. Based on the previous study, the liquefaction potential index was 28.40 and 18.01 at S1 and S2, respectively (Buana and Agung, 2015). Detailed coordinates and locations are presented in Table 1.

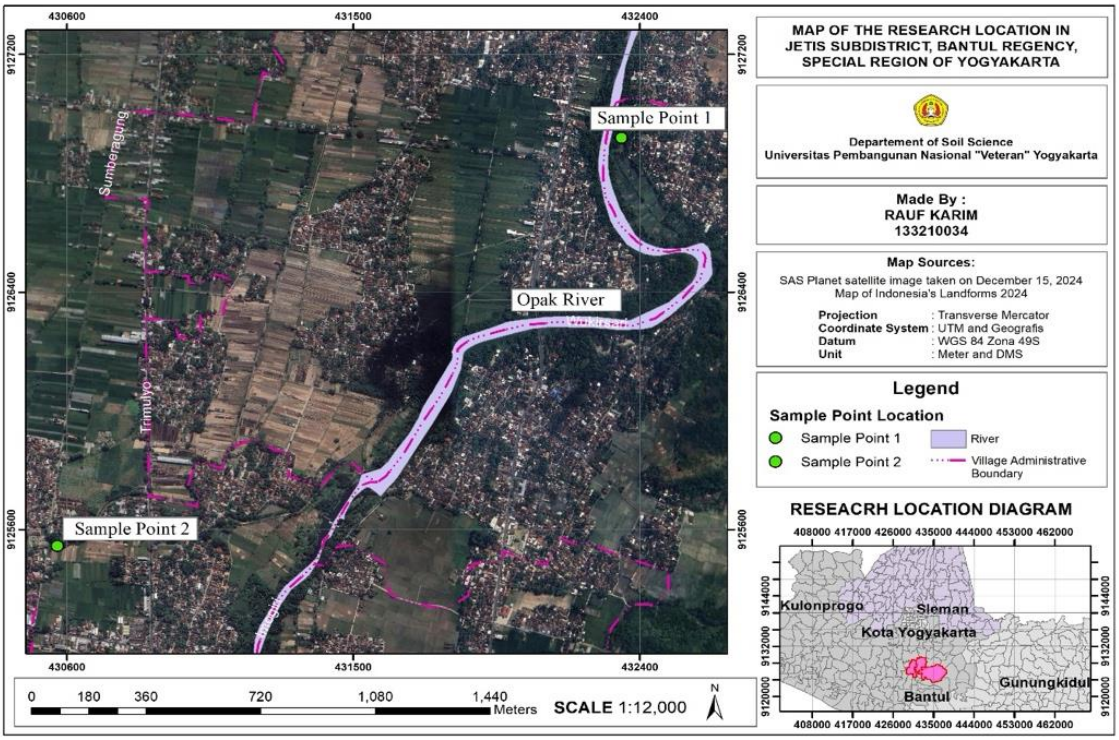

Figure 1. Map of research location in Kapanewon Jetis, Bantul Regency, Special Region of Yogyakarta

Soil samples were taken at the sampling points (Table 1), i.e., disturbed and undisturbed soil samples. Disturbed soil samples were taken using a soil auger, taking care not to exceed the water table. Drilling for disturbed soil sampling was conducted directly at each 50 cm depth interval up to a maximum depth of 300 cm, divided into 6 depth points. Undisturbed soil samples were collected using a soil ring sampler at the soil surface at a depth of 0–20 cm. Samples were then transferred to the laboratory for further analysis. Laboratory analyses carried out were observation and measurement of soil particle size using sieve analysis, soil texture using the pipette method, soil organic carbon using the Walkley and Black method, maximum soil moisture content using the gravimetric method, electrical conductivity using an EC meter, permeability using soil permeability saturation method, redox potential (Eh), and Atterberg Limits (liquid limit, plastic limit or roll, and plasticity index). After the soil samples were tested for several parameters, descriptive statistical analysis was conducted, including frequency distribution, mean, median, mode, standard deviation, and correlation tests between parameters, particularly between the soil maturity index (n-value) and the median value of soil particle size distribution (D_{50}).

Table 1. Sample point collection in Jetis Subdistrict, Bantul Regency

Sampling point location	Location	Land use	Coordinates
S1 (Potential Index: 28.40*)	Trimulyo Village	Perennial trees	7°53'53.1"S 110°23'10.3"E
S2 (Potential Index: 18.01*)	Sumberagung Village	Seasonal crops	7°54'40.7"S 110°22'11.4"E

(*) liquefaction potential index value (Source: Buana and Agung, 2015)

RESULTS AND DISCUSSION

General characteristics of alluvial soil at the study area

The results of field observations in the study area show that both sampling locations have relatively low slopes, i.e., 1 % and 0 % for sample point 1 (S1) and 2 (S2), respectively. These conditions pose a liquefaction potential, according to the Indonesian Geological Agency. The Geological Disaster Management Team from the Center for Groundwater and Geological Disaster Management of the Geological Agency previously classified soil with a slope between 0% and 8.749% or 0° and 5° as one of the determining factors for the potential for liquefaction in an area (Badan Geologi, 2024).

Geologically, the study area is located in a basin structure (graben) known as the Bantul Graben. The Opak Fault cuts through this region, stretching from Parangtritis eastward to Prambanan. The Opak Fault is an active fault line, which was one of the causes of the earthquake in Yogyakarta on May 27, 2006. The earthquake triggered surface wave propagation, which can cause secondary disasters such as liquefaction, especially in the research area (Cahyani et al, 2019). Jetis Subdistrict is located at an elevation of 20 to 100 meters above sea level and is traversed by the Opak River. Both research sample points are located near the Opak River, where the S1 and S2 were 50 and 679 meters from the riverbank, indicating that the soil type in the research location is alluvial.

Soil texture affects water absorption, water availability in the soil, and soil aeration. Additionally, soil texture influences the soil maturity index through the percentage of sand, silt, and clay fractions. Soil texture, maximum soil moisture content, organic matter, plasticity index, redox potential, and electrical conductivity is presented in Table 2.

Table 2. Soil texture, maximum moisture content (MMC), organic matter (OM), plasticity index (PI), redox potential (Eh), and electrical conductivity (EC) in the study area

Location	Depth (cm)	Soil texture	MMC (%)	OM (%)	PI	Eh (mV)	EC (mS/cm)
S1 (Perennial trees)	50	Loam	67.64	0.72	0.24	274	0.051
	100	Sandy Clay Loam	58.27	0.65	2.92	265.33	0.083
	150	Loam	66.65	0.64	18.12	257	0.109
	200	Sandy Loam	49.43	0.43	6.58	257	0.147
	250	Loamy Sand	33.32	0.26	0	255.67	0.416
	300	Loamy Sand	28.22	0.24	0	273.33	0.096

Location	Depth (cm)	Soil texture	MMC (%)	OM (%)	PI	Eh (mV)	EC (mS/cm)
S2 (Seasonal crops)	50	Sandy Loam	69.74	0.76	7.35	270	0.045
	100	Sandy Clay Loam	55.66	0.72	5.31	274	0.051
	150	Sandy Clay Loam	86.12	0.65	13.27	262.33	0.166
	200	Sandy Clay Loam	88.94	0.64	8.82	253.33	0.256
	250	Sandy Loam	50.69	0.43	0	259	0.141
	300	Silty Loam	36.94	0.24	0	264.67	0.09

Differences in soil characteristics were found between the two collected samples (Table 2). The soil in the perennial tree field (S1) is dominated by sand fractions, with a percentage reaching 70.15% and classified as sandy loam, loamy sand, and loamy soil. The soil in the seasonal crop field (S2) exhibits a finer texture with relatively high clay and silt content and, therefore, is classified as sandy clay loam and silt loam. Soil dominated by sandy fractions has good aeration and drainage but low water-holding capacity and nutrient retention.

Based on Table 2, the highest maximum moisture content values in the perennial tree field (S1) are at depths of 50 cm (67.64%) and 150 cm (66.65%), then drop significantly at 300 cm (28.22%). Meanwhile, in seasonal crop fields (S2), the maximum moisture content is highest at depths of 150 cm and 200 cm, with values of 86.12% and 88.94%, respectively. Both land uses have relatively high maximum moisture content values, particularly in the upper layers, which triggers water absorption in the layers and become waterlogged.

Both sample points have low organic matter content (Table 2), which is influenced by the dominant sandy soil texture, which has low adsorption capacity for organic matter. In sandy soil, organic matter is not retained for long and easily leaches into lower layers. Meanwhile, low organic matter content increases the susceptibility or liquefaction potential due to the absence of natural binders between particles that could enhance aggregate stability.

Table 2 shows that both locations have the highest plasticity index at a depth of 150 cm. Meanwhile, the index at depths of 250 cm and 300 cm is 0%, indicating that the soil layers at these depths are dominated by a sandy texture, which has non-plastic and non-cohesive properties. This condition has a significant impact on liquefaction potential.

Samples at the depths of 250 cm (S1) and 200 cm (S2), respectively, showed the highest soil electrical conductivity (EC) (Table 2). Soil with high salinity tends to be easily dispersed, especially in sandy textures. In this study, the perennial tree field has higher EC values compared to the seasonal crop field. This condition indicates that the perennial tree field soil is more prone to dispersion, which can increase liquefaction susceptibility. Moreover, the damage potential in this area may also increase as the vegetation consists of large and hardy plants.

The redox potential (Eh) of the soil at both locations ranged from 253 to 274 mV (Table 2), indicating an aerobic condition. The oxidative or aerobic conditions at the study site indicate a stable soil environment with good drainage. Overall high Eh values also serve as an indicator of soil stability in the context of liquefaction potential. especially in earthquake-prone areas. However, high Eh values alone are not sufficient to guarantee soil stability, especially when other factors such as dominant sand texture and water saturation also contribute to liquefaction.

Additionally, the results of the soil permeability test for both samples were conducted at the soil surface at a depth of 0–50 cm. The test yielded moderately fast permeability values, indicating that the soil has relatively high porosity and is dominated by sand fractions. High permeability values allow water to flow easily and fill soil pores. especially in sandy-textured soils. This condition may influence the potential for liquefaction because water-saturated soil tends to lose its shear strength when pore water pressure increases due to earthquake shocks.

Relationship between soil maturity indices, soil grain size (D_{50}), and liquefaction potential

The soil maturity index is an index used to indicate the level of soil maturity. The determination of this index involves factors such as maximum soil moisture content, soil texture percentage, and organic matter percentage. The soil maturity index can be calculated using the following formula (Pons and Zonneveld, 1965).

$$\textbf{Soil maturity index} = \frac{A - 0.2\,R}{L + 3\,H}$$

Description:
A = soil moisture content in saturated condition or maximum moisture content (%)
R = percentage of silt + sand
L = percentage of clay
H = percentage of organic matter (% C × 1.724)

Soil particle size identification was carried out using a sieve method or sieve analysis with diameters ranging from 4.75 mm to 0.075 mm (SNI 03-3423-1994). The soil median grain size (D_{50}) reflects the dominant size of soil particles and plays a role in identifying the physical characteristics of soil and its liquefaction susceptibility. The results of the analysis and soil maturity category, as well as the calculated D_{50} for each sample, are presented in Table 3.

Table 3. Soil maturity index and median soil particle grain size (D_{50}) of the study area

Location	Depth (cm)	Soil maturity index	Median grain size	Description
S1	50	2.99	0.29	Immature
	100	1.74	0.25	Immature
	150	2.38	0.08	Immature
	200	2.8	0.08	Immature
	250	3.38	0.26	Immature
	300	1.53	0.88	Immature
S2	50	2.57	0.64	Immature
	100	1.66	1.46	Immature
	150	2.24	1.74	Immature
	200	2.46	1.3	Immature
	250	1.97	0.36	Immature
	300	1.06	0.26	Immature

Based on the results of these calculations, it was found that all samples from both sampling locations are immature soil (Table 3). The maturity indices of soil samples are in the range of 1.53–3.38 and 1.06–2.57 in the perennial tree field (S1) and the seasonal crop field (S2), respectively. Smaller indices indicate a greater maturity, suggesting better consolidation and a relatively lower potential for liquefaction in seasonal crop fields. The soil particles in S1 and S2 range from 0.08–0.88 mm (average 0.31) and 0.26–1.74 mm (average 0.96), respectively. This indicates that the soil at the seasonal crop field tends to have larger particles. Ultimately, the combination of a smaller D_{50} value and a higher soil maturity index in the perennial tree field reinforces the liquefaction potential.

Table 4. Summary of the regression model performed between soil maturity index (x) and D_{50} (y)

Location	Formula	R	R^2
Linear model			
S1	$y = -1.3797x + 2.8931$	-0.5623	0.316
S2	$y = 0.3463x + 1.6608$	0.3808	0.145
Quadratic model			
S1	$y = 0.5243x^2 - 2.7612x + 3.6984$	0.8510	0.724
S2	$y = -0.9611x^2 + 3.9236x - 2.7868$	0.5486	0.301

Regression analyses were performed between soil maturity index and soil median grain size (D_{50}), resulting in a non-significant correlation in both linear and quadratic models, and the summary was presented in Table 4. Based on the linear model, the relationship between both soil properties shows a moderate negative correlation (R = -0.5623) and a weak positive correlation (R = 0.3808) at S1 and S2, respectively. The coefficient of determination (R^2) at S1 indicates that soil maturity index only influences 31.61% of the D_{50}, while the remaining 68.39% is influenced by other factors. Meanwhile, the coefficient of determination (R^2) at S2 indicates that soil maturity index only influences 14.5% of the D_{50}, while the remaining 85.5% is influenced by other factors. This negative relationship indicates that as D_{50} increases, the soil maturity level tends to decrease, and vice versa for the positive relationship.

Similar to the linear model, the quadratic model shows no correlation between the soil properties in both locations. The coefficient of determination (R^2) of the quadratic model can only explain 41.09% and 42.26% of the variation in soil maturity index against D_{50} (Table 4). Visually, this pattern will form a peaked curve or inverted parabola at a certain point (depth). However, the non-significant correlation in this analysis indicates that in actual conditions, the optimal soil maturity level does not directly influence the average soil particle size, which in turn does not increase the potential for soil liquefaction.

CONCLUSION

This study examined soil physical properties in two locations in Jetis subdistrict, an area with alluvial soil and liquefaction potential due to the Yogyakarta earthquake nearly two decades ago. The alluvial soil in both locations is characterized by sandy texture, high maximum moisture content, low organic matter, moderately fast permeability, high electrical conductivity, and high potential redox. These combined characteristics indicate immature soil with weak interparticle bonds, making it susceptible to liquefaction, especially in the perennial tree fields, which show higher susceptibility. However, there was no linear or quadratic correlation pattern between soil maturity index and grain particle size (D_{50}). Therefore, further studies are necessary to consider other possible factors.

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