KURVATEK Vol. 9, No. 2, November 2024, pp. 197 – 206
e-ISSN: 2477-7870 p-ISSN: 2528-2670

ANALYSIS OF LIQUEFACTION POTENTIAL USING THE ANALYTICAL HIERARCHY PROCESS METHOD IN BANTUL DISTRICT, YOGYAKARTA PROVINCE, INDONESIA

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How to cite: D. S. Nurhaci, "Analysis of Liquefaction Potential Using The Analytical Hierarchy Process Method in Bantul District, Yogyakarta Province, Indonesia," *Kurvatek*, vol. 9, no. 2, pp. 197 – 206, 2024. doi:10.33579/krvtk.v9i2.5409 [Online].

Abstract — *The earthquake that struck the Bantul district of Yogyakarta on May 27, 2006, with a Richter scale value of 6.3, caused sandboils in various areas in Bantul Regency. These symptoms are referred to as liquefaction events, and the phenomenon is fascinating to research. These symptoms are referred to as liquefaction events, and the phenomenon is intriguing to researchers. Liquefaction in Bantul Regency is induced by the area's Young Volcanic Deposits of Merapi Volcano and shallow groundwater table, which can result in saturated soil during an earthquake. The research was conducted to assess the potential hazards of liquefaction. The data used in this research includes geological maps, groundwater depth maps, fault distance maps, river distance maps, and slope maps. The method used is the Analytical Hierarchy Process (AHP) to determine the weight of each parameter utilized, employing Geographic Information System software to overlay maps based on the obtained weight values, allowing the liquefaction threat potential map to be classified into high, medium, and low threats. According to the findings of this study, the lowland area between the Bedog and Opak rivers has a high liquefaction potential due to the presence of Young Volcanic Deposits of Merapi Volcano going back to the Quaternary epoch and a relatively shallow groundwater table. In contrast, the hilly terrain west of the Bedog River and east of the Opak River has a low liquefaction potential due to Tertiary sedimentary rocks and a deeper groundwater table.*

Keywords*:* Liquefaction, AHP, GIS, groundwater level

I. INTRODUCTION

Liquefaction is a phenomenon in which sediments alter owing to interaction with water and seismic shocks, rendering the lithology incapable of sustaining shaking [18]. The earthquake occurred in the D.I Yogyakarta Province on May 27, 2006, at 06:53:57 WIB with a magnitude of 5.9 at a depth of 33 km, and the epicentre was located 15 kilometres south of the city of Yogyakarta [1]. On June 5, 2006, around 4:00 PM WIB, the Yogyakarta Disaster Management Coordination Unit reported 4,772 fatalities, 17,772 injuries, and damage to 204,831 dwellings in Bantul, Klaten, Yogyakarta, and Prambanan. The Bantul District Disaster Management Agency reported 4,143 deaths, with the most severe damage occurring in Bantul District [3]. Liquification is one of the various seismic impacts noted in this incident. An earthquake with a close epicenter due to its link with the Opak Fault can occur in Bantul Regency, one of the southern volcanic deposit locations with a sand layer and shallow groundwater [12].

Geographic Information Systems (GIS) are instruments that aid in administrating geographical data and information. Spatial data of liquefaction dangers can be stored, arranged, analyzed, and shown using GIS technology. Currently, GIS technology is used in processing information, including managing and resolving issues related to natural conditions or disasters [13]. In the development of the Liquefaction Hazard Potential Map for Bantul Regency, six base maps were used, and their weights and scores were computed using the Analytical Hierarchy Process (AHP) method.

This research aims to create a liquefaction potential map for the Bantul Regency. The map in this study was made by processing data parameters with data weighting from the Analytical Hierarchy Process (AHP) method. Several criteria will be employed, including rock type, groundwater level, fault distance, seismic wave velocity Vs.30, and river distance. So that the liquefaction hazard zones in Bantul Regency, which are classified into three categories: low, medium, and high-risk, can be identified. This map is meant

Received October 7, 2024; Revised October 30, 2024; Accepted October 31, 2024

 DOI : https://doi.org/10.33579/krvtk.v9i2.5409

to give information on areas in the Bantul Regency prone to liquefaction and help improve disaster mitigation efficacy.

A. Geology and Regional Structure

Bantul Regency is geologically dominated by the Young Volcanic Deposits of Merapi Volcano, which result from Mount Merapi's continuous activity. The research area comprises Pre-Tertiary, Tertiary, and Quaternary rock units. Pre-Tertiary rocks are metamorphic rocks that compose the basement and are exposed in the Bayat area of Klaten. The reworking of older Tertiary rocks produced the Quaternary rocks, which are roughly 1.8 million years old and comprise loose to weakly compacted material ranging from clay-sized grains to pebbles [12]. The geological conditions of the research area consist of Rock Units and Formations from young to old as follows: Alluvium Unit (Qa), Young Volcanic Deposits of Mount Merapi (Qmi), Sentolo Formation (Tmps), Wonosari Formation (Tmwl), Nglanggran Formation (Tmn), and Semilir Formation (Tmse).

The Semilir Formation (Tmse), found in the northern portion of the southern hill, contains the oldest exposed rocks in the study area. This formation is characterized by alternating tuff, pumice, tuff, and tuffaceous claystone. It is of Tertiary age, as Oligocene-Miocene. The Lower-Middle Miocene-dated Nglanggran Formation (Tmn) overlies the southern mountains' Semilir Formation (Tmse). This formation is made of an unlayered conglomerate. The Wonosari Formation (Tmwl) is located in the south half of the hills and is made up of reef limestone and layered limestone with clay. This rock formation dates from the Upper Miocene to the Pliocene. The Sentolo Formation (Tmps) is located in the western half of the research area. It comprises limestone and tuffaceous sandstone that dates from the Upper Miocene to Pliocene. The Tertiary-aged rock formation is covered by the Young Volcanic Deposits of Mount Merapi (Qmi) and the Quaternary-aged Alluvial Deposits (Qa). The Young Volcanic Deposits of Mount Merapi (Qmi), Quaternary-aged (Pleistocene – Holocene), are spread across the plains between the Bedog River and the Opak River.

The regional geology of Java can be classified into three major directions: the Meratus Pattern, which runs southwest-northeast, the Java Pattern, which runs west-east, and the Sunda Pattern, which runs northwest-southeast. The Opak River, which flows through Bantul Regency, is a strike-slip fault that runs southwest-northeast from its mouth to Prambanan. Several geoscience specialists believe that the earthquake in the D.I. Yogyakarta region was partially caused by the Opak Fault [11].

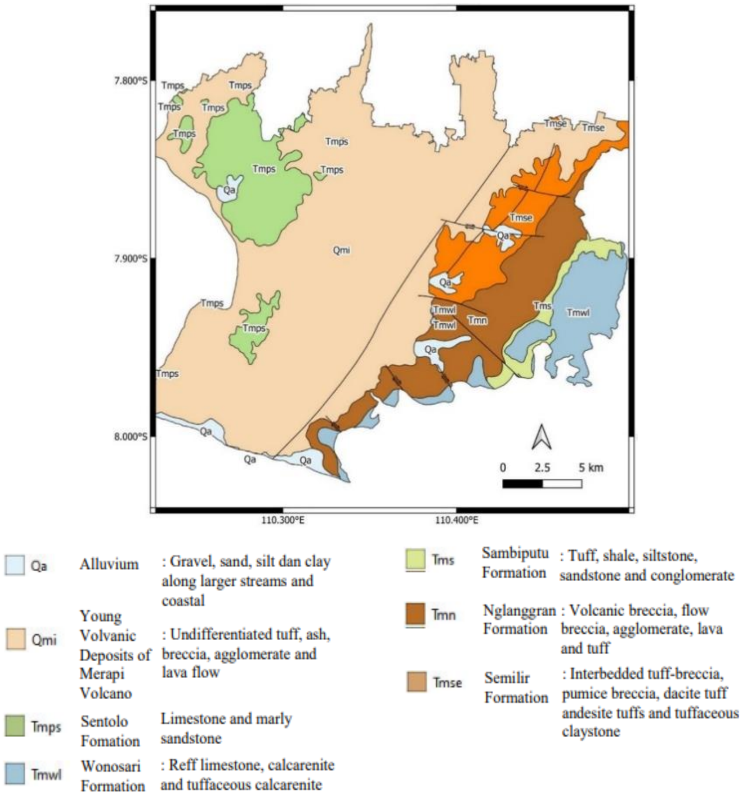

Figure 1. Bantul's surface lithology is based on the Yogyakarta geology sheet maps (1408-2 and 1407-5), Java, scale 1:100,000 [12]

II. Methods

The method used in creating the liquefaction hazard potential map is carried out in several stages, namely data collection, ranking, and weighting, using the Analytical Hierarchy Process (AHP) method. The Analytical Hierarchy Process (AHP) method is used to formulate the weights and rankings of each parameter, which are calculated and implemented in the Geographic Information System (SIG) (Figure. 2).

The Analytical Hierarchy Process (AHP) is a prominent hazard modelling tool that may be used to analyse complex characteristics and make quantitative decisions. This method creates a parameter hierarchy and compares pairs in a matrix to ensure each parameter element has a constant weight ratio [16]. The Analytical Hierarchy Process (AHP) is calculated in multiple steps, which include:

a. In this study, five parameters are used to create a pairwise comparison matrix, with the value of each parameter determined.
b. Parameters are normalised by dividing their values by the entire amount in each column, and the priority weight is calculated by adding and averaging each parameter per row.
c. Following the weights' acquisition, the consistency ratio value must be determined to determine whether the weights are still within logical preferences in general. The research assumes a consistency ratio 0.09, indicating good and acceptable data (CR < 10%).
d. Giving each class a score on each map determines scoring. The highest score implies that the class is most influential in causing liquefaction. The lowest score means that the class has the smallest influence on liquefaction.

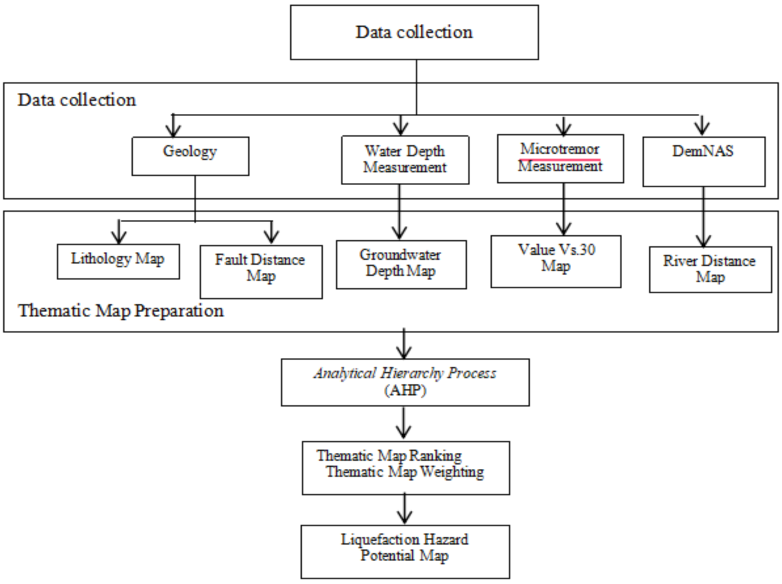

Figure 2. The flow of the research methodology

A. Data acquisition

The possible liquefaction hazard in Bantul Regency is being mapped using various spatial data, including groundwater depth, fault distance, seismic wave velocity Vs.30, and geological data. The information gathered is in many formats and originates from various sources. The spatial data is then integrated into ArcGIS using a geodatabase format. The weighting values are calculated based on the scale [14], which has established standard values in the calculation using the Analytical Hierarchy Process (AHP) (Table 1).

Table 1. Description of the value range used in the pairwise comparisons of AHP [14]

Value	Description
1	Equal significance
3	Moderate significance
5	Strong significance
7	Dominant significancet
9	Extreme significance.
2,4,6,8	Intermediate significances
1/3, 1/5, 1/7, 1/9 and 1/2, 1/4, 1/6, 1/8	Inverse significances

A geodatabase stores geological spatial data, groundwater depth, fault distance, river distance, and seismic wave velocity Vs.30 in vector and raster forms. The Analytical Hierarchy Process (AHP) method determines ranking and weighting. To determine the weight of each component, the appropriate values were selected from Table 1, and the weights for these five components were obtained in Table 2.

Table 2. Pairwise comparison matrix of the main criteria concerning the Goal

Comparison					
Parameter	groundwater depth	River distance	Fault distance	rock unit	rock unit
groundwater depth	1.000	2.000	3.000	5.000	7.000
River distance	0.500	1.000	2.000	3.000	6.000
Fault distance	0.333	0.500	1.000	3.000	5.000
rock unit	0.200	0.333	0.333	1.000	3.000
Value VS 30	0.143	0.167	0.200	0.333	1.000
Total	2.176	4.000	6.533	12.333	22.000

Normalization								
Parameter	groundwater depth	River distance	Fault distance	rock unit	rock unit	Vector Priority	Weight	Eigen Value
groundwater depth	0.460	0.500	0.459	0.405	0.318	2.142	0.428	0.932
River distance	0.230	0.250	0.306	0.243	0.273	1.302	0.260	1.041
Fault distance	0.153	0.125	0.153	0.243	0.227	0.902	0.180	1.178
rock unit	0.092	0.083	0.051	0.081	0.136	0.444	0.089	1.094
Value VS 30	0.066	0.042	0.031	0.027	0.045	0.210	0.042	0.926
Total	1.000	1.000	1.000	1.000	1.000	5.000	1.000	5.172

Consintensi Index (CI)	0.043
Ratio Index (RI)	1.120
Consintensi Ratio (CR)	0.038
CR Description	Konsisten

The next step using the Analytical Hierarchy Process (AHP) method is to calculate the weight of each category of the parameters used to create the liquefaction hazard potential map (Table 3).

Table 3. Weight Values for Each Factor Class and Entire Factors

groundwater depth

Parameter	(1)	(2)	(3)	(4)	(5)	(6)	Weight
0 - 2 m	1.000	2.000	3.000	4.000	5.000	6.000	0.379
2 - 4 m	0.500	1.000	2.000	3.000	4.000	5.000	0.249
4 - 6 m	0.333	0.500	1.000	2.000	3.000	4.000	0.160
6 - 8 m	0.250	0.333	0.500	1.000	2.000	3.000	0.102
8 - 10 m	0.200	0.250	0.333	0.500	1.000	2.000	0.065
>10 m	0.167	0.200	0.250	0.333	0.500	1.000	0.043

River distance

Parameter	(1)	(2)	(3)	(4)	(5)	Weight
0 - 1.5 km	1.000	3.000	5.000	6.000	8.000	0.502
>1.5 - 4.4 km	0.333	1.000	2.000	4.000	6.000	0.232
>4.4 - 7.2 km	0.200	0.500	1.000	3.000	5.000	0.151
>7.2 - 10 km	0.167	0.250	0.333	1.000	3.000	0.076
>10 Km	0.125	0.167	0.200	0.333	1.000	0.039

Fault distance

Parameter	(1)	(2)	(3)	Weight
Fault Zone (100 meters)	1.00	3.00	8.00	0.66
Near the fault zone (>100 - 1000 meters)	0.33	1.00	5.00	0.27
Deep Fault Zone (>1000 meters)	0.13	0.20	1.00	0.07

rock unit

Parameter	(1)	(2)	(3)	(4)	Weight
Sedimentary and alluvial units	1.000	2.000	3.000	5.000	0.471
Clastic sedimentary rock	0.500	1.000	2.000	4.000	0.284
Limestone	0.333	0.500	1.000	3.000	0.171
Volcanic rock	0.200	0.250	0.333	1.000	0.074

Value VS 30

Parameter	(1)	(2)	(3)	(4)	Weight
Medium soil (175 - 350)	1.00	3.00	7.00	9.00	0.60
Hard Soil (>350 - 750)	0.33	1.00	2.00	7.00	0.24
Rock (>750 - 1500)	0.14	0.50	1.00	3.00	0.11
Hard Rock (> 1500)	0.11	0.14	0.33	1.00	0.05

III. Results and Discussion

The Analytical Hierarchy Process (AHP) method was used to rank and weight the data based on the collected information. A related GIS was used for spatial analysis to determine the potential for liquefaction danger. The study performed on that parameter is.

A. Analysis of the physical characteristics of rocks

The geological conditions of the research area according [12] (Figure 3) consist of Rock Units and Formations from youngest to oldest as follows: Alluvial Unit (Qa), Young Volcanic Deposits of Mount Merapi (Qmi), Sentolo Formation (Tmps), Wonosari Formation (Tmwl), Nglanggran Formation (Tmn), and Semilir Formation. (Tmse). The Quaternary Alluvial Deposits (Qa) and the Young Volcanic Deposits of Mount Merapi (Qmi) cover the Tertiary rock formations. The Quaternary (Pleistocene–Holocene) Young Volcanic Deposits of Mount Merapi (Qmi) are dispersed throughout the lowlands between the Bedog and

Opak rivers. Typically, these rocks are made of loose, liquefiable elements like silt and sand. The youngest rocks are found in the Opak River deposits of Holocene Alluvial Deposits (Qa), which are composed of sand, silt, clay, and fine to medium sand that forms sand dunes along the shore. Areas with high liquefaction vulnerability include regions composed of residual soils consisting of non-cohesive soils from the Young Volcanic Deposits of Mount Merapi (Qmi) of Quaternary age, as well as transported soils in the form of Alluvial Deposits composed of sand, silt, and clay in floodplains and sand dunes along the coast.

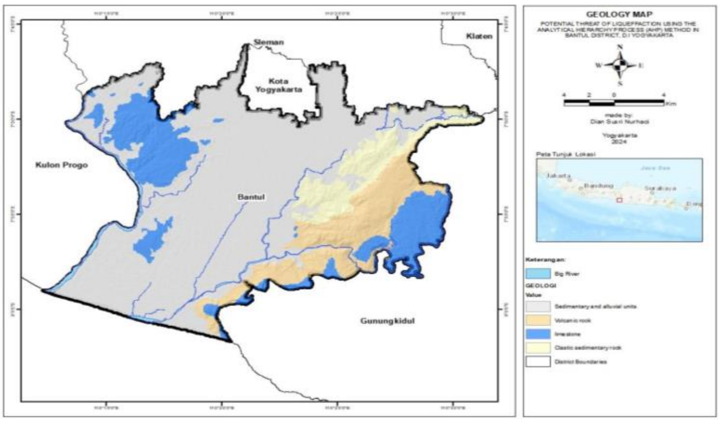

Figure. 3 Geological map of Bantul Regency [12]

B. Analysis of the depth of groundwater

The average depth of the groundwater table in Bantul Regency is less than five meters. When an earthquake happens, the shallow groundwater table is impacted and rises more easily to the surface. Quaternary rock formations are typically poorly compacted, resulting in low strength during seismic activity. The groundwater table in the research area is classified into four categories based on [5] modification for groundwater tables at 0 - 2 meters, >2 - 4 meters, >4 - 6 meters, >6 - 8 meters, >8 - 10 meters, and >10 meters (Figure 4). This limit is used to identify liquefaction since the deeper the groundwater level, the less likely liquefaction will occur. From that border, it can be determined that the intermediate region between the Bedog and Opak rivers has a shallow groundwater table. There are indications of liquefaction, and the groundwater table is less than nine meters deep. There were no symptoms of liquefaction in steep and mountainous areas with deep groundwater tables. Aside from lithology, hydrogeological characteristics are significant because liquefaction can occur in water-saturated soil. Therefore, the position of the groundwater table becomes a determining factor in the occurrence of liquefaction. According to these hydrogeological data, the high liquefaction potential zone is found in the middle section of the Bedog and Opak rivers.

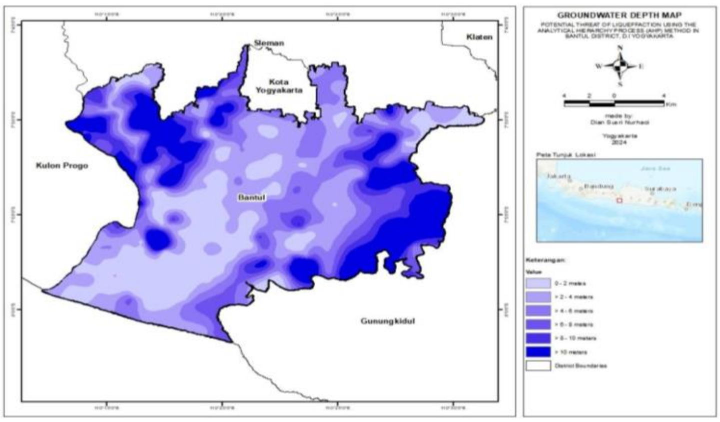

Figure 4. Bantul Regency's Groundwater Depth Map

C. Analysis of Fault Distances

An important factor to study is the seismic aspect. Earthquakes will cause vibrations, where vibrations are the main requirement for liquefaction to occur. The most common source of vibration is the vibration caused by earthquakes. The characteristics of earthquake movements, such as acceleration and the duration of shaking, greatly determine the shear strain that will push the soil sediment particles. The geological structure reflects the extent to which an area is influenced by tectonic activity. The more complex the geological structure that develops in an area, the more it indicates that it tends to be unstable. For the study of this liquefaction potential, the distance to the fault zone is used as a reference for regional stability. Based on the identification of faults in the study location, it is known that the closer to the fault, the higher the risk of liquefaction. The classification of weighting is based on [4]. Based on this study, a fault distance of < 1 km is high risk, a fault distance between 1 km - 5 km is medium risk, and a fault distance of ≥ 5 km is low risk (Figure 5).

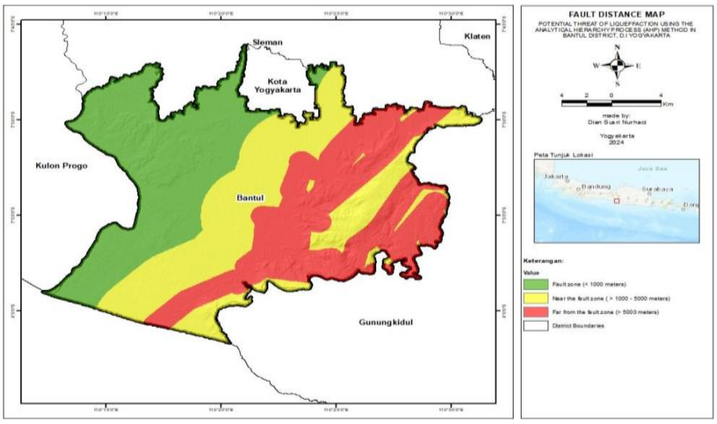

Figure 5. Detailed geomorphological and structural mapping of Quaternary deposits and paleoseismic features at a scale of 1:100,000, combining field data with remote sensing observations based on 8 m resolution DEMNAS and ~10 cm resolution DEM from unmanned aerial vehicle photogrammetry to identify active features in Yogyakarta province [10]

D. Distance Analysis of Rivers

The hydrogeological parameter plays an important role alongside geomorphology and lithology because liquefaction can occur in water-saturated soil, making the groundwater level a determining factor for liquefaction occurrence. The groundwater level is influenced by the distance to the river, with the closest distance to the river being more vulnerable and the high liquefaction potential zone in the middle section between the Bedog River and the Opak River. The river distance is the horizontal distance between a given location and the nearest riverside. The river distance in the research region is classified into four categories based on the modification by [21] 0-1500 meters, >1500-4400 meters, >4400-7200 meters, >7200-10000 meters, and >10000 meters (Figure. 6).

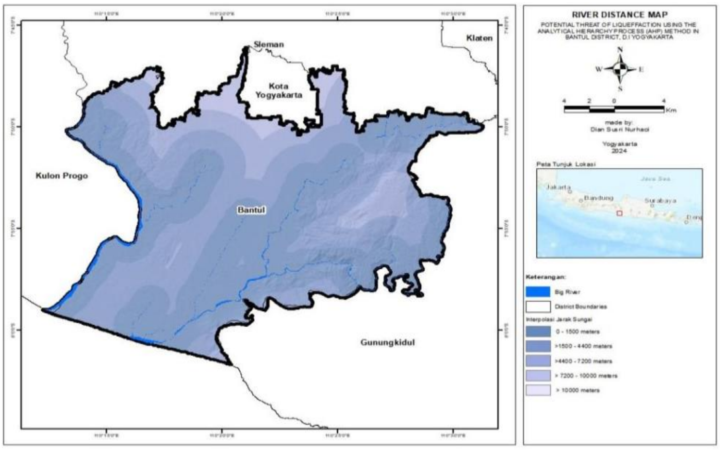

Figure 6. Map of River Distance in Bantul Regency

E. Seismic Wave Analysis Vs.30

The seismic wave analysis Vs30 parameters are based on the impact of earthquake influence. The amplification of seismic waves is only determined by the rock layers up to a depth of 30 meters [19]. In hard rocks, seismic waves travel faster than in soft rocks. The classification of soil types to earthquake risk can be determined based on the shear wave velocity from SNI, 2019, which states that Vs30 ≤ 350 m/s is high risk, Vs30 between 350 m/s and 750 m/s is medium risk, and Vs30 ≥ 750 m/s is low risk. (Figure 7).

This study's Vs30 values range from 175 m/s to 1046 m/s. The value indicates that Bantul Regency falls into the high-risk category for earthquake damage. High-risk classification is caused by the rock having a low shear wave velocity, indicating that the rock is soft [9]. The softer the rock, the higher the risk of earthquakes and liquefaction.

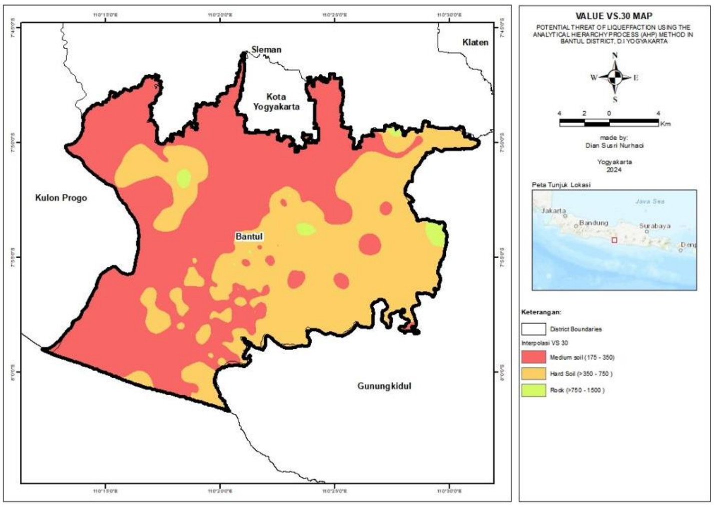

Figure 7. Bantul Regency Seismic Wave Map Vs.30

F. The potential for liquefaction

The liquefaction potential is created by combining six parameters: rock unit, groundwater level, fault distance, river distance, and Seismic Wave Analysis Vs.30. Based on the research results using the Analytical Hierarchy Process (AHP) method, this method is used to determine the class and weight of parameters so that all variables obtained through field observations can be assessed and classified into the used classes. In this study, the highest and lowest values in weighting were produced. The class values for classifying the existing data are divided into three class divisions to determine the potential liquefaction hazard in Bantul Regency, which includes high, medium, and low classes.

Regions with high potential generally consist of young volcanic deposits with a shallow groundwater table, close to rivers, and a Vs.30 value of 175-350. Regions with moderate potential consist of young volcanic deposits and sedimentary rocks, with a moderate groundwater table, Seismic Wave Analysis Vs30 value of 350-750, and are far from rivers. Regions with low potential consist of limestone and volcanic rocks, with a high groundwater table, Seismic Wave Analysis Vs.30 of 750-1500 (Figure 8).

G. High liquefaction hazard potential

High liquefaction hazard potential in the southern and central parts of Bantul Regency. The pattern formed in the high potential class is due to the groundwater depth factor of around 2 meters and geological conditions with alluvial rock units composed of gravel, sand, silt, and clay. The deposits of the Merapi Muda volcano are composed of tuff, ash, breccia, agglomerate, and inseparable lava flows. Both have loose structures and weak particle bonds, making them easily shaken during an earthquake. The factor of proximity to the fault line that runs from the southwest to the northeast, where the area around the fault is an active zone, and the proximity of the fault line to the Opak River, which relatively contains more water.

 DOI : https://doi.org/10.33579/krvtk.v9i2.5409

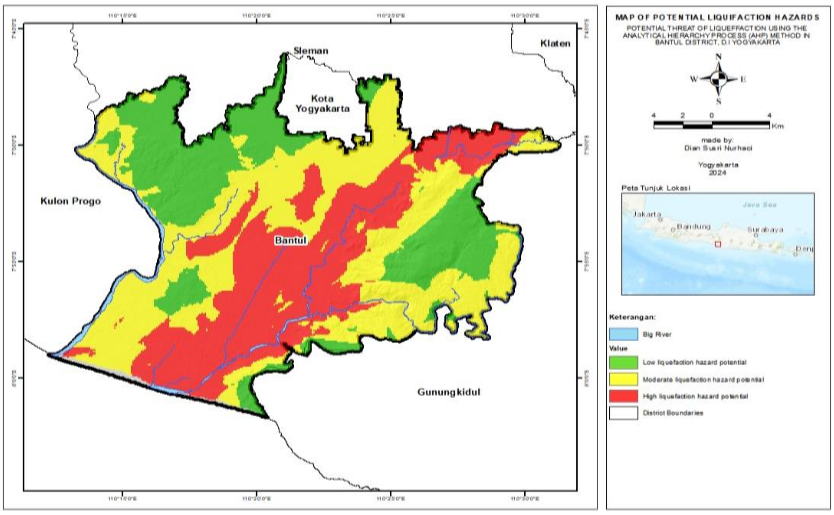

Figure 8. Liquefaction hazard potential map in Bantul Regency, D.I. Yogyakarta Province using the Analytical Hierarchy Process (AHP) method

H. Moderate liquefaction hazard potential

Moderate liquefaction hazard potential in the western and northern parts of Bantul Regency. The pattern formed in the medium potential class is due to the groundwater depth factor ranging > 6 meters and geological conditions with sedimentary rock units composed of tuff breccia, pumice breccia, andesite tuff, and tuff claystone. The deposits of the Merapi Muda volcano are composed of tuff, ash, breccia, agglomerate, and inseparable lava flows. The distance factor from the fault line is more than 1000 - 5000 meters away and has a Seismic Wave Analysis Vs.30 value between 350 to 750 m/s.

I. Low liquefaction hazard potential

The potential danger of liquefaction is low in the western part of Bantul Regency. The pattern formed in the low potential class is due to the factor of groundwater depth ranging > 8 meters and geological conditions with limestone units from the Wonosari formation consisting of reef limestone, calcarenite, and tuff calcarenite, and limestone from the Sentolo formation consisting of limestone and marly sandstone, the lower part of which consists of conglomerate covered by marl and tuff with glass tuff inclusions. The distance factor from the fault line is more than 1000 - 5000 meters away and has a Seismic Wave Analysis Vs.30 value between 350 to 1500 m/s.

J. Validation of the Liquefaction Hazard Map

Based on the validation of liquefaction events during the earthquake on May 27, 2006, which occurred in the Yogyakarta region, resulting in sand eruptions in several places, including Bantul Regency, both maps show a similar distribution of liquefaction potential. In both maps, the Bantul Regency, which has liquefaction potential, is located in the central part of the Bantul Regency, where the groundwater table is shallow, ranging from 2 to 4 meters, and is relatively close to the river. The rock unit is located within the alluvial unit, and the Young Volcanic Deposits of Mount Merapi are near the Opak Fault at 1000 meters.

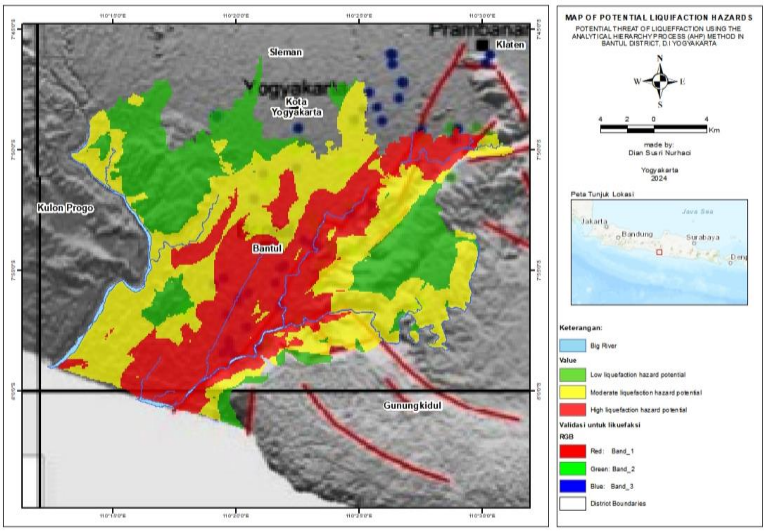

Figure 9. During the Yogyakarta earthquake in May 2006, the liquefaction occurrence map and the liquefaction potential hazard map were superimposed [5] Bantul Regency

IV. CONCLUSION

This study's results have mapped areas potentially at risk of liquefaction hazards based on the Analytical Hierarchy Process (AHP) method in Bantul Regency, Special Region of Yogyakarta. Generally, the potential hazards in the area predominantly fall into the moderate risk category, followed by the high-risk category, then the low-risk category. However, the high-risk category is not dominant. High-risk areas are in Piyungan District, Pleret District, Jetis District, a small part of Imogiri District, Pundong District, Kretek Sanden District, and Bantul District. Low-risk areas are only found in Sedayu District, Pajagan District, Kasihan District, and others with moderate potential. Efforts to minimize the risk of liquefaction hazards can be carried out by avoiding high-risk areas, mitigating education, being prepared, and using early warning instruments. For long-term planning, spatial and regional planning based on more detailed disaster risk analysis is necessary.

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