Exposure and loss assessment of soil liquefaction in coastal area of Kulon Progo, Indonesia

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Abstract. Soil Liquefaction is a phenomenon of loss of strength of the granural soil layers due to increased pore water stress caused by earthquake shocks. Soil liquefaction can cause material and life damage if occurs in the developed area. Kulon Progo Regency based on the Atlas of Liquefaction Susceptibility Zones in 2019, has high susceptibility zones, which has the potential for flow liquefaction, lateral spreading, vertical displacement, and sand boil. This study aims to assess the exposure and loss index in liquefaction hazard zone based on the characteristics of land use and social demographic. The exposure index is obtained from overlaying between susceptibility map and liquefaction exposure variables, when the loss assessment is done by simulating the losses in several earthquake moment magnitude scenarios. Study results show that high exposure surrounding the residential zone in the south of the Wates Urban Area and the construction location of the Yogyakarta International Airport. There are settlement areas potentially affected by lateral spreading in Glagah, Karangwuni, Banaran, and Karangsewu Villages. While the results of the loss assessment show that transport infrastructure and residential buildings are the most affected objects when liquefaction phenomena occur due to the earthquake. Managing the expansion of settlement area through zoning regulation and technical engineering approach is needed to reduce losses due to future liquefaction phenomenon.

1 Introduction

The Kulon Progo coastal area has been the focus of various researches for years on the topic of disaster, especially earthquake and tsunami disasters. However there are other disaster threats that need special attention in the development of the coastal region of Kulon Progo Regency, namely soil liquefaction due to the earthquake.

Liquefaction is the phenomenon of loss of soil strength due to an increase in pore tension caused by dynamic loads from an earthquake. Liquefaction can occur if the maximum surface acceleration reaches >0.1 g with earthquake strength >5 on the Ritcher Scale or >VII on the Mercali Scale [1].

Liquefaction generally occurs in granular or coarse-grained soils and has very little cohesion value. Characteristics include gravel and dominant sand with little or no clay content [2].

Based on the Atlas of the Indonesian Soil Liquefaction Susceptibility Zone, the coastal area of Kulon Progo Regency is described as being dominant in a high liquefaction susceptibility zone, which has the potential to cause flow liquefaction, lateral displacement, lateral displacement, vertical displacement, and sand boil) [3].

Liquefaction were recorded as having occurred when a large magnitude 6.3 earthquake shook Yogyakarta and surrounding provinces on May 27, 2006, which damaged building structures and identified liquefaction symptoms including sandblows, lateral shifts and land subsidence [4]. This needs to be watched out for in the future considering that the geological structure of the Kulon Progo coastal area is largely a uniformly graded sand layer, as well as very high seismic activity conditions because it is close to a subduction zone and has many active faults on land.

Liquefaction mitigation activities are urgently needed to reduce the risk in vulnerable areas, including those that can be done through spatial planning with zoning regulations and strict building requirements with technical engineering approach [5]. To develop appropriate mitigation measures, projected impacts of disasters are needed.

This study aims to assess the level of exposure and losses in each liquefaction susceptibility zone around the Yogyakarta International Airport development site which is part of the coastal areas of Temon Subdistrict, Wates Subdistrict, Panjatan Subdistrict, and Galur Subdistrict, in Kulon Progo Regency. The location of the construction of the new airport is partly in the high liquefaction susceptibility zone in Temon Subdistrict based on maps released by the Geological Agency. The results of this study are expected to be a simulation of the impact of losses due to faction if it occurs in the future.

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2 Method

Assessment of exposure and losses due to liquefaction requires phases: updating land use maps, identifying demographic characteristics, selecting damage scenarios, exposure index analysis, and loss index analysis. The liquefaction susceptibility zone data on the scale in question was obtained by updating the liquefaction susceptibility zone map obtained from the Indonesia Liquefaction Susceptibility Atlas in 2019. Existing land use data were obtained from *Rupa Bumi Indonesia* maps of Kulon Progo Regency which was updated based on field observations.

2.1 Exposure Index Assessment

Exposure index is an estimate of the negative impacts that can occur due to soil liquefaction which are described in index value. The greater the Exposure index value means that a location is very vulnerable to experiencing a large negative impact if a liquefaction phenomenon.

In this study using risk elements on a medium scale to identify the level of Exposure. used land use and population density variables to produce exposure indices [6]. Population density was identified in the village unit, based on data from the Subdistrict document in Figures 2019. The exposure index map was generated by combining the values of the results of the weighting of the two variables.

Table 1. Liquefaction Exposure Variables

Variable	Parameter	Weight
Land Use	Built-Up Area	0.5
	Wetland Agriculture	0.4
	Dry Land Agriculture	0.3
	Other Vegetation	0.2
	Water Body	0.1
Population Density (People/Ha)	> 3500	0.5
	2500-3500	0.4
	1500-2500	0.3
	500-1500	0.2
	< 500	0.1

Source: [7]

2.2 Loss Index Assessment

Slightly different from the exposure index, the loss index only evaluates material that can be measured in units of currency. The compensation value from the estimated damage occurred in each zone of land liquefaction exposure is based on the Disaster Loss Assessment calculation. Disaster loss assessment is a methodology for estimating impacts and losses from disasters based on economic calculations and individual needs as a basis for considering post-disaster reconstruction needs [8].

2.3 Exposure Scenarios

The selection of weights in the calculation of a loss index is based on the damage level scenarios and will produce the damage level curves [8]. In the context of soil liquefaction, the level of damage refers to the strength of earthquake shocks which are the main source of soil liquefaction.

Table 2. Liquefaction Loss Assessment Variables

Category	Loss Value (Rp.000,000)	Weight (%)		
		High	Medium	Low
Permanent Settlement	1.8/m^2 + 5%	70	40	10
Primary and Seconday Road	1000/Km^2	100	50	10
Tertiary Road	500/Km^2	100	50	10
Primary Infrastructure	at development cost	100	50	10
Agriculture	22/Ha	100	50	10
Government Office	4122/Ha	100	50	10
Commercial, Industry, and Warehouse	7093/Ha	100	50	10

Source: [9]–[11]

The stregth of an earthquake shaking is described in units of moment magnitude (M_w). Soil liquefaction can occur starting on an earthquake magnitude scale of 4.5 Mw in swampy areas or river borders and 5.0 Mw at suitable locations for residential areas, with the condition that peak acceleration in bedrock > 1.5 g [12]. While in the zone of moderate liquefaction susceptibility, it can experience an impact starting in an earthquake with a magnitude moment of 6 M_w. So that the scenario of weighting economic losses can be prepared which is shown through the following table.

Table 3. Weighting Scenarios of Economic Losses

Category	Weight (%)			
	Lateral Spread	High	Medium	Low
1st Scenario: Earthquake of 4.5 M_w				
Settlement	10	0	0	0
Other Land Use	10	0	0	0
2nd Scenario: Earthquake of 5.0 M_w				
Settlement	40	0	0	0
Other Land Use	50	0	0	0
3rd Scenario: Earthquake of 6.0 M_w				
Settlement	70	40	10	0
Other Land Use	100	50	10	0
4th Scenario: Earthquake of 7.0 M_w				
Settlement	100	70	40	10
Other Land Use	100	100	50	10

Source: [9], [12], [13]

3 Result and Discussion

3.1 Study Area

Kulon Progo Regency is located in the Special Province of Yogyakarta, and is generally divided into mountainous and coastal areas. Geomorphologically, the Kulon Progo region consists mostly of alluvial plains and fluvial plains in the middle and east sides, fluvio marin plains in the south side, and has elongated denudational mountains on the west side consisting of andesite and limestone [14].

The coastal area of Kulon Progo Regency is dominated by sand-silt soil texture which can produce flow slides when the sediment shakes due to earthquake with a strength of> 4.5 Mw [15]. This type of dry sand and sand can be very dangerous when wet due to rising groundwater due to earthquake, because it has medium-high permeability.

Based on a map of soil liquefaction susceptibility zones, there is a high susceptibility zone in the Galur and Temon districts on the south side. Lateral zone can also be identified in the high liquefaction susceptibility zones. Lateral spreading potential is identified by radial buffers as far as 130 m from perennial stream or river in the high liquefaction zone [16], [17]. 775.74 Ha of area was identified as indicated as having potential lateral movement in the event of liquefaction (Figure 1). This area is spread over Temon District (68.76 Ha), Wates (39.24 Ha), and Galur (289.46 Ha) (Table 4). This region has similar characteristics, which have a rough soil texture, close to stream, have a shallow depth of groundwater tables, and also located in a high earthquake hazard zone.

Table 4. Distribution of Liquefaction Susceptibility Zones in Each District

District	Susceptibility Zones (Ha)			
	None	Medium	High	Lateral Spread Potential
Temon	499.81	2,374.29	751.58	68.76
Wates	282.82	2,369.31	430.49	39.24
Panjatan	563.65	2,629.86	1,222.98	7.38
Galur	0.00	2,096.32	767.73	289.64

3.2 Exposure Assessment

Exposure index is the results of overlay between population density and the existing land use. Population density is a quantitative variable that is commonly used in assessing exposure. Population density illustrates the distribution of population in sub-regional units that reflects the magnitude of the number of people who are potentially victims of disasters [18]. The value of population density is directly proportional to the level of liquefaction exposure. Population densities in the villages of Wates and Panjatan are the highest in the study area, as shown in Figure 2. Both are subdistrict capitals, and specifically for Wates is also the capital of Kulon Progo Regency. Wates function as a government center and commercial center in Kulon Progo makes it the most vulnerable to liquefaction in terms of social exposure.

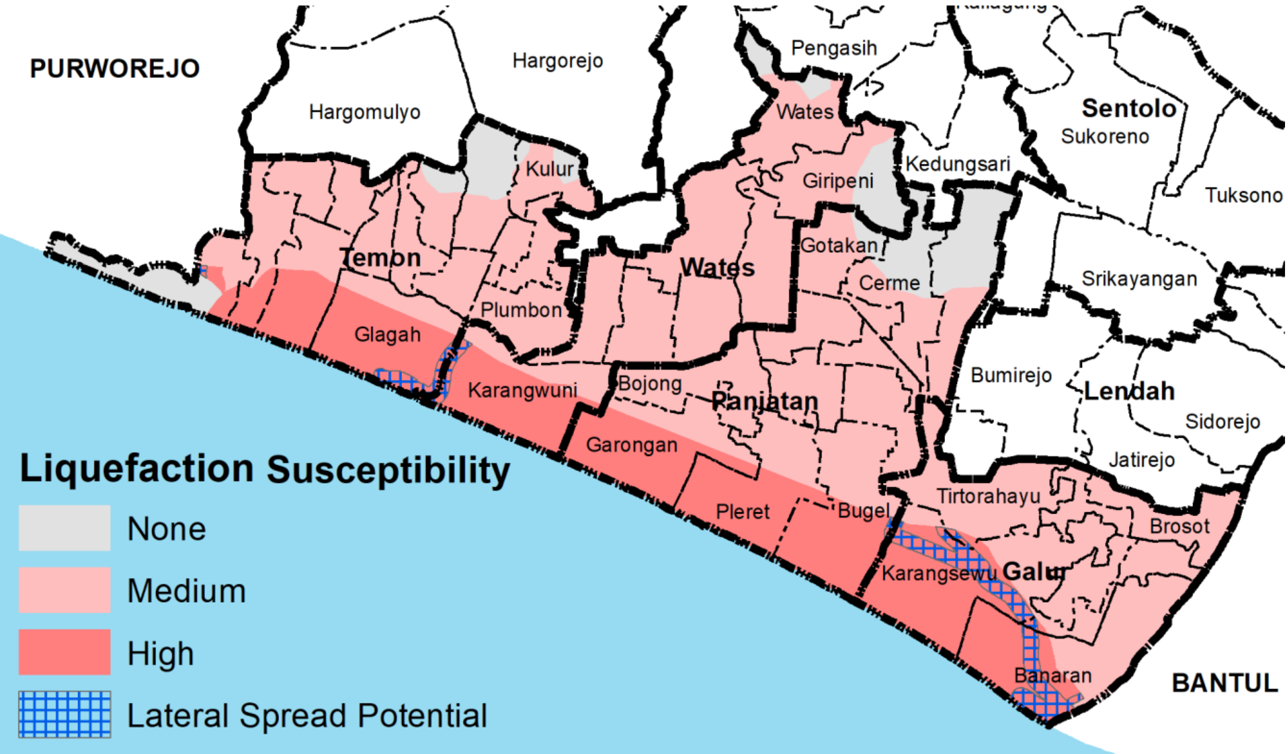


Fig. 1. Liquefaction Susceptibility Zone Map

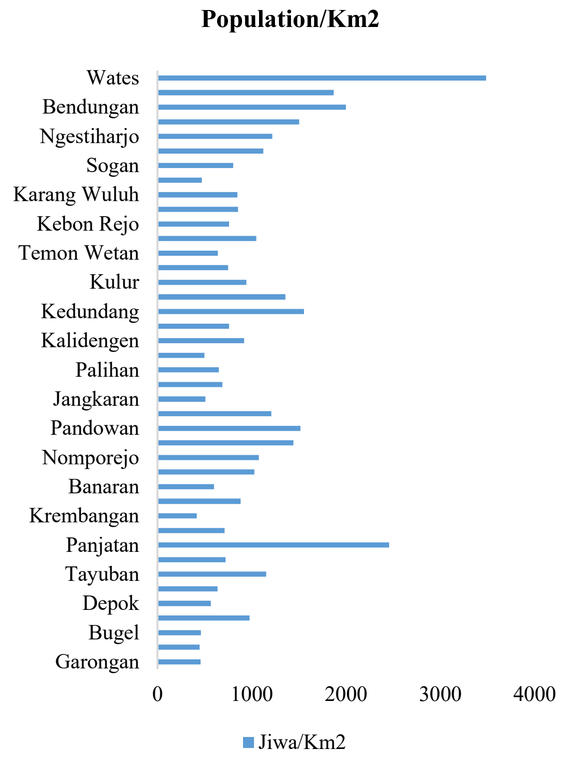
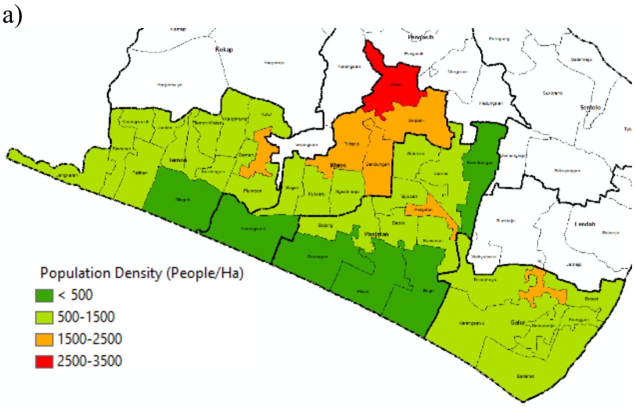


Fig. 2. Population Density in Each Village

The land use variable is used to describe socioeconomic activities in the Coastal Areas that are vulnerable to seismic disasters [7]. The weighting of each type of land use is sorted by its effect on the socio-economic activities of the population. Because agricultural activities are the main economic activity in this region, they get the highest weight after residential land use (Figure 3). The results of exposure index mapping based on population density and land use are presented through Figure 4.

As the result of overlaying process, High exposure zones are identified spread over settlement area in Temon and Galur district, including Yogyakarta International Airport & Aerotropolis. Land Value Capture approach in developing of this area will affect on the future exposure and risk. Through appropriate zoning regulation, the urban development should not to be directed to form high density in areas with high susceptibility and lateral spread potential

a)



b)

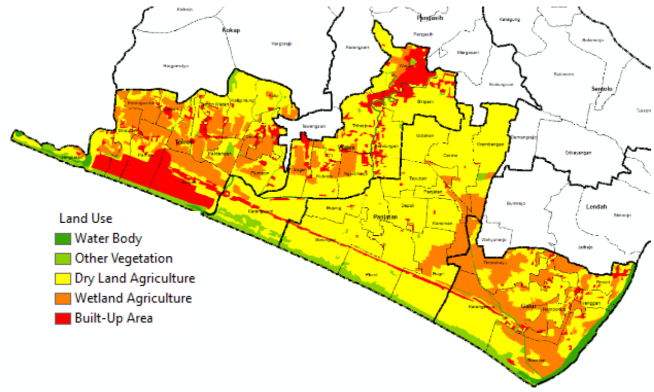


Fig. 3. Liquefaction Exposure Variable Maps:
a) Population Density; b) Land Use

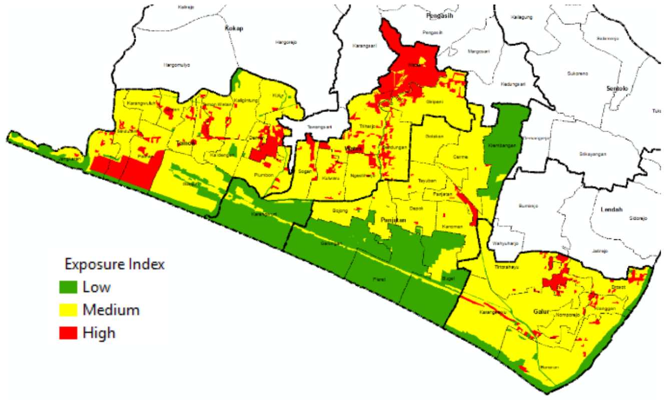


Fig. 4. Liquefaction Exposure Index Map

3.3 Loss Assessment

The loss index is identified through the elements of vulnerability that can be measured in units of currency, in this case the cost of rebuilding the objects that are vulnerable to soil liquefaction. The calculation of loss index is divided into 4 scenarios of earthquake moment magnitude which triggers the soil liquefaction phenomenon, on a scale between 4.5 Mw -> 7.0 Mw. The results are shown in Table 5 and Figure 5.

Table 5. Loss Calculation Result
Based on Earthquake Magnitude Moment Scenarios

Object	Loss Value (Rp.000.000)			
	4.5 M_w	5.0 M_w	6.0 M_w	7.0 M_w
Settlement	4,601	63,989	581,079	1,831,227
Education Facility	-	37	1,113	5,006
Health Facility	-	10	293	1,319
Transportation	-	610,000	3,050,242	6,101,210
Office	-	-	510	2,552
Commercial	-	-	1,402	7,011
Total	4,601	674,037	3,634,717	7,948,712

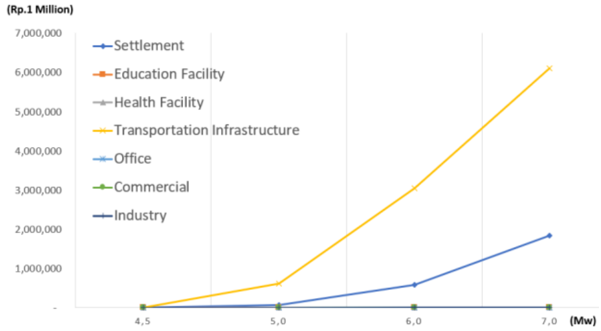


Fig. 5. Loss Calculation Result Based on Earthquake Magnitude Moment Scenarios

Estimates of losses due to soil liquefaction in 4 sub-districts within the Kulon Progo Coastal Area, range between Rp.4.6 billion - >Rp.7.9 trillion. Mostly dominated by losses due to damage to transportation infrastructures and residential buildings. Social infrastructure are estimated to be affected by damage on the earthquake magnitude scale >5.0 $M_{w,}$ even some, such as commercial and office buildings, have only been affected on a magnitude > 6.0.

There are 217 houses in the zone of lateral movement potential that should be relocated, and the existing zone can be designated as protected area in spatial plan. There are also 2037 residential buildings in the high liquefaction susceptibility zones. Technological engineering efforts are needed, such as strengthening soil structures and building construction improvements.

The study result show that transportation infrastructure could suffer damage on the earthquake magnitude scale >5.0 M_w with economic losses reaching Rp 610 billion – Rp 6.1 trillion, including the New Yogyakarta International Airport. The airport's construction site is located in sandy soil, with shallow groundwater depths of 0.40-19.50 m with a semi-stressed aquifer system [19], making it susceptible to liquefaction. however, in its development, protective measures have been taken to reduce disaster risk, such as dynamic compaction method in runway construction and rapid impulse compaction in the construction of terminals and other supporting facilities [20]. While other infrastructure, such as road networks, require appropriate mitigation measures or even readjustment in some segments, to ensure their function as part of the evacuation systems and logistics distribution systems during disaster emergency period.

Besides using high-cost modern method and equipment, strengthening soil structure also can be applied by a number of simple methods in residential zones, such as bamboo micropile, infiltration wells with piezometer pipes, and planting soil-binding plants such as bamboo or baobab [21].

4 Conclusion

Liquefaction is one of the phenomena to watch out for in the development of the coastal area of Kulon Progo Regency, in addition to the tsunami and earthquake disasters. High exposure in the urban areas of Wates and around the Yogyakarta airport's aerocity complex, indicates the importance of controlling urban expansion so that it does not have an impact on increasing future risks. In various earthquake shaking scenarios, the loss is very large in the use of residential land and transportation infrastructure. the results of this simulation are expected to be an illustration of the preparation of the capacity of the government and local communities in dealing with the liquefaction phenomenon on the future.

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