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RESEARCH ARTICLE

Soil Behavior and Liquefation Potential During Earthquake in Kulonprogo, Yogyakarta, Indonesia

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Abstract

Indonesia is a country that is prone to natural disasters such as earthquakes and landslides, especially in areas along the Pacific Ring of Fire. The region of Kulonprogo in Yogyakarta, has a unique geotechnical profile that poses particular challenges in assessing soil behavior under seismic events. This study investigates the liquefaction potential and dynamic soil behavior in Kulonprogo during an earthquake scenario, using a combination of Deterministic Seismic Hazard Analysis (DSHA) and Next Generation Attenuation (NGA) models. These approaches allow for precise evaluation of seismic hazards by analyzing ground motion predictions based on past events and site conditions. Using data from the 2006 Yogyakarta earthquake and the Pacific Earthquake Engineering Research (PEER) database, the model the soil response and assessing potential liquefaction are conduted. Kulonprogo's soil primarily consists of loose sands and silts, which are prone to liquefaction, especially under strong ground shaking. Key findings show significant variations in soil behavior, with peak ground acceleration values reaching approximately 0.1 g. The analysis indicates that maximum surface pressure decreases with depth, with values around 0.09 kPa at the surface, dropping to nearly 0 kPa at 30 meters. Maximum acceleration profiles show surface accelerations peaking at 2.2 g, highlighting the susceptibility of shallow soil layers to liquefaction. Relative displacement profiles indicate notable deformation, with displacements reaching about 0.03 m at the surface, decreasing significantly with depth. These results underscore the importance of understanding local geological conditions for accurate seismic hazard assessments and structural safety evaluations. The findings contribute to the development of targeted mitigation strategies and inform earthquake-resistant design practices, ultimately enhancing disaster resilience in Kulonprogo and similar seismically active regions in Indonesia.

Keywords: Soil Behavior, NGA Model, Earthquake, Peak Ground Acceleration, Liquefaction

1. Introduction

1.1 Background

Earthquakes pose a significant threat to infrastructure and communities, especially in seismically active regions with loose, saturated soils that are prone to liquefaction (Nath et al., 2018) (Green and Bommer, 2019; Lai, et al., 2021). In such areas, seismic waves can drastically alter soil properties, leading to severe ground deformations, foundation failures, and even building collapse (Roshan and Pal, 2023). Kulonprogo, located in the Yogyakarta region of Indonesia, is particularly susceptible to these risks due to its geological and tectonic setting within the "Ring of Fire," a major zone of active volcanoes and frequent seismic activity (De Priester, 2016). The 2006 Yogyakarta earthquake underscored this vulnerability, causing extensive damage and highlighting the critical need to understand soil behavior and liquefaction potential in the region (Enashai et al., 2007). Given the region's susceptibility to seismic hazards, research on soil response and liquefaction risk assessment is crucial to enhancing disaster resilience and informing infrastructure development in Yogyakarta.

Liquefaction occurs when loosely packed, water-saturated soils temporarily lose strength and behave like a liquid due to the sudden increase in pore water pressure from seismic shaking (Ishihara, 1993; Kuswandi et al., 2020; Aditama et al., 2021). This phenomenon is more likely in areas with sandy or silty soils, where ground vibrations disrupt the soil structure, leading to a reduction in effective stress and subsequent ground instability. The characteristics of liquefiable soils in research area varied geological layers that composed of volcanic, sedimentary, and alluvial deposits (Amalina et al, 2022). Those make it essential to evaluate how these soils will respond under different levels of ground shaking. Understanding this behavior not only informs risk assessments but also aids in designing foundations and structural systems that can withstand potential ground deformations during earthquakes.

To assess liquefaction potential and soil behavior during seismic events, this study applies Deterministic Seismic Hazard Analysis (DSHA) and Next Generation Attenuation (NGA) models (Razman, 2019). DSHA is a widely used method to quantify site-specific seismic hazards, as it considers historical earthquake events and tectonic characteristics to estimate potential ground motion (Ayele et al., 2021). The NGA model, on the other hand, incorporates empirical data to predict ground motion intensity based on known fault mechanisms, providing a realistic representation of ground shaking scenarios. In this study, data from the 2006 Yogyakarta earthquake, retrieved from the Pacific Earthquake Engineering Research (PEER) database, is used to calibrate these models, enhancing the accuracy of seismic hazard and liquefaction potential assessments in the research area. Integrating DSHA and NGA provides a comprehensive framework to evaluate earthquake-induced soil behavior and identify high-risk areas for liquefaction (Steward et al., 2016).

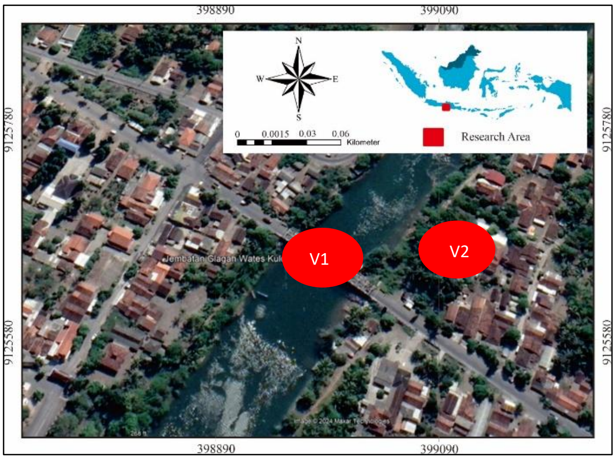

Fig. 1. Research Area

The objectives of this research are: first, to investigate the soil properties and liquefaction susceptibility in the research area as shown in Fig 1.; and second, to establish a reliable seismic hazard model that accounts for the historical earthquake data. By examining peak ground acceleration (PGA), shear wave velocity, and other critical parameters, this study identifies areas of heightened risk where liquefaction could threaten structures and infrastructure. The findings aim to contribute to earthquake-resistant design practices and land-use planning, which are particularly relevant in densely populated or strategically significant areas. Furthermore, this research provides valuable insights that can be used by engineers, urban planners, and policymakers to develop resilience strategies and inform future construction projects within Indonesia's seismically active zones.

This study seeks to enhance understanding of the dynamic interplay between soil behavior and seismic forces in the context of the Kulonprogo region's unique geological setting. Through a combined application of DSHA and NGA models, backed by empirical data from the 2006 earthquake, this research offers a detailed examination of liquefaction potential and soil response. This insight is critical for risk mitigation, informing not only the engineering field but also emergency preparedness efforts aimed at minimizing the potential impacts of future earthquakes in the Yogyakarta region and similar areas within Indonesia's Ring of Fire..

2. Regional Geology and Seismicity

The Kulon Progo Mountains, as described by Van Bemmelen (1949), are a large dome known as the "Oblong Dome," stretching from the northeast to the southwest. This dome structure has a flat peak called the "Jonggrangan Plateau," which is composed of coral limestone and marl, forming a karst topography in Jonggrangan Village. This area also has a number of old volcanoes, such as Mount Gajah, Mount Ijo, and Mount Menoreh, which show past volcanic activity that leaves lithologies in the form of andesite, basaltic, and dacite.

Kulonprogo stratigraphy consists of various formations, starting with the Nanggulan Formation which is Middle Eocene to Oligocene in age and is composed of sandstone, marl, and lignite. Then followed by the Old Andesite Formation which includes volcanic breccia and lava deposits, as well as the Jonggrangan Formation and Sentolo Formation which are Miocene in age. Meanwhile, alluvial deposits and sand clusters are spread along rivers and beaches. The regional structure shows radial faults around the dome foot that form a pattern extending parallel to the dome, while around Mount Menoreh there are synclinal and west-east faults that separate it from Mount Ijo (Syafri et al., 2013)

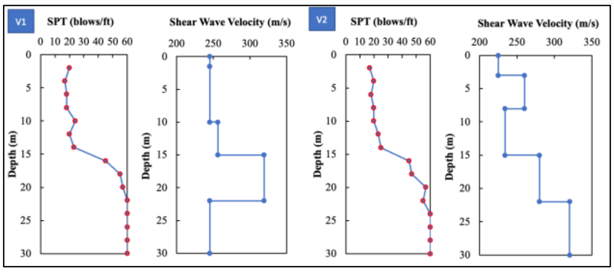

Fig 2. Results of N-SPT and Shear Wave Velocity calculation in the reasearh area

In Fig 2. illustrates the soil condition with distribution of shear wave velocity (Vs) with depth for two separate borehole locations (V1 and V2). The data reveals varying shear wave velocities with depth, indicating distinct layers of subsurface materials. In V1, Vs values range from approximately 250 m/s near the surface to below 200 m/s at depths beyond 20 meters, reflecting a transition from stiffer to less stiff layers. Conversely, V2 shows a gradual increase in Vs values from around 200 m/s at the surface to approximately 300 m/s at intermediate depths, before decreasing at deeper levels. These variations suggest heterogeneous soil conditions, with potential implications for seismic site response and foundation design considerations in the area.

The seismicity of Kulonprogo and its surroundings has recorded a number of large earthquakes, including those in 1867, 1943, and 2006, which are associated with the activity of the Opak Fault (as shown in Fig.3).

Fig 3. Yogyakarta Earthquake in 2006 (Hariadi, 2019)

Although the exact location of this fault is not yet fully known, its striking movement is estimated to cross the southwest to northeast. Based on the Indonesian Seismic Standard (SNI 1726: 2019), the Kulonprogo area has a maximum ground motion acceleration (PGA) value between 0.3 and 0.4g, indicating a potential moderate risk of ground shaking due to earthquakes.

3. Methods

This study's methodology for assessing soil behavior and liquefaction potential during earthquakes in Kulonprogo, Yogyakarta, utilizes deterministic seismic hazard analysis (DSHA), ground motion predictions, and soil dynamic analysis. The key steps are as follows:

3.1 Deterministic Seismic Hazard Analysis (DSHA)

The DSHA method begins by defining an earthquake scenario based on magnitude and epicenter distance relative to the site, fault modeling, and local soil conditions (Thentaus et al., 2003; Mualchin, 2011). In this case, the region's seismic history, including significant events like the Yogyakarta Earthquake in 2006, informs our selection of potential earthquake magnitudes (Griffin et al, 2019). Distance from the fault line to the site is carefully measured, while fault parameters are characterized for accurate fault modeling. Ground motion intensity and Ground Motion Prediction Equations (GMPEs) are selected based on local site conditions, to accurately capture the seismic wave propagation through varying geological layers (Douglas and Edwards, 2016; Qodri et al., 2021; Qodri et al., 2022).

GMPEs are critical for estimating ground shaking intensity at the site. This study uses the NGA-West2 model by Abrahamson et al. (2014) to simulate realistic ground motion parameters, sourced from the Pacific Earthquake Engineering Research (PEER) database as shown in Fig.4 (Qodri et al., 2022). Using this model, ground motion inputs account for research area soil-specific attenuation and amplification characteristics, which are essential in estimating peak ground acceleration (PGA) and spectral response at different periods (Mondal and Kumar, 2023) (Somantri et al., 2023) (Mase et al 2023).

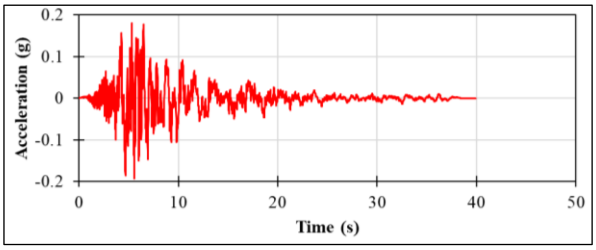

Fig 4. Yogyakarta Earthquake in 2006

Using this model, ground motion inputs account for research area soil-specific attenuation and amplification characteristics, which are essential in estimating peak ground acceleration (PGA) and spectral response at different periods (Mondal and Kumar, 2023; Somantri et al., 2023; Mase et al 2023).

3.2 Soil Behavior Analysis

The dynamic response of soils is analyzed in both frequency and time domains using DEEPSOIL Application (Hashash and Park, 2002). In the frequency domain, an equivalent linear approach is applied to approximate soil behavior (Poul and Zerva, 2018). Time domain analysis includes linear, equivalent linear, and nonlinear methods, allowing detailed assessment of soil response under seismic loading (Arsyan and Siyahi, 2006; Adampira et al., 2015). The soil's dynamic shear properties, including maximum shear modulus ($Gmax$) and shear wave velocity (Vs), are factored into the model (Hussien and Karray, 2015; Manan et al., 2023). Parameters such as unit weight, shear modulus ratio, and pore water pressure generation are carefully controlled, providing a comprehensive view of soil behavior under cyclic loading.

This step involves gathering soil property data, including soil layer thickness, unit weight, shear modulus ratio (G/Gmax), and elastic half-space conditions. Dynamic properties such as shear wave velocity (Vs = 1,100 m/s), unit weight (22 kN/m^2), and damping ratio (5%) are set to accurately represent the soil's mechanical behavior under seismic conditions (Phillips and Hashash, 2009). Different soil types are modeled using established parameters: for sandy soils, parameters are based on Seed and Idriss (1971), while clayey soils use Vucetic and Dobry (1991) ratios.

The ground motion input data, sourced from the PEER database, are selected from the NGA-West2 dataset to represent expected earthquake ground motion in the region (Ancheta et al., 2014). The use of NGA models for ground motion attenuation aids in refining earthquake motion characteristics to the soil types specific to Kulonprogo. This input is crucial for modeling the energy transmitted through soil layers during an earthquake.

The results of this seismic and soil response analysis include, Acceleration (g) vs. Time (sec): Tracks ground acceleration over time and nd PGA and Strain Profiles: Maps maximum PGA and strain values across soil depth, identifying zones of high liquefaction risk.

4. Results

The spectral matching approach is applied to simulate ground motion acceleration at points V1 and V2 based on the characteristics of the 2006 Yogyakarta earthquake. The red line in the figures represents the original acceleration time history recorded during the event, while the blue dashed line corresponds to the spectral-matched acceleration. For both locations, the spectral matching technique ensures compatibility between the target spectrum and the modified ground motion, maintaining the essential seismic characteristics. This process is particularly valuable for site-specific seismic design, where precise acceleration values are crucial for structural assessments.

The analysis highlights differences in ground motion at V1 and V2 due to varying subsurface conditions. The input spectral-matched acceleration results in a peak ground acceleration (PGA) of approximately 0.1 g at both sites as illustrated in Fig 5. Furthermore, Pic 6 presents the PGA profiles for two borehole locations, V1 and V2, at varying depths up to 30 meters. For V1, the PGA remains relatively constant at approximately 0.1 g from the surface down to about 20 meters, before slightly decreasing at greater depths. In contrast, V2 shows a peak ground acceleration of around 0.2 g at the surface, which then decreases gradually to about 0.1 g at depths of 20 meters and below. These values provide insight into the amplification factors influenced by silty sand properties and earthquake mechanisms in the area.

The Fig 7 provides detailed data on soil behavior and liquefaction potential during an earthquake in research area. Two sets of data, V1 and V2, display profiles of pressure (kPa), maximum acceleration (g), and relative displacement (m) as functions of depth (up to 30 meters).

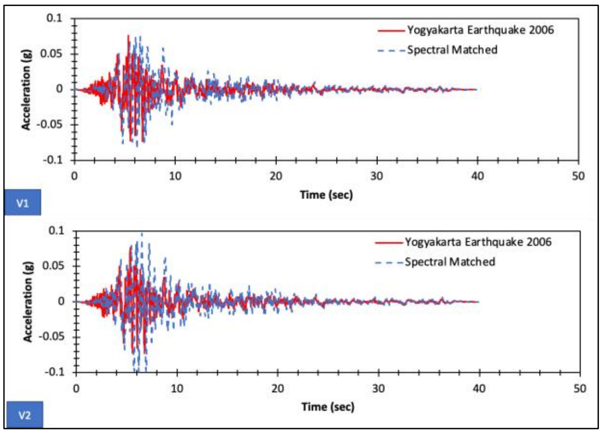

Fig 5. Response spectra in the research area during earthquake

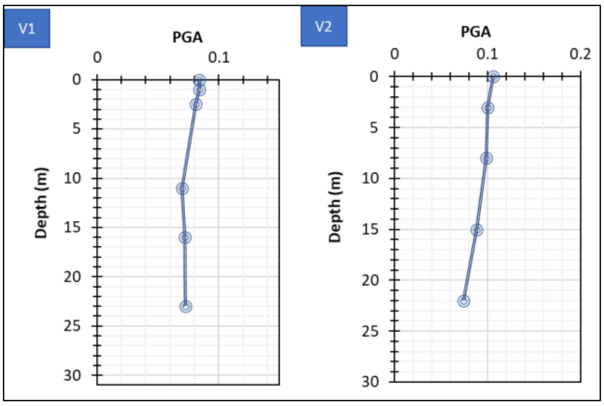

Fig 6. Peak ground accelerations (PGA) in the research aarea during earthquake

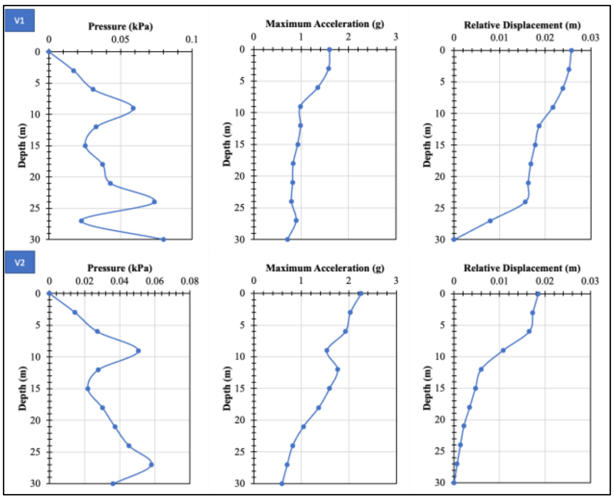

Fig 7. Soil behaviour in the research area during the earthquake

In the pressure profiles, the maximum surface pressure is approximately 0.09 kPa, decreasing with depth. For V1, pressure decreases to around 0.03 kPa at 10 meters, fluctuating between 0.01 and 0.05 kPa at depths of 15 to 25 meters, before reaching nearly 0 kPa at 30 meters. V2 shows a similar trend, starting at about 0.09 kPa on the surface, dropping to 0.04 kPa at 10 meters, fluctuating between 0.02 and 0.04 kPa, and approaching 0 kPa near 30 meters. These fluctuations indicate the presence of different soil layers, which could influence liquefaction potential (Qodri, 2023).

The maximum acceleration profiles indicate significant surface acceleration, peaking at approximately 2.2 g for V1 and 2.1 g for V2. This decreases gradually to around 0.5 g at a depth of 20 meters and further drops to nearly 0.2 g at 30 meters. The high surface acceleration suggests that shallow soil layers are exposed to intense seismic forces, which could trigger liquefaction, while deeper layers experience reduced seismic impact.

The relative displacement profiles show notable deformation in the upper layers, reaching about 0.03 m at the surface for both V1 and V2. Displacement decreases to around 0.01 m at a depth of 10 meters and gradually drops to nearly 0 m at 30 meters. This indicates that the upper 10 meters of soil are most susceptible to deformation during an earthquake, enhancing liquefaction risk. These detailed measurements highlight the need for targeted mitigation strategies, such as soil compaction or deep foundation solutions, to protect infrastructure in Kulonprogo from seismic hazards. At shallow depths, the relative displacement is larger because the soil has a softer consistency, while at deeper depths, the relative displacement is small indicating a denser and more stable soil. Similar patterns are seen at both locations, although there are slight variations due to differences in soil characteristics at each point. This indicates that the soil response to dynamic or seismic loads is greater in shallow layers than in deeper layers (Elia and Rouainia, 2014).

5. Conclusions

The research conducted on soil behavior and liquefaction potential during earthquakes in Kulonprogo, Yogyakarta, highlights the critical need for understanding the region's unique geological and seismic characteristics. By employing Deterministic Seismic Hazard Analysis (DSHA) and Next Generation Attenuation (NGA) models, the study provides a comprehensive assessment of seismic hazards and soil response. The findings reveal significant variations in shear wave velocity and soil properties across different geological formations, which influence the region's susceptibility to liquefaction. The analysis of ground motion data, particularly from the 2006 Yogyakarta earthquake, underscores the importance of site-specific seismic design, as local soil conditions can significantly amplify seismic forces, increasing the risk of ground deformation and infrastructure damage.

The study's results emphasize the necessity for targeted mitigation strategies to enhance disaster resilience in Kulonprogo. The identification of high-risk areas for liquefaction, based on peak ground acceleration and soil displacement profiles, informs the development of earthquake-resistant design practices and land-use planning. By providing detailed insights into the dynamic interplay between soil behavior and seismic forces, this research aids engineers, urban planners, and policymakers in crafting effective resilience strategies. These efforts are crucial for minimizing the potential impacts of future earthquakes in the Yogyakarta region and similar seismically active zones in Indonesia

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