Liquefaction potential identification in the Central Sulawesi using gravity inversion model

D Fauzik¹, A Haris², A A Martha³ and A Riyanto²

¹Department of Physics, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia
²Geoscience Study Program, Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Indonesia, Depok 16424, Indonesia
³Meteorological, Climatological, and Geophysical Agency (BMKG), Jakarta 10610, Indonesia

Corresponding author’s email: aharis@sci.ui.ac.id

Abstract. Liquefaction is one of the effects following an earthquake, it is the soil strength loss due to the vibration of an earthquake. The earthquake which struck with a 7.7 magnitude on September 28th 2018 in Donggala and Palu, Sulawesi caused a series of disastrous events including a tsunami and aftershock liquefaction in Balaroa and Petobo, causing many casualties. The liquefaction can be investigated and possibly predicted by identifying and interpreting the subsurface structures. This paper identifies the geological structures in the subsurface using the gravity method. The study was carried out by 3D inversion modelling at locations 119.6–120.2 BT and 0.6–1.2 LS based on gravity data. The gravity data was gained from Global Gravity Model plus (GGMplus). The study from satellite and the Bouguer anomaly in the Central Sulawesi shows that it has gravity of -50 to 130 mGal. The 3D inversion model of the subsurface shows low density contrast around the areas of Palu, Balaroa, and Petobo with values of -0.055 to -0.05 gram/cm³ where these low density depths have been identified from 0–125 meters below the surface and even deeper to the southern part of the study area. This low density contrast is in accordance with the geological conditions of the Palu which is dominated by porous sediment layers which are capable of storing fluids that are the main factor in causing the liquefaction.

Keywords: Liquefaction, earthquake, tsunami, gravity, subsurface modelling

1. Introduction
On September 28th, 2018, Tsunami and liquefaction were occurred with magnitude of 7.7 in the Central Sulawesi, as shown in figure 1. Liquefaction is the soil strength loss due to the vibration of an earthquake [1]. Liquefaction occurs as the loose sandy soil has a good porosity as it is saturated with water. The liquefaction with the land cracking caused severe to total damage, while the land shifting caused minor damage [2]. Identification of landslide and liquefaction in a dense populated area needs more in-depth study to prevent any further victims and damage in the future. The subsurface structure of the Palu area and its surroundings can be assessed using the gravity method [3]. The gravity method is used as it has the ability to distinguish rock density from an anomalous source against the surrounding rock density [4]. This variability of density lead to the subsurface geological structures. Furthermore, the spectral density analysis is also used to determine shallow and deep discontinuities.
GGMplus provides a computerized gravitational field map for all regions on Earth within the 60° geographical latitudes and adjacent sea zones along the coastline [5]. In addition, the gravity data from satellites also provides accessible and valuable information for this paper.

2. Methodology
This study assessed the gravity data using a combination of GRACE (ITG2010), GOCE (TIM-4) and EGM2008 satellites. The detailed analysis was presented in figure 2. This data resulted in the Free Air Anomaly (FAA) and topographic which later would be used for Bouguer Anomaly analysis. The Bouguer Anomaly was then processed using the moving average method to get the residual anomaly. Finally, the 3D inversion was processed to create the subsurface model. This model was important to identify the areas with high potential of liquefaction in the Central Sulawesi.

3. Results and discussion
Quantitative interpretation in this study performed the 3D residual anomaly inversion modelling above the topography of the region. Modelling on topography create a subsurface density distribution model by displaying the surface topography, thus the model is closer to the actual density. Three study areas were analysed where they are densely populated which are called area 1, area 2 and area 3 as shown in figure 3. The scale bar showed the density where the blue–green to yellow–red indicating low and high density, respectively.

3.1. Area 1: Nearby Palu Bay
Figure 4 shows the model in the Area 1 nearby the Palu Bay. The green colour indicates that the rock has a low density and is located 1000 meter under the surface. The surrounding area has a higher density (orange colour). This phenomenon may cause landslide as the low density rock slips through a denser rock underneath. The rock density is relatively lower to the Northern part of the study area. The Palu – Koro fault system is deformed due to the low rock density.

Figure 1. The study location of Central Sulawesi is shown in the blue box.
The identified rock density contrast value ranges from -0.602 to 0.432 gram/cm³, where high density contrast is in the west of Palu Bay (0.3 gram/cm³) and low density rocks indicated in Palu Bay (ranging from 0.15 to 0.4 gram/cm³). In figure 5a, this density contrast seems to have a pattern where it is weaker to the North (Palu Bay). Figure 5b shows the homogenous rocks on both sides of the Palu Bay.
3.2. Area 2: Palu, Balora and Petobo

The Area 2 model is shown in figure 6 where the weak zone with low density starts from the surface (0 meter) to the 125 meter depth. The density decreases by the deeper depth, indicating high fluids are contained in this sediment allowing the liquefaction when the earthquake hits in Balaroa and Petobo. The rock density contrast ranges from -0.055 to 0.068 gram/cm³. High density values are located along the western part (0.04–0.06 gram/cm³), while the low rock density value is in the middle part of the study area (-0.055–0.05 gram/cm³).

The density contrast in this area does not differ significantly, indicating that Palu, Balora and Petobo are dominated with the homogeneous rock that has a low density as figured in figure 7a. However, in figure 7b, the density is decreasing by the depth indicating the potential of liquefaction.
Figure 6. The density model in the Area 2: Palu, Balora and Petobo.

Figure 7. (a) The vertical slice to the North, (b) the horizontal slice in Area 2: Palu, Balora, Petobo.
3.3. Area 3: Dolo and Biromaru

Figure 8 shows a significant density contrast in the Area 3, marked with a red and dark blue. This area has no low density rock nearby the surface. However, the low density rock is found in the depth of 600 meter under the surface, indicating the low potential of liquefaction. The low density rock is visible at 625 to 750 meter, and significantly deeper than the Area 1 and 2. The rock density contrast has -0.054 to 0.047 gram/cm³.

The high density values are in the west and east while the low rock density values are located in the middle part, so it is obvious that this density contrast is caused by a fault line. In figure 9a, The density contrast value in this region does not have a significant difference which indicates that around Dolo and Biromaru are dominated by homogeneous rocks. The significant different density shows that the lithological changing is caused by the Palu–Koro fault.

![Figure 8. The density model in the Area 3: Dolo and Biromaru.](image)

![Figure 9.](image)
Figure 9 (continued). (a) The vertical slice to the North, (b) the horizontal slice in Area 3: Dolo and Biromaru.

4. Conclusion

Based on the 3D subsurface modeling, the weak zones are located in the Palu, Balaroa and Petobo areas at 0–125 meters depth, where the density contrast ranging from -0.055 to -0.05 gram/cm$^3$ is lower than the surrounding area. As the weak zone occurs under 1 km depth, the potential of liquefaction is high in this area. In the Dolo-Biromaru region, the low-density rock is found at 600 meter depth. This low density contrast is caused due to the Palu-Koro fault system.

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