

Gravity Modeling to Understand the Subsurface Geology of the Central Part of West Bandung Regency (Citatah Karst Area, Cipatat-Padalarang)

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Abstract

Understanding the subsurface system of the central part of West Bandung Regency (including Karst Area), Indonesia, is an important undertaking carried out by geological and geophysical investigations. This research aims to identify geological subsurface features, especially faults, that have an impact on geohazards in the area. To achieve this goal, deep analysis of geology, geomorphology, and geophysical data is conducted. The central part of West Bandung regency is crossed by the Cimandiri Fault, which is located east of the transitional zone between the frontal subduction of Java and the oblique subduction of Sumatra. The preliminary result shows that the active fault has an impact on geohazards (earthquakes and landslides) in the area. Gravity reduction, regional and residual separation, as well as forward modeling with the Pluoff Equation, are all parts of the examination of the gravity data. A second-order polynomial trend surface was subtracted from the entire Bouguer gravity grid to create the residual gravity anomaly map. The amplitudes of the anomalies range from -12 to 8 mGal. The density distribution from the inverse calculation using 4 horizontal line sections (AB, CD, EF, and GH) was set up in the range of -0.3 to $+0.3$ g/cc. Geological surface markers for the model can be correlated with the information from the Cianjur Sheet geological map. Regional structure is also interpreted in the model to show the main structure of the reverse fault in the study area.

Keywords: Active fault, Citatah karst, Gravity, Geohazard, Landslide, Seismicity, Subsurface

Introduction

Citatah Karst Area is in Cipatat and Padalarang Districts of West Bandung Regency, West Java Province in Indonesia. The study area of Citatah Karst is 103.20 km², spanning 27 km from Cipatat to Padalarang. The area has many exciting tourist destinations, which cover natural tourist attractions such as Stone Garden, Citarum River, and climbable stone cliffs [1]. The number of tourists in West Bandung throughout 2016 was approximately 1.8 million. Besides that, there are mining industries for andesite, limestone, sand, and marble. Industries are the main economic sources for those areas, however, some of them must close operation, and the land will be converted for other land use [2]. The agriculture of the area is also quite renowned, as the area produces vegetables and various fruits such as avocado, guava, and banana. Old tea plantations in the area have now been developed into the palm, quinine, clove, coffee, and rubber plantations.

Karst landscapes pose engineering problems and ground collapse can be a significant geohazard in many areas. Several things must be considered for those who live in karst areas, which usually create property damage and human losses [3]. In addition to disrupting groundwater flow and karst terrain stability, development in karst areas raises the risk of sinkhole inundation and sinkhole collapse.

The Central part of West Bandung Regency has several prevalent problems: Landslide, which is caused by the Cimandiri Fault and Dextral-Horizontal Fault [4], loss of springs, as well as social conflicts (exploitation and conservation) [5].

This study uses an integrated analysis of geological, geomorphological, geophysical, and seismological primary and secondary data. The study is aiming at locating the Rajamandala segment faults

or fractures in the Central part of West Bandung Regency and understanding its impact on geohazard, especially on landslides and earthquakes. The faults are suspected as a geohazard factor in earthquakes and landslides. However, previous research is mostly focused on measuring the activeness of Cimandiri fault [6-8].

Materials and methods

This research applies different approaches: geological, geomorphological, and geophysical. The geomorphological approach with its type of observation and analyses has recently attracted the attention of specialists in various parts of the world. The availability of data sets is also determining the quality of research; using a topography map with a scale 1:25.000 and DEMNAS with a spatial resolution of 8 m. The analysis and interpretation of geological structures are conducted by using the overlay method between DEM SRTM and topographic map [9].

Geological setting

The Java Island is dominated by 4 main faults system, namely the east-west back arc-thrust of Barabiskendeng; the northeast-southwest strike-slip fault of Cimandiri, the southeast-northwest Citanduy fault in West Java, and the northeast-southwest Central Java Fault [10,11]. These faults were generated since the Neogene by compressional forces [12,13]. The Cimandiri fault is an active fault with a slip rate of about 6 to 10 mm/y [14]. The Citanduy and the Central Java faults are a pair of major strike-slip faults (wrench faults) that formed the geological features of Central Java and caused a northward shift of the Quaternary volcanic arc in this area [11]. Besides those 4 faults, there are several smaller faults, which include the east-west Lembang fault in West Java. Structural trends of Java Island are classified into 4 groups, i.e., Meratus (southwest-northeast), Sunda (north-south), Java (west-east), and Sumatra Trends (northwest-southeast) [11].

Geologically (**Figure 1**), the Citatah karst area is surrounded by volcanic products, then there is the Citatum formation which consists of breccia (Mtb) and sandstones (Mts). Lastly, there is the Rajamandala formation which consists of claystone (Omc) and limestone (Oml). The limestone zone is known as the Citatah karst area.

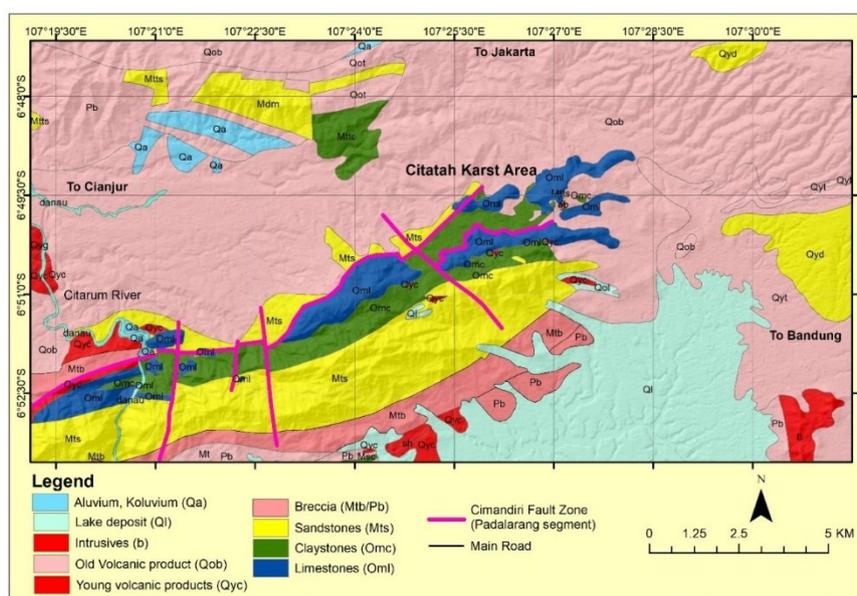


Figure 1 Geological map of the study area, modified from Cianjur Sheet geological map (Sudjatmiko, 1972). The purple box is the study area.

Faults in Indonesia are usually classified as active, potentially active, uncertain, and inactive [14,15]. However, the term of an active fault in Indonesian government regulation related to spatial planning is yet to be defined. The only term existing in regulations is the capable fault, a synonym of an active fault, which is in regulation No. 4/2018 for the Safety of Nuclear Power area by the Indonesian Nuclear Energy Regulatory Agency. Recently, according to a report from the Centre of National Seismic Study [14], there

are 36 active faults in Java, 12 of which are in West Java (Lembang fault and Cimandiri fault) within the Bandung basin [6-8,14]. In regional mapping, the existence of fault structures is identified by using DEM-SRTM, topographic map, and air photo interpretation; field inspection & surveying; and trenching & dating. The mapping of lineament from the published map and previous research in eastern margin of the Bandung basin were also taken into consideration.

Cimandiri fault represents the Meratus pattern in West Java. It lies northeast-southwest, formed from Late Cretaceous to Early Eocene, and is the oldest pattern in Java [16]. There are some studies about the Cimandiri fault, the fault is left lateral [6], but others suggest a reverse fault [8,17]. It indicates a left-lateral slip with an oblique dominant thrust fault in the south [18]. The average horizontal displacement of the Cimandiri fault is 0.5 - 1.7 cm/year [19].

The fault has 3 segments: Cimandiri, Nyalindung-Cibeber, and Rajamandala. In the past, various research was conducted on these segments: The sub-surface structure of the Cibeber segment using magnetotelluric [7,20]; dimension and lineament of the Cibeber segment using MT method [20]; characteristic of movement based on morphometry analysis [8]; and analysis of Nyalindung segment based on phase tensor [21].

Geomorphology

The area is famous since 42 karst hills appear on the limestone of Rajamandala formation. It has a morphological picture as follows: in the north, there are sedimentary slopes and intrusives; in the west, there are volcanic slopes and volcanic clastic alluvial fans (**Figure 2**). It has a morphology from medium to steep. In the southern part, there is a lake bottom. The main morphology of which consists of karts and sedimentary slopes. It has a slope above 15 ° and the slope in the middle and southern part is below 15 °. The elevation data for the area studied range from 210 to 975 MSL. Almost 25 % of the study area is above 750 MSL. The land cover is mostly plantations, grassland, and shrubs of about 74 % of the total area. Paddy fields, forests, and vacant areas cover about 14 % of the total area, while the developed area is about 12 % [1]. About 3 % or 340 hectares of it is exploited as a mining area. Ancient Citarum, the biggest and the longest river in West Java is located in the western part of this area. The geomorphological analysis is extracted and collected from the terrain analysis of satellite images and SRTM.

More than half of landslide occurrences were recorded in areas with slopes higher than 15 °, which also correlates with a high population [22], with the affected areas mainly in its mountainous side. High weathering processes have created steep slopes, and this causes the area to be prone to landslides, as well as human activities which plays important role in landslide occurrences.

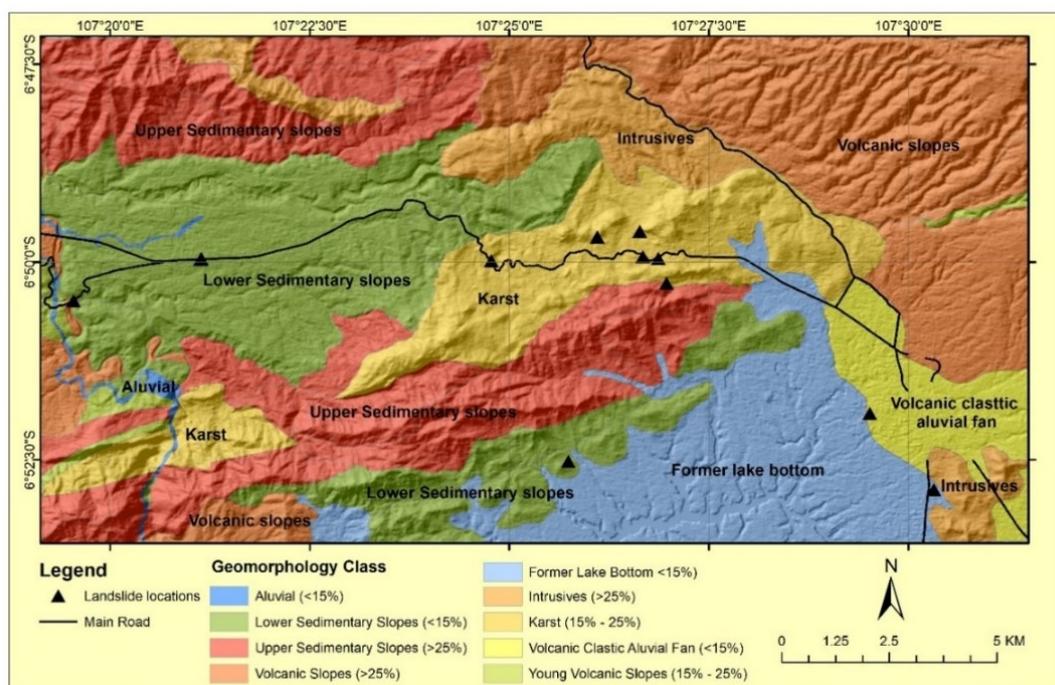


Figure 2 Geomorphological map of study area using based on digital elevation model national (DEMNAS) from Agency of Geospatial Information of Indonesia.

Geophysics

The geophysical method is used to identify the exact location of active subterranean faults. Ground penetrating radar [23], geoelectric method [24], gravity method [25], and HVSR inversion method [26], are several geophysical methods commonly used to detect subsurface structures.

Gravity

In this research, the gravity method is mostly used to determine subsurface geological structures based on variations in the density value of rock (**Table 1** [27]).

Table 1 Rock types of density values.

Rock type	Density range (gr/cm ³)	Average (gr/cm ³)
Overburden (Topsoil)	-	1.92
Soil	1.20 to 2.40	1.92
Clay	1.63 to 2.60	2.21
Gravel	1.70 to 2.40	2.00
Sand	1.70 to 2.30	2.00
Sandstone	1.61 to 2.76	2.35
Shale	1.77 to 3.20	2.40
Limestone	1.93 to 2.90	2.55
Dolomite	2.28 to 2.90	2.70

The corrections made to gravity data included effects caused by variations in elevation, latitude, topography, instrument drift, and earth tides. The first correction is for the removal of instrumental drift and tidal gravity variations. The instrumental drift was estimated using a loop scheme for the relative gravimeter survey, assuming linear drift for repeat observation in the local base.

The tidal gravity effect is estimated using the Longman algorithm [28], heoretical value that is set up in Scintrex CG5 gravimeter. The sensitivity of the instrument is specified in terms of standard deviation (< 5 μ Gal), residual long-term drift (< 0.02 mGal/day), and reading resolution 1 μ Gal. To remove the effect of the gravity variation with latitude, the gravity data were reduced using the 1980 International Gravity Formula. Free-air and Bouguer gravity corrections were made using sea level as a datum. The corrections for gravity anomaly are calculated based on standard procedure [29], and more detail can be seen in similar data processing from the work such as; [30-31].

After data processing, we attempt to present a simple illustration of quick modeling calculation. The inverse calculation from residual anomaly was conducted to obtain the contrast density distribution as a subsurface model. The physical parameter distribution will be calculated in the scheme of 2.5 D subsurface modeling. The forward calculation using a set of rectangular prisms can be calculated using Pluoff equation [32]. The more general matrix notation of forward calculation for synthetic data with a model parameter can also be expressed as follow;

$$d = Gm \quad (1)$$

where d is an array of gravity fields in mGal, G is Kernel matrix to accommodate source geometry and distance between observation location and source location, m is an array of model parameters in g/cc.

Generally, the linear inverse problem for Eq. (2) is solved to get the estimated value of a model parameter. Residual gravity anomaly as observational data input is used in the computation for the solution of the inversion problem (a minimum-norm solution). The inverse problem is under-determined and the computational scheme in this work also involves the initial model (set up as the default form of a uniform model parameter). The miss-fit data for k -iteration is calculated using root-mean-square-error (RMSE). The minimum-norm solution is updated iteratively in the k -iteration using the following equation;

$$\hat{m}^{k+1} = \hat{m}^1 + \Delta m^k \quad (2)$$

where \hat{m}^1 is an array of the initial model (old model parameter), \hat{m}^{k+1} is an array of the updated model (new model parameter), and Δm^k is a perturbation model parameter. Perturbation model is calculated using the following equation;

$$\Delta m^k = G^T D [D G G^T D + \varepsilon I]^{-1} D (d^{obs} - G \hat{m}^k) \quad (3)$$

where ε is the damping factor, I is the identity matrix, and D is the normalized matrix with diagonal elements [33]. Superscript T and -1 in Eq. (3) shows the notation of transpose and inverse matrix, d^{obs} is the array of gravity observation in mGal.

Results and discussion

Gravity

The survey carried out on the 11th - 26th of August 2020 centered on Claystone (Omc) and Limestone (Oml). Stations were placed on a 100 to 500 m average interval. Gravity data were acquired using a Scintrex CG5 gravity meter for 175 observations. A local base station was chosen on BM6 of the PPSDM Geominerba Campus. This local base station was then tied into the absolute gravity base station at the DG1 of Bandung Geological Museum. The corrections made to gravity data included effects caused by variations in elevation, latitude, topography, instrument drift, and earth tides (standard procedure can be seen in the textbook [29]). The first correction is for the removal of instrumental drift and tidal gravity variations. The instrumental drift was estimated using a loop scheme for the relative gravimeter survey, assuming linear drift for repeat observation in the local base. The mean drift for all data is -0.164 mGal.

The tidal gravity effect is estimated using the Longman algorithm [28], for a theoretical value that is set-up in Scintrex CG5 gravimeter. For this survey, the tidal gravity effect is in the range of -0.055 to $+0.179$ mGal. To remove the effect of the gravity variation with latitude, the gravity data were reduced using the 1980 International Gravity Formula. Free-air and Bouguer gravity corrections were made using sea level as a datum and 2.57 g/cc as the Bouguer reduction density. A density of 2.57 g/cc was average value from several samples in the study area (near PPSDM Geominerba Campus). The gravity anomaly map shows in **Figure 3(a)** is subtracted with regional anomaly (2nd order polynomial trend surface analysis) to get the residual anomaly map (**Figure 3(b)**).

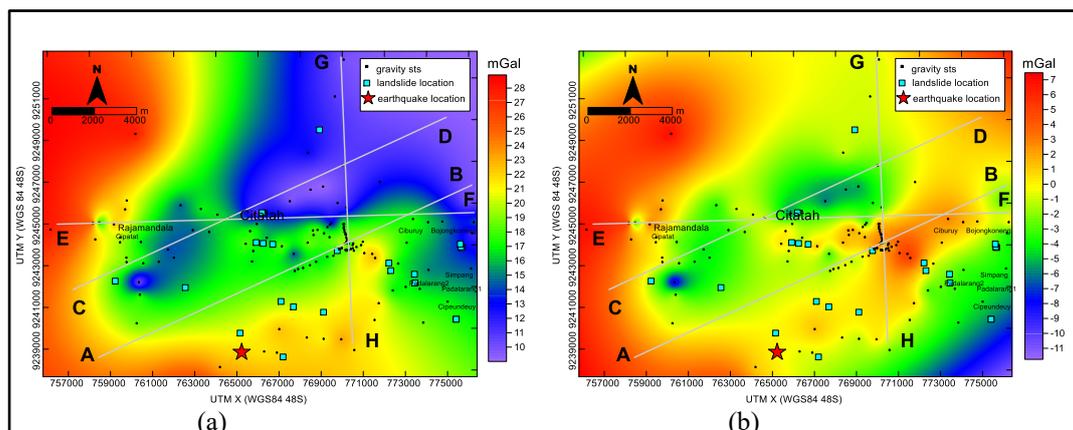


Figure 3 Gravity map; (a) Bouguer anomaly and (b) residual anomaly.

After data processing, we attempt to present a simple illustration of quick modeling calculation. The inverse calculation from residual anomaly (**Figure 3**) were conducted to obtain the contrast density distribution as a subsurface model. The subsurface images can then be analyzed and correlated with geological surface maps in the study area. The physical parameter distribution will be calculated in the scheme of 2.5 D subsurface modeling. The location of line section relative to W-E in the study area.

The density distribution from the inverse calculation (as explained in the methodology and Eqs. (1) - (3)) using a 4-line section; AB, CD, EF, and GH (**Figures 4 - 7**). Contrast density bounds for inverse calculation were set up in the range of -0.3 to $+0.3$ g/cc. The geological surface marker for the model can be correlated with the information from Cianjur Sheet geological map (**Figure 1**). Regional structure is also interpreted in the model (**Figures 4 - 7**) to show the main structure of reverse fault in the study area.

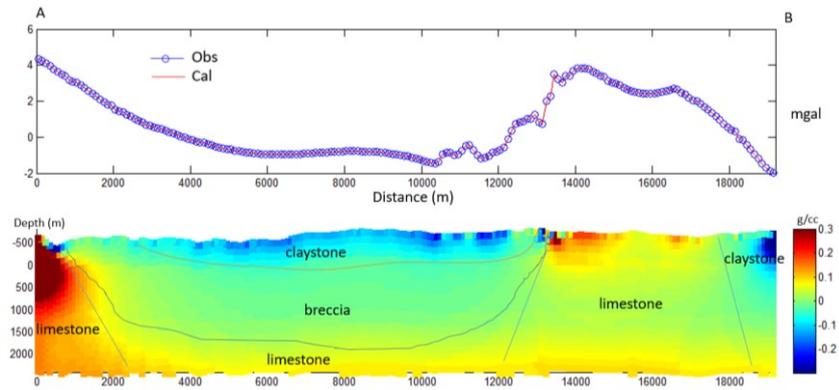


Figure 4 Model line A-B.

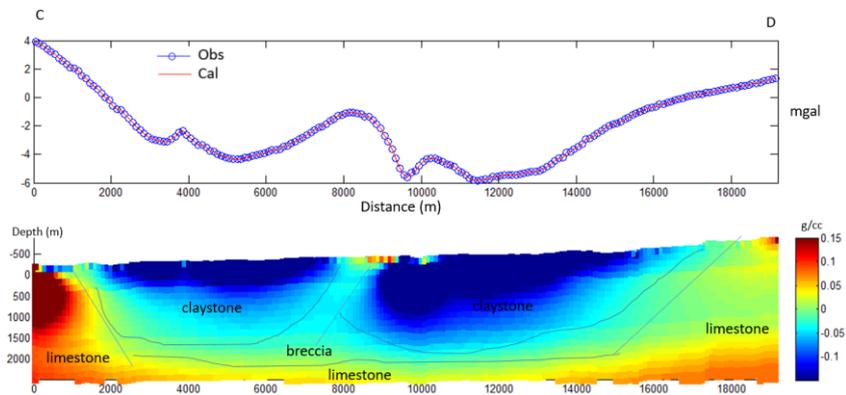


Figure 5 Model line C-D.

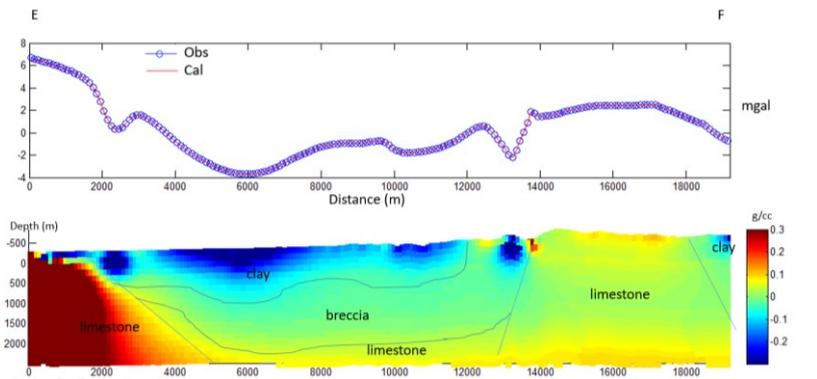


Figure 6 Model Line E-F.

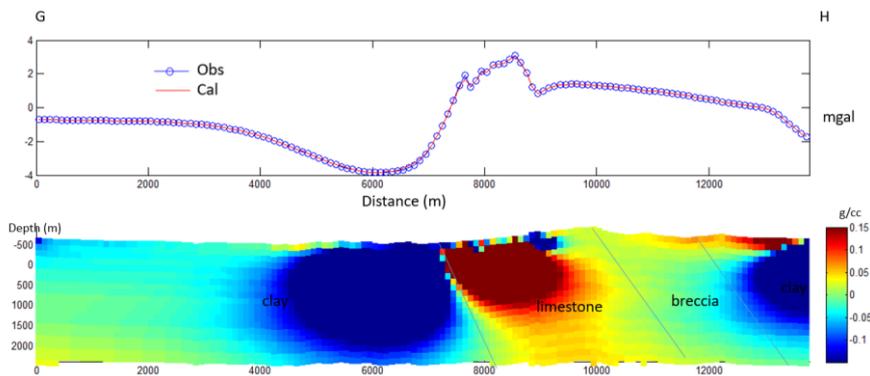


Figure 7 Model Line G-H.

From model interpretation (**Figures 4 - 7**), we can see that there are ground fault models of the Cimandiri fault close to the surface. Low density (blue) shows volcanic product or claystone, and high density (red color) shows compact rocks (limestone). It can be concluded from the gravity profile that not only morphology but also stratigraphy and structure have an important role in triggering landslides. The geophysical method helps us to understand the subsurface condition, therefore, a preliminary understanding of the subsurface is helpful to deduce the possible mechanisms of landslides [34]. Earth's surface rocks have brittle behavior and fracture in response to high forces unless they are gently deformed. When brittle rocks fracture, faults form, and one side of the fracture zone is displaced concerning the other. A form of the fault where displacement has occurred along a horizontal axis is known as a strike-slip fault. Shear strains occurring on the crust cause these faults [35].

Seismicity hazard

There are 3 destructive seismic hazards in West Bandung Regency (**Table 2**) [15]. The other earthquake data are collected from the USGS website available at <https://earthquake.usgs.gov/> (**Table 3**). The gravity result supports the thesis that the Cimandiri fault zone has an impact on seismic hazard. Past research identified the active faults system in West Java based on earthquake hypocentre determination, relocation, and focal mechanism analysis [18]. By re-examining seismograms, they successfully located 168 shallow earthquakes in mainland West Java between 2009 and 2015.

Table 2 Destructive seismic hazard event in west Bandung regency.

No. dates	Epicenter	Magnitude	Damage
1. 15/12/1910	Rajamandala	-	Cracks on the wall
2. 28/08/2011	6.92 ° S - 107.52 ° E	3.3 SR	103 houses damages
3. 04/09/2011	6.88 ° S - 107.40 ° E	4.5 SR	104 houses damages

The Lembang, Cimandiri, and Baribis faults, as well as other active faults in West Java, are visible in the seismicity pattern as multiple clusters of occurrences. According to earlier investigations, the Lembang fault's focal mechanism shows a left-lateral strike-slip. The focal mechanism in the Cimandiri fault likewise exhibits a left-lateral strike slip. However, the study shows that it changes to a thrust fault towards the south, and around the Baribis fault zone a thrust fault is shown, but it becomes oblique to the east. **Figure 8** shows earthquakes in the West Bandung Regency and landslides between 2009 to 2021 from Center of Volcanology and Geological Hazard Mitigation of Indonesia. It seems that geohazards (earthquakes and landslide) is spreading in all areas in West Bandung regency.

Table 3 Seismic event in west Bandung regency.

No. dates	Epicenter	Magnitude
1. 02/08/1985	7.038 ° S - 107.475 E	4.9 SR
2. 12/12/1986	7.115 ° S - 107.392 E	5.3 SR
3. 16/09/1998	6.801 ° S - 107.707 E	4.4 SR
4. 19/09/1999	6.84 ° S - 107.57 ^o E	3.1 SR
5. 26/02/2003	6.95 ° S - 107.475 E	4.0 SR
6. 16/10/2004	7.009 ° S - 107.297 E	4.1 SR
7. 06/04/2005	7.05 ° S - 107.44 ^o E	3.5 SR
8. 15/04/2005	6.892 ° S - 107.464 E	4.4 SR
9. 17/06/2005	7.066 ° S - 107.298 E	4.1 SR
10. 31/12/2006	7.078 ° S - 107.293 E	4.3 SR
11. 01/11/2012	6.762 ° S - 107.529 E	5.7 SR
12. 26/02/2013	6.998 ° S - 107.294 E	4.9 SR
13. 28/02/2014	7.0215 ° S - 107.407 E	4.1 SR

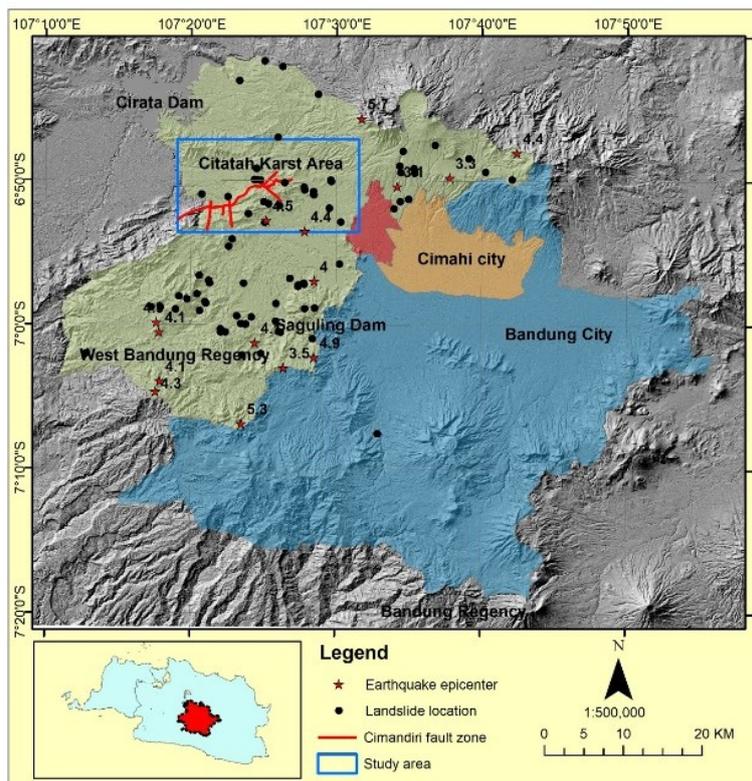


Figure 8 Citatah Karst Area in west Bandung regency and distribution of earthquake (1985 - 2014) and landslide (2009 - 2021), the map based on DENMAS from the Agency of Geospatial Information of Indonesia [9].

Landslide hazard

Gravity acting on a slope is the main cause of landslides, however, other important and dynamic elements act as triggers: Earthquakes produce stresses that weaken slopes and physically result in slope movement; erosion and undercutting of slopes by streams, rivers, glaciers, or waves increase slope angles and decrease slope stability; saturation of slopes by precipitation weakens soil and rock by reducing cohesion and increasing the pressure in pore spaces, as well as the over- and under-weighting of slopes for facilities, roads, and other purposes.

Extreme fluctuations in the weather, temperature and wind direction are characteristics of Indonesia's tropical climate, which has 2 seasons: The dry season and the rainy season. Such climatic conditions, along with moderately varied surface topography and chemically and physically diverse rock conditions, result in productive soil.

The occurrence of natural disasters including floods, landslides, forest fires, and drought are only a few of the unfavorable effects that this condition can have on humans. In many areas of Indonesia, environmental damage tends to worsen with the passage of time and an increase in human activity, leading to an increase in the frequency and severity of natural disasters (drought, landslides, and floods). Landslides in Indonesia cause more deaths and economic losses than is generally understood, and they also cause a bigger annual loss of property than any other geohazard, including earthquakes, volcanic eruptions, and tsunamis.

The landslide area we observed is mainly located around km 23 in the Citatah district which is the oldest transportation route connecting Padalarang and Cianjur (**Figure 9**). The national road from Bandung to Jakarta has 2 alternatives; firstly, Padalarang - Cianjur - Bogor - Jakarta which is the oldest route in use since colonial era, and Padalarang - Purwakarta - Bogor - Jakarta. Additionally, a toll road is recently used.

For many years, the transportation route is rife with landslides. The landslide zone itself varies from 0.25 to 0.5 hectare. The base material of this area is claystone and the material quarter that has undergone weathering to volcanic tuff breccia. The physical property of the soil is loose and soft rocks. In dry conditions, weathering soil resistance to steep slopes is fine, but when saturated with water, then the material collapses easily.

One of the areas prone to landslides is Padalarang, which is exploited for limestone. Mining becomes one of the main sources of livelihood. The type of landslides here was categorized as compound landslides with 22.29 - 44.28 ° slope, especially in Citatah Village. Landslides in Citatah are mostly located in gentle morphology with high tectonic on claystone, with an elevation between 575 and 600 meters above sea level.

In general, the landslide location can be mapped by observing exposed landslide on the surface. The rest can only be mapped by topography and aerial photo analysis. Based on the geological map of the Cianjur Sheet, Java [36], the disaster area comprises volcanic breccia, flow breccia, and lava sediment from Old Volcanoes (Qob). These rocks are generally coarse-grained, sometimes the coating easily decays with relatively thick weathering soil. The Citatah area is a landslide vulnerable zone, especially on slopes with the material composed of Batuasih Formation (claystone), and is included in the Cimandiri Fault zone.



Figure 9 Landslides on KM 23 in the Citatah Karst Area.

Discussion

Geohazards have the potential to influence development in karstic areas. Consequently, a strong transportation network and infrastructure are required to support the development planned. To accomplish that, the crucial infrastructure must be positioned in a way that takes into account the local geology. Ministry of Energy and Mineral Resources has already announced the need of integrated geological analysis for urban planning in karstic area. It stated that the existence of active faults should be considered. In Indonesia, government regulations are needed to protect against the hazard of surface faulting. The regulation is needed as a guideline on how to deal with a fault avoidance zone. Regulation for the fault avoidance zones along active faults should be designed to minimize the potential for surface fault rupture damaging engineering structures. If government regulations are not possible, the need for the Indonesian National Standardization (SNI Standar Nasional Indonesia) is also urgent in this area. The guidelines should include the fault avoidance zone with routinely required specific distances even if there is no readily apparent geomorphic evidence or subsurface evidence for faulting. Other regulations or guidelines released on these issues recommend an appropriate calculation method for determining what a reasonable fault avoidance zone.

The Citatah karst region has potential in many ways, but it also runs the risk of powerful earthquakes and landslides. These geohazards have an impact on Citatah's spatial organization. The growth of the population in West Bandung frequently has an impact on development, which in turn raises questions about how land is being used. It is a critical issue for significant development when conservation land is converted to exploitation. To be ready for a landslide, one must be knowledgeable about landslides, landslide kinds, and likely affected locations. In West Bandung Regency, landslides take place frequently. Cililin, Lembang, and Cipatat are the 3 clusters that should be given priority.

Geohazards are phenomena caused by geological processes and result in natural damage, loss of property, and loss of life. The Citatah Karst Area needs a comprehensive mitigation work, and identifying the subsurface system is one of the most important things in preliminary survey for a geohazard mitigation effort. It can be used as a reference in making spatial planning regulation from local government.

Conclusions

The Central part of West Bandung Regency Area's underlying density structure is shown by the gravity analysis results. This region's subsurface system has a low-density zone that may be linked to volcanic products and claystone sediments that predominate at the surface and a high-density zone that may be linked to compact rocks (limestone). The Cimandiri fault zone is a thrust fault zone, according to the gravity model. It is congruent with the research area's tectonic backdrop, which is a horizontal compressional zone formed by the collision of the Australian-Indian and Eurasian plates, which have been moving toward the northeast [12].

The identification of the Central part of the West Bandung Regency area's subsurface system has the potential to be included into a set of planning management tools that local and national governments can utilize to evaluate long-term sustainable land use. Last but not least, urban areas are crucial in preventing urban sprawl when a compact city system is used to distribute functions between the city core and a buffer zone. However, it is important to start planning with the existence of an active fault in mind.

A further suggestion to manage geohazards (landslides) in the study area is environmental monitoring for cracks or unstable slopes along the road system. Some environmental parameters such as water surface also needs to be monitored. Direct monitoring to see real condition in the field is also important especially during rainy seasons. Other than that, engineering treatments like grouting or terracing should also be applied in some areas. The placement of construction in slope area; such as restaurants, houses, or parking is increasing on the instability of the slope, it can be inferred from irregular patterns of vegetation, crack on houses, houses that tend toward valleys, and cracking on the road. The environmental management for slope conservation is revegetation, slope design, and drainage design. Revegetation is to control groundwater and rainfall and also strengthen slope toe, slope design is sloping the slope using steps, and drainage design is lining as an effort to keep the water flowing flow does not enter the body of the slope.

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