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RESEARCH ARTICLE

Geo-Environment Aspects Assessment Applied In Land Stability Determination Of A Disaster-Prone Area: A Case Study Around The Lembang Active Fault Zone, On The Western Part Of Bandung Basin, Indonesia

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Abstract

Rainfall, landforms, lithology or soil characteristics, and geological structures are geo-environment aspects that might be used to assess stability of the land in a disaster-prone area, e.g. in a case of study around the Lembang active fault zone of the western part of Bandung Basin, Indonesia.

In this study, such geo-environment aspects were weighted and scored constantly in five class of value and importance, due to its influence on the land stability. After this scoring method applied, firstly, a land capability of the research area in relation to disaster potential will be recognized and used to analyze its land stability.

According to such analyses, the study area can be divided into two zones of land stability, i.e. (i) moderate area which dominates the research area, and (ii) non-stable or unstable area near Lembang active fault zone. The dominant moderate and unstable area show that the fault zone has still widely affected the surroundings landscape and its physical characteristics. In fact, the current evaluation of existing landuse show that the development has been carried out intensively on these areas. It indicates that the development of the area is contituted as a high risk activity. Therefore, in this case, a good spatial planning or an environmental good governance must be applied appropriately in such disaster-prone area.

Keywords: *Geo-environment aspects, Land stability, Stable area, Moderate area, Unstable area, Disaster-prone area*

1. Introduction

The study area is located at the western part of Bandung Basin, which cover the area of West Bandung Regency, West Java Province, Indonesia (Figure 1). Situated between 60º 41' - 70º 19' S and 107º 22' - 108º 05' E, the area has 1,305.77 km² wide. West Bandung Regency consists of 15 districts, i.e. Lembang, Parongpong, Cisarua, Ngamprah, Cikalong Wetan, Padalarang, Cipeundeuy, Cipatat, Batujajar, Cipongkor, Cililin, Sindangkerta, Cihampelas, Rongga, and Gununghalu. This regency has a fairly high regional development potential as a result of the existence of tourist areas in the western part of Bandung Basin, especially at Lembang, Cipatat, and Cisarua Districts. In addition, the Jakarta - Bandung High Speed Train railway, where Padalarang is a connecting station, causes an intensive development of West Bandung Regency.

Along with the intensive development of West Bandung Regency, the population has been significantly growing. It might cause an uncontrolled land use and a risk of natural disaster, if the spatial planning of the West Bandung Regency is not properly implemented (Putri et al., 2020). Moreover, some part of this region is a disaster-prone area, due to the existence of Lembang Active Fault on the northern part (Golany, 1976; Sanny, 2017; Supendi et al., 2018; Nugraha et al., 2019; Usman et al., 2023). Therefore, it is necessary to study and evaluate whether the area has a good spatial planning or not, in accordance with the vulnerability and stability of the land based on environmental geological aspects (Legget, 1973; Kivell, 1993; Steiner et al., 2000; Xu et al., 2011). This efort has to be done in order to minimize the occurrence of negative impacts and realize the sustainable development in this region. The environmental geology aspects may consist of raifall, landforms, lithology/soil characteristics, and developed geological structures, (Henry and Basciano, 1979; Bell et al., 1987; Buttrick et al., 1993; Atapour & Aftabi, 2002; Wirosoedarmo et al., 2014; Geremia et al., 2015). These environmental components actually constitute a combination between physical geology and climate aspects. By combining such aspects, an appropriate development plan on the point of view of its land stability can be produced to minimize a risk of natural disaster.

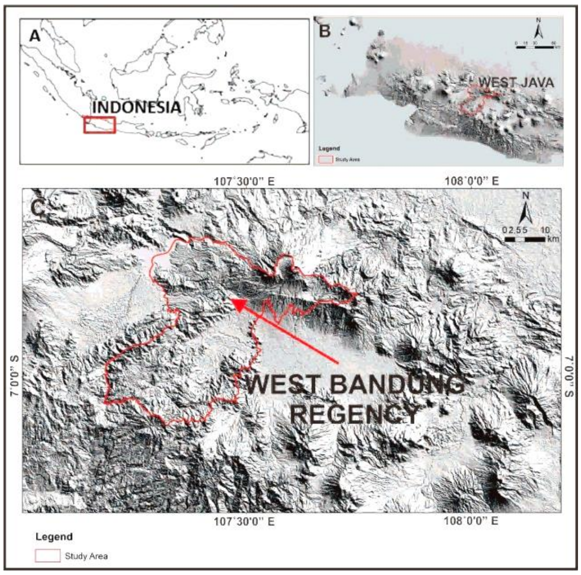


Fig. 1. (A) Location of the research area situated in Indonesia. (B) The research area is located in West Java Province. (C) The boundary of the research area, as well as the boundary of West Bandung Regency, indicated by a red line polygon

2. Materials and Methods

In a good spatial planning, a characteristic analysis of the land is needed, including all natural resources contained in it and above it (Marsh, 1978; Conyers and Hills, 1990; Catanese and Snyder, 1992; Luthfianihuda, et al., 2017). Based on such analysis, then, a stability of the land can be realized as:

1. Stable Area, a land that may be appropriately developed.
2. Moderate Area, a land that may be developed with some considerations.
3. Unstable Area, a land that is unlikely to be developed, because it will have economically and physically broad consequences.

Areas that have a potential for natural hazards are very necessary to manage (Karwan and Wallace, 1984). This land management is related to the form of mitigation in reducing the impact of natural disasters. By using geo-environment aspects assessment, a good land management can be realized through the level of flexibility of an area to be developed, both as domestic and non-domestic areas (Oktariadi, 2009).

Current environment conditions are influenced by the initial hue of geological conditions. Thus, the geo-environment aspects assessment will consist of physical and climate aspects as constraints or resources. To determine the capability of land in relation to disaster potential, an assessment is carried out based on below considerations.

1. *Slope;* An aspect that is closely related to the stability of a land when the area will be developed to be domestic or non-domestic usage. Slope is one of the most important factor which can be given the highest weight in geo-environment assessment. The steeper the slope, the worse the assessment.
2. *Soil or Rock Characteristics*: These lithological characteristics are greatly closed to the engineering properties of soil or rock. This data is commonly used as the basis of building construction. The weaker the soil or rock bearing capacity, the worse the assessment.
3. *Geological Structure*: Geological structure is the result of deformation of the Earth's Crust. Although it has implications to the forming of natural resources, yet, it affects the engineering properties of soil or rock and causes geological disasters. Geological structure can be analyzed by *Fault Fracture Densuty (FFD) method* (Hidayatillah et al., 2024). The higher the density, the worse the assessment.
4. *Rainfall*: Rainfall is another important factor for the assessment, due to its influence to the water balance. It may supply the water needs of the area. However, it may also cause some geological and hydrometeorological disasters. Thus, the higher rainfall intensity, the worse the assessment.

In analyzing land capability, an assessment for each aspect mentioned above is performed on the basis of score and weight method from Howard and Remson (1978). The range of score and weight is defined between 1 and 5, where score is given based on the level of capability and weight is related to the degree of importance. Highest score is 5 and indicates a very high level of land capability in relation to face a disaster potential. Lowest score is 1 and indicates that the area is not capable to face the disaster (very vulnerable). The highest value of weight is also 5 and indicates a very important aspect in assessment. The lowest value is 1 and indicates that the aspect is really not important. However, if the aspect cannot be used in the assessment, the value of weight then will be given as 0.

The total score (Σx) will be obtained from superimposed of all geo-environment aspects. While the average total score ($\bar{x}$) can be calculated from the total score divided by the number of data (n). This average total score or mean is needed to determine standard deviation (δx) with a formula $\delta x = \sqrt{\frac{\Sigma(\bar{x}-x)^2}{n-1}}$. Standard deviation is used as criterion to classify the capabilities of the land (see Table 1). The standard deviation classification method shows how much a feature's attribute value varies from the mean (Wallace & Boulton, 1968; Tempiem & Silapunt, 2021).

Table 1. Land capability class based on statistic calculation approach, by emphasizing values above and below the mean, the standard deviation classification helps show which features are above or below an average value

Land Vulnerability Class	Criterion
Very Low	$Min.Score$ to $X - 1\frac{1}{2}\delta x$
Low	$> \left(X - 1\frac{1}{2}\delta x\right)$ to $< \left(X - \frac{1}{2}\delta x\right)$
Intermediate	$\left(X - \frac{1}{2}\delta x\right)$ to $< \left(X + \frac{1}{2}\delta x\right)$
High	$\left(X + \frac{1}{2}\delta x\right)$ to $\left(X + 1\frac{1}{2}\delta x\right)$
Very High	$> X + 1\frac{1}{2}\delta x$

Furthermore, based on such classification, the stability of the land can be determined into three clasess, i.e. stable area, moderate area, and unstable area, as mentioned at the first paragraph (Luthfianihuda, et al., 2017). Finally, an evaluation of the urban development will be carried out to see whether the current existing land use is suitable or not with the result of assessment.

This evaluation stage describes the level of flexibility of a region to be developed and management efforts through recommendation of a good spatial panning and also providing an alternative solution of land use.

3. Result

3.1 Slope (Weight 5)

According to its characteristics which might be stable or unstable and its relationship to the existence of Lembang active fault zone, slope is then given weight 5. Lembang active fault zone may be associated with the suroundings minor faults. If a big earthquake can activate the Lembang Fault, thus, it will potentially cause a great mass movement around the study area, especially at a steep morphology. This possibility becomes the most important key to the development of the area, so it must be given the highest value of weight in the scoring method. In the study area, slope can be distinguished into five classes, modified after van Zuidam (1985), with the following scores (see also Figure 2) :

1. Plain/Flat (0° - 2°), a flat morphology which has an excellent slope stability to be loaded with buildings. It does not have a potential of mass movement (score 5).
2. Ramp/Gently Sloping (2° - 4°), a gentle morphology which has a good slope stability. Similar with a plain morphology, it does not have a potential of mass movement (score 4).
3. Slightly Steep (4° - 8°), an undulating morphology that has a moderate slope stability and potential of mass movement (score 3).
4. Steep (8° - 16°), a morphology that has a poor slope stability and a high potential of mass movement. If infrastructures will be built on this slope, a good structural based response must be applied in this case (score 2).
5. Very Steep (> 35°), a morphology which has a very poor slope stability and a very high potential of mass movement. It must be relatively avoided in the building of infrastructures. (score 1).

The study area is dominated by steep to slightly steep slopes, which can be related to the genetic of this area. Morphogenetically, this area was formed by a combination of tectonic activities and volcanic process. Lembang Fault zone constitutes a big signature of tectonic activities, while Mount Tangkubanperahu is an actual signature of volcanic process in this area. Both tectonic and volcanic process might form a steep morphology as well as the present morphology of West Bandung Regency.

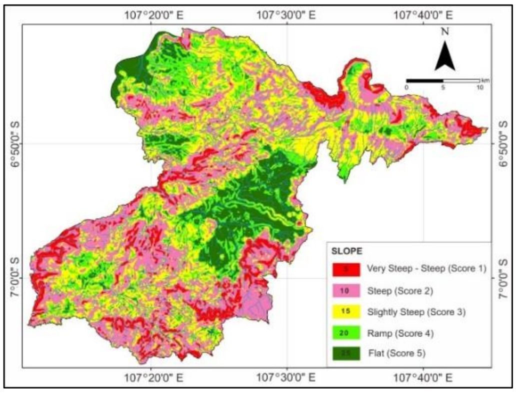


Fig. 2. Slope conditions of the study area which are distinguished into five classes of score, modified after van Zuidam's slope classification (1985)

3.2 Soil or Rock Characteristics (Weight 4)

Soil or rock characteristics, in erosion possibility, bearing capacity, and resistance of downslope or lateral movements, might be considered as a basis of scoring in land vulnerability assessment and given weight 4. Its relationship to the existence of Lembang Fault Zone also affects the importance of soil/rock characteristics in the assessment. Comparing to the weight of slope, then, this parameter is weighted one level below the slope. However, the resistance of downslope movements will be more dependent on the shear strength of the slope material than the characteristics of the soil or rock itself.
In land assessment, learning about basement rock properties become more important than just analyzing soil characteristics. Soil can be determined by knowing the type of rocks (lithologic type). Based on Regional Geological Maps of Cianjur, Bandung, and Sindangbarang - Bandarwaru with a 1 : 100,000 of scale (Sudjatmiko, 1972; Silitonga, 1973; Koesmono and Suwarna., 1996), the research area can be divided into five classes of rock unit such as follow (Figure 3) :

1. Igneous Rocks; the rocks that tend to be impermeable layers. They are very hard and dense. They may difficult to erode and have an amazing rock bearing capacity. Therefore, these rocks are assigned at the highest score in the assessment (score 5).
2. Clastic Sedimentary Rocks; composed by conglomerate, breccia, sandstone, and siltstones. Due to their age and genetics, these rocks have good ability to resist an erosion with ideal bearing capacity, and resistance of downslope or lateral movements, especially for lithology with a fine texture. The ability of these rocks, related to the fondation of infrastructures, are good but bellow the igneous rock's score (score 4).
3. Pyroclastic Rocks; consist of rocks deposited from volcanic eruptions, with a high value of erosion possibility but a low value of bearing capacity and resistance of downslope or lateral movements, such as tuff, pumiceous tuff, lapilli, and laharic breccia. Thus, the areas composed by these deposits have a moderate score for the development (score 3).
4. Alluvial Deposits; the deposits which are accumulated on a flat area with a very high possibility of erosion and the lowest bearing capacity. They have also a very low resistance of lateral movement. Thus, because of its properties as loose deposits, such deposits are really poor for the regional development (score 2).
5. Carbonate Sedimentary Rocks; composed of reef limestones and clastic limestones. The characteristics of these rocks in erosion possibility, bearing capacity, and resistance of downslope movements are quite high as sedimentary rocks. Yet, because of its behaviour to easily soluble and form a complex secondary porosity, thus, these rocks are given the lowest score in regional development assessment (score 1).

In general, the study area is dominated by pyroclastic rocks which can be related to the genetic of this area. Geologically, this area was influenced by a Quaternary volcanic process (e.g. Mount Tangkubanparahu) that produced a moderate characteristic of soil and rock. Its condition may affect a stability of the slope to be more moderate, eventhough Lembang Fault Zone is situated in this area.

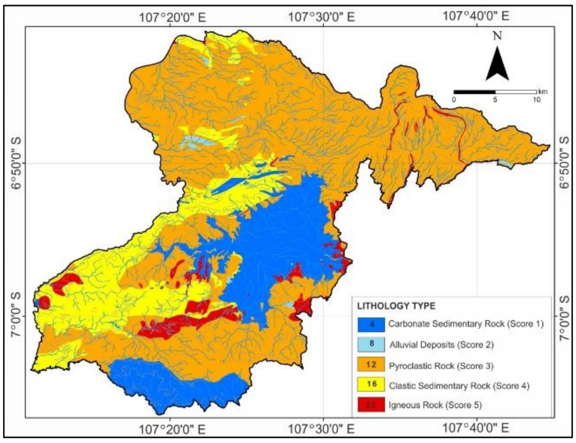


Fig. 3. Five classes of rock unit composed the study area, modified after Sudjatmiko (1972), Silitonga (1973), and Koesmono et al. (1996)

3.3 Density of Geological Structures (Weight 4)

Density of geological structures indicate the frequency of faults, fractures, and joints developed per unit area. This parameter is directly related to the existence of Lembang Fault Zone in the research area. Similar with the soil or rock characteristics, the density of geological structures are given weight 4 in the assessment, one level below the weight of slope. Such weight has been applied due to the reason that a high density of geological structure cannot be confirmed directly as a weak zone. It needs to be verified by the soil or rock characteristics. Based on fault fracture density analysis of geological structures, the study area can be divided into five classes of land capabilities as follows (Figure 4) :

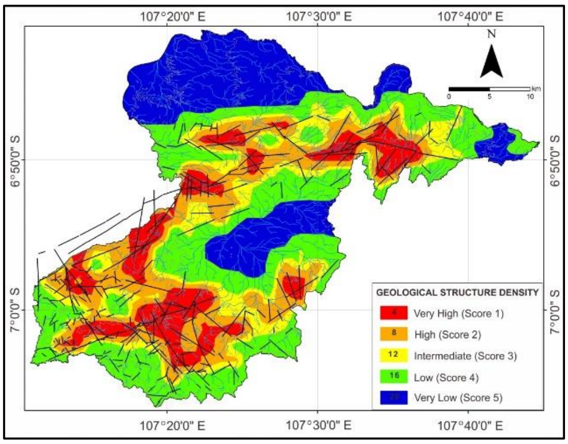


Fig. 4. Five classes of land capabilities based on fault fracture density analysis

1. Very low density of geological structure; the area with a very little deformation which is very suitable for the development (score 5).
2. Low density of geological structure; it is scored one level below previous class. The area is sufficiently deformed, but it is still good for the urban development (score 4).
3. Intermediate density of geological structure; a moderately deformed region with a fifty-fifty chance of the development (score 3).
4. High density of geological structure; it has a high risk level of infrastructure damage of the area. So that, it is not suitable for the urban development (score 2).
5. Very high density of geological structure; it is very vulnerable to the occurence of geological disasters, thus, it has the lowest score in the assessment (score 1).

The fault fracture density map mentioned above shows that the study area is actually dominated by a tectonic activity and can be classified as a disaster-prone area. It needs an engineering or structural based approach in the development of the area.

3.4 Rainfall (Weight 3)

Rainfall is the amount of water falling on to the surface of Earth, a part of climate parameters that can influence the stability of the region. Large amount of rainfall may cause a mass movement in some part of the area. However, such vulnerability of a land will increase if the amount of rainwater is significant loading in a slope and reduces the slope stability. This parameter, in this case, is highly dependent on soil or rock characteristics and the density of geological structures. Therefore, the parameter of rainfall is given weight 3 in the assessment (moderately important).

The rainfall data was obtained from Badan Meteorologi Klimatologi dan Geofiska (BMKG), i.e. an agency of climates data management in Indonesia. There are three rain gauge stations which can be used to determine the annual rainfall in the study area, such as follows (see also Table 2) :

(i) Montoya Farm Rain Gauge Station, Cidadap, located at the southern part of the study area,
(ii) Margahayu Rain Gauge Station, located at the northern part of the study area near Lembang Fault, and
(iii) Cipicung Rain Gauge Station, located in the northeastern part of the study area.

Table 2. The annual rainfall which were measured in 2021 at three rain gauge stations located in West Bandung Regency (BMKG, 2022)

Rain Gauge Station	Current Latitude	Current Longitude	Current Elevation (m asl)	Rainfall 2021 (mm)
Cipicung	-6,72629	107,32761	239	764,2
Margahayu Lembang	-6,80303	107,64815	1238	1175,0
Montoya Cidadap	-7,02628	107,31191	1049	2806,6

Furthermore, the rainfall distribution pattern was made on the basis of Isohyet Method which can provide a more representative map. Due to the avaibality of rain gauges, this method was then performed using the function of Inverse Distance Weighting (IDW), i.e. an approach of interpolation for estimating unmeasured rainfall data based on existing rain gauge stations. By using IDW and Isohyet Method, the rainfall data from three rain gauge stations mentioned above can describe the overall condition of rainfall in the West Bandung Regency.

Thus, according to such method, the study area can be influenced by five classes of annual rainfall such as follows (Figure 5) :

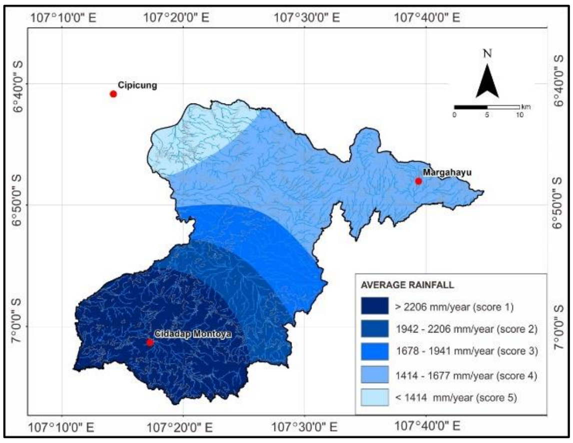


Fig. 5. Three classes of rainfall influenced the study area based on annual rainfall data in 2021 from three Rain Gauge Station located in West Bandung Regency (BMKG 2022)

1. Zone with annual rainfall less than 1414 mm; located in the northwestern part of the study area, this zone is relatively far from disaster, especially from flood and landslides, due to a lack of rainfall in certain months (score 5).
2. Zone with annual rainfall between 1414 – 1677 mm; located in the northern part of the study area. Although Lembang Fault developed in this zone, however, disaster does not frequently occur due to a lack of rainfall in certain months (score 4).
3. Zone with annual rainfall between 1678 – 1941 mm; located in the middle part of the study area. Such zone is good for the urban development, yet, its annual rainfall may cause inundation in a flat morphology and landslide in a steep morphology (score 3).
4. Zone with annual rainfall between 1942 – 2206 mm; located also in the middle part of the study area. Similar with previous zone, such amount of rainfall is vulnerable for a hydrometeorological disaster, e.g. inundation and landslide (score 2).
5. Zone with annual rainfall more than 2206 mm; located in the southern part of the study area. Many rivers developed in this zone are chanelling rainfall on the surface and become a big potential of hydrometeorological disaster, such as landslides that have occurred at Gununghalu area on April and May 2024 (score 1).

Based on the distribution of those annual rainfall, the northern part of the study area is relatively safe and far from the occurence of hydrometeorological disaster. However, some facts about the exchanges of land use and land cover (LULC) at the southern part (upstream area) can cause some floods in the northern part (downstream area).

4. Discussion

4.1 Land Capability Assessment

According to the weight and score of each geo-environment aspects mentioned above, land capability of the region, in its relationship with the stability of the area, can be calculated. By overlying all of the geo-environment aspects, then, 26.956 total scores of the land capability were obtained. The lowest score is 17 and the highest score is 80, while the value of mean is 50 with a calculated standard deviation is about 12. Furthermore, the total scores are statistically divided into five classes of land capability based on such standard deviation, see Table 3 below.

Table 3. Land capability class based on statistic calculation approach, by emphasizing values above and below the mean, the standard deviation classification helps show which features are above or below an average value

Land Vulnerability Class	Criterion	Score
Very Low	$Min.Score$ to $X - 1\frac{1}{2}\delta x$	17 - 32
Low	$> \left(X - 1\frac{1}{2}\delta x\right)$ to $< \left(X - \frac{1}{2}\delta x\right)$	> 32 to < 44
Intermediate	$\left(X - \frac{1}{2}\delta x\right)$ to $< \left(X + \frac{1}{2}\delta x\right)$	44 to < 56
High	$\left(X + \frac{1}{2}\delta x\right)$ to $\left(X + 1\frac{1}{2}\delta x\right)$	56 to 68
Very High	$> X + 1\frac{1}{2}\delta x$	> 68

The study area is dominated by a very low to low capability of the land, see Figure 5. An intermediate capability are delineated on the northern part of the study area, while a high and a very high land capabilities are unsignificant and distributed locally on some little region around the northwestern part of the study area. However, such map shows that the study area is contituted as an unstable area (prone area). In urban development, it needs to be proceeded using a structural based response, i.e. an approach using engineering and design modifications.

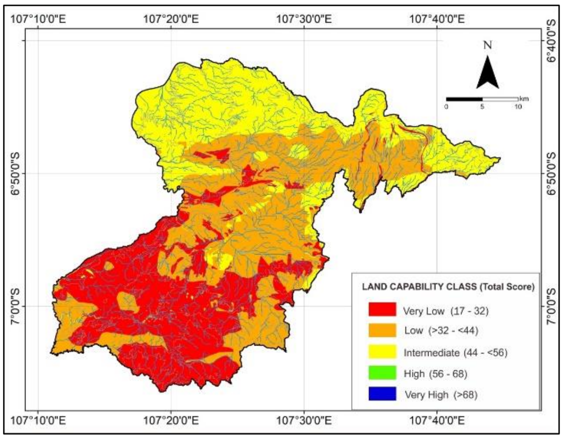


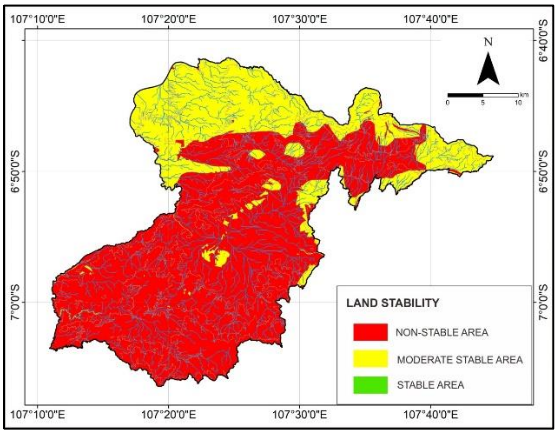
Fig. 6. Land Capability Map of the study area based on statistical calculation of geo-environment aspect

4.2 Land Stability Analysis

Theoritically, the Map of Land Capability mentioned above can be then distinguished into three zones of land stability. Nevertheless, in this case, the study area may only have two zones of land stability, i.e. moderate stable and non stable areas, due to the unsiginificant stable area on the northwestern part that might be still affected by Lembang Fault Zone (see Figure 7).

In detail, the land stability of the study area is described such as follows :

1. Moderate Stable Area; this area indicates the capability of the land with some natural obstacles for the development. Thus, it needs a structural-based approach to minimize the obstacles. Two main obstacles defined in this area are a steep slope condition and a high density of fractures that might cause the formation of weak zones.
2. Non Stable Area (Unstable Area); this area indicates a low to very low capability of the land to be developed. This prone area mostly dominates the study area, where Lembang Fault Zone is a part of this zone. Such zone has a steep to very steep slope and a high to very high density of geological structures. It has also a very high risk of failure when the structural-based approach is implemented in this area, due to the potential geological hazards occurred such as earthquakes and landslides.



Fig, 7. Land stability zones of the study area that are delineated on the basis of dominated land capability

The dominant land stability zone shows that the study area constitutes a disaster-prone area. The regional development should have been adjusted to such land stability zone, before a significant negative impact of the development occurred at the area. Moreover, some existing landuse at such prone area, especially near the Lembang Fault zone, have been dominated by settlement and industrial areas. The current conditions of the existing landuse were observed directly using an unmanned aerial vehicle (UAV) called drones. This aerial photo observation was performed in one of the areas representing the non-stable area, near Lembang Fault Zone, which can be seen in Figure 8.

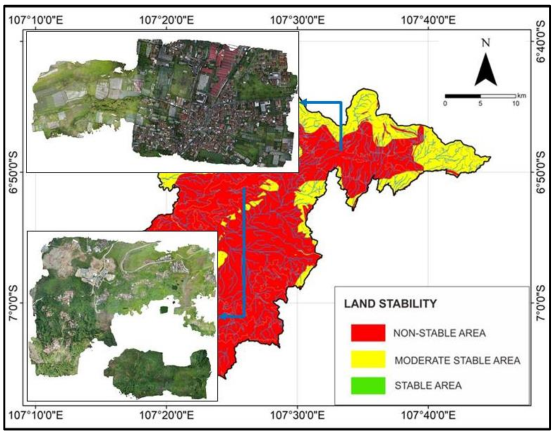


Fig. 8. Existing landuses on the prone area that are captured by a drone aerial photograph method

Based on the results of a drone aerial photograph method performed in the study area, which was focused on the prone area, it can be seen that there is still an intensive urban development in such area. Thus, it should be reviewed whether the spatial planning of the area must be revised or the structural based response applied in all development activities. If the second option is choosed, as a consequence, it has to be anticipated with a high cost of urban development and a good mitigation of natural disaster. In the prone area, a good mitigation can only be carried out by minimizing a vulnerability of the disaster occurence in the area and maximizing a capacity of the area to handle the disaster.

5. Conclusion

Based on geo-environment aspects assessment applied in land stability determination of a disaster-prone area, the study area is divided into two classes of land stability, i.e. moderate stable and non-stable areas. There is no stable area in the region, due to the strong influence of Lembang Fault Zone. Lembang Fault Zone might be connected to the outside fault zones such as Cimandiri Fault Zone on the southwestern part and Baribis Fault Zone on the northern part of the study area. In this case, it is very reasonable if the study area is classified as a disaster-prone area.

The current evaluation of existing landuse shows that there are many development activities in such region, especially for the settlement areas. In a simple mindset, it can be concluded that the development of West Bandung Regency is not in accordance with the concept of good Environmental Social Governance (ESG). However, in a disaster-prone area, a good ESG can only be carried out by minimizing a vulnerability of the disaster occurence and maximizing a capacity of the area to handle the disaster. Consequently, a structural based approach mus be applied with a high cost of urban development. Thus, geo-environment aspects assessment, as a good spatial planning or an environment good governance, should have been applied before the area is developed.

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