Distribution and Characteristic of Landslides in Volcanic Mountains of West Java, Indonesia

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Abstract

West Java is the most risky province to landslide events in Indonesia due to extreme geo-morphological condition, climatic condition and densely populated with immense development activities. This study aims to explore distribution and characteristic of landslide in West Java. Geomorphological and archive inventories were prepared for the selected study area. The geomorphological inventory contains information about landslides that occurred before 1994, whereas the archive inventory includes recent landslides (1994 to 2010). Frequency-size statistics has been used to explore characteristics of landslide maps and to understand evolution of landscape in the study area due to slope movement. This study reveals that prepared landslide map includes a substantial fraction of all landslides at all scales (small-medium-large). However, archive inventory was incomplete in size aspect due to the limitation of landslide mapping technique. Geomorphological inventory showed rollover whose position is same with available literature. The rollover was interpreted as self-organized criticality of the area and limitation of inventory techniques.

Keywords: distribution, characteristic, landslides, West Java

Introduction

Indonesia is one country in Southeast Asia that is prone to natural hazards such as earthquakes, tsunamis, landslides, floods, and volcanic eruptions. These hazards are mainly generated by the fragile geology and the extreme climatic conditions of the country. Number occurrence of hydro-meteorological disasters dominates total of natural disaster events in Indonesia, approximately 80% of total, only 20% is geophysical disasters. Landslide is one of geophysical disasters that frequently occurs in hilly regions in Indonesia with the number of occurrences has sharply increased from 2000 to 2009 (DIBI, 2012). The landslides are
primarily triggered by heavy rains. Other possible the landslides are triggered by earthquake and anthropogenic activities such as deforestation, road cutting, and mining. Nowadays, more and more people are affected by landslide disaster in Indonesia because of high density of population and ill-planned development in the country (Marfai et al., 2008).

When landslides are talked of in Indonesia, volcanic mountains along the collision zone of tectonic plates are the most prone area to instability. Cepede et al. (2010) reported that main effect of landslides could be found in Java (52%), Sulawesi (24%) and Sumatera (18%). The landslide disaster loss in Java is usually high because of high frequency of events as well as high density population (Hadmoko et al., 2010). It has been reported that a thousand of landslide disasters occurred in Java during the period of 1990-2005, which killed more than 1,112 people and injured 395 people. As the nation’s economic and administrative region, Java, particularly West Java has become the most populous area while economically and marginalized communities are often forced to occupy landslide prone areas. In addition, extensive infrastructure development, such as construction of national highways, railways, and roads has taken place in West Java recently. All these activities give rise to new landslide hazardous areas leading to increased landslide occurrence in future. Therefore, this research is targeted to explore distribution and characteristic of landslides in West Java.

Study area

This study was carried out in southern part of West Java Province, which covers a total of 3,659 km² between 7° 0’0” S to 7°20’0” S latitudes and 107°10’0” E to 107°50’0” E longitudes (Figure 1). It covers some parts of the Central Volcano Sedimentary Zone and the Southern Mountain Zone. The Central Volcano Sedimentary Zone is covered by products from Late Miocene to Pliocene magmatic arc, while Southern Mountain Zone is formed by subduction of the oceanic Indian plate beneath the continental Eurasian plate, and is characterized by earthquakes and active volcanoes. It consists of volcanic arc products interstratified with Late Eocene to Early Oligocene sedimentary formations.

Materials and method

Bureau of Coordinating Survey and National Mapping of Indonesia has produced aerial photos on a scale of 1:50,000 back in 1994. These aerial photos were used in the study to identify landslides. In this process, two main steps were followed: 1) landslide boundaries were first identified using photogrammetric techniques and later, 2) they were drawn digitally in GIS environment over the topographical maps. During identification and digitization, the scarps, failed and moving masses, direction of mass movement, length and breadth were also marked. Furthermore, landslides that occurred from 1994 to date were also added in the
inventory map. Due to unavailability of recent aerial photos, however, landslides that occurred after 1994 were referred to from the landslide archives. The recent landslides do not leave any morphological signature on this topographic map. Therefore, we used Google Earth image to assist identification of landslide boundary and to minimize mapping error of landslide features on topographic maps. A field investigation was carried out in March 2012 in order to verify the landslide location and update the information. Here, geo-morphological inventory refers to the inventory that produced from aerial photos, while other ones is an archive inventory.

Figure 1: Three main physiography belt of West Java (modified after Van Bemmelen 1949), b) distribution of volcano (modified after Bronto 2008), and c) geological units in the study area according time scale

The landslide inventories contain information about size (i.e., area, length, breadth, slope) of each slope movements. Frequency-size statistics has been used to explore characteristics of landslides and to understand evolution of landscape in the study area due to slope movement. Most of landslide inventories contain information about the area of individual landslides rather than other sizes (i.e., volume, length, breadth, and slope), because it is readily measured in maps by using GIS software (e.g., ILWIS, ArcGIS). Hence, landslide frequency-area distribution is frequently used in analysis of frequency-size statistics. The
frequency-area distribution for landslides can be presented using both cumulative and non-cumulative distribution. The cumulative frequency-area distribution is expressed by Eq. (1), while non-cumulative is given by Eq. (2).

\[ N_{CL} = C \cdot A_L^{-\alpha} \]  
(1)

Where, \( N_{CL} \) is the cumulative number of landslides with area greater than or equal to the area \( A_L \). In a diagram with logarithmic axes, the Eq. (1) is represented by a straight line, with \( \alpha \) equal to the gradient of the interpolated straight line and \( C \) is equal to the intercept on the y axis.

\[ -\frac{dN_{CL}}{dA_L} = C'A_L^{-\beta} \]  
(2)

Where \( \beta \) is the power-law, and \( C' \) is a constant of non-cumulative distribution.

Many empirical observations have shown that landslides follow power-law frequency-size statistics. The term of power-law refers to mathematical relationship between two quantities such as number of landslide and its size, where the frequency of landslides increases rapidly to a maximum value and then decrease following a power-law. Several authors (e.g., Turcotte 2004; Rouai and Kharim 2005) argued that power-law behavior of landslide is a consequence of self-organized critical (SOC) behavior.

Because of SOC behavior, the non-cumulative frequency-area distribution usually satisfies the power-law behavior (Wu et al. 2011). The value of the power-law exponent \( \beta \) is called the scaling exponent. This is generally related to triggering factors, geomorphologic characteristics, and landslide history, or indicates whether the slope movement is dominated by the many small slides, or the rarer large slides (Weissel et al. 2001). It was noticed by Guzetti et al. (2002a) that range of value for the exponent \( \beta \) is generally 2.0±0.5 km\(^2\) for various geographic locations, geologic settings and landslide triggering mechanisms. Indeed, the power-law (\( \beta \)) is obtained from frequency of landslides with medium to large areas, whereas the frequency of landslides with small areas shows the rollover effect.

**Results and analysis**

A total 336 landslides were identified and mapped in the study area (Figure 2a). The aerial photo interpretation recognized 266 landslides, while the remaining was identified from archives. The landslide sizes including projected area, length, breadth and slope as illustrated in Figure 2(b). General character of landslide in the study area can be recognized from histogram as seen in Figure 3.

The dimension criteria such as size, length, breadth, area and slope of landslide were determined. The result revealed that the slope of landslides range from 5 to 50 degrees with
mostly clustered in 10 to 15 degrees. About 80% of landslides have size less than 2.5 ha. The length of landslide was concentrated at a range of 150 m to 300 m while the breadth at 100 m to 200 m. Landslide breadth was found to be half of the landslide length, and it shows a linearly increasing trend (Figure 3b). Similarly, frequency of landslide gradually decreases with the increase of dimension of landslide such as slope, area, length and breadth (Figure 3a).

Table 1 shows that the geomorphological inventory is characterized by large size of landslide. For archive inventory, a few large landslides were reported in the study area. The landslide area ranges from $1.24 \times 10^{-4}$ to 1.11 km$^2$, where landslides that occurred before 1994 range from $1.24 \times 10^{-4}$ to $8.84 \times 10^{-2}$ km$^2$. Both inventories have similar range of slope, i.e., 5 to 50 degrees. In case of width of landslide, the geomorphological inventory informs that landslides range from $7.14 \times 10^{-5}$ to $1.60 \times 10^{-3}$ km, while the landslides that occurred from 1994 to 2012 was found to have range between $6.92 \times 10^{-6}$ to $2.80 \times 10^{-4}$ km. The length of landslide in the study area ranges from $2.06 \times 10^{-5}$ to $2.02 \times 10^{-3}$ km. The geomorphological

Figure 2: a) Landslide maps in the study area consists of geomorphological and archive inventories, and b) illustration of landslide size was used in this study, i.e., area, length, breadth or width, and slope of landslides
inventory shows that landslides range from $7.14 \times 10^{-5}$ to $2.02 \times 10^{-3}$ km, while the archive inventory indicates a smaller range of landslides (i.e., $2.06 \times 10^{-5}$ to $5.99 \times 10^{-4}$ km).

The cumulative frequency versus landslide area ($A_L$) for three landslides inventories are plotted in log-log graph (Figure 4a). The curve can be fitted by a power law function for landslide areas greater than $1.23 \text{ km}^2$ for landslide inventory and map A, and $2 \times 10^{-2} \text{ km}^2$ for map B, respectively. The exponent, $\alpha$, of the power law function ranges between 0.998 and 1.870 where the coefficient, $C$, is six thousand times smaller for the curve fitting frequency-area on map B. This is caused by a greater relative number of large slope movements at map A.

Figure 3: Physical dimension of landslides: slope, length, breadth, and area

The cumulative frequency-size distribution could be restrictive and misleading (Pelletier et al., 1997), thus non-cumulative statistics has also been applied in this study. The derivative of the cumulative number ($N_{CL}$) of landslides with area greater or equal to a landslide area ($A_L$), was plotted as a function of the $A_L$ for the three maps in Figure 4b. A
rollover was observed at map A that shown by decreasing frequency density for small landslide areas (i.e., $2 \times 10^{-2}$ km$^2$). This was same with rollover position of historical inventory in central Italy analyzed by Guzetti et al. (2002b). The rollover may be found in all frequency curves, which is interpreted by some authors (e.g., Wu et al., 2011; Chen, 2012) due to SOC, while this was identified by others (e.g., Guzetti et al., 2002a; Van Den Eeckhaut et al., 2007) as the drawbacks of landslide mapping techniques.

Table 1 Summarize the main statistic-feature of landslide size

<table>
<thead>
<tr>
<th>Landslide inventory (Map A and B)</th>
<th>N</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area ($m^2$)</td>
<td>336</td>
<td>1.11E+06</td>
<td>1.24E+02</td>
<td>1.11E+06</td>
</tr>
<tr>
<td>Slope (degree)</td>
<td>336</td>
<td>45.35</td>
<td>4.65</td>
<td>50.00</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>336</td>
<td>1590.36</td>
<td>6.92</td>
<td>1597.28</td>
</tr>
<tr>
<td>Length (m)</td>
<td>336</td>
<td>2001.93</td>
<td>20.59</td>
<td>2022.52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Map A: Geomorphological inventory (landslides that occurred before 1994)</th>
<th>N</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area ($m^2$)</td>
<td>266</td>
<td>1.10E+06</td>
<td>5.91E+03</td>
<td>1.11E+06</td>
</tr>
<tr>
<td>Slope (degree)</td>
<td>266</td>
<td>45.35</td>
<td>4.65</td>
<td>50.00</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>266</td>
<td>1525.87</td>
<td>71.41</td>
<td>1597.28</td>
</tr>
<tr>
<td>Length (m)</td>
<td>266</td>
<td>1926.04</td>
<td>96.48</td>
<td>2022.52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Map B: Archive inventory (landslides that occurred from 1994 to 2012)</th>
<th>N</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area ($m^2$)</td>
<td>70</td>
<td>8.83E+04</td>
<td>1.24E+02</td>
<td>8.84E+04</td>
</tr>
<tr>
<td>Slope (degree)</td>
<td>70</td>
<td>45.00</td>
<td>5.00</td>
<td>50.00</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>70</td>
<td>272.87</td>
<td>6.92</td>
<td>279.79</td>
</tr>
<tr>
<td>Length (m)</td>
<td>70</td>
<td>578.51</td>
<td>20.59</td>
<td>599.11</td>
</tr>
</tbody>
</table>

The presence of rollover at map A is probably indicates a transformation of triggering factors slope movements in the study area. In case of landslide, geological processes and triggering factors are internal pressure or constraints of system. The pressure builds the system until it exceeds threshold shown by rollover (Figure 4b). Here, mega-earthquake might be main triggering factor for landslides that occurred before 1994 which has led to huge slope movement. Later, the system has evolved into an organized form. Anthropogenic activities such as road constructions and plowing of farmlands are external constraints of system, which are disrupting the self-organized of natural system. This identified as major factor of causing recent landslides (map B) which is characterized by small sizes. This is real because previous section describes that study area immense with development activities.
Lack of archives and difficulties identifying signature of landslides in the field are main drawbacks of the archive inventory in the present work. The archives were obtained from the newspaper, which contain general information particularly location, date and time occurrence, name of victims and material losses. By referring to the archives, surveyors visited the location of slope movement to investigate the boundaries of landslides. However, the field work could not recognize the signature of landslide appropriately, because the rapid vegetation growth, erosion process, and human actions (e.g., agricultural activities, construction practices) had erased them in a matter of months or seasons. On the other hand, visual interpretation of aerial photos might underestimate the number of landslides, because the large landslide more readily identified than smaller ones. Vegetation can hinder small landslide observation from aerial photographs. The humid tropical climate leads a rapid vegetation growth, so landslide signatures will be quickly disappeared.
Figure 4: Frequency-area statistics of landslide using a) cumulative frequency distribution, and b) non-cumulative frequency distribution on a log-log scale. Red squares represent all landslide dataset, blue circles represent landslides that occurred before 1994 (Map A), and black triangles represent landslides that occurred after 1994 to 2012 (Map B).

Later, non-cumulative frequency distribution was fitted for areas greater than rollover for finding a power-law ($\beta$). Despite map B and all landslide datasets do not show rollover in Figure 4b, the power-law ($\beta$) could be generated from the frequency of area greater than $6 \times 10^4$ km and $2 \times 10^2$ km for map B and all landslide data, respectively. They were considered as transition position between medium-large size and small size of landslides. The result revealed an exponent, $\beta$, of 1.55 for map A, 0.43 for map B, and 1.60 for overall landslide datasets. The exponents map A and entire landslide data were found in range suggested by Guzetti et al. (2002a), but not for map B due to differences in the character of inventories. Comparing to other landslide maps, the archive inventory (map B) is more incomplete in terms of landslide size. This is in accordance to the statement Guzetti et al. (2005), that complete inventory is not applicable to historical or archive inventory. Because depicting boundaries between the failure areas (depletion, transport and deposition areas) and unaffected terrain in the field is not easy. Natural processes and the anthropogenic activities are considered as major issues in recognizing landslide features in the field.

Conclusions

The inventory map consists of a total of 366 landslides, of which 21% were obtained from the archive inventory. The landslide shaped sizes in terms of area, length, breadth, and slope were derived from the landslide inventories. Except for the slope, the landslides in geomorphological inventory are characterized by large sizes while they are small in the archive inventory. This was also evidenced by power-law and coefficient for both cumulative and non-cumulative distributions of landslide area. Rollover was exhibited in geomorphological inventory, and its position was similar to the historical inventory of landslides in central Italy. The rollover behavior of landslides indicates that evolution of landscape of the study area following SOC (self organized criticality) model and demerits of landslide mapping techniques.

References


