Rainfall Landslide in Sedimentary and Sub-Metamorphic Rock – an Example in Kaoping River Basin

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Abstract

Many researches employed several landslide-related factors such as the slope-aspect, size, lithology etc. to study the landslide assessment. Utilizing the landslide inventory delineated by 1:5000 high resolution aerial photo, this article explored the landslide characteristics, such as the landslide area, slump direction and air current for two different rock types in Kaoping River basin during the period of 2009 Typhoon Morakot. It is found that the air current direction is the dominant factor for landslides triggered by a heavy rainfall in Kaoping River basin. The number and size of landslides in slate is larger than the sedimentary rock. This indicates the slate region in Kaoping River basin is more likely to take place landslide; however, the landslide characteristic in size distribution is similar.

Key Words: Landslide, Lithology, Air Current, Kaoping River Basin

1. Introduction

Recently, the landslide hazard assessment plays an important role in minimizing the risk of fatality and property damage. Predicting the deposition quantity of landslides is essential in protecting inhabitants in the impact zone. If landslide spatial distribution obeys a certain law, it would be very useful in disaster prevention. However, prediction of landslide size and location is a complicated issue. Many severe landslides including slides, slumps, avalanches, and debris flows have been reported in Taiwan [1–5]. Chen et al. [4] reported more than 1000 soils slips, debris flows, and large, complex landslides caused by 2004 Typhoon Mindulle. Influence by the track of typhoon and mountain terrain, the typhoon dumped more than 2000 mm and over 100 mm/hr intensity of rain during July 2 to July 4, 2004 in central and south Taiwan.

The number of landslides per unit area is 0.27/km² and the intensity of landslides (area of landslide per unit area) is 0.84 ha/km² [1]. Chang and Slaymaker [3] showed that the heavy rainfall accompanied with extreme Typhoons in Taiwan is responsible for landslide activity acceleration. In Taiwan, slope failure associated with annual high intensity precipitation from typhoons usually occurs on structurally weak rocks. Lee et al. [6] had taken SPOT images before and just after 1999 Chi-Chi earthquake for landslide recognition on central Taiwan. The result explored that the size of the landslides ranged from about 0.1 to 10 ha with a maximum of 28 ha and a

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minimum of 0.01 ha. The landslide inventory shows an inverse relationship between the logarithmic number of landslides and landslide size, and shows sound record above 0.4 ha.

In prediction of a landslide, to capture the main landslide-related factors plays an important role. Many studies employed several landslide-related factors in their landslide estimation. For example, Bui et al. [7] used nine landslide related-factors, including slope, slope-aspect, elevation, lithology, land use, soil type, distance to roads, distance to rivers and distance to faults, to study the landslide assessment. Youssef et al. [8] used 11 landslide-related factors, including altitude, curvature, distance from stream network, distance from road, distance from fault, stream power index, topographic wetness index, soil type, as well as geology, slope, and aspect, to prepare a landslide susceptibility assessment. Yalcin [9] and Duman et al. [10] reported that rock unit properties and structures represent two main factors in landslide occurrence. The intensity of landslide is closely related to rock structure and terrain.

Igwe [11] studied the landslide characteristic on sedimentary and metamorphic terrains of West Africa. He concluded that the landslides on sedimentary terrain were mainly shallow, low-volume slumps controlled by sheared along the impermeable bedding plane. The landslides on metamorphic terrain were complex translation and rotational movements. That is, different rock units have different landslide susceptibilities. For example, Hearn and Hart [12] concluded that for any given rock the landslide density is proportional to the slope angle as shown in Figure 1. The landslide density in mica schist is highly dependent on the slope angle. However, landslide density in slate/shale or limestone is moderated. The landslide characteristic is dependent of rock types.

Due to the particular geographical location and geological condition, Taiwan suffers from many natural hazards, such as earthquake, typhoon, flooding and landslide, which often cause series fatality and property damages. In 2009, Typhoon Morakot attacked Taiwan during August 6 to August 10. More than 1,500 mm of precipitation was collected in one day and more than 3,000 mm of the rainfall was accumulated in the mountainous area. In Kaoping River basin, the river flow peaked at 27,447 m$^3$/s on August 8, and exceeded 20,000 m$^3$/s for a total of nine hours. Several towns along the upper river were destroyed by flooding and landslides, died up to 500 people.

Tsai et al. [13] pointed out a total of 9333 landslides (22,590 ha) was detected from change detection analysis of satellite images in 2009 Typhoon Morakot. Most of the detected landslides are smaller than 10 ha. Less than 5% of them are larger than 10 ha but together they constitute more than 45% of the total landslide area. Spatial analysis of the detected landslides indicates that most of them have average elevations between 500 m to 2000 m and with average slope gradients between 20 and 40.

This article aims to study the landslide characteristics such as the landslide size, geometry, and slump direction for two rocks in Kaoping River basin during the period of Typhoon Morakot. It will be helpful to capture the key factors on landslide disaster in Taiwan.

2. Study Area– The Kaoping River Basin

Kaoping River is a major river in southern Taiwan. The headwaters originate near Yushan mountain (EL. 3,952 m), see Figure 2. The river flows through a series of rugged canyons then is emptying into the Taiwan Strait. The length of this river is 171 kilometers and is draining a rugged area on the western side of the Central Mountain Range. Almost half the total basin has an elevation greater than 1,000 m. Only about 20 percent of the basin is lower than 100 meters. The highest elevation of the watershed is located in the northeast region and then de-
scends along the mountain ridge to the southwest region. With an average annual discharge of 8.45 km³/year, Kaoping River is the second largest of Taiwan’s rivers by volume.

The Chaozhou Fault divides the basin into two geological regions [14], the strata in west of the fault is the sedimentary rock mainly included sandstone, siltstone, shale and mudstone. The main strata in east of the watershed is the Chaozhou formation (Co), this formation belongs to a class of Miocene sub-metamorphic rocks, with the majority of which consists of slate and phyllite as well as dark gray quartz sandstones with thickness of over 1000 m around this area.

3. Methodology

There were many landslide-related studies by satellite images in this study region [6,13,15], however the resolution of landslide inventory is proper to qualitative description on landslide, but not adequate accuracy for quantitative study on the impact factor of landslide. To improve the accuracy of database, landslide inventory of this study of Kaoping River basin was developed in 1:5000 scale of high resolution aerial orthophotos and
has been done by manual judgement of experienced expert. A total of 30,834 landslides were documented after Typhoon Morakot as shown in Figure 3. There were 9,582 landslide in sedimentary rock in the west part and 21,252 landslide in sub-metamorphic rocks in the east part, the maximum landslide area is up to 3,510,800 m².

Each landslide size and geometric length are calculated by the GIS software. The slump direction of a landslide is determined as the bearing angle of sliding direction, which was recognized by aerial photo, and digital elevation model, DEM. Along the slump direction, the length of each area is calculated and defines as the landslide length. The width of each landslide is calculated perpendicular to slump direction. The average aspect of each landslide or hillslope is calculated based on a 5 x 5 m grid DEM before the landslides.

Landslides inventory in Kaoping River basin of Typhoon Morakot event is shown in Figure 3. The left part of landslides in green color is located in the region of sedimentary rock. The right part in red is distributed in the sub-metamorphic rocks, slate mainly, region.

4. Landslide Distribution Characters in Different Rocks

4.1 Size of Landslide

The size of each landslide in sedimentary rock and slate region is calculated by GIS software and plotted together in Figure 4 for comparison. A small number of severe landslides such as the size greater than 100,000 m² are not appeared in the Figure. It is found the range of large-size landslide to small-size landslide is very close. That is, most of the landslide size ranges from 500 m² to 14,000 m². However, for each size the number of landslides in slate region is larger than the sedimentary rock region. This indicates the slate is more likely to landslide triggered by rainfall than sedimentary rock.

For both rocks, the number of small-size landslides is higher than the large-size landslides. In order to compare the composition in landslide size for two different rocks, we plot the size distribution in a form like the grain-size-distribution curve known in soil mechanics as Figure 5. In the figure, the %finer for each size is defined as the number of landslide area smaller than this size and divided by the total number of landslide. It is found that the size distribution characteristic is similar for both rocks.
rocks. It means the composition of landslides in size for different rocks (sedimentary rock and slate) triggered by a heavy rainfall is similar. However, at the same number of % finer, the landslide area of slate is bigger than the area of sedimentary rock. This points out that the slate region has the potential of higher landslide magnitude in the rainfall event. For quantifying the landslide area, we develop two formulas of % finer — landslide area relationship for both lithological regions, respectively. The formula is shown as following.

For sedimentary rock,

\[
\log_{10}(\% \text{ finer}) = \frac{\log_{10}(A)}{1.133e^{0.102\log_{10}(A)}}; \quad R^2 = 0.8835
\]  

(1)

For sub-metamorphic rock,

\[
\log_{10}(\% \text{ finer}) = \frac{\log_{10}(A)}{1.094e^{0.104\log_{10}(A)}}; \quad R^2 = 0.9715
\]  

(2)

where, % finer is the number of landslide area smaller than this size and divided by the total number of landslide, A is the landslide area (m²) which the minimum area is limited by 1500 m².

4.2 Geometry of Landslide

According to the shape of landslide as plotted in Figure 6, it concludes that most of the length (a) of landslides range from 50 to 200 m for sedimentary rock, but range from 50 to 500 m for slate. In the same manner, most of the width (b) of landslides range from 50 to 150 m for sedimentary rock, but range from 50 to 300 m for slate. Furthermore, the ratio of length to width (a/b) is calculated for each landslide and plotted in Figure 7. It is founded that the ratio of a/b is almost between 1 to 3 for sedimentary rocks, but for slate ranges from 1 to 6. It means the landslides in slate are narrower shaped than those in sedimentary rock region. This may contribute by the difference of rock structures in two type rocks. However, it needs more field investigation and detail researches. Combining the Figures 6 and 7, we plot the relationship between a/b ratio and landslide size for each rock.

Figure 5. The finer percentage of landslides for each size in slate and sedimentary rock regions.

Figure 6. The distribution of length and width of each landslide area in two different rocks.

Figure 7. The ratio of length to width of each landslide area for two different rocks.
landslide shown as Figure 8. It is also found that most of the size of landslide in slate region is larger than those in sedimentary rocks. The small-size landslide area reveals a higher value of a/b ratio than the large-size landslide. This indicates the small-size landslide is restricted to a narrow range along the slump direction. However, the large-size landslide slumps more extensive wide along the slump direction.

4.3 Impact Factor of Landslide

It is shown in Figure 9 that most of the landslides in both sides of Kaoping River are slumped to the south in sedimentary rock or slate region. However, the most of slope direction as shown in Figure 10 is direction to the west. This means the landslide direction is not coinciding to the direction of slope aspect. It indicates that the slope aspect is not the predominated factor for these landslides in Kaoping River basin.

The Figure 11 illustrated the wind direction of Meinong and Jiaxian weather stations during the period of typhoon [16]. Locations of station can be found in Figure 2, Meinong station located at the start-point of Kaoping River into mountain area, Jiaxian station located at the middle stream of river. The average wind direction in hours is adopted during Aug. 6 to Aug. 10 in this paper. Influence by the track of typhoon and mountain terrain, the wind direction begun in north-west then tuned into south-west, after then South, and last became to South-East. Figure 11 illustrated the wind direction maintain a long duration in south-west and south direction. In this period, it was also the high intensity rainfall occurred from the rainfall record. As shown in Figure 9, the slump direction of landslide was facing to the wind direction

![Figure 8](image8.png)

**Figure 8.** The relationship of a/b ratio and size for each landslide area in two different rocks.

![Figure 9](image9.png)

**Figure 9.** The slump direction distribution of landslides for different rocks.

![Figure 10](image10.png)

**Figure 10.** The distribution of slope aspect for two different rocks.
in the intense rainfall period. For comparison, we also plot both the occurrence percentage of wind and slump directions together in Figure 12. The result shows that there is about 65% of wind direction occurred in the south to south-west directions and about 50% of landslide slumped to south-east to south-west directions. From the Figures 11 and 12, it is concluded that there is a high correlation between the landslide direction and the wind current direction during the typhoon event.

**Figure 11.** The distribution of wind direction at Meinong and Jiaxian weather stations.

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>Meinong</th>
<th>Jiaxian</th>
</tr>
</thead>
<tbody>
<tr>
<td>North</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>North-East</td>
<td>30</td>
<td>10</td>
</tr>
<tr>
<td>East</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>South-East</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>South</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

**Figure 12.** The distribution of occurrence percentage of wind direction and slump direction in the Typhoon Morakot.

<table>
<thead>
<tr>
<th>Wind Direction</th>
<th>Sedimentary rock</th>
<th>Slate</th>
</tr>
</thead>
<tbody>
<tr>
<td>NE</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>E</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>SE</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>S</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>SW</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>NW</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

5. Conclusions

Comparing to topographic aspect in Kaoping River basin, the air current of Typhoon Morakot was an important impact factor to cause the hillslope landslide. There is a high landslide correlation between the directions of a hillslope to the wind current. The number of landslides in slate for each size is larger than the sedimentary rock. This indicates the slope in slate region in Kaoping River basin is more likely to slide, however, the landslide characteristic in size distribution is similar. The landslides in slate region triggered by heavy rainfall are narrower shaped than sedimentary region. The ratio of length to width of landslide area ranges from 1 to 6. The small-size landslide is restricted to a narrow range along the slump direction. On contrast, the large-size landslide slumps more extensive wide along the slump direction. However, it needs more detail researches to investigate the relationship of landslide behavior and the rock lithology in Kaoping River basin.

References


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