Analyzing the Geomorphologic and Geometric Characteristics of Rainfall-induced Shallow Landslides

Shou-Hao, Chiang[1]
[1]Center for Space and Remote Sensing, National Central University, No.300, Jhongda Rd., Jhongli Dist., Taoyuan City, Taiwan 32001
Email: gilbert@csrsr.ncu.edu.tw

KEY WORDS: Shallow Landslide, Geometric Feature, Typhoon, Landslide Geometry Generating Algorithm, Logistic Regression

ABSTRACT: Previous landslide prediction studies have focused on the assessment of location of landslides. Besides location, landslide geometric features (i.e., size and shape) are important factors that influence the distribution and dynamics of landslides. Statistical methods have been used to determine the frequency-size or frequency-volume relationships of landslides, through examining landslide inventories. However, the question of what sets their size and shape is unanswered. In this study, a landslide geometry generating algorithm (LsGA) is developed for quantifying landslide geometric features, including area, perimeter, upper length, lower length, average length and average width, with incorporating an existing landslide inventory and digital elevation model (DEM). The Kaoping watershed in Southern Taiwan is selected as the study area, and the landslide inventory prepared after Typhoon Morakot (August 2009) were applied for LsGA analysis. Landslide geometric features generated by LsGA were then used to correlate to geo-environmental factors, such as slope and contributing area (CA), in a logistic regression model. Preliminary findings are: (1) smaller landslides are generally longer than larger landslides, (2) the upper length of small landslides is relatively wider than large landslides, (3) small landslides are more likely to be observed over gentle slopes, and (4) small landslides are more likely to be observed over lower part of slopes (high CA value, near channels).

1. INTRODUCTION

Landslides are frequently triggered by rainfalls in steep terrain. Previous studies have used empirical approaches by focusing on the modeling of landslide potential sites (e.g. Guzzetti et al. 2007; Montgomery and Dietrich 1994; Chiang et al. 2012; Chang et al., 2014). Besides location, however, landslide geometric feature is another important variable that interacts the distribution and dynamics of shallow landslides (Casadei and Dietrich, 2003). Much progress has been made in determining potential locations of shallow landslides and in defining threshold storms likely to initiate landslides, but the question of what sets their size and frequency is unanswered. Common approaches include examining landslide inventories, and determining the relationship between the frequency of mapped landslides and their size (Hovius et al., 1997; Malamud et al., 2004; Guzzetti et al., 2009). While informative, such statistical considerations do not allow us to explain why a specific landslide is of a particular size or a shape. To our knowledge, there is no systematic method available for quantifying the geometric feature of landslides across landscapes.

In fact, few indices have been designed for describing landslide geometric features. The major two are landslide length L and width W. L is the longest linear axis of the landslide, and W is perpendicular to L. Extending indices such as L×W and L/W are also used to describe the shape of landslides (Casadei and Dietrich, 2003; Taylor and Malamud, 2012). These indices are all based on non-topologic features of landslide polygon, ignoring topologic information, such as the gravity-directional influences from topographic and hydrologic controls. In this project, the "landslide geometry generating algorithm (LsGA)" is developed for quantifying landslide features, by considering flow direction driven by topography. In the study, total 9 indices are designed for the algorithm, and details will be introduced in the followings.

2. STUDY AREA

Study Area is a small proportion of Kaoping watershed is extracted, with the area of 32.4 km^2. In this study, Typhoon Morakot (Aug. 2009) with cumulative rainfall of 1803 mm (in 4.5 days~ 400 mm/day) that has induced a significant number of landslides is selected for the analysis.

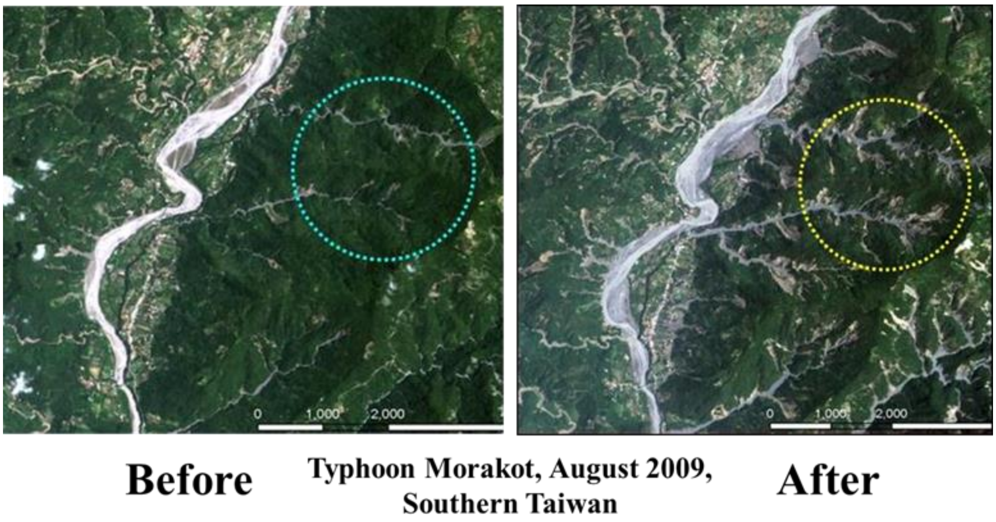

Figure 1. Satellite images (Formosat-2) taken before and after Typhoon Morakot (2009).

3. METHODS AND MATERIALS

3.1 Landslide geometry generating algorithm (LsGA)

The landslide geometry generating algorithm (LsGA) proposed in this study is used to identify the length of the upper boundary, the lower boundary and lateral boundaries of landslide scars. To understand the relative position of each boundary on a slope, the LsGA applys flow direction algorithm for the position determination in a grid format. Fig. 2 demonstrates an example: the upper boundary of a landslide (US) is the intersection boundary for upstream flows flowing into a landslide polygon; the lower boundary of a landslide cell (DS) is the intersection boundary for downstream flows flowing outward downstream non-landslide areas; and when a boundary is not categorized as an upper boundary or a lower boundary, it is defined as the lateral boundary (LS). Table 1 lists the details of the nine indices that can be automatically generated by LsGA.

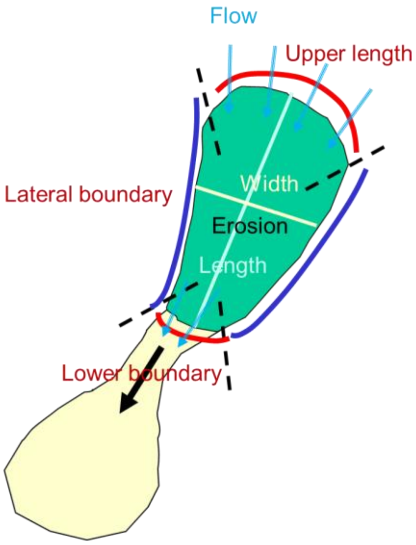

Figure 2. The identification of upper boundaries, lower boundaries and lateral boundaries of a landslide scar.

Table 1. Indices to describe the geometric features of shallow landslides

Index type	Description	Index	Calculation	Notation
Geometry	Area	A_s	$\sum_n a_n$	*n*, the cell number of landslide polygon
	Perimeter	P_L	$U_s+L_s+D_s$	The summation of all boundaries
	Total length of upper	U_S	$\sum_i U_{S_i}$	*i*, the number of upper boundary segments

	boundary			
	Total length of Lower boundary	D_S	$\sum_j D_{S_j}$	*j*, the number of lower boundary segments
	Total length of Lateral boundary	L_S	$\sum_k L_{S_k}$	*k*, the number of lateral boundary segments
	Average Length	$\overline{L_S}$	$L_S/2$	Average length along flow direction
	Average Width	$\overline{W_S}$	$(D_s+U_s)/2$	Average length perpendicular to flow direction
Ratio	Length-to-Width Ratio	α	$\overline{L_S}/\overline{W_S}$	Ratio of average length to average width
	Lower to Upper Ratio	β	D_s/U_s	Ratio of length of lower boundary to length of upper boundary

3.2 Landslide inventory

This study manually prepared the landslide inventory, and particularly, the landslide scars and landslide runouts were mapped separately. For LsGA analysis, terrain variables are derived from 20-m DEM, including slope and contributing area (CA).

Figure 3. Landslide inventory mapped manually with separating landslides (in orange) and runouts (in yellow).

4. RESULS AND DISCUSSION

4.1 Statistics of landslide geometry

With applying the LsGA, three most effectively used for describing the landslide geometric features, Area, Ls-Ws ratio and Us-Ds ratio were selected to discuss their statistical properties (Table 2). First, due to >1 of the averages of Ls-Ws ratio and Us-Ds ratio, it's found in general, the landslide feature analyzed in this study is relative elongate and transvers triangular, which can be relevant to the experience in the field observations. In addition, their probability distributions (Figure 4) show similar pattern, meaning the analysis approach for landslide area (Guzzetti et al., 2009) can be potentially applied for quantifying Ls-Ws and Us-Ds.

Table 2 Statistics of measured area, Ls-Ws ratio and Us-Ds ratio

Geometry	Area (ha)	Ls/Ws	Us/Ds
Mean	11.2	2.8 (>1)	2.6 (>1)
STD	15.5	2.4	3.0
Max	91.2	20	22
Min	1.2	0.4	0.2
Range	90	19.6	21.8

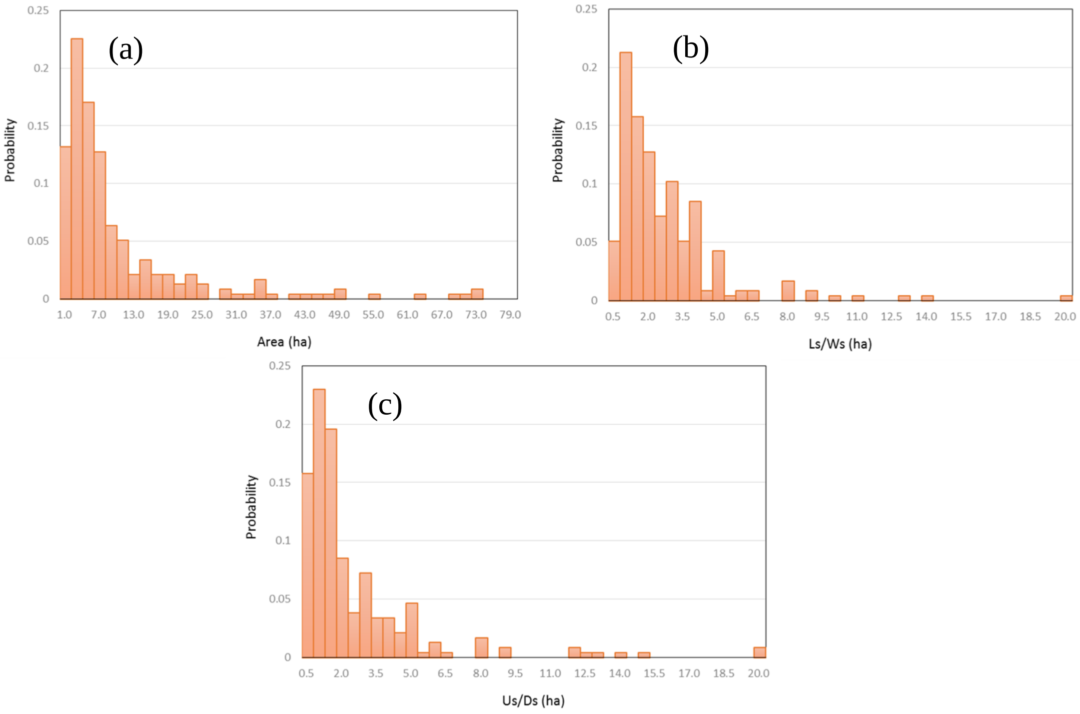

Figure 4 The probability distributions of landslide (a) Area (ha), (b) Ls-Ws ratio and (c) Us-Ds ratio.

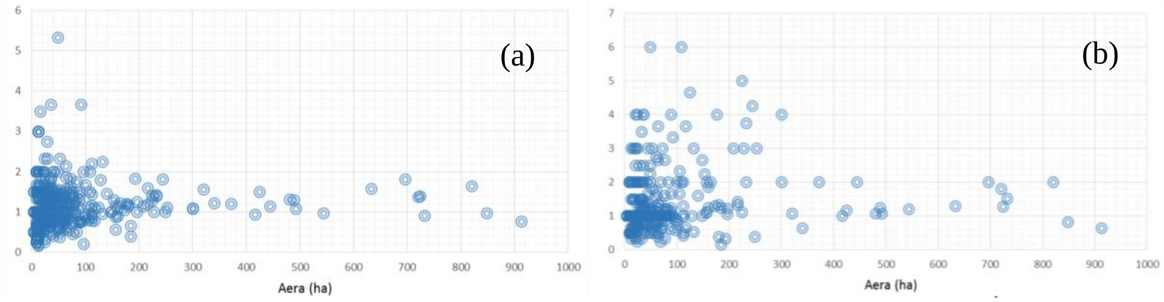

Figure 5. Scatter plots of landslide area vs. (a) Ls-Ws ratio and (b) Us-Ds ratio.

However, the landslide size may be relevant to landslide shape. Figure 5 show that with the increase of landslide size (area, in ha), the Ls-Ws ratio and Us-Ds ratio are close to 1, indicating a more rounded feature than elongated, although high variation of the two shape parameters is presented when landslide size is relatively small.

4.2 Modeling landslide geometry across landscapes

In this study, cluster analysis (k-means) is performed to seek possible categorized landslide features which can be described by their size, Ls-Ws ratio and Us-Ds ratio. Table 3 summarizes the cluster analysis result, and when three group is requested, the outcome produced groups with distinguished difference in size. In general, Group 1 represents small landslides with relatively long shape; Group 2 represents middle size with shape that is relatively not too long; Group 3 represents large landslide with more short-rounded shape.

Table 3 The summary of cluster analysis

Cluster	Group 1	Group 2	Group 3
Area (ha)	5.7	27.6	73.6
Ls/Ws	1.9	1.2	1.0
Us/Ds	2.4	3.9	1.7

* values are group centroid of area, Ls-Ws ratio and Us-Ds ratio

This study further correlated the three groups to topographic variables, slope (slope mean and slope range) and contributing area (mean of logCA and range of logCA), via logistic regression analysis. In is fund that, both small size and large size landslides are prone to present in relatively gentle slopes. However, small ones are over downslopes while large are presented in upslopes. Therefore, the study may conclude the specification of landscape for landslides with different size and shape. Based on the data from this study: small landslides are more likely to be observed over gentle slopes, while small landslides are more likely to be observed over lower part of slopes (high CA value, near channels).

Table 4 Logistic regression result

Model and Variable		Coefficient	P-value
Group 1 (Small)	Intercept	4.836	.079
	Slope (mean)	-.027	<0.05
	Slope range	-.147	<0.01
	logCA (mean)	2.719	<0.01
	logCA range	-2.452	<0.01
Group 2 (Large)	Intercept	7.627	.163
	Slope (mean)	-.104	<0.05
	Slope range	.056	<0.05
	logCA (mean)	-6.123	<0.01
	logCA range	3.740	<0.01

5. CONCLUSION

In this study, a landslide geometry generating algorithm (LsGA) is developed for quantifying landslide geometric features, including area, perimeter, upper length, lower length, average length and average width, with incorporating an existing landslide inventory and digital elevation model (DEM). Based on the landslide inventory prepared after Typhoon Morakot (August 2009), this study uses LsGA to analyze landslide geometric features, and also applied cluster and logistic regression to correlate to topographic variables, including slope and contributing area (CA). Preliminary findings are: (1) smaller landslides are generally longer than larger landslides, (2) the upper length of small landslides is relatively wider than large landslides, (3) small landslides are more likely to be observed over gentle slopes, and (4) small landslides are more likely to be observed over lower part of slopes (high CA value, near channels).

REFERENCE

Casadei, M. and Dietrich, W.E., 2003. Controls on shallow landslide width. In D. Rickermann & C.L. Chen (eds.), Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment; Proceedings of the Third International DFHM Conference. Davos Switzerland, September 10-12, 2003: 91-102.

Chang, K.T., Chiang, S.H., Chen, Y.C., Mondini, A.C., 2014. Modeling the spatial occurrence of shallow landslides triggered by typhoons. Geomorphology 208 137-148.

Chiang S.H., Chang K.T., Mondini A.C., Tsai B.W., and Chen C.Y., 2012. Simulation of event-based landslides and debris flows at watershed level. Geomorphology, 138: 306-318

Guzzetti F., Peruccacci S., Rossi M., and Start CP., 2007. Rainfall thresholds for the initiation of landslides. Meteorology and Atmospheric Physics, 98: 239-267.

Guzzetti, F., Ardizzone, F., Cardinali, M., Rossi, M., Valigi, D., 2009. Landslide volumes and landslide mobilization rates in Umbria, central Italy, Earth Planet. Sci. Lett., 279(3), 222–229.

Guzzetti, F., Mondini A.C., Cardinali M., Fiorucci F., Santangelo M., Chang K.T., 2012. Landslide inventory maps: New tools for an old problem. Earth-Science Reviews 112 (1), 42-66.

Hovius, N., Stark, C. P., Allen, P. A., 1997. Sediment flux from a mountain belt derived by landslide mapping, Geology, 25(3), 231–234.

Malamud, B. D., Turcotte, D. L., Guzzetti, F., Reichenbach, P., 2004. Landslide inventories and their statistical properties, Earth Surf. Processes Landforms, 29(6), 687–711.

Montgomery D.R. and Dietrich W.E., 1994. A physically based model for topographic control on shallow landsliding. Water Resources Research, 30: 1153-1171.

Wieczorek G.F., and Glade T., 2005. Climatic factors influencing occurrence of debris

flows. In Debris Flows Hazards and Related Phenomena, Jakob M, Hungr O. (eds). Springer: Berlin; 325-362.