Landslide interpretation and magnitude-frequency statistics analysis in the Lushan Basin, Taiwan

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Abstract

The Lushan Hot Spring area in Nantou County, Taiwan, suffered serious sediment disasters after typhoons Sinlaku and Jangmi in 2008, and following Typhoon Morakot in 2009. The basin's landsldies after the typhoons brought rain was examined using the frequency-area statistics distribution. The critical state indices attributed to landslide frequency-area distribution are discussed and the marginally unstable characteristics of the study area indicated. The landslides were interpreted from Spot 5 images before and after disastrous events. The results of the analysis show that the power-law landslide frequency-area curves in the basin for different rainfall events-induced tend to coincide with a line. The temporal trend of the rainfall-induced landslide frequency-area distribution shows 1/f noise and scale invariance. The landslide frequency-area distribution could be estimated in advance by three-parameter inverse-gamma distribution with a critical slope of 1.0.

Introduction

Four disastrous typhoons made landfall on Taiwan in 2008. Two medium intensity typhoons, Kalmaegi and Fung-Wong, arrived in July, while two more intense typhoons, Sinlaku and Jangmi, landed in September. These typhoons were characterized by high accumulative rainfall (up to 1,608 mm from Sinlaku) and strong intensity (161 mm/hr during Kalmaegi). In August 2009 Typhoon Morakot, combined with the southwest currents, brought 3,060 mm of rain, exceeding the annual average rainfall of 2,493 mm in Taiwan from 1949 to 2007 (Water Resource Agency, 2008). Morakot brought torrential rains that caused 619 fatalities and economic losses for agricultural of up to NT$ 19,400 million, the second highest losses in the history of Taiwan.

The linear trend of the landslide frequency-area curve for larger landslides in log-log plot can be found through least-squares regression as:

$$\log N(A) = \tau \log A + S \qquad (1)$$

where N(A) is the number of landslides of area A, τ is the slope of the line defining the relationship, and S is the slope intercept.

In the study, the unstable state of the basin after typhoon induced landslide's frequency-area distribution is explored. The purpose of this study is to enhance knowledge of the unstable state of a basin using data from landslides, debris flows, and subsequent sediment disasters.

Study Method

The Lushan Hot Spring area is situated in Nantou County in Central Taiwan. Taluowan Creek and a branch, Mahaipu Creek, flow through the Lushan hot spring area. Stream waters flowing through Taluowan, Mahaipu, and Zhuoshui sub-basins converge on the Wushe reservoir. The contribution area above the hot springs area is roughly 51.7 km^2. The basin elevation ranges from 1,500 to 3,000 m, with the hot spring area located at the lower elevation at 1,500 m (Fig. 1). The DEM analysis shows that the slope is steep, with 86 % of the slope in the basin over 22o (40 %). Over 90 % of the land in the upper basin is used for forests. Land use around the hot spring area largely consists of human activities such as hotels, vegetable farms, and tea.

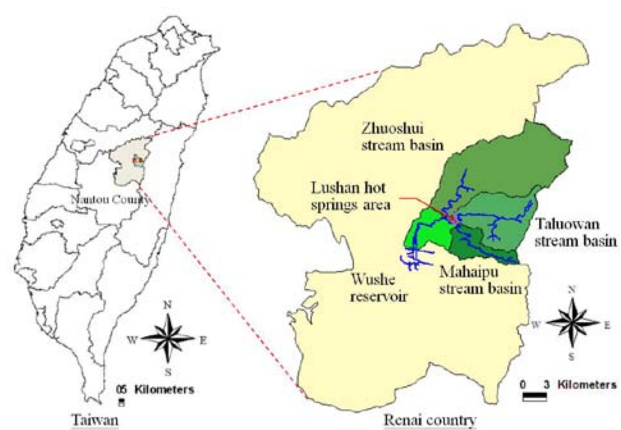

Fig. 1 Site location and elevation in Lushan hot springs area

The average annual rainfall from 1950 to 2008 is about 2,438 mm/yrs, but in 2008 cumulative rainfall reached 3,860 mm in the area. The highest daily rainfall recorded was 433 mm, during Typhoon Sinlaku in September of 2008 (Water Resources Agency, 2008).

Historical rainfall events that induced landslide disasters in the basin include typhoons Herb (1996), Toraji (2001), Mindulle (2004), Sinlaku and Jangmi (2008), and Morakot (2009). The daily rainfall histograms at the Lushan rain gauge station show the cumulative rainfall was 1,275 mm for Herb, 336 mm for Toraji, 584 mm for Mindulle, 1,139 mm for Sinlaku, 540 mm for Jangmi, and 698 mm for Morakot.

The geology in the basin is Lushan layer characterized by fragile argillite, slate, and phyllite (Fig. 2).

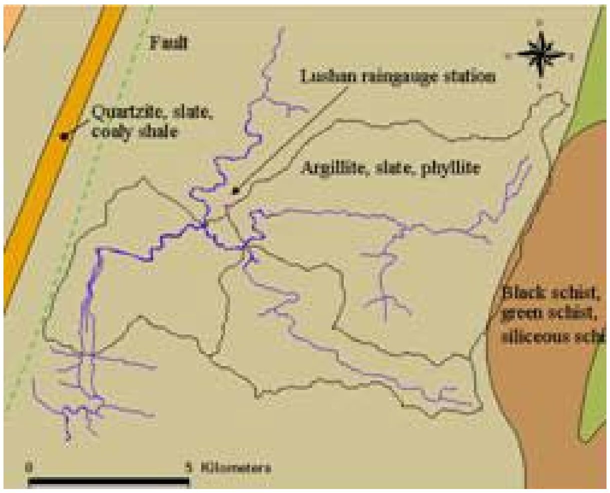

Fig. 2 Geologic conditions for Lushan basin (source CGS, 2008)

The methodology for the case study consists of Spot 5 image interpretation for landslides augmented by field investigation. The pixel spacing of the Spot 5 land-merging images is 2.5 m. Landslides are digitalized by hand in ArcGIS polygon command using the differences of Spot images before and after typhoon events and their areas are calculated. Landslide area and frequency statistics are in log-log plot (power-law) and fit in least-squares regression for larger landslides.

Landslide Evolution

A flash flood occurred in the Lushan Hot Springs area on 15 September 2008 during Typhoon Sinlaku. The flash flood was initiated by a breached landslide dam around 15:00-16:00 PM, as recalled by local residents. The flash flood initiated after a cumulative rainfall of 938 mm and an intensity of 47 mm/hr. The flash flood overwhelmed both stream sides of 50 hotels, collapsing two building, and depositing sediments in the streambed up to 5-6 m deep. The sediment disaster buried one person and injured two (Fig. 3).

The landslide area was 11.08 km^2 (21.4 %) after Typhoon Herb (1996) and 4.08 km^2 (7.9 %) after Typhoon Toraji (2001) (source SWCB, 2001). The landslide area after Typhoon Mindulle (2004) was 1.96 km^2 (3.8 %), after Sinlaku and Jangmi (2008) 3.38 km^2 (6.5 %), and after Morakot (2009) 3.3 km^2 (6.4 %). These landslide areas were interpreted from Spot 5 satellite images with a 2.5-m resolution (Fig. 4). In recorded history, the 1996 landslides exhibited the greatest area, while the lowest number of slides was recorded in 2001. The number of landslides has increased abruptly since 2004 (Fig. 5). The greater area of landslides in 1996 and lower number of landslides in 2001 may be attributable to the lower resolution of the Spot 2 images.

Fig. 3 Field photos before and after sediment disasters (A), C) photos on February 3, 2008 and C), D) on October 18, 2008)

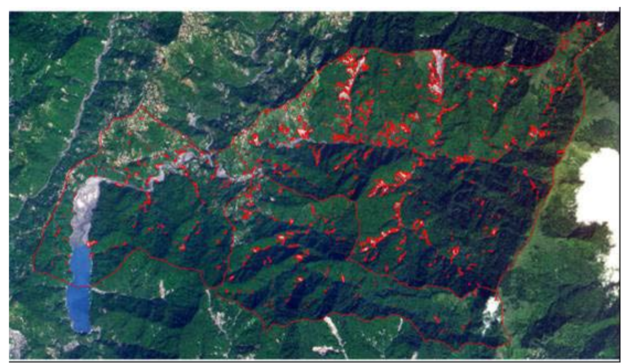

Fig. 4 Historical landslides interpretation from Spot 5 images in the study basin after Typhoon Morakot (taken October 21, 2009))

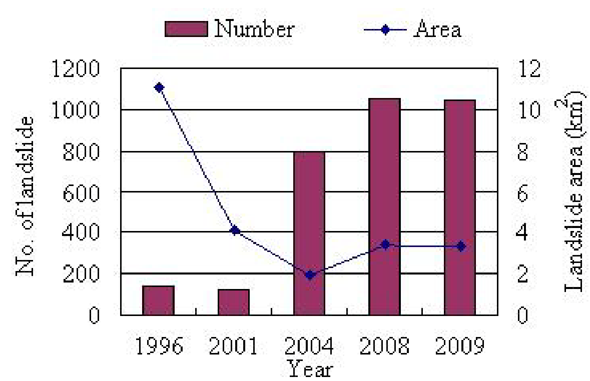

Fig. 5 Changes in number of landslides and total area in the basin in recent years

Results

The landslide frequency-area distribution shows a linear trend for larger landslides in the log-log plot (Fig. 6). The noncumulative frequency-area distribution of historical landslides is calculated based on the derivative of the cumulative number (Nc) of landslides with area greater than or equal to the value A and plotted as a function of the landslide area (A) using the procedure of Crosta et al. (2003). The fitting is performed according to the ($-dNc/dA = bA^{-\beta}$) relationship, and the best-fit power-law model (log-log plot) is obtained by linear regression. The curves have a similar distribution for the historical landslide inventory after Typhoon Mindulle-induced landslides. The curves show that the landslide frequency-area curves are similar for larger landslides (> 2×10^{-3} km^2). The curves for years 2004, 2008, and 2009 are similar, while recent years show a higher frequency of small landslides (< 2×10^{-3} km^2) than the curve in 2004. The least square fits for larger landslides and corresponding rainfall are:

$\ln Y = -1.94 \ln X - 0.99$, $r^2 = 87$ % (for 1996 Typhoon Herb) (2)

$\ln Y = -1.42 \ln X + 1.34$, $r^2 = 88$ % (for 2001 Typhoon Toraji) (3)

$\ln Y = -2.12 \ln X - 1.80$, $r^2 = 93$ % (for 2004 Typhoon Mindulle) (4)

$\ln Y = -2.02 \ln X - 0.64$, $r^2 = 95$ % (for 2008 Sinlaku and Jangmi) (5)

$\ln Y = -1.96 \ln X - 0.46$, $r^2 = 95$ % (for 2009 Morakot) (6)

The landslide frequency-area distribution for larger landslides is closed since 1996 (induced by Typhoon Herb) until recent years (Fig. 6).

The comparable slope in recent years is 2.0 for a non-cumulative landslide frequency-area distribution in the basin and in the unstable state the value is identified as 1.0 in cumulative distribution using the sandpile model (Bak et al., 1988). A higher rainfall results in a larger cumulative frequency of landslides per year and a pre-defined curve for its unstable state is capable of estimating the potential landslide magnitude for hazard mitigation.

Conclusions

Instabilities in the Lushan basin such as landslides, debris flows, and flash floods cause subsequent sediment deposits in flatter areas. Flash flood initiation was attributed to breaches in a landslide dam. The breached dam thus acts as an external force to initiating the processes by which a river basin reaches the unstable state. The landslide magnitude-frequency distribution may be one of the indexes to indicate the state of a basin. If the sediment disaster in 2008~2009 is defined as a worst state of the basin, the exponent slope is 1.0 for a cumulative landslide frequency-area distribution. The landslide power law distribution, breached landslide dam, and attributed flash floods and sediment deposition were all components of the basin from a stable state to an unstable state. The temporal trend of rainfall-induced landslide frequency-area distribution shows the 1/f noise and scale invariance characteristic. In the unstable state, the landslide area probability density fitted by three-parameter inverse-gamma distribution with a critical slope of 1.0 can be used for designation of landslide magnitude.

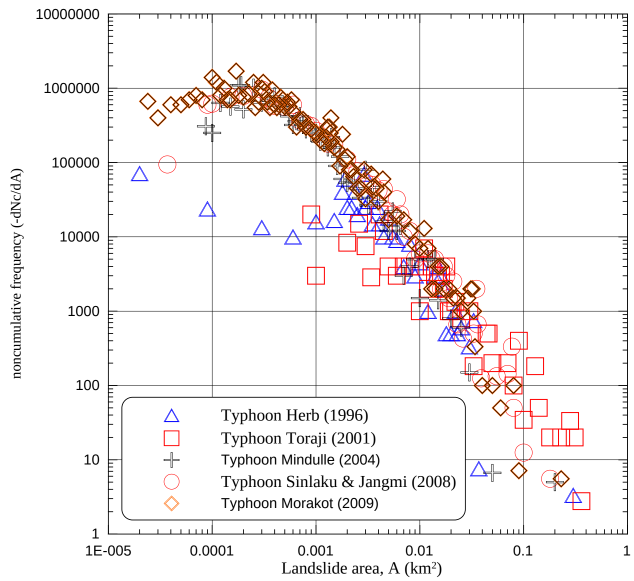

Fig. 6 Landslide frequency-area distribution for the study area

Acknowledgments

Financial supports from the National Science Council of the Republic of Taiwan under contract NSC 99-2625-M-415-003-MY3 is appreciated.

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