Extreme-rainfall Data as a Basis for Landslide Warnings: a Case Study of a Road in Central Taiwan

Ji-Yuan Lin¹, Jen-Chih Chao², Cheng-Lin Wu¹ and Wei-Fang Hsieh⁴

¹ Professor/Chair, Department of Landscape and Urban Design, Chaoyang University of Technology, Taiwan
² Postdoctoral fellow, Department of Landscape and Urban Design, Chaoyang University of Technology, Taiwan
³ Graduate student, Department of Construction Engineering, Chaoyang University of Technology, Taiwan
⁴ Assistant Professor, Department of Landscape and Urban Design, Chaoyang University of Technology, Taiwan
E-mail: Ji-Yuan Lin(jylin@cyut.edu.tw), Jen-Chih Chao(jenchihchao@gmail.com), Cheng-Lin Wu(apy40456@gmail.com), Wei-Fang Hsieh(wfhsieh@cyut.edu.tw)

Abstract. In recent years, an increase in extreme rainfall events linked to global warming has led to increases in the number and intensity of disasters such as landslides, landslips, and debris flows in Taiwan. This study focuses on the impact of such events, especially during typhoons, on County Road 89: the main traffic artery in Renai Township, Nantou County. Specifically, it will use an inverse distance weighting method (IDW) to analyze how rainfall at the four rainfall stations in Nantou, located at Renai, Ruiyan, Cuiuan and Cuihua, may relate to damage events at the 12.3k, 22.53k, 32.5k, 46.3k, and 49k points on County Road 89. Then, landslide road-damage warning ranges will be drawn up using various combinations of data, including cumulative rainfall, maximum rainfall within a 24-hour period, and I-R alert model (I: rainfall intensity, R: cumulative rainfall), with an I-T alert model (I: rainfall intensity, T: rainfall duration) for comparison. This will yield an optimal warning value for the landslide-prone area of the focal road. Finally, data from County Road 89 will be compared against data from the Lishan landslide area, to ascertain whether/how such warning values should differ across geographic areas. The results are expected to usefully inform follow-up disaster prevention planning as well as further academic research on this topic.

1. Introduction
As global warming has intensified, Taiwan’s climate has changed rapidly, and extreme rainfall events have caused higher-than-expected numbers of landslides, rockslides, and debris-flow disasters, especially in mountainous areas. This problem has been magnified by the loosening of geological strata in the wake of the 921 earthquakes that struck the island in 1999. When concentrated rainfall occurs in an already earthquake-damaged area, damage to roads becomes highly likely. This study focuses primarily on the relationship between roadside slope collapses, on the one hand, and on the other, rainfall intensity, cumulative rainfall, rainfall delay, maximum hourly rainfall and maximum 24-hour cumulative rainfall, with the goal of predicting the critical aspects of a severe-rainfall event that are most likely to cause slope damage to a particular busy road in Nantou County, Taiwan. Secondarily, it will look at differences in optimal slope-damage warning values across two
regions. As well as serving as a basis for future research, the results are expected to usefully inform disaster-prevention planning.

2. Study area

2.1. Overview of geographic location and environment

Nantou County Road 89 is located in Renai Township, between Lishan and Wushe, as shown in Figure 1. The focal part of this road, slightly more than 53km long and varying between 3m and 6m in width, connects Provincial Highway 14A in the northeast to Provincial Highway 8 in the southwest. The slopes of some of its sections are quite steep, with relatively broken geology, in part due to serious overuse of the hillsides along the route or farming. In recent years, it has been ravaged by earthquakes, windstorms and floods, and traffic has been interrupted almost every time heavy rain has fallen.

![Figure 1. Damage locations and types, Nantou County Road 89, 2001-2013.](image)

The main geological structures near County Road 89 are the Meixi Fault and Wushe Syncline. Both follow roughly the same route as the road itself, which is located mostly to the west of the syncline’s axis but intersects with it in many places. The stratum in the area is northeast and southwest, and slopes 50°-70° to the southeast. The area’s hillsides are mostly reverse or diagonal slopes, and this is why shallow collapses and rockfalls are so prevalent there. The Meixi fault is a reverse fault, located on the northwest side of the focal road and passing through the slope below it. Because the area’s slate is easily moved by gravity, it is prone to extensive breakage and subterranean migration.

The present paper’s secondary study area, Lishan, is located in Heping Township in central Taiwan, and mainly comprises Lishan Village at the intersection of the main branch of the Zhongheng Highway (also known as Provincial Highway 8) and the Yilan Branch Road (Provincial Highway 7A), at an elevation of 1,950 meters. The elevation in this study area is mainly distributed between 1,400-1,600 meters.

The Lishan area consists of paleo-collapsed land located near the western edge of the ridge beam belt in the west wing of Taiwan’s Central Mountain Range (Liao et al., 2011) [1]. Its stratum belongs to
the central Oligocene Lushan layer. The rock layer in the sliding zone is almost all weak slate, which is cleaved and has a small particle size, making it highly susceptible to weathering and fragmentation. This, in turn, allows water to infiltrate it easily. As well as this high permeability, the sliding layer covering the fresh-rock disc is characterized by its loose structure, uneven particle-size distribution, and low bonding strength. It is mainly composed of weathered slate, slate cuttings and fragments of the clay interlayer.

2.2. Previous disasters

Based on prior work by Jhou (2014), Ye (2015), Liu (2016), and Hu (2018) [2-5], as well as surveys by Jiansheng Engineering Consultants and Kenis Engineering Consultants. Taichung Branch, Soil and Water Conservation Bureau (2016) report on ground-slide monitoring and system maintenance in the Dalishan area noted that monitoring of changes in the stratum and groundwater had been occurring since a remediation project was completed in 1992 [6]. To date, as shown in Figure 2, 14 automatic monitoring stations, each equipped with a TDR stratum-sliding surface-observation system, have been installed in the Dalishan area. These include the R-1 automatic monitoring station on the slope behind Lishan (G-1, B-4, B-5, B-9, B-11, B-13, R-1, C-1, and C-2); the Lishan Hotel, Songmao (S-1, S-2, and S-3); the Old Tribal District (L-1); Xinjiayang (J-1); and four other places. For the purposes hereof, the Lishan Rainfall Station of the Central Meteorological Administration at Fushoushan Farm and the Landslide Monitoring Station (comprising B4 in Lishan Elite District, J1 in Xinjiayang District, L1 in Old Tribal District, and S1 in Songmao District) will be treated as five distinct monitoring stations when it comes to analyzing rainfall data from 2012 to 2016.

**Figure 2.** Distribution map of automatic ground-slide monitoring stations in the Lishan landslide area as of 2016.

Source: Agricultural Committee of the Executive Yuan, with modifications by Wu.
Rainfall in Taiwan is largely seasonal, but also affected by terrain. In the Lishan area, about 73% falls between April and September each year. From 2012 to 2016, 16 rainfields in total, and during Typhoon Morakot in 1999, 19 rainfields in total.

3. Relationship between rainfall and events

3.1. Rainfall interpolation

Rainfall data is necessary for meaningful analysis of slope-collapse events. However, there will not necessarily be a rainfall station in close proximity to where such events occur. Therefore, it is necessary to interpolate data from the nearest rainfall stations to arrive at an estimate of the rainfall at the location of the slope collapse. In this study, therefore, four rainfall stations near Nantou County Road 89 were used for this purpose – namely, Cuiluan, Ruiyan, Cuifeng, and Renai – and inverse distance weighted interpolation (IDW) used to weight the known rainfall data. In IDW, the farther the distance, the smaller the weight, and vice versa, as per the following formula,

\[ Z_0 = \frac{\sum_{i=1}^{n} Z_i \frac{1}{d_i^k}}{\sum_{i=1}^{n} \frac{1}{d_i^k}} \]  

3.2. Rainfall events

The concept of a “rain event” is useful in discussing how rainfall data relates to slope damage. There are six main methods for separating rain into rain events, each of which is explained in Table 1. The fifth and sixth methods were proposed by Chan (2002) as improvements upon the third and fourth methods, respectively. This study utilized the fifth method for rain-event division, because the time of the rain field cut by method 1, 2, and 4 is too long, and the rain delay and rainfall intensity of method 5 are between methods 3 and 6, the results obtained by the rain field cutting are relatively moderate [7].

Table 1. Six rain-event separation methods.

| Method | Correction method | Start of rain | End of rain |
|--------|------------------|---------------|-------------|
| 1      | No rain for previous 24 hours | No rain for 24 consecutive hours |
| 2      | No rain for previous 12 hours | No rain for 12 consecutive hours |
| 3      | Hourly rainfall is greater than 4mm | Rainfall is less than 4mm for three consecutive hours |
| 4      | Cumulative rainfall of 10mm in the first 24 hours | Cumulative rainfall is less than 10mm for 24 hours |
| 5      | Hourly rainfall is greater than 4mm | Rainfall is less than 4mm for six consecutive hours |
| 6      | Cumulative rainfall of 10mm in the first 12 hours | Cumulative rainfall is less than 10mm for 12 hours |

4. Results and discussion

In this study, rainfall during the 19 discrete focal rainfall events in the Lishan Landslide Area and on Nantou County Road 89 were compared against one another, and the warning values of the I-T Model, I-R model, R-I model (R: cumulative rainfall, I: rainfall intensity) and other modes of alter model were analyzed. The results are presented in Figures 3, 4, and 5. Among all these events, only during the 69 torrential rains and Typhoon Sula did accumulated rainfall reach the Lishan Automatic Monitoring Station’s rainfall-attention benchmark value: i.e., cumulative rainfall of 1) more than 250mm in 24 hours and 2) more than 350mm in 48 hours. For Typhoon Fanbin, Typhoon Suli, Typhoon Hare, Typhoon Rhododendron and Typhoon Meiji, the cumulative total rainfall averaged about 200mm. Because there was no damage case for reference in the Lishan landslide area, our analysis is mainly based on large-displacement and small-displacement cases.
Figure 3. I-R warning value of Lishan and Nantou 89th country roads.

Figure 4. I-T alert values for Lishan and Nantou County Road 89.

Figure 5. Lishan and Nantou County Road 89 RI warning values.
It can be seen from Figures 3 and 4 that when R=250mm, most of the damage or large-displacement cases at I=5mm/h will occur. Such results are consistent with those regarding critical rainfall in the Renai Township debris flow, reported by debris flow disaster prevention information. Using the RI alert model proposed by Chen et al. (2013), many studies have only considered the effect of a single factor, usually accumulated rainfall or rainfall intensity. In our proposed RI warning model, on the other hand, the impact of maximum hourly rainfall and maximum 24-hour cumulative rainfall are also considered as potential damage factors [8]. The latter model roughly indicates that the rainfall warning value for Nantou County Road 89 is RI=65 (cm)^2/h, whereas that for the Lishan landslide area is much lower.

5. Conclusion
The study used IDW to analyze 19 discrete extreme rainfall events in the Lishan landslide area and on Nantou County Road 89, and thereby identify the corresponding rainfall-warning value ranges for each of these two sites. The conclusions of such analysis are as follows.
First, when average rainfall intensity on Nantou County Road 89 was greater than 10mm, or the rainfall delay exceeded 18 hours, or when average rainfall intensity was greater than 7mm, there was likely to be damage to slopes adjoining the road.
Second, in the Lishan landslide area, about 75% of cases did not result in slopes being destroyed. In the Nantou road-destruction cases, the average delay was 52 hours, rainfall intensity was 11.13mm/h, and total accumulated rainfall was 578.5mm; whereas in Lishan, the average delay was 29 hours, rainfall intensity was 9.31mm/h, and total accumulated rainfall was 270mm (i.e., less than half of the average total accumulated rainfall of the Nantou damage cases). The Lishan case had fewer large-displacement cases because of its shorter rainfall times and less rainfall.
In 1993, a number of drainage-remediation projects were completed in Lishan District. However, rainfall events from 2013 to 2016 did not affect the groundwater level in this area, making the interrelationship of rainfall, groundwater and displacement in the ground-slide area more difficult to discern. Although the proposed RI warning model did not have access to accurate critical rainfall values, it nevertheless proved capable of approximating the critical-rainfall trend.

6. References
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