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Rainfall intensity–duration thresholds for the initiation of landslides in Zhejiang Province, China

Tuhua Ma [a], Changjiang Li [a,*], Zhiming Lu [b], Qiyun Bao [c]

[a] Zhejiang Information Center of Land and Resources, 310007 Hangzhou, PR China
[b] Computational Earth Science Group (EES-16), Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[c] Zhejiang Institute of Geology and Mineral Resources, 310007 Hangzhou, PR China

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ABSTRACT

Zhejiang Province, located in the southeast coastal region of China, is highly prone to rainfall-triggered landslides because of its geologic, geomorphologic, and climatic settings. The rainfall–landslide relationship is critically important for predicting rainfall-induced landslides. This study defines landslide-triggering rainfall intensity–duration thresholds for the entire Zhejiang region; and the 62 individual areas that comprise the region, based on 1569 shallow landslides which occurred from 1990 to 2013 and their corresponding detail rainfall records from 2457 rain gauges in the region. The results indicate that the rainfall thresholds vary spatially over the region. For rainfall durations from 1 to 24 h, the threshold tends to increase from the northwestern part of Zhejiang to its southeastern coastal region; and it is lower in the central and coastal hill–basin regions than that in the western and southern mountainous regions. Variability of the threshold in space is mainly affected by the slope-forming materials and terrain slope gradients. Different soil types have different thresholds, and the thresholds for weathered rock slides are generally higher than those for soil slides. For the soil–weathered rock on slopes, the slope gradient has no obvious influence on the thresholds when the slope angle is <30°; the thresholds have an obviously increasing trend with the increase of slope angles in the range of slope angles from 30 to about 40°; and when slope angle is larger than about 40°, the thresholds rapidly decrease with gradient on the whole. These findings will facilitate the improvement of warning systems for regional rainfall-triggered landslides.

1. Introduction

Rainfall-induced landslides are well known to have a wide spatial and temporal distribution and a high frequency of occurrences (Campbell, 1975; Lumb, 1975; Nilsen et al., 1976; Crozier, 1986; Wieczorek, 1987; Glade et al., 2000; Aleotti, 2004; Li, 2004; Guzzetti et al., 2007; Keefer and Larsen, 2007; Sassa and Canuti, 2008; Li et al., 2010, 2011, 2012; Montrasio et al., 2011, 2012; Giannecchini et al., 2012; Dowling and Santi, 2014; Ma et al., 2014).

The rainfall–landslide relationship is critically important for predicting rainfall-induced landslides. Caine (1980) collected a set of rainfall data near 73 shallow landslides reported worldwide and obtained a threshold envelope to discriminate critical triggering conditions for the landslides by fitting the rainfall conditions on an intensity (I)–duration (D) graph. Following this approach, various global, regional, or local rainfall thresholds for triggering landslides have been presented in the literature (e.g., Cannon and Ellen, 1985; Wieczorek, 1987; Cannon, 1988; Larsen and Simon, 1993; Wilson and Wieczorek, 1995; Wieczorek et al., 2000; Aleotti, 2004; Guzzetti et al., 2007, 2008; Brunetti et al., 2010; Sengupta et al., 2010; Giannecchini et al., 2012). Besides the I–D thresholds, thresholds based on the total event rainfall (R) (Campbell, 1975), rainfall event (E)–duration (D) thresholds (Cannon and Ellen, 1985), and rainfall event (E)–intensity (I) thresholds (Jibson, 1989) were also proposed in the literature. In this study, we focus on the I–D threshold.

Landslides induced by the rainfall are the result of the conjunct action of water and several other factors such as geological, topographical, and soil conditions as well as vegetation. These spatially varying factors will result in variation of rainfall thresholds for the initiation of landslides from location to location in an area (Li et al., 2010). However, except for a few researchers who studied the lithological and seasonal influence on rainfall thresholds (Peruccacci et al., 2012), the influence of soil, terrain, and vegetation on rainfall thresholds has rarely been systematically investigated. This may be attributed to the lack or deficiency of precise information on the locations and the times (dates) of landslide occurrences and the underlying rainfall conditions associated with these landslides. The key to the determination of rainfall intensity–duration thresholds for the initiation of landslides in an area is to acquire accurate information on the locations and the dates of landslide occurrences and the rainfall conditions that resulted in the slope failures in the area. However, in many countries and

* Corresponding author.
E-mail addresses: zjigmr@mail.hz.zj.cn (C. Li), zhiming@lanl.gov (Z. Lu).

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regions, landslide inventory maps are created mainly by means of landslide interpretations from aerial photographs or satellite images (Casadei et al., 2003; Guzzetti, 2006). Annual landslide inventories are rarely done; instead, inventory maps are generated sometimes years after major landslide events (Casadei et al., 2003). This means that for most of the mapped landslides the exact date of occurrence is often unknown, which makes it difficult to correlate a landslide with its triggering event (Van Westen et al., 2006) and to investigate the influence of topographical, lithological, and soil conditions, as well as vegetation on rainfall thresholds.

Mountainous and hilly terrain accounts for about two-thirds of the land surface in China. Landslides occur almost every year in the country's hilly and mountainous regions and result in significant losses of life and property. For instance, from 1995 to 2011, about 16,000 people died caused by landslides in China (Liu et al., 2009; Li and Ma, 2011). Serious casualties such as the catastrophic debris flow event triggered by an intense rainfall on 7 August 2010 in the Zhouqu County of Gansu Province, China, destroyed the entire Zhouqu town and killed 1364 people with an additional 401 people listed as missing (Li and Ma, 2011). However so far, only a few researchers explored the relationship between the occurrence probability of landslides and the rainfall level (e.g., Li et al., 2011; Ma et al., 2014), and almost no work has been done on the investigation of rainfall intensity–duration relationship for the initiation of landslides in China.

Zhejiang Province, located in the southeastern coastal region of China, belongs to a subtropical monsoon zone. Owing to its geologic, geomorphologic, and climatic settings, the region is highly prone to rainfall-triggered landslides (Li, 2004). In 2003, a real-time prediction system for the spatial and temporal probability of rainfall-triggered landslides in Zhejiang Province was developed (Li et al., 2010). The verification studies on the performance of the system during the period from 2003 to 2007 in the region show that the system is generally effective and can provide useful and timely guidance to prepare for landslide hazards (Li et al., 2010). However, the prediction using this system has some uncertainties because of the limited data available. In the last decade, an improvement on the landslide inventory in the Zhejiang region has been significant, and new data obtained from intensive field surveys are constantly added to the inventory. Rainfall thresholds, defined as the value of rainfall intensity that is associated with slope failure events observed in the past for a given rainfall duration, may be used as a supplement to the prediction system. Therefore, in this study, based on 1569 shallow landslides from field surveys and their corresponding hourly rainfall records from 2457 rain gauges during the 1990–2013 period in the region, we determined rainfall intensity–duration (*I*–*D*) thresholds in its 62 hilly and mountainous counties and cities (the delimitation of the different counties/cities and their area codes are given in Table 1 and Fig. 9) that are prone to rainfall-triggered landslides; and we discussed the spatial variability of the threshold and its correlation with soil types and terrain slopes.

2. Study area

The study area, Zhejiang Province, is located in the southeastern coastal region of China (Fig. 1) and lies between latitudes 27°02′ N and 31°11′ N and longitudes 118°01′ E and 123°25′ E, with a continental area of 101,800 km^2. This province, with a population of about 70 million, is one of the most concentrated regions in terms of population and one of the most economically developed areas in China. As shown in Figs. 1 and 2, the region is complex in landform and greatly different in relief. The hilly and mountainous terrain with elevation above 300 m accounts for 70.6% of its total area, some basins with different sizes are scattered among the hills and mountains, and the entire terrain is inclined from the southwest toward the northeast and drops in a step form. The mountainous areas with elevation above 500 m are mainly distributed in the west and south where terrain tends to be steep

Table 1
Rainfall intensity (*I*)–duration (*D*) thresholds for the initiation of landslides in different areas of Zhejiang Province.[a]

♯	Code	Area	Landslide type	Number of landslides	Equation	Range (h)
1	HZH	Huzhou City	S, DF	4	$I = 30.50D^{-0.55}$	$1 \le D \le 24$
2	DGX	Deqing County	S, DF	23	$I = 28.43D^{-0.37}$	
3	CXG	Changxing County	S, DF	7	$I = 45.38D^{-0.48}$	
4	AJI	Anji County	S, DF	37	$I = 42.00D^{-0.38}$	
5	HGH	Hangzhou City	S, DF	5	$I = 25.29D^{-0.28}$	
6	TLU	Tonglu County	S, DF	16	$I = 36.62D^{-0.42}$	
7	CAZ	Chunan County	S, DF	12	$I = 28.59D^{-0.43}$	
8	XIS	Xiaoshan District	S	2	$I = 25.81D^{-0.47}$	
9	JDS	Jiande City	S	49	$I = 39.94D^{-0.44}$	
10	FYZ	Fuyang City	S	15	$I = 38.17D^{-0.41}$	
11	YHS	Yuhang District	S, DF	13	$I = 32.63D^{-0.31}$	
12	LNA	Linan City	S, DF	30	$I = 27.00D^{-0.38}$	
13	SXG	Shaoxing City	S, DF	13	$I = 42.29D^{-0.43}$	
14	XCX	Xinchang County	S, DF	26	$I = 44.26D^{-0.45}$	
15	ZHJ	Zhuji City	S, DF	46	$I = 30.23D^{-0.43}$	
16	SGZ	Shengzhou City	S, DF	15	$I = 37.54D^{-0.46}$	
17	JHA	Jinhua City	S	16	$I = 38.36D^{-0.41}$	
18	WYX	Wuyi County	S, DF	5	$I = 32.05D^{-0.65}$	
19	PJG	Pujiang County	S, DF	7	$I = 31.61D^{-0.51}$	
20	PAX	Panan County	S, DF	7	$I = 50.24D^{-0.45}$	
21	LXZ	Lanxi City	S	17	$I = 40.14D^{-0.42}$	
22	YWS	Yiwu City	S	8	$I = 61.97D^{-0.54}$	
23	DGY	Dongyang City	S, DF	7	$I = 35.88D^{-0.53}$	
24	YKG	Yongkang City	S	1	$I = 18.85D^{-0.33}$	
25	QUZ	Quzhou City	S	32	$I = 56.67D^{-0.62}$	
26	CSN	Changshan County	S	14	$I = 60.35D^{-0.64}$	
27	KHU	Kaihua County	S, DF	5	$I = 43.83D^{-0.60}$	
28	LGY	Longyou County	S	9	$I = 50.61D^{-0.52}$	
29	JIS	Jiangshan City	S	36	$I = 41.26D^{-0.58}$	
30	LSD	Lishui City	S, DF	16	$I = 29.36D^{-0.45}$	
31	LGQ	Longquan City	S, DF	16	$I = 45.44D^{-0.59}$	
32	QTN	Qingtian County	S, DF	22	$I = 51.13D^{-0.43}$	
33	YNH	Yunhe County	S, DF	15	$I = 55.46D^{-0.43}$	
34	QYX	Qingyuan County	S, DF	77	$I = 50.36D^{-0.39}$	
35	JYP	Jinyun County	S	7	$I = 32.71D^{-0.41}$	
36	SCZ	Suichang County	S, DF	60	$I = 52.20D^{-0.62}$	
37	SGY	Songyang County	S	25	$I = 26.60D^{-0.50}$	
38	JGN	Jingning District	S, DF	34	$I = 55.17D^{-0.42}$	
39	NGB	Ningbo City	S, DF	22	$I = 62.24D^{-0.45}$	
40	XSZ	Xiangshan County	S, DF, S/W	10	$I = 71.65D^{-0.43}$	
41	NHI	Ninghai County	S, S/W	29	$I = 77.48D^{-0.48}$	
42	YYO	Yuyao City	S, DF	142	$I = 45.46D^{-0.35}$	
43	CXI	Cixi City	S, DF	2	$I = 40.00D^{-0.36}$	
44	FHU	Fenghua City	S, DF	6	$I = 51.09D^{-0.36}$	
45	TZZ	Taizhou City	S, S/W	25	$I = 122.87D^{-0.53}$	
46	YHN	Yuhuan County	S	1	$I = 58.94D^{-0.39}$	
47	SMN	Sanmen County	S, DF	11	$I = 48.24D^{-0.43}$	
48	TTA	Tiantai County	S, S/W	5	$I = 78.33D^{-0.48}$	
49	XJU	Xianju County	S	50	$I = 57.24D^{-0.43}$	
50	WLS	Wenling City	S/W	1	$I = 146.36D^{-0.55}$	
51	LHI	Linhai City	S, DF	5	$I = 53.28D^{-0.39}$	
52	WNZ	Wenzhou City	S	49	$I = 40.75D^{-0.34}$	
53	DTO	Dongtou County	S	5	$I = 85.71D^{-0.41}$	
54	YJX	Yongjia County	S, DF	30	$I = 51.85D^{-0.39}$	
55	PYG	Pingyang County	S	79	$I = 42.77D^{-0.24}$	
56	CNA	Cangnan County	S, DF	29	$I = 59.45D^{-0.35}$	
57	WCZ	Wencheng County	S, DF	29	$I = 55.97D^{-0.38}$	
58	TSZ	Taishun County	S	74	$I = 57.80D^{-0.43}$	
59	RAS	Ruian City	S, DF	42	$I = 62.71D^{-0.36}$	
60	YQZ	Yueqing City	S, S/W, DF	148	$I = 114.75D^{-0.51}$	
61	ZOS	Zhoushan City	S, S/W	25	$I = 85.16D^{-0.43}$	
62	DSH	Daishan County	S	1	$I = 85.71D^{-0.41}$	
63	ZJ	Zhejiang Province (Mean of all areas)	S, S/W, DF	1569	$I = 52.86D^{-0.45}$	

[a] Area, the area where the threshold was defined. Landslide type: S, soil slide; S/W, soil and/or weathered rock slide; DF, debris flow.