Study on the combined threshold for gully-type debris flow early warning

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Abstract

Gully-type debris flow induced by high-intensity and short-duration rainfall, frequently cause a great loss of properties and causalities in mountainous regions of Southwest China. In order to reduce the risk by geohazards, early warning systems have been provided. A triggering index can be detected in an early stage by the monitoring of rainfall and the changes in physical properties of the deposited materials along debris flow channel. Based on the method of critical pore pressure for slope stability analysis, this study presents critical pore pressure thresholds in combination with rainfall factors for gully-type debris flow early warning. The Wenjia gully, which contains an enormous amount of loose materials, was selected as a case study to reveal the relationship between the rainfalls and pore pressure, which can be used as a combined warning threshold. A three-level early warning system (Zero, Attention, and Warning) is adopted and the corresponding judgement conditions are defined in real-time. Based on this threshold, several rainfall events in recent years have been validated to prove that such a comprehensive threshold may be a reliable approach for the early warning of debris flows to safeguard the population in the mountainous areas.

Keywords: gully-type debris flow, pore pressure, rainfall threshold, early warning

1. Introduction

Debris flows occur in mountainous area in Southwest China every year during the rainy season. Gully-type debris flows are mainly triggered by high-intensity short-duration rainfall causing a runoff-induced effect. They are partly initiated by shallow landslides distributed along the gullies (Kean et al. 2013). The fast growth of the population and economic development in these areas increase the frequency of catastrophic accidents and consequent socio-economic losses. The Wenchuan earthquake on May12, 2008, Yushu earthquake on April 14, 2010, Lushan earthquake on April 20, 2013, Ludian earthquake on August, 3 2014 and the Nepal earthquake on April, 25 2015 trigged thousands of landslides and cracked mountains which made these areas prone for debris flow development under rainstorm conditions (Shieh et al. 2009). In the Chi-Chi earthquake area Taiwan, numerous co-seismic landslides were triggered as well, causing the continuous triggering of debris-flows during 10 years after the earthquake (Yu et al. 2013b). These catastrophic events have greatly shocked the local people and government, because of the human vulnerability to natural hazards as well as the lack of knowledge on natural disaster prevention and mitigation. For the descendant, there is an urgent demand for an effective method to reduce the hazard and risk. Therefore, researchers have been working on the forecast of debris flow occurrence and setting up of early warning systems for several decades. At the regional scale, the methods for shallow landslides early warning are mostly based on statistical models which have already been proved their importance in landslide prevention and mitigation (Baum and Godt 2009; Guzzetti et al. 2007b; Keefer et al. 1987; Segoni et al. 2014; Shuin et al. 2012; Tropeano and Turconi 2004). Generally, one or two parameters were selected for the assessment of rainfall thresholds, e.g. rainfall intensity and duration (Cannon et al. 2008; Guzzetti et al. 2007a; Guzzetti et al. 2007b; Keefer et al. 1987), antecedent precipitation (Glade et al. 2000), and cumulative rainfall(Guo et al. 2013). Besides, Baum and Godt (2009) presented a combination threshold, including cumulative rainfall threshold, rainfall intensity-duration threshold and antecedent water index or soil wetness for the shallow landslide forecasting. At the local scale, physical methods (e.g. numerical simulation) were used to find relationships among rainfall, soil properties, and pore pressure and their contributions to slope stability (Chae and Kim 2011; Iverson 1997; Peng et al. 2014; Thiebes 2012; van Asch et al. 2013). However, detailed information related to landslide triggering are required to establish the site-specific thresholds, which are very difficult to extrapolate to other places due to the large variation in soil properties between different regions. In the Chenyulan River Watershed of Taiwan, debris flows were frequently triggered by Typhoons. Yu et al. (2013a) selected several decade identified factors related to topography, geology, and hydrology, to develop a normalized critical rainfall factor combined with an effective cumulative precipitation and maximum hourly rainfall intensity index for the forecast of gully-type debris flows. The model which is partly based on a runoff-induced mechanism has been successfully applied to the Wangmo River catchment, Guizhou Province, Southwest China (Yu et al. 2014).

In Southwest China, the strong earthquake shocks caused a significant rise in the frequency of debris flow. Researchers have already paid great attention to the mechanism, movement characteristics, and thresholds of debris flow in these shocked areas (Guo et al. 2013; Huang et al. 2015a; Yin et al. 2010; Yu et al. ; Zhou and Tang 2013). The long-term effect by earthquakes cause the region become a high risk area, and particularly the gullies in mountain with no debris flows before become the debris flow gullies at present. Unfortunately, there is a significant lack of available data in these areas, e.g. the rainfall events which are very important to understand the debris flow triggering threshold. But in the earthquake shocked regions, numbers of unstable slope or loose deposited material distributed along the catchments. Therefore, rainfall is not the only triggering factor for debris flow occurrence. Thus, during this study, pore pressure in slope stability analysis have been considered for gully-type debris flow forecasting. The goal of the here presented study is to propose a comprehensive method for such kind of debris flow early warning by real-time monitoring of rainfall and changes in pore pressure in the deposited material along channel in Southwest China. The infinite slope stability analysis was applied to identify the critical stability conditions of the deposited material. Then, a comprehensive warning threshold for rainfall and critical pore pressure will be presented, which includes both rainfall conditions and soil properties. Finally, verification and revision has been discussed to search a practical and useful method for reducing the risks of debris flows in Southwest China.

2. Study area

The Wenjia gully is located at the north of Qingping town, Mianzhu city, Sichuan province, Southwest China, and has a catchment area of 7.8 km^2 and a 5.2 km long main channel, as shown in Fig. 1. The elevation of this study area ranges from 860 m to 2,400 m above sea level (Fig. 2a), and the main valley with slope inclinations between 30° and 70° has been deeply incised by the Mianyuan river. The average yearly temperature is about 16 ℃, and the climate is mild semi-tropical and moist with abundant rainfall and four distinguishable seasons. Eighty percent of the rainfall is concentrated in three months from July to September.

Before the Wenchuan earthquake on May12, 2008, the Wenjia catchment was covered by rich vegetation, and the channel was smooth and stable, as shown in Fig.3 (a). At that time, few geological disasters occurred in this region. Therefore, many farmers settled down at the foothills along the Mianyuan River. Qingping town downstream of the Wenjia channel's outlet (Fig 3 a & b). During the earthquake, a giant landslide occurred upstream in the catchment at the top of the watershed, which generated abundant co-seismic rock fall material and finer landslide deposits on a platform with an elevation of 1,300 m above sea level (Fig. 1, the photograph at left bottom of the main map). These loose solid erodible materials could easily transform into debris flows during a rain storm. Shortly after the earthquake on Sep. 24, 2008, one rainfall event caused the first debris flow in this gully. The catastrophic debris flow triggered by a heavy rainfall on August 13, 2010, with a peak discharge of 1,530 m^3/s and a total volume of 4.5×10^6 m^3, caused many victims and the burying of reconstructed houses, most of the downstream check dams along the channel (Yu et al. 2012).

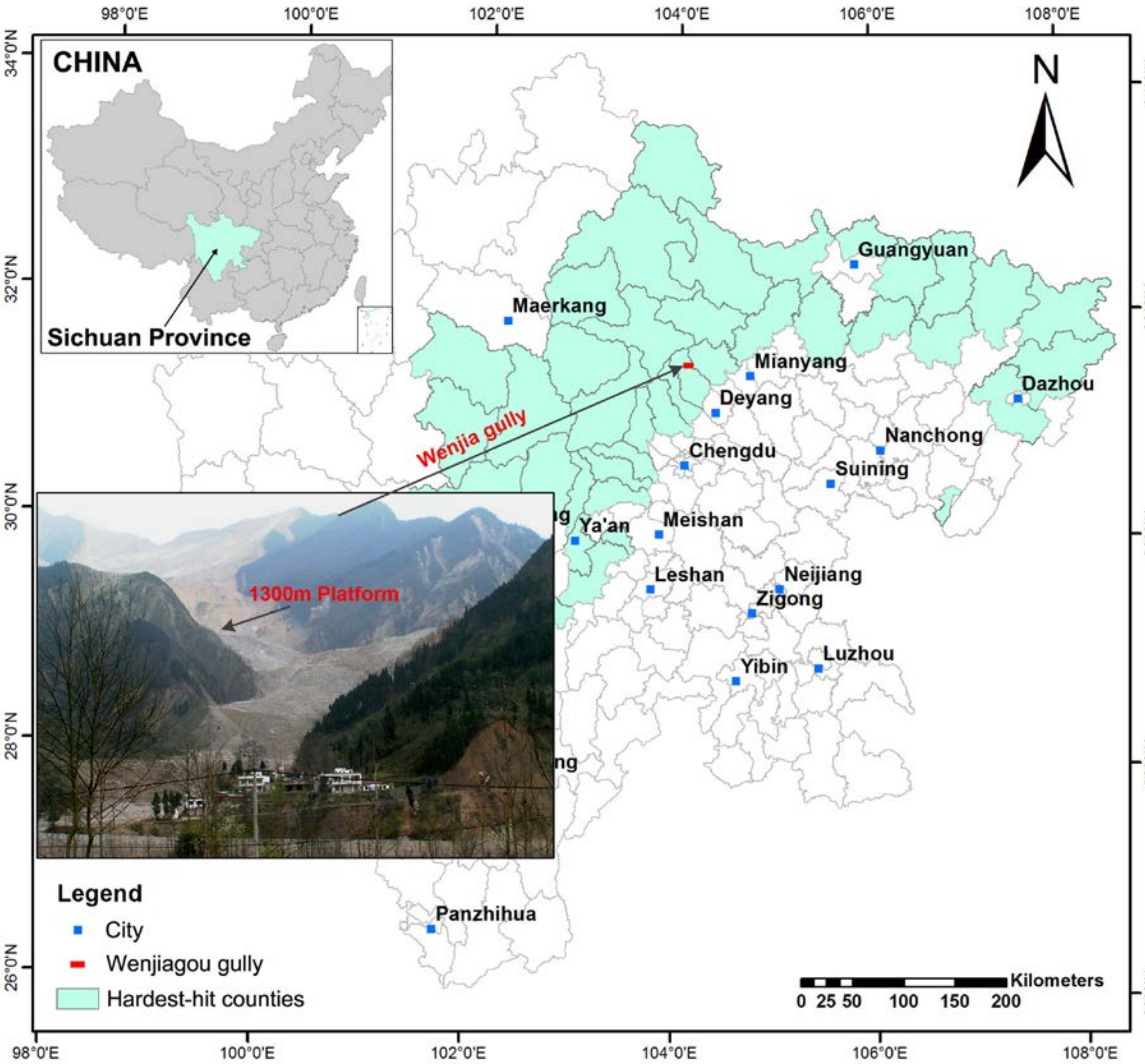

Fig. 1. Location of Wenjia gully modified from Huang et al. (2013). The inset photograph of Wenjia gully at the left bottom was taken from the other side of Mianyuan River on August 10, 2008.

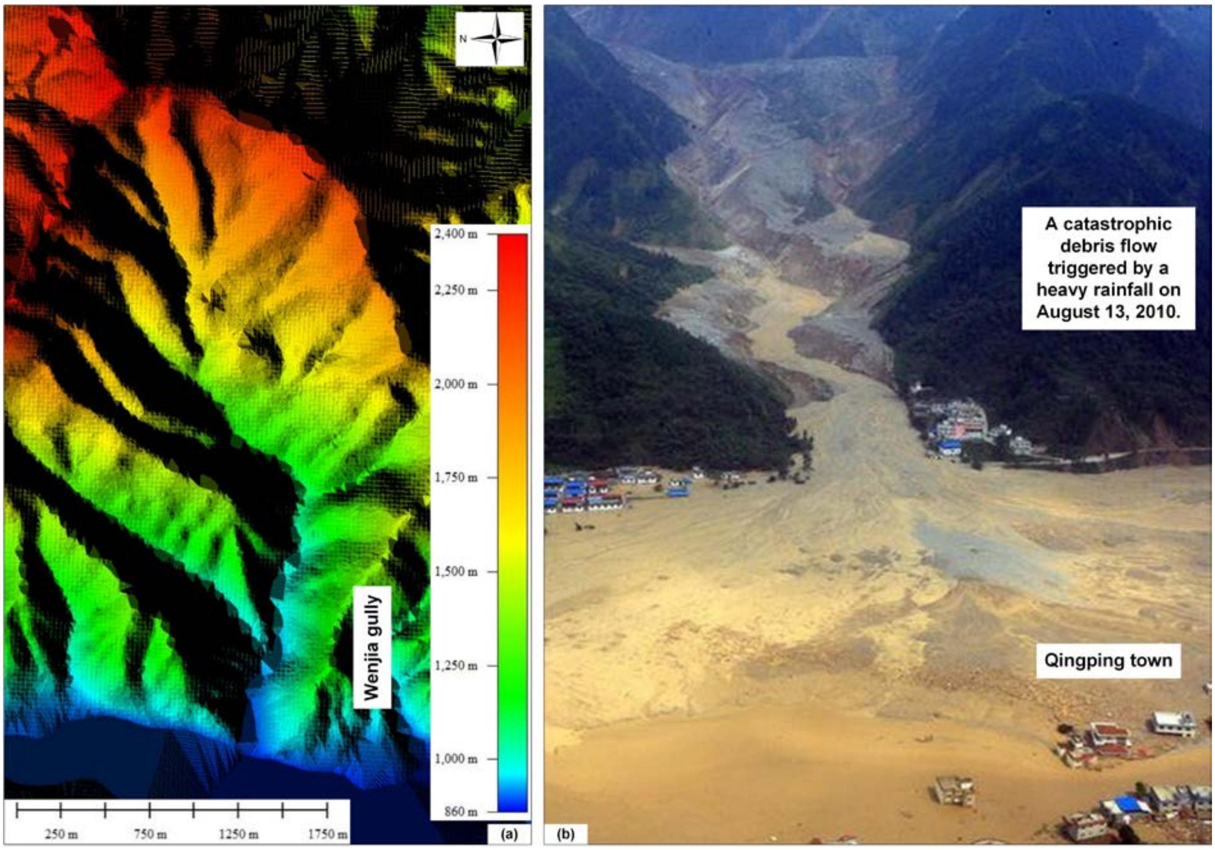

Fig. 2. DEM map of Wenjia gully and photo on the debris flow event (August 13, 2010)

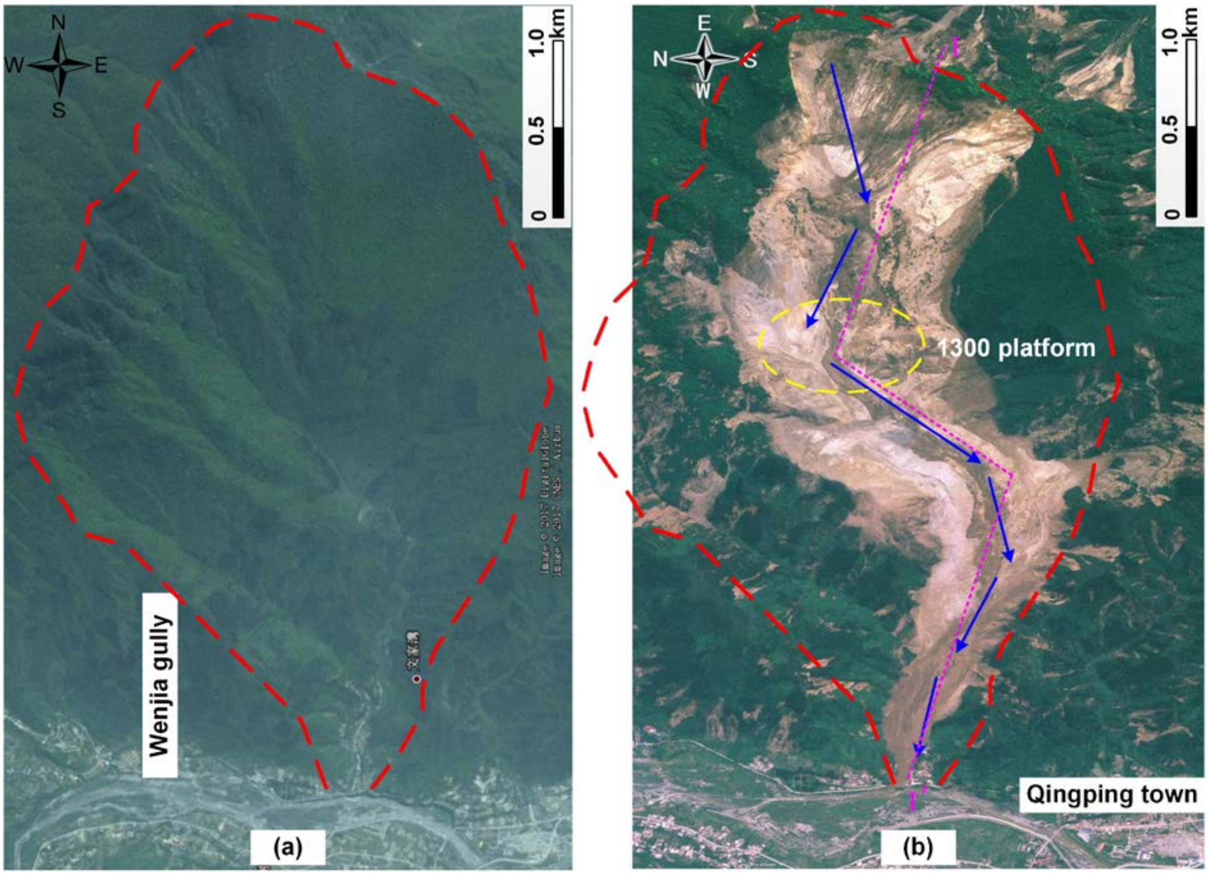

Fig. 3. Aerial image of Wenjia gully (a. image from Google Earth on Dec. 31, 2007; b. aerial photograph taken on May 18, 2008)

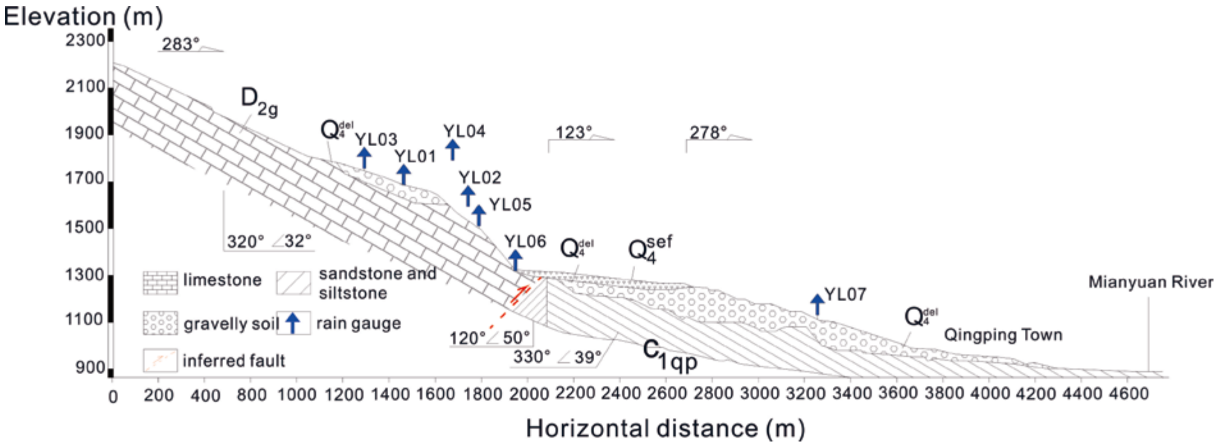

Fig. 4. Geological profile of the main channel of Wenjia gully

Fig. 4 is the geological profile of cross section Ⅰ-Ⅰ' in Wenjia gully (Fig. 3b). The exposure strata are Guanwushan Group (upper devonian period) with limestone, and Qingping Group (cambrian perod) with sandstone and siltstone. Field investigation also shows that the main loose deposits are located at the 1300 platform (Fig 1 & 3). During heavy rains, the intense surface run-off may cause the unstable slope collapse into the channel, maybe bed failure or run-off scouring of the loose deposited material. This explains why there would be giant debris flow occurrence in this gully, e.g. the debris flow event on August 13, 2010 above-mentioned.

3. Methodology

According to Terzaghi theory in soil mechanics, the shear strength of material at a point within a slope can be expressed as Eq. (1).

$$\tau = c + (\sigma - u)\tan\phi \tag{1}$$

where τ is the shear strength of the slope material, c is the effective cohesion of the material, ϕ is the effective friction angle of the material, σ is the total stress normal to a potential slip surface, and u is the pore pressure. Generally, the strength parameters (c,ϕ) of the slope material mainly determined the stability of the slope and the potential position of the slip surface.

Rainfall infiltrates into a hillslope, always accumulating in a saturated zone above a permeability barrier, and increases the pore pressures within the slope material. Based on the Terzaghi's work, the increase in u would cause the effective overburden stress ($\sigma - u$) to decrease, and therefore the decrease of the shear strength until the slope fails. A formula to calculate the critical level of the pore pressure, for a highly idealized model of an infinite slope composed of cohesionless materials ($c = 0$) has been presented by Keefer et al. (1987), assuming both slip surface and piezometric surface are parallel to the ground surface. For all these assumptions, the critical pore pressure can be calculated by Eq. (2).

$$u_C = Z \times \gamma_t \times \left(1 - \frac{\tan\theta}{\tan\phi}\right) \tag{2}$$

where Z is the depth of slip surface, γ_t is the total unit weight of the slope material, and θ is the slope inclination, the other parameters are the same to those mentioned-above.

Since the deposited material along the channel usually is loose and has a grain shape, it can be regarded as an infinite slope composed of cohesionless materials. Therefore, the critical pore pressure (Eq. 2) can be used to calculate the stability of the source area. Then pore pressure and rainfall monitoring sensors were installed in the Wenjia gully to capture the real-time data and put forward a comprehensive warning threshold for forecasting debris flow occurrence. The history events about rainfall with debris flow occurrences and non-occurrences have been collected for this study from 2008 to 2018. Fortunately, three debris flow events with detailed rainfall and pore pressure monitoring data have been recorded, which could be an important evidence to prove the presented methodology.

3.1 Data analysis

Data were collected from the literature about the occurrence of debris flows in the Wenjia gully and from technical reports and documents presented by government agency. Since there is a large difference in debris flow frequency before and after the Wenchuan earthquake, only the data after quake were used for the analyses and set-up of an early warning system (Table 1). There were no debris flow events after 2014, so the rainfall data are omitted in the table.

Table 1. Primary rainfall events in the catchment of Wenjia gully (2008-2018), added from Xu (2010) & Yu et al. (2012)

Time	Maximum hourly rainfall intensity (I_h: mm/h)	Accumulated precipitation (R_{dt}: mm)	Debris flow occurrence or not	Volume of debris flow (m^3)
Sep. 24, 2008	30.5	88.0	Yes	5.0×10^5
Jul. 18, 2009	20.5	70.5	No	-
Aug. 25, 2009	28.9	86.7	No	-
Sep. 13, 2009	15.4	84.6	No	-
May 27, 2010	10.5	34.9	No	-
Jun. 13, 2010	5.5	95.1	No	-
Jul. 25, 2010	11.6	89.6	No	-
Jul. 31, 2010	51.7	60.2	Yes	$1.0\sim2.0\times10^5$
Aug. 13, 2010	**70.6**	**185.0**	**Yes**	$\mathbf{4.5\times10^6}$
Aug. 19, 2010	31.9	72.6	Yes	3.0×10^5
Sep. 18, 2010	29.0	52.0	Yes	1.7×10^5
Sep. 22, 2010	24.5	81.2	No	-
May 2, 2011	5.6	35.8	No	-
Jul. 5, 2011	12.5	61.3	No	-
Jul. 21, 2011	23.5	63.2	No	-
Jul. 30, 2011	18.2	78.3	No	-
Aug. 16, 2011	10.5	44.3	No	-
Aug. 21, 2011	13.6	76.6	No	-
Sep. 7, 2011	15.2	51.3	No	-
Oct. 27, 2011	8.5	36.9	No	-
Jul. 21, 2012	30.5	76	No	-
Aug. 14, 2012	68	109	Yes	3.2×10^4
Aug. 17, 2012	41	89.5	Yes	7.8×10^4
Aug. 18, 2012	69	104.5	No	-
Sep. 16, 2012	12	44	No	-
Sep. 25, 2012	4.5	52	No	-
Jun. 19, 2013	33.5	62	No	-
Jun. 29, 2013	16.5	41.5	No	-
Jun. 30, 2013	40.5	94	No	-
Jul. 4, 2013	32	98	No	-
Jul. 8, 2013	53	195	Yes	34.4×10^4
Jul. 10, 2014	51.5	67	No	-
Aug. 8, 2014	50.5	68.5	No	-
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Table 1 shows that the number of debris flows decreases with time, from 2008 to 2014. Several years after the earthquake, however, giant debris flows still caused catastrophic losses, which alarmed the public and government because of its huge destructive power and long-term impact. Particularly on Aug. 13, 2010, a great rainstorm lasting for 2 hours during midnight, triggered a giant debris flow, which buried the Qingping town in the Mianyuan River floodplain. According to the inventory report, the maximum deposition height was up to 6 m. Most of the check dams located in the downstream part of the Wenjia gully collapsed and lost their effectiveness after passing of the debris flow. Meanwhile, it eroded the channel bottom over a depth of about 13 m (Yu et al. 2012).

Pore pressure and rainfall monitoring sensors have been installed for understanding their relationship, and the link with debris flow occurrence. The real-time monitoring system in the Wenjia gully includes 7 automatic rain gauges and 5 pore pressure monitoring instruments. The installation was finished by April 1, 2012 (see Table 2, Figure 4 and Figure 5). It can be seen that all rain gauges are arranged in the upstream part of the Wenjia gully catchment, while pore pressure monitoring sensors are distributed along the mainstream of the Wenjia gully, with a depth of 1 m below the ground surface.

The 2012, heavy rainfall event on August 14, which triggered a debris flow has been caught totally by the real-time monitoring system. During the rainstorm, monitoring sensors YL05, YL06 and SY02, SY05 lost the connection with the monitoring center. The other monitoring sensors worked well, as shown in Fig. 6 and Fig. 7. The figures show that the rainfall was almost concentrated in two hours from 17:00 until 19:00. The amount of precipitation was highly variable along the channel of the Wengjia gully. The maximum hourly rainfall intensity is 73.5 mm/hr (YL01, 17:00), and the cumulative maximum rainfall is 118 mm (YL04). The receive frequency is every 5 minutes during the rainfall event, which is defined as the moment that hourly rainfall amount is more than 5 mm/h, and the end is when the hourly rainfall amount is less than 5 mm/h, and this should last for at least 6 h.

Table 2. List of monitoring devices in the Wenjia gully

No.	Longitude	Latitude	Elevation(m)	Photo
YL01	E104°8'21"	N31°33'32"	1652	
YL02	E104°7'55"	N31°33'11"	1390	
YL03	E104°8'39"	N31°33'14"	1671	
YL04	E104°8'16"	N31°32'47"	1490	
YL05	E104°7'47"	N31°32'39"	1433	
YL06	E104°7'46"	N31°33'29"	1280	
YL07	E104°7'9"	N31°32'59"	1025	
SY01	E104°8'12"	N31°33'9"	1210	
SY02	E104°8'11"	N31°33'9"	1212	
SY03	E104°8'11"	N31°33'8"	1208	
SY04	E104°7'49"	N31°32'55"	1092	
SY05	E104°7'48"	N31°32'56"	1081	

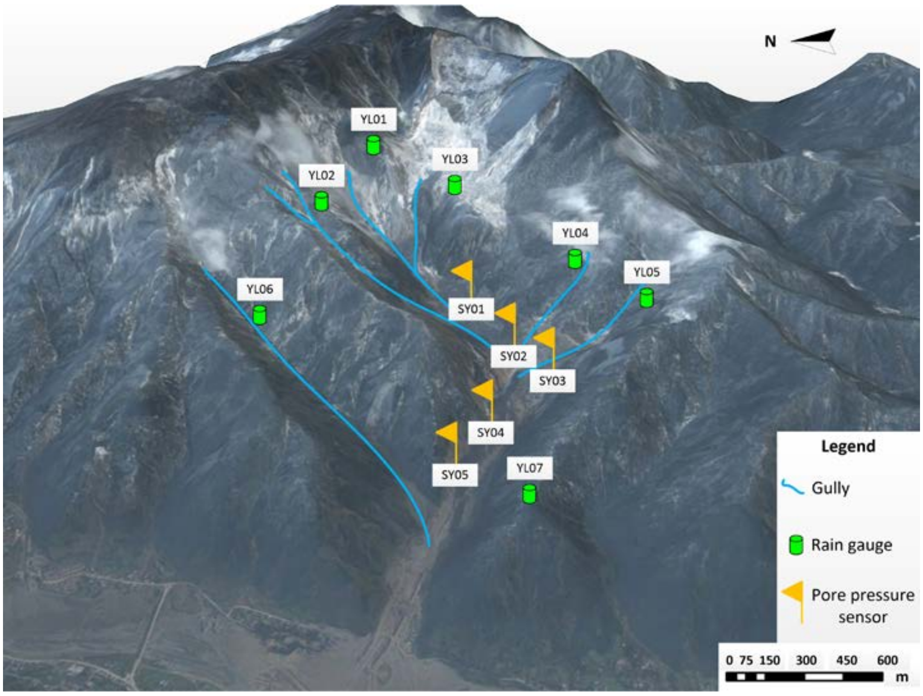

Fig. 5. Layout map of the monitoring devices installed in the Wenjia gully (The base map is from Google Earth, the date of background image is Dec. 18, 2010).

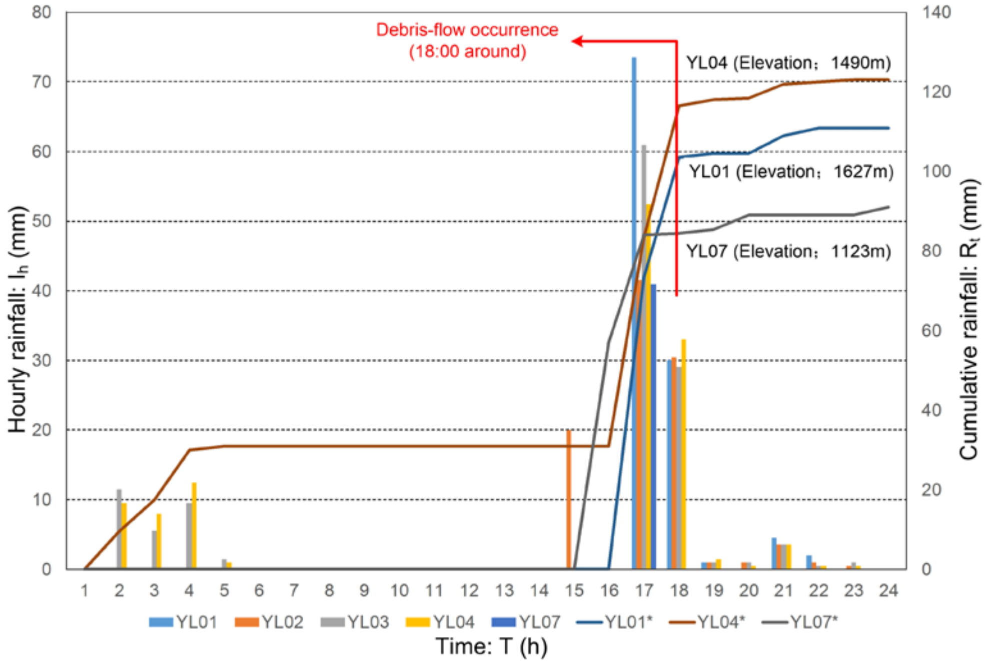

Fig. 6. The rainfall in Wenjia gully on Aug. 14, 2012 (the column graphs are hourly rainfall and the single line curves are cumulative rainfall)

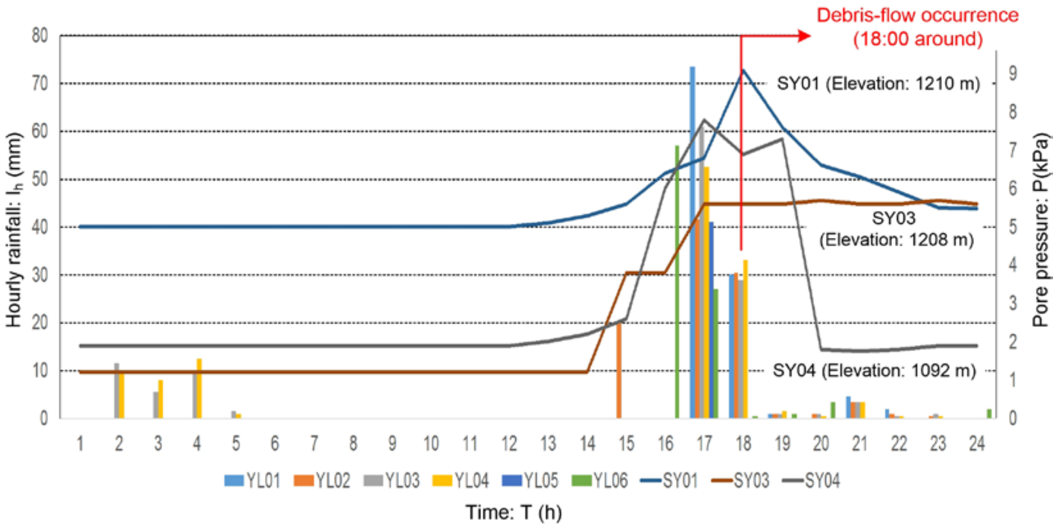

Fig. 7. The rainfall and pore pressure in Wenjia gully on Aug. 14, 2012 (the column graphs are hourly rainfall and the single line curves are pore pressure)

The maximum hourly rainfall and cumulative rainfall are not found in the highest part of the catchment. The variety in cumulative maximum rainfall is larger than the variety in maximum hourly rainfall intensity. The Fig. 7 shows the relation between hourly rainfall and pore pressure: the small amount of rain from 2:00 to 5:00 with a maximum hourly rainfall of 12.5 mm did not trigger any change in pore pressure. However, during the concentrated rain period between 15:00 and 18:00 there was a sudden rise of the pore pressure. The debris flow was triggered adjacently when it reached the maximum rise of the pore pressure. The highest value of the pore pressure is 9.1 kPa (SY01) at 18:00, 5.7 kPa (SY03) at 20:00 and 7.8 kPa (SY04) at 17:00. The sudden rise of pore pressure, therefore may be a good indicator for contributing to the gully-type debris flows occurrence.

3.2 Warning threshold for the Wenjia gully

In order to improve the warning thresholds for forecasting the debris flow occurrence, which do not just represent a simple relationship between rainfall and debris flow occurrence, the pore pressure of landslide deposits was incorporated into the assessment of a threshold. Critical pore pressure for bed failure generating debris flows can be estimated with Eq. (2). The total unit weight of deposit material at 1300 platform in the Wenjia gully is around 21 ± 2 kN/m^3, average slope inclination of 18.5°, and average effective friction angle is 27.5° by consolidated undrain indoor test. Thus, the critical pore pressure of the deposited material can be calculated by Eq. (3).

$$u_C = (6.79 - 8.22) \times Z \qquad (3)$$

Obviously, it's a linear function, as shown in Fig. 8. According to the real-time monitoring system, therefore, the critical pore pressure should be 6.79~8.22 kPa at the depth of 1 m below the ground surface. According to Table 1, on Aug. 14, 2012, there was a debris flow with run-off volume of 3.2×10^4 m^3, and before the debris flow event pore pressure monitoring data show its maximum value was up to 9.1 kPa (SY01), 7.8 kPa (SY04) and 5.7 kPa (SY03). Obviously, SY01 has already exceeded the upper threshold of critical pore pressure (8.22 kPa), which means that the critical pore pressure might be an important factor in debris flow occurrence.

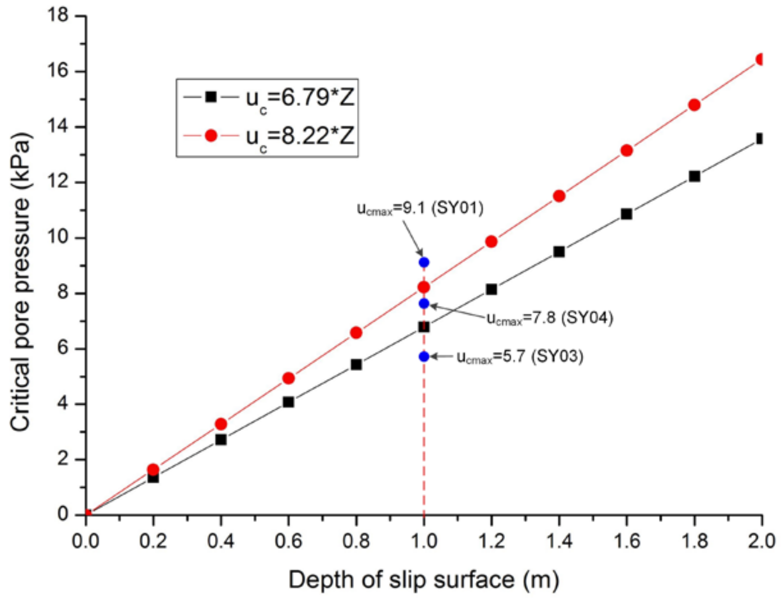

Fig. 8. The critical pore pressure with probable depth of slip surface in the Wenjia gully

Considering the acquired available data, the maximum hourly rainfall (I_h: mm) and cumulative rainfall (R_t: mm) are selected as the basic triggering rainfall parameters for the rainfall threshold, and the critical pore pressure (u_c) has been defined as a supporting factor in forecasting debris flow occurrence. For each rainfall event with or without debris flow occurrence, R_t (Cumulative rainfall) and I_h (Hourly intensity), can be plotted in a X-Y field, like the debris flow event on Aug. 13, 2010 (Fig. 9 Tag A). The red line drawn under the lowest rectangle points which represent debris flow occurrences under such rainfall conditions. The area between the line and the x and y axes defines combinations of R_t and I_h with a zero probability of debris flow occurrence. The gradient is an uncertain parameter which can be determined by experts' experiences and historical data sets (Huang et al. 2015b). Then, the rainfall threshold can be defined by Eq. (4) in Fig. 9 (Tag C).

$$R_t + 2.4 I_h = 120 \tag{4}$$

where R_t is the cumulative rainfall (mm), I_h is the maximum hourly rainfall (mm).

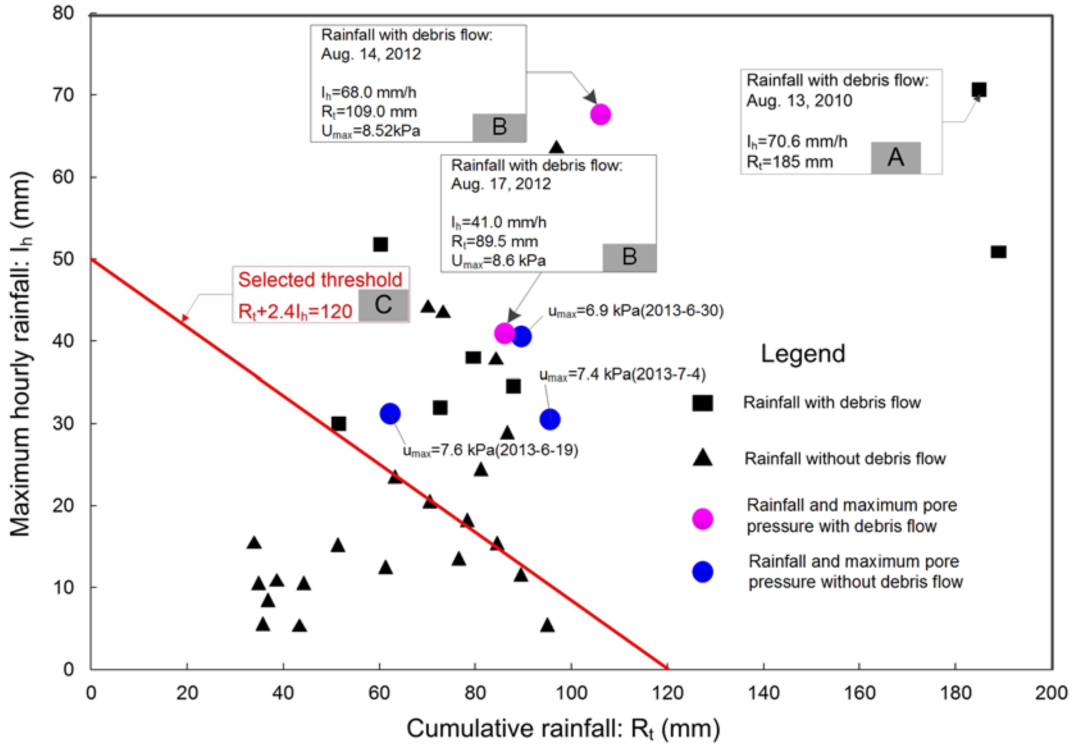

Fig. 9. Warning threshold combined with rainfall and pore pressure

While above the red line, the probability of debris flow occurrence is higher. But among these points, there are 8 rectangular points with debris flow. The possibility of debris flow occurrence can be predicted correctly up to 62% by rainfall threshold, which seems to be fine as a preliminary assessment. If the pore pressure monitoring data has been considered, in Figure 8, there are three blue circular points without debris flow, but two magenta points show debris flow happened. The different between them is that maximum pore pressure has exceeded the critical pore pressure line (8.22 kPa). Therefore, the rainfall threshold and pore pressure threshold need to be combined during forecasting debris flow occurrence, then there must be a much higher possibility of successful prediction. For a given rainfall event, the starting point and its trend can be calculated and plotted in Fig. 9. In order to verify in real time whether the trend line exceed the warning threshold. More detail information will be discussed with an example as follow.

4. Example of application

In order to make a better use for the presented method, early warning criteria have to be simplified to make a clear understanding for the study area. Therefore, a three-level early warning system has been proposed for the Wenjia gully, as shown in Table 3. At level one there is low possibility of debris flow occurrence. At level two there is a chance of debris flow occurrence in the near future, and warning messages need to be sent to local authority and countermeasures need to be discussed. At level three there is very likely to occur right now, therefore, local residents need to be alerted and forbidden going to the threatened places.

Table 3. Recommended warning levels for Wenjia gully

Warning level	Trigger	Response
Ⅰ	Default level. Not exceeding rainfall threshold and critical pore pressure.	**Null**: but data are checked daily. Weekly monitoring bulletin.
Ⅱ	Attention level. Exceeding rainfall threshold but critical pore pressure not.	**Watch**: data are checked more frequently. Daily monitoring bulletin. Authority and expert are alerted. Preparing for alarm.
Ⅲ	Alert level. Exceeding both of rainfall threshold and critical pore pressure.	**Warning**: data are checked even more frequently. Two monitoring bulletins per day. Local people are alerted.

In order to explain how the presented method can be used in a real-time debris flow early warning case, the rainfall on Jul. 8, 2013 has been selected as an application (Fig. 10). The small circular magenta solid points connected by a magenta line shows the course of the real-time monitored data during this rain storm, with the cumulative rainfall on the X axis and hourly rainfall intensity on the Y axis. The Tag A in Fig. 10 shows the rainfall data at 17:00 on Jul. 8, 2013, with a pore pressure of 3.00 kPa at that time. Three hours later at 20:00 (Tag B), the real-time rainfall has exceeded the rainfall threshold, but the pore pressure didn't exceed the critical pore pressure (6.3 kPa < 6.79 or 8.22 kPa) indicating that the warning information stayed in level Ⅱ. One hour later at 21:00 (Tag C), the pore pressure did exceed the lower critical pore pressure (7.8 kPa > 6.79 kPa) indicating that debris flow had a much higher possibility to occur. Further, the pore pressure went up to 8.7 kPa over the upper critical pore pressure (8.22 kPa), and triggered a debris flow occurrence finally (Tag D).

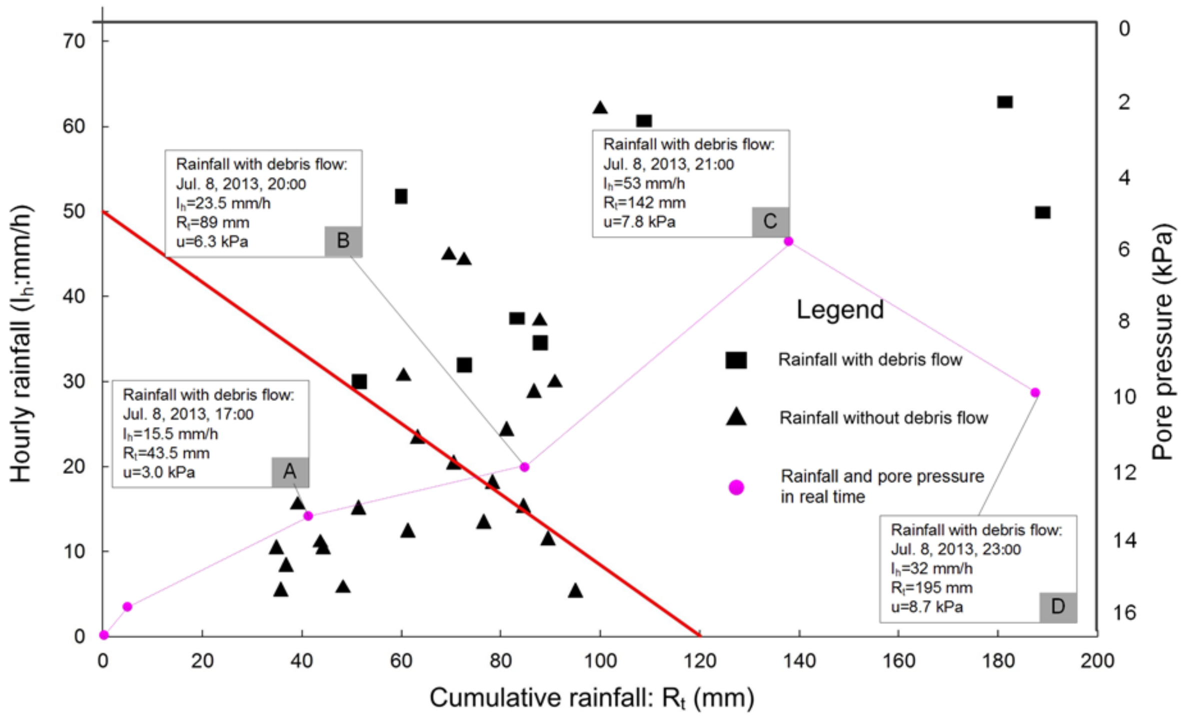

Fig. 10. Case application of the presented method in Wenjia gully (Jul. 8, 2013)

The case study shows that how to use this presented combined warning threshold in a real-time way during a rain storm. In 2014, two heavy rainstorms (Table 1) both have exceeded the rainfall threshold, but pore pressure did not cross the critical pore pressure during the whole course of the rainfall. Therefore, a warning message has been sent to the local government with a median possibility of debris flow occurrence. At last, fortunately no debris flow occurred during these rain storms. Therefore, the presented comprehensive warning threshold can be used as a helpful tool for debris flow prediction in mountainous area, especially in this earthquake area of Southwest China where a lot of loose material is available.

5. Discussion and conclusion

Gully-type debris flow, usually triggered by high-intensity and short-duration rainstorms cause serious harm to human lives and properties every year in the mountainous region of Southwest China. Therefore, in order to prevent such natural disasters, there is an urgent requirement for an effective method to predict debris flow occurrence. The combined warning threshold proposed and discussed in this paper, not only use the common rainfall threshold, but also include the critical pore pressure determined by a hydro mechanical stability model.

Two rainfall triggering factors: maximum hourly rainfall and cumulative rainfall, have been selected to establish a simple rainfall threshold as a baseline for debris flow early warning. Critical pore pressure can be used as a combined threshold to make the warning threshold better in practical usage. The Wenjia gully was selected as a case study for a detailed explanation of the presented method, for the great volume of deposited materials triggered by Wenchuan earthquake along the channel. The results show that the combined threshold can play a great role in debris flow predicting, at least reduce the mistaken alerts for debris flow occurrence compared to use of only a rainfall threshold. However, such a combined warning threshold still has some restrictions. First, the critical pore pressure is a linear function with the depth of a potential slip surface, which is difficult to determine in an actual gully by the real time monitoring system. In this study, one-meter depth of the slip surface was selected as a possible condition for this preliminary study. Second, the study area still focused on the Wenjia gully, therefore the presented method can't be used in other gullies directly. But in the near future, different gully-type debris flows will be researched, and more subsequent work need to be carried on for a better understanding of debris flow prediction. Finally, the most complex problem is the final determination whether to alert the local population, and whether some reactions need to be done immediately, or later. Debris flow early warning is not an imminent hazard but is just regarded as a potential danger. In spite of these limitations, the methodology presented in this paper has reached the goal to establish a preliminary combined warning threshold for gully-type debris flow prediction. In the future studies, the critical pore pressure threshold which are dependent on topography, geology, and soil properties, can be determined by long-term field monitoring, and more important by debris flow tests in laboratory with different slope angles, and depths of slip surface to reduce the loss of properties and lives.

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References

Baum RL, Godt JW (2009) Early warning of rainfall-induced shallow landslides and debris flows in the USA Landslides 7:259-272 doi:10.1007/s10346-009-0177-0

Cannon SH, Gartner JE, Wilson RC, Bowers JC, Laber JL (2008) Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California Geomorphology 96:250-269 doi:10.1016/j.geomorph.2007.03.019

Chae B-G, Kim M-I (2011) Suggestion of a method for landslide early warning using the change in the volumetric water content gradient due to rainfall infiltration Environmental Earth Sciences 66:1973-1986 doi:10.1007/s12665-011-1423-z

Glade T, Crozier M, Smith P (2000) Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical “Antecedent Daily Rainfall Model” Pure and Applied Geophysics 157:1059-1079

Guo X-j, Cui P, Li Y (2013) Debris flow warning threshold based on antecedent rainfall: A case study in Jiangjia Ravine, Yunnan, China Journal of Mountain Science 10:305-314 doi:10.1007/s11629-013-2521-z

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2007a) The rainfall intensity–duration control of shallow landslides and debris flows: an update Landslides 5:3-17 doi:10.1007/s10346-007-0112-1

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2007b) Rainfall thresholds for the initiation of landslides in central and southern Europe Meteorology and Atmospheric Physics 98:239-267 doi:10.1007/s00703-007-0262-7

Huang J, Huang R, Ju N, Xu Q, He C (2015a) 3D WebGIS-based platform for debris flow early warning: A case study Engineering Geology 197:57-66 doi:10.1016/j.enggeo.2015.08.013

Huang J, Ju NP, Liao YJ, Liu DD (2015b) Determination of rainfall thresholds for shallow landslides by a probabilistic and empirical method Natural Hazards and Earth System Sciences 15:2715-2723 doi:10.5194/nhess-15-2715-2015

Huang R, Huang J, Ju N, He C, Li W (2013) WebGIS-based information management system for landslides triggered by Wenchuan earthquake Natural hazards 65:1507-1517

Iverson RM (1997) The physics of debris flows Reviews of geophysics 35:245-296

Kean JW, McCoy SW, Tucker GE, Staley DM, Coe JA (2013) Runoff-generated debris flows: Observations and modeling of surge initiation, magnitude, and frequency Journal of Geophysical Research: Earth Surface

118:2190-2207 doi:10.1002/jgrf.20148

Keefer DK et al. (1987) Real-Time Landslide Warning during Heavy Rainfall Science 238:921-925

Peng J, Fan Z, Wu D, Zhuang J, Dai F, Chen W, Zhao C (2014) Heavy rainfall triggered loess-mudstone landslide and subsequent debris flow in Tianshui, China Engineering Geology doi:10.1016/j.enggeo.2014.08.015

Segoni S, Rosi A, Rossi G, Catani F, Casagli N (2014) Analysing the relationship between rainfalls and landslides to define a mosaic of triggering thresholds for regional-scale warning systems Natural Hazards and Earth System Science 14:2637-2648 doi:10.5194/nhess-14-2637-2014

Shieh C-L, Chen Y, Tsai Y, Wu J (2009) Variability in rainfall threshold for debris flow after the Chi-Chi earthquake in central Taiwan, China International Journal of Sediment Research 24:177-188

Shuin Y, Hotta N, Suzuki M, Ogawa K-i (2012) Estimating the effects of heavy rainfall conditions on shallow landslides using a distributed landslide conceptual model Physics and Chemistry of the Earth, Parts A/B/C 49:44-51 doi:10.1016/j.pce.2011.06.002

Thiebes B (2012) Integrative Early Warning. In: Landslide Analysis and Early Warning Systems. Springer, pp 215-219

Tropeano D, Turconi L (2004) Using historical documents for landslide, debris flow and stream flood prevention. Applications in Northern Italy Natural Hazards 31:663-679

van Asch TWJ, Tang C, Alkema D, Zhu J, Zhou W (2013) An integrated model to assess critical rainfall thresholds for run-out distances of debris flows Natural Hazards 70:299-311 doi:10.1007/s11069-013-0810-z

Xu Q (2010) The 13 August 2010 catastrophic debris flows in Sichuan Province: characteristics, geneticmechanism and suggestions. Journal of Engineering Geology 18:596-608

Yin Y, Wang H, Gao Y, Li X (2010) Real-time monitoring and early warning of landslides at relocated Wushan Town, the Three Gorges Reservoir, China Landslides 7:339-349 doi:10.1007/s10346-010-0220-1

Yu B, Li L, Wu Y, Chu S (2013a) A formation model for debris flows in the Chenyulan River Watershed, Taiwan Natural Hazards 68:745-762 doi:10.1007/s11069-013-0646-6

Yu B, Ma Y, Wu Y (2012) Case study of a giant debris flow in the Wenjia Gully, Sichuan Province, China Natural Hazards 65:835-849 doi:10.1007/s11069-012-0395-y

Yu B, Ma Y, Wu Y (2013b) Case study of a giant debris flow in the Wenjia Gully, Sichuan Province, China Natural Hazards 65:835-849 doi:10.1007/s11069-012-0395-y

Yu B, Zhu Y, Wang T, Chen Y, Zhu Y, Tie Y, Lu K (2014) A prediction model for debris flows triggered by a runoff-induced mechanism Natural Hazards:1-21

Zhou W, Tang C (2013) Rainfall thresholds for debris flow initiation in the Wenchuan earthquake-stricken area, southwestern China Landslides 11:877-887 doi:10.1007/s10346-013-0421-5