Nat. Hazards Earth Syst. Sci. Discuss., doi:10.5194/nhess-2016-149, 2016
Manuscript under review for journal Nat. Hazards Earth Syst. Sci.
Published: 10 May 2016
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A preliminary study on the comprehensive threshold for debris-flow early warning

Xiaoqiang XUE, Jian HUANG
State Key Laboratory of Geohazard Prevention and Geoenvironment Protection
Chengdu University of Technology, Chengdu, Sichuan 610059, China
E-mail: huangjian2010@gmail.com

Abstract

Debris-flows not only cause a great loss of property, but also kill and injure people every rainy season in the mountainous regions of China. In order to reduce hazard and risk, several methods of assessing rainfall thresholds have been provided at present, based on statistical models. However, the limited rainfall data with debris-flow occurrence or non-occurrence makes threshold analyses very difficult. This paper, therefore, presented a kind of comprehensive threshold consisting of pore-water pressure from Terzaghi theory, and rainfall factors from frequent usage for predicting debris-flow occurrence. Rainfall and pore pressure data has been collected in a number of locations in Wenjiagou gully to assess critical rainfall and pore pressure values for debris flow initiation. The three-level early warning criteria (Zero, Attention, and Warning) has been adopted and the corresponding judgement conditions has been defined based on monitoring data in a real-time way. Finally, it is suggested that the combination of these two critical values might be a useful approach in a warning system for safeguarding of population in debris-flow prone areas.

Keywords: debris flow, comprehensive threshold, pore-water pressure, Wenjiagou gully

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1. Introduction

A great number of debris-flows occurred in mountainous area every year in a rainy season. The fast population increase and high speed economic development in these areas always caused considerably catastrophic accidents and socio-economic losses. On Aug. 7 2010, a giant debris flow from Luojiayu gully and Sanyanyu gully at Zhouqu County, Gansu Province, China, killed 1765 people living on the densely urbanized fan (Tang et al. 2011). Additionally in Southwestern China, 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 Nepal earthquake on April, 25 2015 trigged thousands of landslides and cracked mountains which are easy to develop into debris-flow under rainstorm condition. It's much similar to the Chi-Chi earthquake area (Taiwan), where numerous co-seismic landslides were triggered as well, and causing the continuous debris flows for 10 years after the earthquake (Yu et al. 2013b). These catastrophic events also indicated that the human vulnerability to natural hazards as well as the lack of knowledge on natural disaster prevention and mitigation. So that there is an urgent demand for an effective method to reduce the hazard and risk. Therefore, researchers have been working on forecasting debris-flow occurrences and setting up early warning systems. Especially on the regional scale, the methods for debris-flow early warning are frequently based on statistical models which have already been proved their importance in predicting debris-flow occurrence (Baum and Godt 2009; Guzzetti et al. 2007b; Keefer et al. 1987; Segoni et al. 2014; Shuin et al. 2012; Tropeano and Turconi 2004). Several parameters were selected for the assessment of rainfall thresholds mainly including 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). Baum and Godt (2009) used a combination of a cumulative rainfall threshold, rainfall intensity-duration threshold and antecedent water index or soil wetness for shallow landslide forecasting.

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Although widely used in the mountainous areas, these approaches are currently affected by some drawbacks which still restrain a fully operational application to early warning systems. One of the main problems is the lack of available data about rainfall with debris-flow occurrence or non-occurrence. Parameters selected for forecasting debris-flow occurrences are commonly limited to rainfall information, especially for a single gully. Chenyulan River Watershed in Taiwan, there are many debris flows triggered by Typhoon each time. After previous research identified 47 factors related to topography, geology, and hydrology, a normalized critical rainfall factor was suggested with an effective cumulative precipitation and a maximum hourly rainfall intensity (Yu et al. 2013a). The model produces a good assessment of the probability of occurrence of debris flows in the study area, and can be used in other regions.

Consequently, this paper presents a recent study on establishing one comprehensive threshold for predicting debris-flow occurrence based on the rainfall records and a possible new indicator – pore pressure measured under the ground surface. The purposes of this paper are: (i) to propose a new method for establishing a comprehensive threshold for forecasting debris-flow occurrence; (ii) to introduce the application and improvement of the comprehensive threshold with a case study.

2. Study area

Wenjiagou gully located at the north of Qingping town, Mianzhu city, Sichuan province, Southwest China, 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 300 m to 1,600 m above sea level, and the valley with slope inclinations between 30° and 70° has been deeply incised by the Mianyuan river. The average yearly temperature of 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.

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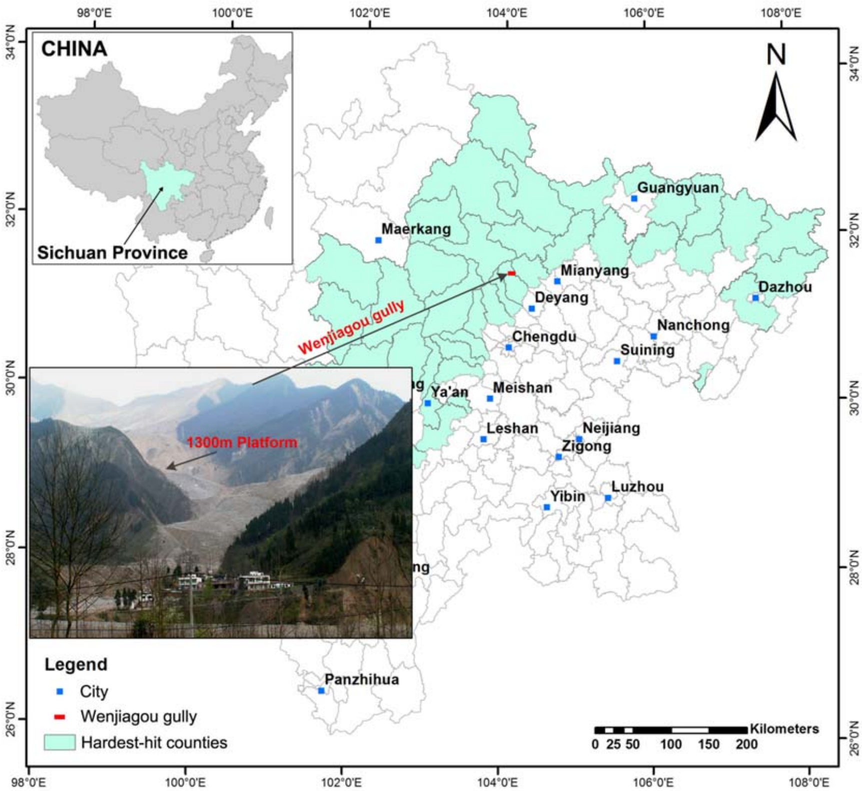

Fig. 1. Location of Wenjiagou gully modified from Huang et al. (2013). The inset photograph of Wenjiagou gully at the left bottom was taken from the other side of Mianyuan River on August 10, 2008.

Before the Wenchuan earthquake on May12, 2008, the Wenjiagou catchment was covered by rich vegetation, and the channel was smooth and stable. At that time, few geological disasters occurred in this region. Therefore, many farmers settled down at the foothills along the Mianyuan River.

After the earthquake, a giant landslide occurred upstream in the Wenjiagou 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 transform into debris-flows during rainy season (Shieh et al. 2009). 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

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burying of houses, and the most downstream dam in the catchment (Yu et al. 2012).

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).

$$t = c + (\sigma - \mu)\tan\phi \tag{1}$$

where t 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 μ is the pore-water 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, also including the parameter (σ) determined by the height and inclination of the slope and the density of the slope material, and the distribution of pore-water pressure (μ) within the slope.

Rainfall infiltrates into a hillslope, always accumulating in a saturated zone above a permeability barrier, and increases the pore-water pressures within the slope material. Based on the Terzaghi's work, the increase in μ would cause the effective overburden stress ($\sigma - \mu$), and therefore combining with the decrease of the shear strength until the slope fails. Presumed by Keefer et al. (1987), there exists a critical level of the pore-water pressure (μ_c) for any given slope, facilitating the potential slip surface to develop, and causing the slope become unstable. In order to propose a formula to calculate the critical level of the pore-water pressure, a highly idealized model of an infinite slope composed of cohesionless materials ($c = 0$) has been presented in Keefer et al. (1987), where both slip surface and piezometric surface are parallel to the ground surface. For all these assumptions, the critical pore-water pressure can be calculated by Eq. (2).

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

where Z is the depth of slip surface, γ_t is the total unit weight of the slope material, and θ is

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the slope inclination, the other parameters are the same to those mentioned-above.

In this respect, the Wenjiagou gully was selected as the case study area, and the pore-water pressure and rainfall monitoring sensors were installed in-situ to capture the real-time data for verifying these formulas and put forward a warning threshold for forecasting debris-flow occurrence finally. For this purpose, the history events about rainfall with debris-flow occurrences and non-occurrences have been collected during the initial research, unfortunately, none of those data has any pore-water pressure information. Even though several years have already passed under the real-time monitoring system, there are still limited available data for this research (Huang et al. 2015a).

3.1 Data analysis

Several methods were provided to collect available data, including debris-flow inventory maps, 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 (Table 1).

Table 1 shows that the number of debris-flows decreases with time. Two years after the earthquake, however, several 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 until 6 m. Most of the check dams located in the downstream part of the Wenjiagou gully collapsed and lost their effectiveness after passing of the debris-flow. It eroded the channel bottom over a depth of about 13 m (Yu et al. 2012).

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Table 1. Primary rainfall events in Wenjiagou gully (2008-2011), 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**	**227.0**	**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	-

Therefore, pore-water pressure and rainfall monitoring sensors have been installed for the relationship analyzes between rainfall, pore-water pressure and debris-flow occurrence. The real-time monitoring system in the Wenjiagou gully includes 7 automatic rain gauges and 5 pore-water pressure monitoring instruments, which have been completely finished until April 1, 2012, as shown in Table 2 and Figure 2. It can be seen that all rain gauges are arranged at the upstream of each branch gully in the Wenjiagou gully, and pore pressure sensors are located along the mainstream of the Wenjiagou gully in the deposits.

In 2012, a heavy rainfall event on August 14 triggered a debris-flow, which 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

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shown in Figure 2, Figure 3 and Figure 4.

Table 2. List of monitoring devices in Wenjiagou gully

No.	Longitude	Latitude	Elevation(m)	Purposes
YL01	E104°8'21"	N31°33'32"	1652	To gain the rainfall in the study area, and analyze the relationship between rainfall and debris-flow occurrence.
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"	1166	
YL07	E104°7'9"	N31°32'59"	1025	
SY01	E104°8'12"	N31°33'9"	1210	To gain the pore-water pressure, and analyze the relationship between pore-water pressure and debris-flow occurrence. All of them were buried at a depth of 1 m under the ground.
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	

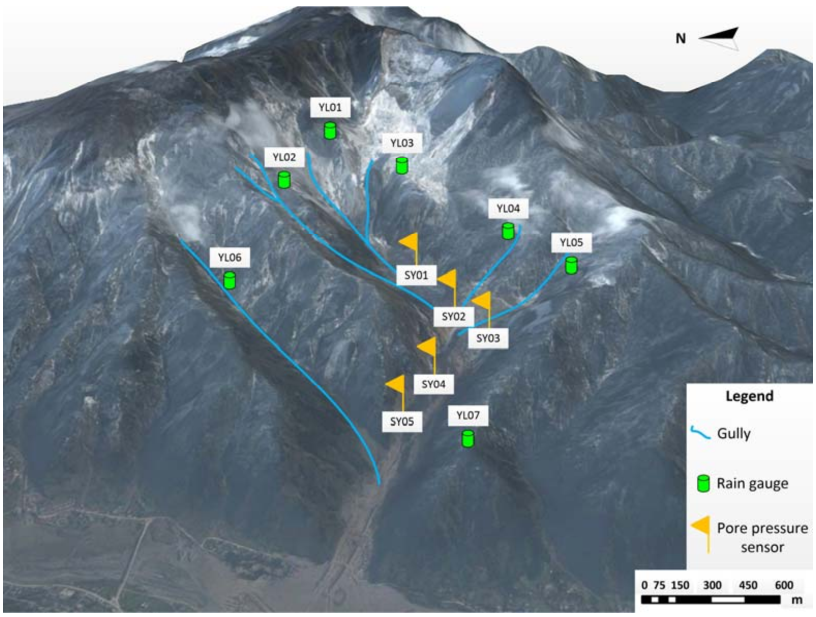

Fig. 2. Layout map of the monitoring devices installed in Wenjiagou gully (The base map is from Google Earth, the date of background image is Dec. 18, 2010).

Figure 3 and Figure 4, 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 Wengjiagou gully. The maximum hourly rainfall intensity is 73.5 mm (YL01), and the standard deviation is 12.76. The cumulative maximum rainfall is 118 mm (YL04), and the standard deviation is 14.75.

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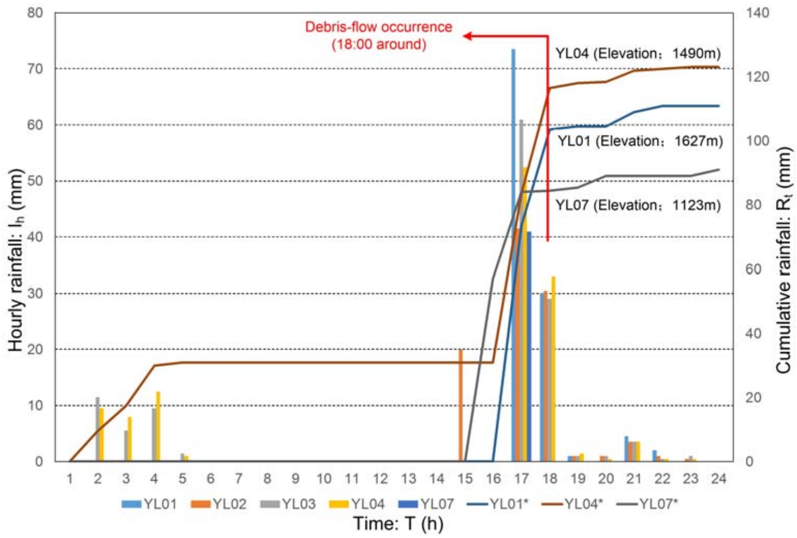

Fig. 3. The rainfall in Wenjiagou gully on Aug. 14, 2012 (the column maps are hourly rainfall and the single line maps are cumulative rainfall)

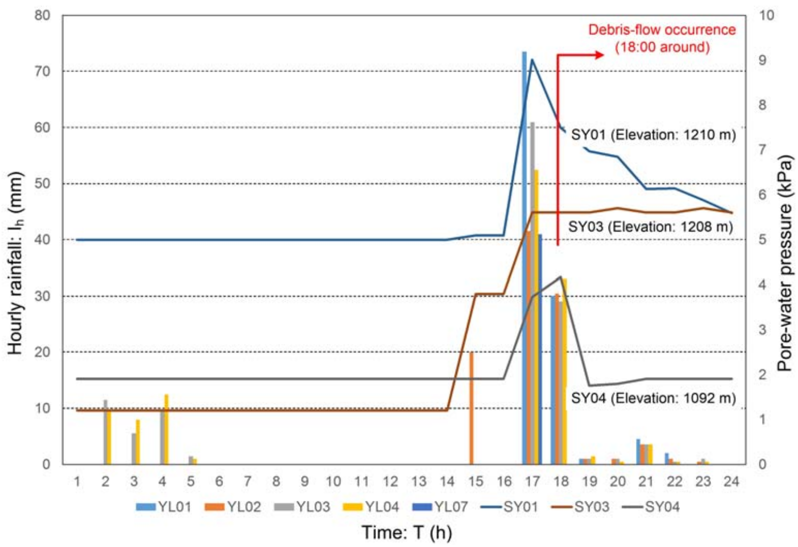

Fig. 4. The rainfall and pore-water pressure in Wenjiagou gully on Aug. 14, 2012 (the column maps are hourly rainfall and the single line maps are pore-water pressure)

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 Figure 4 shows the relation between hourly rainfall and pore-water 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

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change in pore-water pressure. However, during the concentrated rain period between 17:00 and 19:00 there was a sudden rise of the pore-water pressure. The debris flow was triggered adjacently when it reached the maximum rise of the pore-water pressure. The highest value of the pore-water pressure are 9.01 kPa (SY01) at 17:00, 5.7 kPa (SY03) at 20:00 and 4.17 kPa (SY04) at 18:00. The sudden rise of pore-water pressure may be a good indicator for the triggering of debris-flows.

3.2 Comprehensive threshold for debris flows

In order to improve the warning thresholds for forecasting the debris flow occurrence, which not just represent a simple relationship between rainfall and debris-flow occurrence, the pore-water pressure of landslide deposits was incorporated into a comprehensive threshold for it is an important geotechnical parameter in the physical models of debris-flow generation. Back to the critical pore-water pressure Eq.(2) above-mentioned, combing with the results from field investigation in the Wenjiagou gully on Oct. 8, 2010, the total unit weight of landslide deposits in the Wenjiagou gull is 21.05 kN/m^3, the slope inclination of 18.5°, and the effective friction angle of the deposited material is 27.5°. Thus, the critical pore-water pressure of the deposited material can be calculated by Eq. (3).

$$\mu_c = 7.52 \times Z \tag{3}$$

It's a linear function obviously, as can be shown in a graph (Figure 5). If the slip surface of the deposited material is at the position of 1 m depth under the ground, the critical pore-water pressure should be 7.52 kPa. With a redundant consideration of 25% in depth of slip surface, the critical pore pressure is between 5.64 kPa and 9.40 kPa (Figure 5). However, up to present in the real-time monitoring system, only 3 events of debris-flow occurrences were captured (August 14, 2012; August 17, 2012 and July 9, 2013). When the debris flow occurred, the pore-water pressure and cumulative rainfall information are demonstrated with line graph and column graph respectively (Figure 6). The average of monitoring critical pore-water pressure decrease with time, comparing to the rise of cumulative rainfall. It indicates that the critical pore-water pressure for debris-flow occurrence can be

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revised and adjusted by itself. Meanwhile, the theoretic critical pore-water pressure ($\mu_c = 7.52$ kPa) can be used to predict the debris-flow occurrence, by considering a probability of 25% in the depth of slip surface. Therefore, the thresholds of critical pore-water pressure from 5.64 kPa to 9.40 kPa can be used to supplement the warning threshold for debris-flow prediction in the Wenjiagou gully.

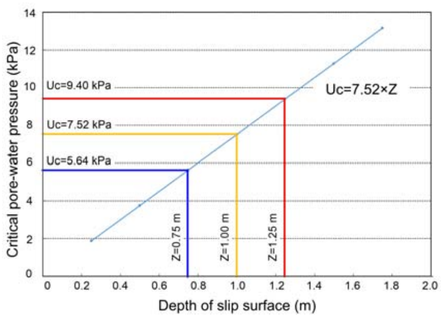

Fig. 5. The theoretic critical pore-water pressure of deposited material in the Wenjiagou gully

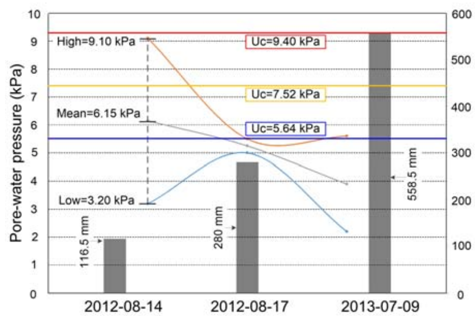

Fig. 6. The monitoring critical pore-water pressure of deposited material in the Wenjiagou gully

Considering the acquired available data, based on the methodology above methioned, the maximum hourly rainfall (I_h: mm) and cumulative rainfall (R_t: mm) are selected as the basic triggering rainfall parameters for the comprehensive threshold, and the theoretical critical pore-water pressure (U_c) has been defined as an assistant factor in forecasting debris-flow occurrence. For each rainfall event with or without debris-flow occurrence, R_t and I_h, can be plotted in a X-Y field, like the debris-flow event on Aug. 13, 2010 (Fig. 7 Tag A). The rainfall threshold for predicting debris-flow occurrence can be defined and calculated by Eq. (4) and Figure 7 (Tag C). The line separates these debris-flow occurrences from non-occurrences, and indicating that when rainfall starting the point (cumulative rainfall & hourly rainfall intensity) can be calculated in a real-time and plotted into the diagram. While the point crosses the line, which shows the probability of debris-flow occurrence is much higher. More detail information can be found in Zhuang et al. (2014) and Huang et al. (2015b).

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

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

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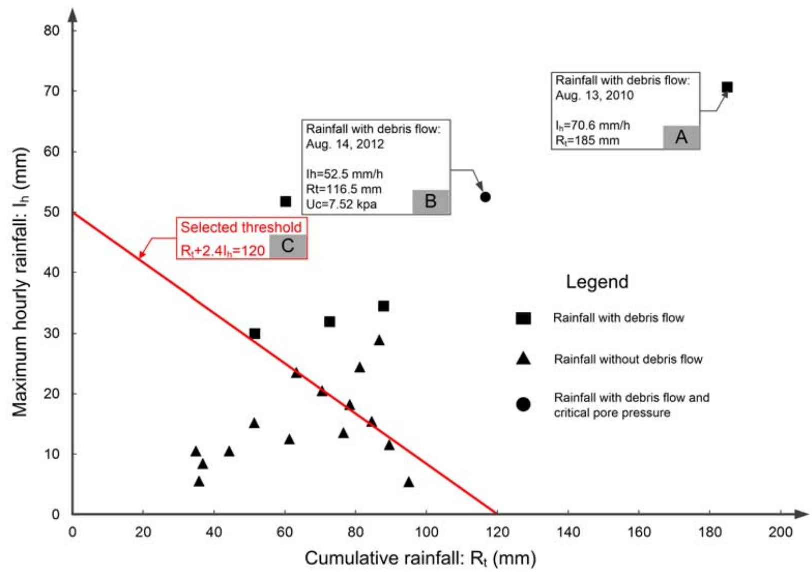

Fig. 7. Rainfall threshold based on maximum hourly rainfall and cumulative rainfall

Figure 7 shows thirteen points (86.7%) of collected rainfall events (Table 1) with no debris flows lying below the threshold line, and two error points above this line. However, as mentioned above, only the rainfall threshold may not be enough to predict debris-flow occurrence. Pore-water pressure, therefore, has been selected to refine the warning threshold. Figure 5 and Figure 6 show that the critical pore-water pressure (U_c) above a certain threshold is also a valuable indicator for forecasting debris-flow occurrence. Based on the verification of theoretical and real-time monitoring pore-water pressure, the threshold for pore-water pressure (U) to predict the probability of debris flow occurrence, can be defined by Eq. (5) based on the Eq. (2) and Eq. (3).

$$U \geq U_c \tag{5}$$

When both of the two thresholds are satisfied, there must be a very high possibility of debris-flow occurrence. More available data will make the thresholds more reliable and accurate for debris-flow prediction.

4. Example of application

In order to make a better use for the debris-flow early warning, some criteria have to be simplified

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for the preliminary stage. Therefore, a three-level early warning system has been proposed for the Wenjiagou gully, as shown in Table 3.

Table 3. Recommended warning levels for Wenjiagou gully

Warning level	Trigger	Response
I	Default level. Eq. (4) is not satisfied or $U \leq 5.64$ kPa.	**Null**: but data are checked daily. Weekly monitoring bulletin.
II	Attention level. Eq. (4) is satisfied or 5.64 kPa < U < 9.40 kPa.	**Watch**: data are checked more frequently. Daily monitoring bulletin. Authority and expert are alerted. Preparing for alarm.
III	Alert level. Eq. (4) is satisfied or $U \geqslant 9.40$ kPa.	**Warning**: data are checked even more frequently. Two monitoring bulletins per day. Local people are alerted.

At level one (Blue) there is no risk of debris-flows. At level two (Orange) 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. Level three (Red) there is very likely to occur right now, therefore, local residents need to be alerted and forbidden going to that place.

In order to show how this presented method can be used in debris-flow early warning, a heavy rainfall event on Jun. 19, 2013 (YL01 & SY01) has been selected as a case application (Figure 8). The red circle solid points give the real-time monitoring rainfall information of the event, with cumulative rainfall on the X axis and hourly rainfall intensity on Y axis. The Tag A in Figure 8 shows the monitored rainfall at 7:00 am on Jun. 19, 2013, and the U-value of the pore-water pressure is 7.00 kPa at that time. One hour later at 8:00 am (Tag B), the real-time rainfall has exceeded the rainfall threshold, but the maximum measured U-value didn't met the critical value given in Eq. (5) (5.64 kPa < U=7.60 kPa < 9.40 kPa) which indicated the warning level stayed in Orange. Finally, the rainfall went down after 8:00 am, and no debris-flow occurred during this rain event.

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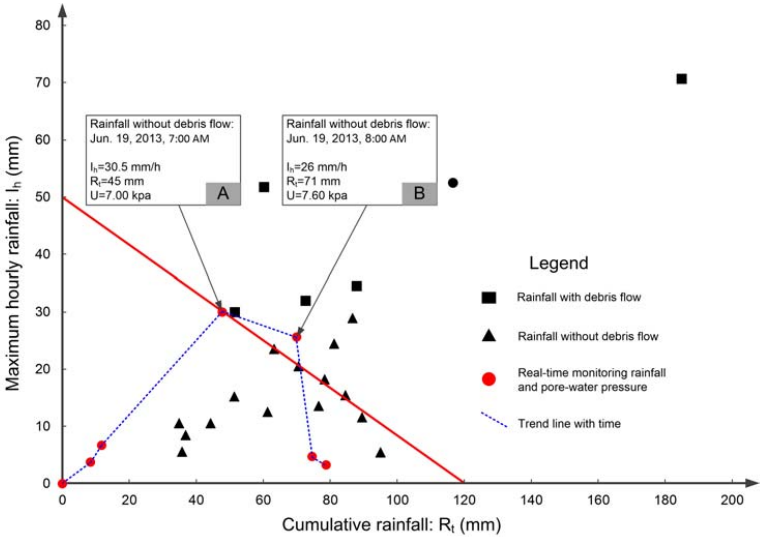

Fig. 8. Case application of the presented method in Wenjiagou gully (Jun. 19, 2013)

This case study shows, that it is worthwhile to continue to test the presented comprehensive threshold as a useful tool for debris-flow prevention and mitigation in mountainous area at a preliminary stage. The comprehensive threshold can be improved and modified as long as more data are available during subsequent studies in the future.

5. Discussion and conclusion

Debris-flow, usually triggered by rainstorm every year in the mountainous region in Southwest China, always cause significant harm both in human and property losses. Therefore, in order to prevent such natural disaster there is an urgent requirement for effective methods to predic debris-flow occurrence. The comprehensive threshold is provided and discussed in this paper, which not only use the common rainfall threshold, but also include the critical pore-water pressure from theoretical analysis of slope stability.

Two triggering factors: maximum hourly rainfall versus cumulative rainfall, and pore-water pressure, have been selected to establish a comprehensive threshold for debris-flow occurrence prediction. The Wenjiagou gully was selected as a case study for a detailed explanation of the

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provided method, and the results show that it is worth the effort to test further this approach for the early warning of debris-flows, especially at the preliminary stage. However, the assessment of a comprehensive threshold cannot be extended, to larger areas. Moreover the collection of pore-water pressure data in a distributed way is a rather cumbersome and costly undertaking and will be restricted to dangerous catchments like the Wenjiagou gully. Another the complicated problem is the final determination whether to alert local population, and whether compulsory actions need to be done at once, or a period of time later. Debris-flow early warning is not an imminent hazard but is just regarded as a potential danger. In spite of the limitations, the method has reached the goal to establish a comprehensive threshold for debris-flow early warning, and more subsequent work will be carried on in the future.

Acknowledgements

This study was financially supported by the National Natural Science Foundation of China (Grant No. 41521002 and No. 41302242), Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20135122130002), and State Key Laboratory of Geo-hazard Prevention and Geo-environment Protection (Chengdu University of Technology) (Grant No. SKLGP2013Z007). The authors also give great thanks to Prof. Theo van Asch for his review of an earlier version of this paper and for his suggestions to polish the language, which greatly improved the quality of the manuscript.

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