A preliminary study on the comprehensive threshold for debris-flow early warning

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Abstract

Debris-flows not only cause a great number of property loss, but also kill and injure people every rainy season in mountainous region of China. In order to reduce hazard risk, several methods of rainfall thresholds have been provided at present, frequently according to the statistical models relying on rainfall exceedance. However, the limited rainfall data with debris-flow occurrence or non-occurrence always caused threshold analysis to become very difficult. This paper, therefore, presented a comprehensive threshold combined with the factors of pore-water pressure and rainfall, which are the most important inducing parameters during debris-flow occurrences. The three-level early warning criteria (Zero, Attention, and Warning) has been adopted and the corresponding judgement conditions has been defined based on real-time monitoring data. Finally, a case study, Wenjiagou gully is introduced to show that the detail application of the provided method, and the results also indicate that it's likely to 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

1. Introduction

Accompanied by fast population increase and high speed economic development in developing countries, a great number of debris-flows occurred in mountainous area every year in rainy season, which always caused considerably catastrophic accidents and socio-economic losses. On Aug. 7 2010, a debris flow at Zhouqu County, Gansu Province, China, took about 1765 people's lives 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 and Ludian earthquake on August, 3 2014 trigged thousands of geo-hazards, which also indicated that the human vulnerability to natural hazards as well as the lack of knowledge on natural disaster prevention and mitigation. People living in mountainous regions have been deeply sensitized so that there is an urgent demand for an effective method to reduce the hazard risk. Therefore, researches have been working on forecasting debris-flow occurrences and setting up warning systems. Especially in regional scale, the methods for debris-flow early warning are frequently based on statistical models relying on rainfall exceedance, and which have already been proved their importance in predicting debris-flow occurrences several decades before (Baum and Godt 2009; Guzzetti et al. 2007b; Keefer et al. 1987; Segoni et al. 2014; Shuin et al. 2012; Tropeano and Turconi 2004). Usually, there are several parameters selected for the study of rainfall threshold, 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) as well. At the meantime, Baum and Godt (2009) used a comprehensive threshold with a combination of cumulative rainfall threshold, rainfall intensity-duration threshold and antecedent water index or soil wetness for shallow landslide forecasting.

Although those approaches widely used in the mountainous areas, they are currently affected by some drawbacks which still restrain a fully operational application to early warning systems. One of the main problems is lack of available data about rainfall with debris-flow occurrence or non-occurrence, e.g. most of mountainous area in Southwestern China. Even though there are enough data for statistical model, parameters selected for forecasting debris-flow occurrences are commonly limited to rainfall information, e.g. Yu et al. (2013) presented a normalized critical rainfall factor with an effective cumulative precipitation and a maximum hourly rainfall intensity, based on the existing topographic and geological factor.

Consequently, this paper presents a recent study on establishing one comprehensive threshold for predicting debris-flow occurrence based on the two main factors: rainfall records above the ground surface and pore pressure under the ground surface. The purposes of this paper are: (i) to propose a method for establishing a comprehensive threshold by the limited available data; (ii) to introduce the application and improvement of the comprehensive threshold for debris-flow early warning 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 between mountains is deeply cut by the Mianyuan river with an inclination of hill slope from 30° to 70° . The average yearly temperature of about 15.7 ℃, and general climate is mild semi-tropical moist climate with abundant rainfall and four distinguishable seasons. Most of the rainfall are concentrated in the three months from July to September about 80 % of the annual precipitation every year.

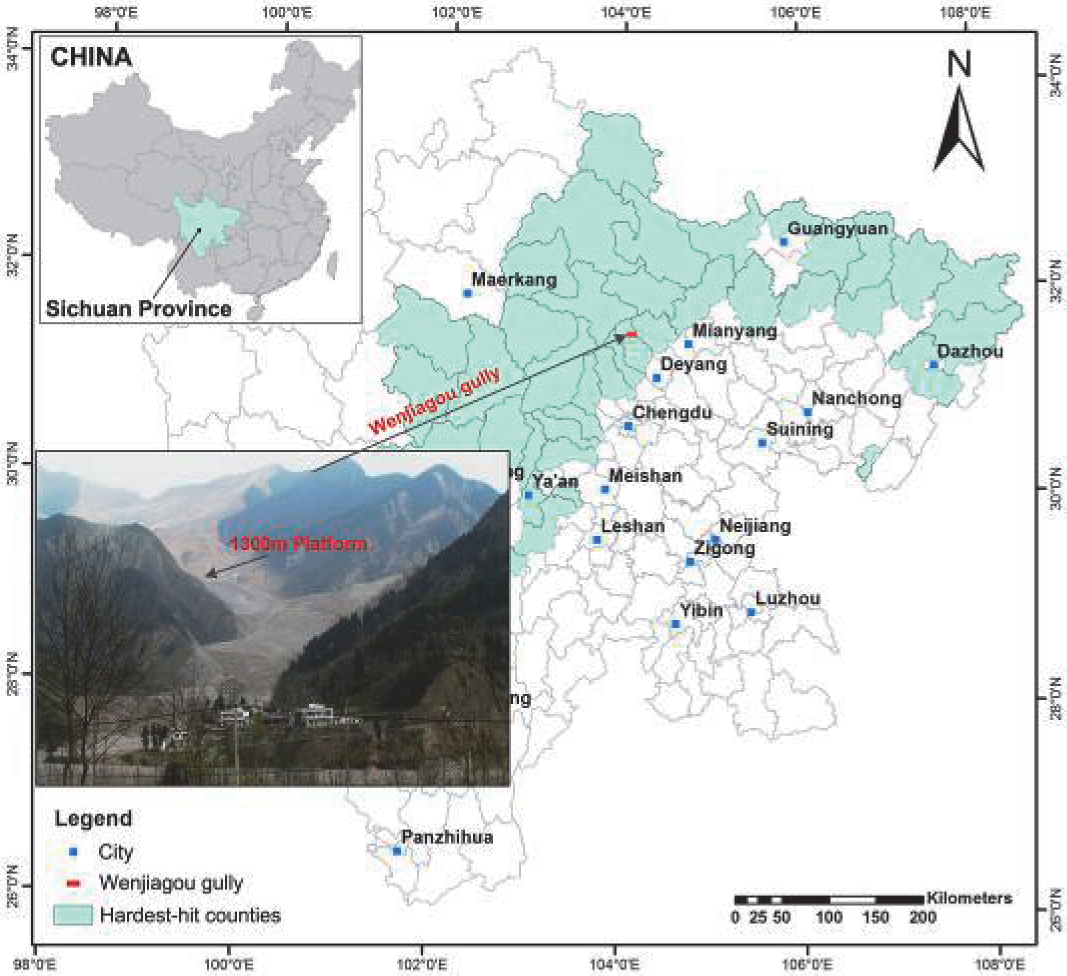

Fig. 1. Location of Wenjiagou gully modified from Huang et al. (2013). The inset photograph of Wenjiagou gully at the left bottom was taken from the other side of Mianyuan River on August 10, 2008.

Before Wenchuan earthquake on May12, 2008, this area was covered by rich vegetation, and the channel was smooth and stable. At that time, there is few geological disasters occurred in this region. Thus, so many farmers settled down at the foothills along the Mianyuan River. However after earthquake, there was a giant landslide occurred at the top of mountain, which caused abundant co-seismic rock falls and landslides deposited in the gully, particularly at the platform with an elevation of 1,300 m above sea level (Fig. 1, the photograph at left bottom of the main map). These deposits are very likely to provide a large amount of loose solid materials that were easily eroded and developed into debris-flow in rainy season (SHIEH et al. 2009). Unfortunately, the catastrophic debris-flow triggered by a heavy rainfall on August 13, 2010, the peak discharge of which is up to 1,530 m^3/s and the total volume of which is up to 3.1 × 10^6 m^3, which caused 7 persons dead, 5 missing, 39 injured and 479 houses buried, and the most downstream dam in the catchment as well (Yu et al. 2012).

3. Methodology

The presented method for forecasting debris-flow occurrence mainly consisted of two main components: (i) collect history events about rainfall with debris-flow occurrences and non-occurrences, (ii) establish a comprehensive threshold based on events analysis and real-time monitoring data.

3.1 Data analysis

Usually, data set is a solid foundation to establish statistical model of rainfall threshold for debris-flow early warning system. Therefore, several methods were provided to collect more available data for the following study, including debris-flow inventory maps, technical reports and documents presented by government agency. Moreover, for the reason that there are too many differences before and after the earthquake in the study region, so the integrated data are mainly about rainfall events with debris-flow occurrences and non-occurrences, which occurred after the Wenchuan earthquake in Wenjiagou gully, as shown in Table 1.

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	-

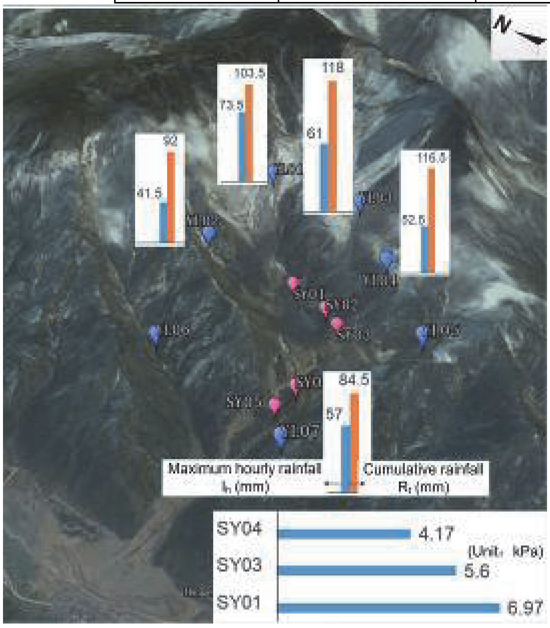

Fig. 2. Layout map of the monitoring sensors in Wenjiagou gully, the meaning of pink tags are shown in Table. 2. The insert column maps are monitoring data at 18:00 on Aug. 14, 2012 (The base map is from Google Earth, Dec. 18, 2010, and the elevation of sight is 5.01 km).

It can be seen from the Table 1, the number of debris-flow occurrence was going down as a tendency. Two years later after the earthquake, several giant debris-flows happened again, which caused catastrophic losses and shook the public and government for its huge destructive power and long-term impact. Particularly on Aug. 13, 2010, a great rainstorm lasting for 2 hours in the midnight triggered a giant debris flow in the gully, which buried the Qingping town at the mouth of gully and Mianyuan River. According to the inventory report, the maximum deposition height was up to 6 m, and most of the check dams located at the downstream of gully collapsed and lost their effectiveness after the passing of debris-flow, which eroded the channel bottom over a depth of about 13 m (Yu et al. 2012).

3.2 Comprehensive threshold for debris flow

Debris-flow occurrence is a complex process, which is not only triggered by rainfall but also linked to other factors (Itakura et al. 2005; Osanai et al. 2010; Yu et al. 2012). Therefore, in order to improve the warning thresholds which not just represent a simple relationship between rainfall and debris-flow occurrence, the pore-water pressure of landslide deposit was selected into comprehensive threshold consideration for it is an important geotechnical parameter in physical model study of debris-flow.

Table 2. List of monitoring sensors 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.
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	

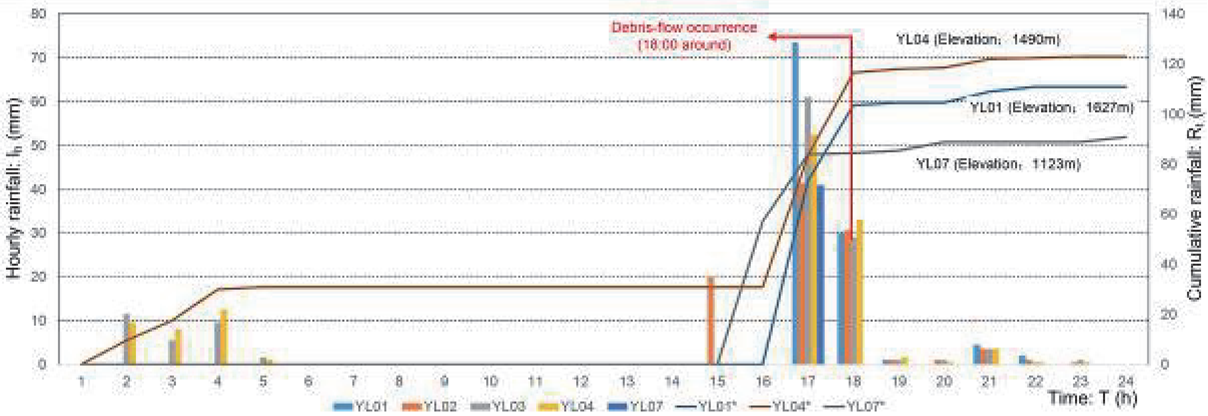

Fig. 3. The rainfall in Wenjiagou gully on Aug. 14, 2012 (the column maps are hourly rainfall and the single line maps are cumulative rainfall)

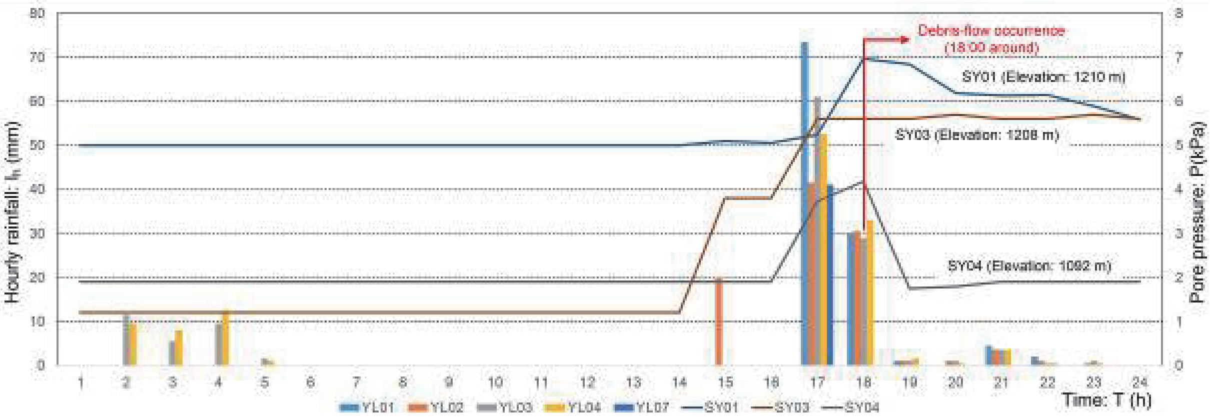

Fig. 4. The rainfall and pore-water pressure in Wenjiagou gully on Aug. 14, 2012 (the column maps are hourly rainfall and the single line maps are pore-water pressure)

Therefore, pore-water pressure and rainfall monitoring sensors have been selected to complement the data set and prepared for the relationship analysis among rainfall, pore-water pressure and debris-flow occurrence. The real-time monitoring system in Wenjiagou gully include 7 automatic rain gauges and 5 pore-water pressure monitoring instruments, as shown in Fig. 2 and Table 2. During the rainy season in 2012, there was a heavy rainfall event which happened on August 14 and caused a small debris-flow occurrence. During the rainstorm, monitoring sensors (YL05, YL07 and SY02, SY05) were lost connection from the local site to the monitoring center. Except the four sensors, other monitoring sensors worked well and received the monitoring data, as shown in Fig. 2, Fig. 3 and Fig. 4.

It can be seen in Fig. 2 and Fig. 3, the rainfall was almost concentered in two hours from 17:00 to 18:00, and the amount of precipitation were very different along the channel of Wengjiagou gully. The maximum hourly rainfall intensity is 73.5 mm (YL01), and the standard deviation of which is 12.76. The cumulative rainfall is 118 mm (YL03), and the standard deviation of which is 14.75. It means that the maximum of hourly rainfall and cumulative rainfall are not the one on the top of mountain, and the difference of cumulative rainfall is much larger than the maximum hourly rainfall intensity. The Fig. 4 is to show the relation between hourly rainfall and pore-water pressure, it can be seen that small rain won't trigger any change in pore-water pressure from 2:00 to 5:00 with the maximum hourly rainfall of 12.5 mm. However, the pore-water pressure has increased fast when the concentrated rain occurred from 17:00 to 18:00, and triggering a debris-flow occurrence. The values of sudden change are 1.97 kPa (SY01), 4.4 kPa (SY03) and 2.27 kPa (SY04) with an average of 3.19 kPa, which indicated that a sudden rise of pore-water pressure played a very important role in debris-flow occurrence.

According to the above-mentioned introduction, several factors have been used to research on rainfall threshold for debris-flow prediction. But the limited available data still make it's very difficult to establish an effective threshold, particularly in a short time. Therefore, 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 comprehensive threshold, and the change value of pore-water pressure (R_c) has been defined as an independently required factor in forecasting debris-flow occurrence.

Based on the collected rainfall events with debris-flow occurrence and non-occurrence, R_t and I_h, two related rainfall parameters triggering debris-flow occurrence, then can be plotted on a single graph with x and y axes, e.g. a heavy rainfall with debris-flow occurrence on Aug. 13, 2010 as shown in Fig. 5 (Tag A). Hereafter, combined with the approach proposed by Jan et al. (2002) and modified by Zhuang et al. (2014), the rainfall threshold for predicting debris-flow occurrence can be defined and calculated, as shown in Equation 1 and Fig. 5 (Tag C).

$$R_t + 2.4 I_h = 120 \quad (1)$$

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

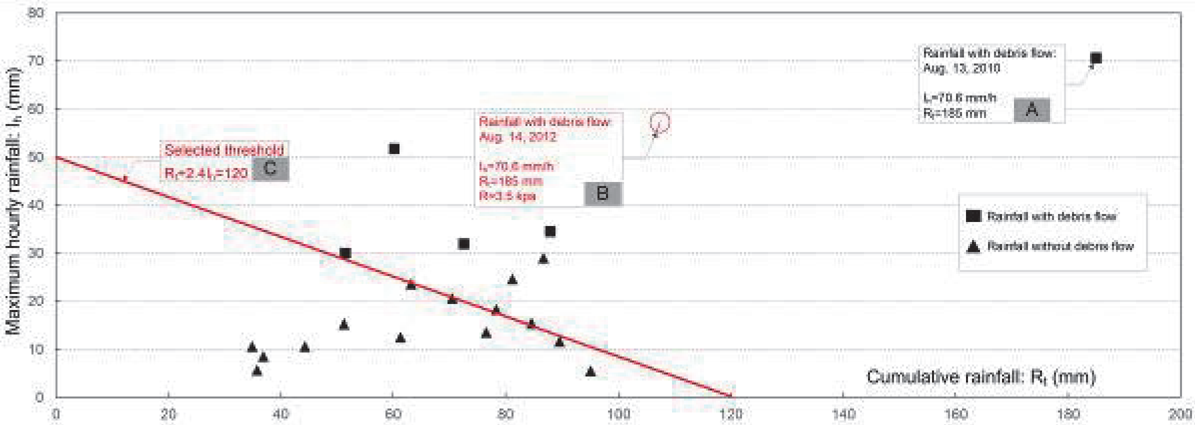

Fig. 5. Rainfall threshold based on maximum hourly rainfall and cumulative rainfall

It can be seen in Fig. 5, there are thirteen points of rainfall events with debris-flow non-occurrence under the rainfall threshold, and two error points above the rainfall threshold. The ratio of right points is 86.67%, which is much suitable for the emergency and preliminary application under the initial stage. However, as mentioned above, only rainfall threshold is not enough to predict debris-flow occurrence. Pore-water pressure, therefore, has been selected to supplement the warning threshold. According to the pore-water pressure monitoring data, the change value of pore-water pressure (R_c) is much more important to trigger debris-flow occurrence, as shown in Fig. 4. Thus, the judgement condition of R_c is defined as Equation 2.

$$R_c \geq 3.5 \quad (2)$$

While both of the two equations (Eq. 1 and Eq. 2) are satisfied, there must be a very high possibility of debris-flow occurrence. Therefore, the combined comprehensive threshold can be used to forecast debris-flow occurrence in the near future. Along with more available data collected, the supplement and improvement will make it become more reliable and accurate for debris-flow prediction.

4. Example of application

Presently, it is known that trying to forecast debris-flow occurrence and alert people is a very complex work in practice. Therefore, some implications has to be done for a better use. For the preliminary stage, a three-level early warning criteria to response after each warning level has been adopted, as shown in Table 3.

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

Table 3. Recommended warning levels for Wenjiagou gully

Warning level	Trigger	Response
Ⅰ level	Default level, both of Eq. 1 and Eq. 2 are not satisfied.	**Null**: but data are checked daily. Weekly monitoring bulletin.
Ⅱ level	Any one of Eq. 1 or Eq. 2 is satisfied.	**Watch**: data are checked more frequently. Daily monitoring bulletin. Authority and expert are alerted. Preparing for alarm.
Ⅲ level	Both of Eq. 1 and Eq. 2 are satisfied.	**Warning**: data are checked even more frequently. Two monitoring bulletins per day. Local people are alerted.

In order to show how this presented method used in debris-flow predicting, a heavy rainfall event on Jun. 19, 2013 has been introduced as a case application, as shown in Fig. 6. The circle solid points were the real-time rainfall information, with cumulative rainfall in X axis and hourly rainfall in Y axis. E.g. the Tag A in Fig. 6 shows the monitoring rainfall data at 7:00 am on Jun. 19, 2013, and the change value of pore-water pressure (R_c) is 2.1. After one hour later at 8:00 am (Tag B), the real-time rainfall has been exceeding the rainfall threshold, but the R_c didn't met the Eq. 2 ($R = 2.4 < R_c$) which indicated the warning level was in Orange, and there was no need to send warning message at this level. Finally, the rainfall went down after 8:00 am, and there was no debris-flow occurrence during the rainy time on Jun. 19, 2013.

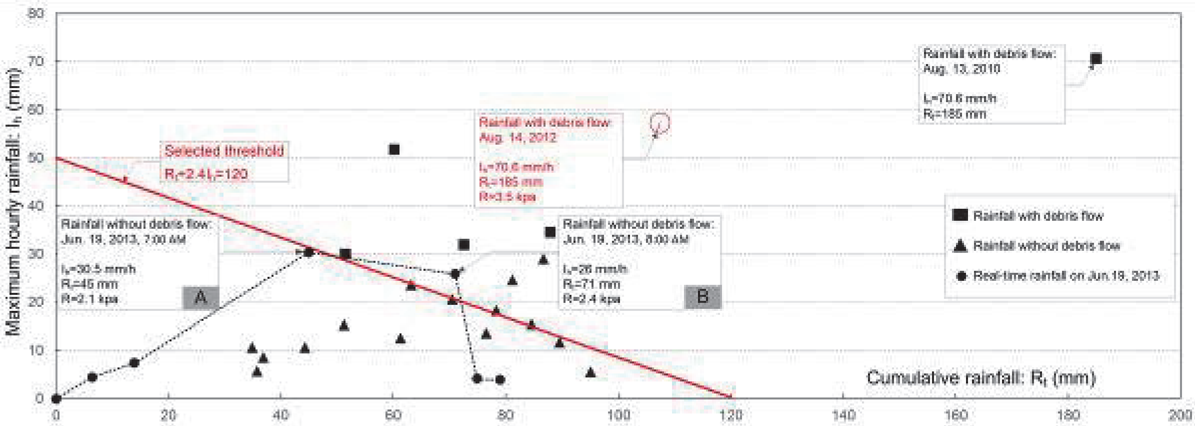

Fig. 6. Case application of the presented method in Wenjiagou gully (Jun. 19, 2013)

According to the case study, we can conclude that the comprehensive threshold can make a great favor in predicting debris-flow occurrence in Wenjiagou gully. At least it's very useful for debris-flow prevention and mitigation in mountainous area at a preliminary stage. Moreover, the comprehensive threshold can be improved and modified as long as more available data collected during the subsequent study in the future.

5. Discussion and conclusion

Debris-flow, usually triggered by rainstorm every year in the widely mountainous region in Southwest China, which always cause significant harm both in human and property losses. Therefore, in order to prevent such natural disaster there is an emergency requirement for an effective method for debris-flow occurrence prediction. The comprehensive threshold is provided and discussed in this paper, which not only can deal with the insufficient of rainfall threshold used before, but also meet the lack of available rainfall events with debris-flow occurrence or non-occurrence.

Based on the two triggering factors of rainfall, maximum hourly rainfall and accumulative rainfall, combined with the internal factor of pore-water pressure frequently used in mechanism analysis, have been selected to establish a comprehensive threshold for debris-flow occurrence prediction. Hence, Wenjiagou gully was selected as the case study for a detail explanation of the provided method, and the results show that it's indeed a well approach for debris-flow prevention and mitigation, especially at the preliminary stage. However, there still are some limitations while using this method to another similar regions. The basic restriction is this comprehensive threshold which has the usage limitation for the special area (Wenjiagou gully). Another the most complicated problem is the final determination whether to alert local population, and any compulsory actions need to be done at once, or a period of time later. Debris-flow early warning is just regarded as a potential danger, and which is not an imminent hazard. In spite of the limitations, the method has reached the goal of establish a comprehensive threshold for debris-flow early warning based on the limited available data, and provide a foundation for improvement and modification during the subsequent study in the future.

Acknowledgements

This study was financially supported by the State Key Laboratory of Geo-hazard Prevention and Geo-environment Protection (Chengdu University of Technology) (Grant No. SKLGP2013Z007) and National Natural Science Foundation of China (Grant No. 41302242).

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