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 threshold 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 by field monitoring data. 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, there are several rainfall events in recent years have been validated in Wenjia gully, which prove that such a combined threshold may be a reliable approach for the early warning of gully-type debris flow to safeguard the population in the mountainous areas.

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

1. Introduction

Gully-type debris flow, a kind of common geohazards in Southwest China, is mainly triggered by high-intensity short-duration rainfall causing a runoff-induced effect. Most of them are initiated by shallow landslides distributed along the gullies in mountainous region (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 and empirical conclusion, and 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). In the beginning, one or two parameters were selected for the assessment of rainfall thresholds to forecast landslide occurrence, 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). Hereafter, Baum and Godt (2009) presented a combination threshold, including cumulative rainfall threshold,

53   rainfall intensity-duration threshold and antecedent water index or soil wetness for the shallow

54   landslide forecasting. At the local scale, physical methods (e.g. numerical simulation) were used to

55   find relationships among rainfall, soil properties, and pore pressure and their contributions to slope

56   stability (Beven and Kirkby 1979; Chae and Kim 2011; Deb S. K. and El-Kadi A. I. 2009; Iverson

57   1997; Michel G. P. and Kobiyama M. 2016; Peng et al. 2014; Thiebes 2012; van Asch et al. 2013).

58   However, detailed information related to landslide triggering are required to establish the site-specific

59   thresholds, which are very difficult to extrapolate to other places due to the large variation in soil

60   properties between different regions. Yu et al. (2013a) selected several identified factors related to

61   topography, geology, and hydrology, to develop a normalized critical rainfall factor combined with an

62   effective cumulative precipitation and maximum hourly rainfall intensity index for the forecast of

63   gully-type debris flows. The model which is partly based on a runoff-induced mechanism has been

64   successfully applied to the Wangmo River catchment, Guizhou Province, China (Yu et al. 2014).

65   Unfortunately, strong earthquake shocks in Southwest China caused a significant rise in the

66   frequency of debris flow during recent years. The long-term effect by earthquakes cause the region

67   become a high-risk area, and particularly the gullies in mountain with no debris flows before become

68   the debris flow gullies at present. The mechanism, movement characteristics, and thresholds of debris

69   flow in these shocked areas, therefore, have been paid great attention by researchers, e.g. Guo et al.

70   (2013), Huang et al. (2015a), Yin et al. (2010), Yu et al. (2014), Zhou and Tang (2013) and so on. But

71   these models still mainly focused on rainfall threshold, with no consideration about the rise of loose

72   deposited material and unstable slope distributed along the catchments. Therefore, during this study,

73   pore pressure in slope stability analysis have been considered for establishing a combined threshold.

74   The goal of the presented study is to propose a comprehensive method for gully-type debris flow early

75   warning by real-time monitoring of rainfall and changes in pore pressure in the deposited material

76   along channel in Southwest China. The infinite slope stability analysis was applied to identify the

77 critical stability conditions of the deposited material. Then, a comprehensive warning threshold for

78 rainfall and critical pore pressure will be presented, which includes both rainfall conditions and soil

79 properties. Finally, verification and revision would been discussed to search a practical and useful

80 method for reducing the risks of gully-type debris flow in Southwest China.

81 **2. Study area**

82 The Wenjia gully is located at the north of Qingping town, Mianzhu city, Sichuan province,

83 Southwest China, and has a catchment area of 7.8 km^2 and a 5.2 km long main channel, as shown in

84 Fig. 1. The elevation of this study area ranges from 860 m to 2,400 m above sea level (Fig. 2a), and

85 the main valley with slope inclinations between 30° and 70° has been deeply incised by the Mianyuan

86 river. The average yearly temperature is about 16 ℃, and the climate is mild semi-tropical and moist

87 with abundant rainfall and four distinguishable seasons. Eighty percent of the rainfall is concentrated

88 in three months from July to September.

89 Before the Wenchuan earthquake on May12, 2008, the Wenjia catchment was covered by rich

90 vegetation, and the channel was smooth and stable, as shown in Fig.3 (a). At that time, few geological

91 disasters occurred in this region. Therefore, many farmers settled down at the foothills along the

92 Mianyuan River. Qingping town downstream of the Wenjia channel's outlet (Fig 3 a & b). During the

93 earthquake, a giant landslide occurred upstream in the catchment at the top of the watershed, which

94 generated abundant co-seismic rock fall material and finer landslide deposits on a platform with an

95 elevation of 1,300 m above sea level (Fig. 1, the photograph at left bottom of the main map). These

96 loose solid erodible materials could easily transform into debris flows during a rain storm. Shortly

97 after the earthquake on Sep. 24, 2008, one rainfall event caused the first debris flow in this gully. The

98 catastrophic debris flow triggered by a heavy rainfall on August 13, 2010, with a peak discharge of

99 1,530 m^3/s and a total volume of 4.5×10^6 m^3, caused many victims and the burying of reconstructed

100 houses, most of the downstream check dams along the channel (Yu et al. 2013b).

101

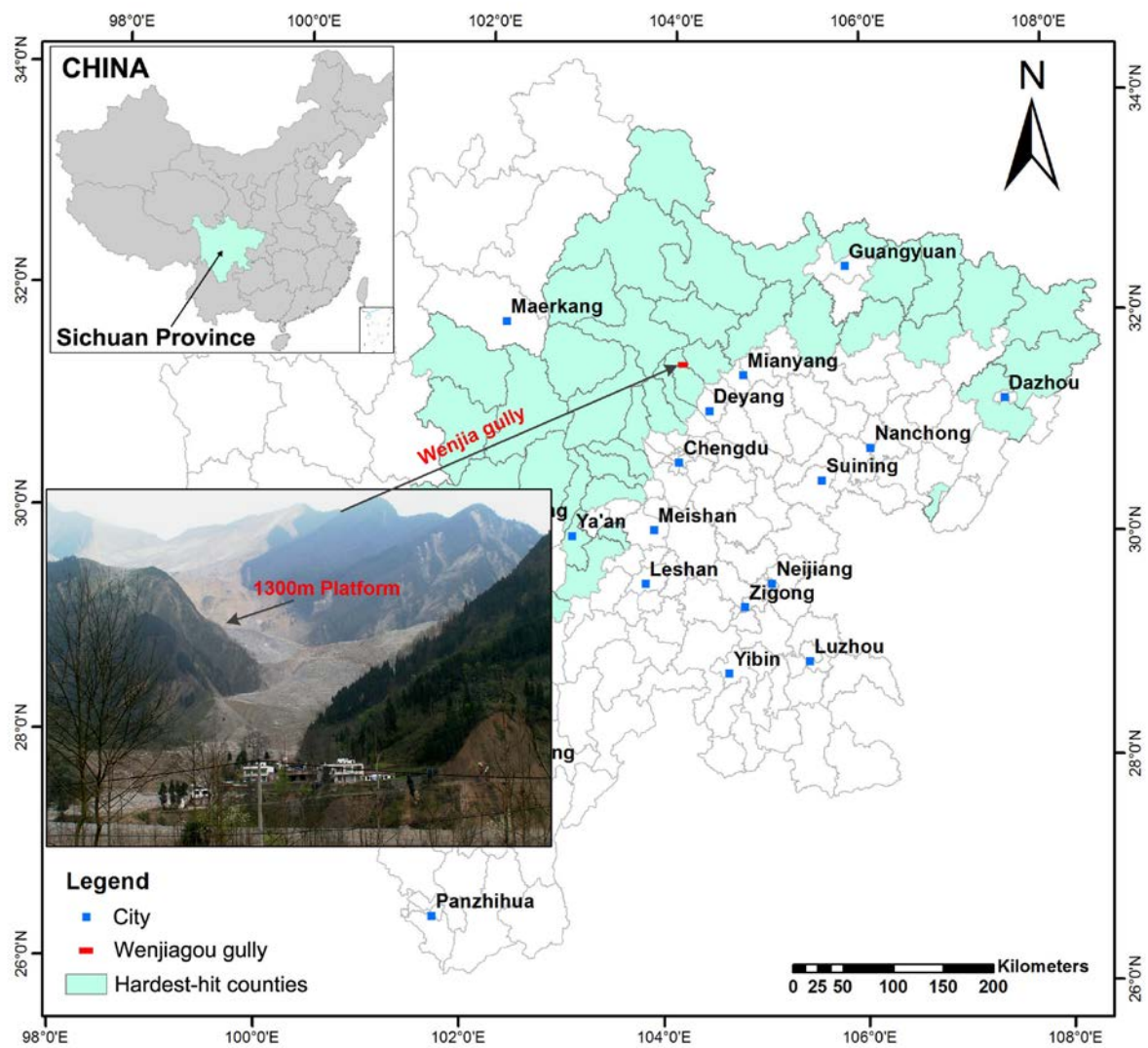



Fig. 1. Location of Wenjia gully modified from Huang et al. (2013). The inset photograph of Wenjia gully at the

103   left bottom was taken from the other side of Mianyuan River on August 10, 2008.

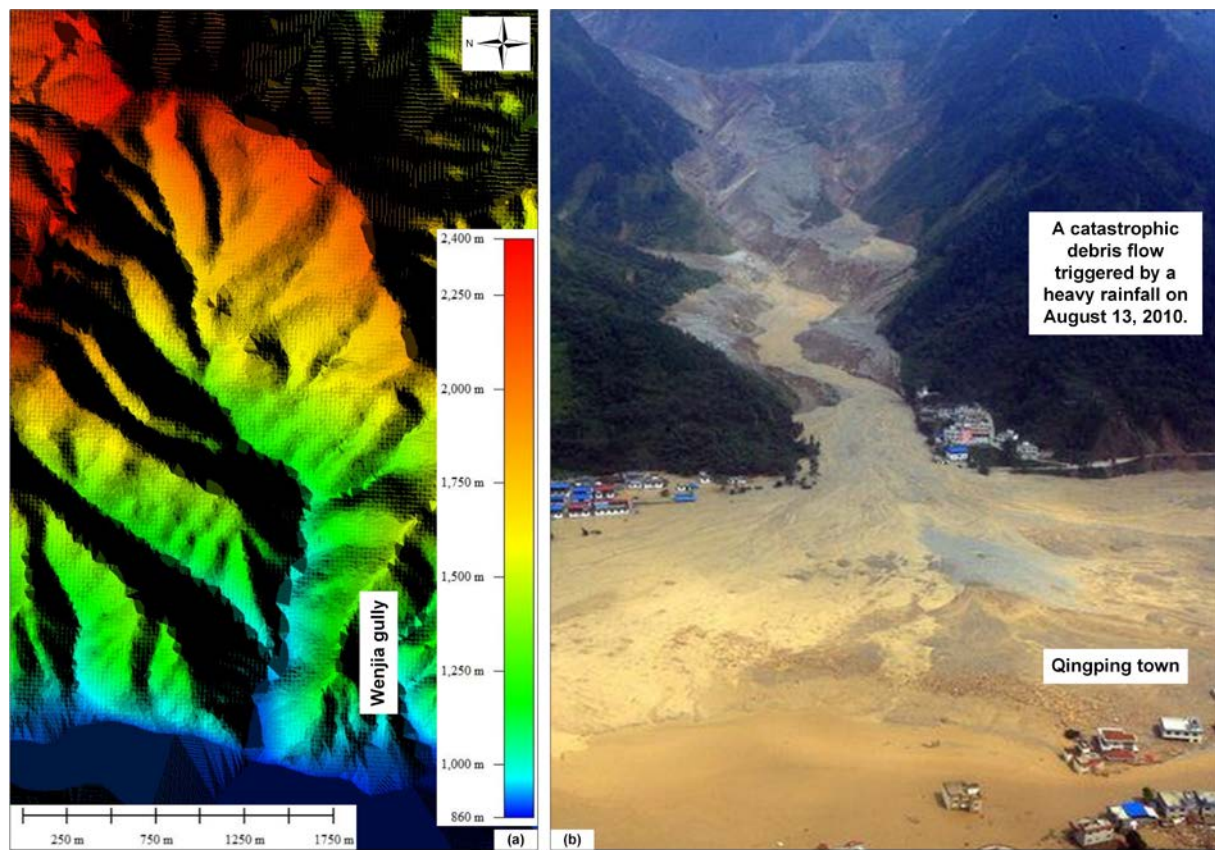



Fig. 2. DEM map of Wenjia gully and photo on the debris flow event (August 13, 2010)

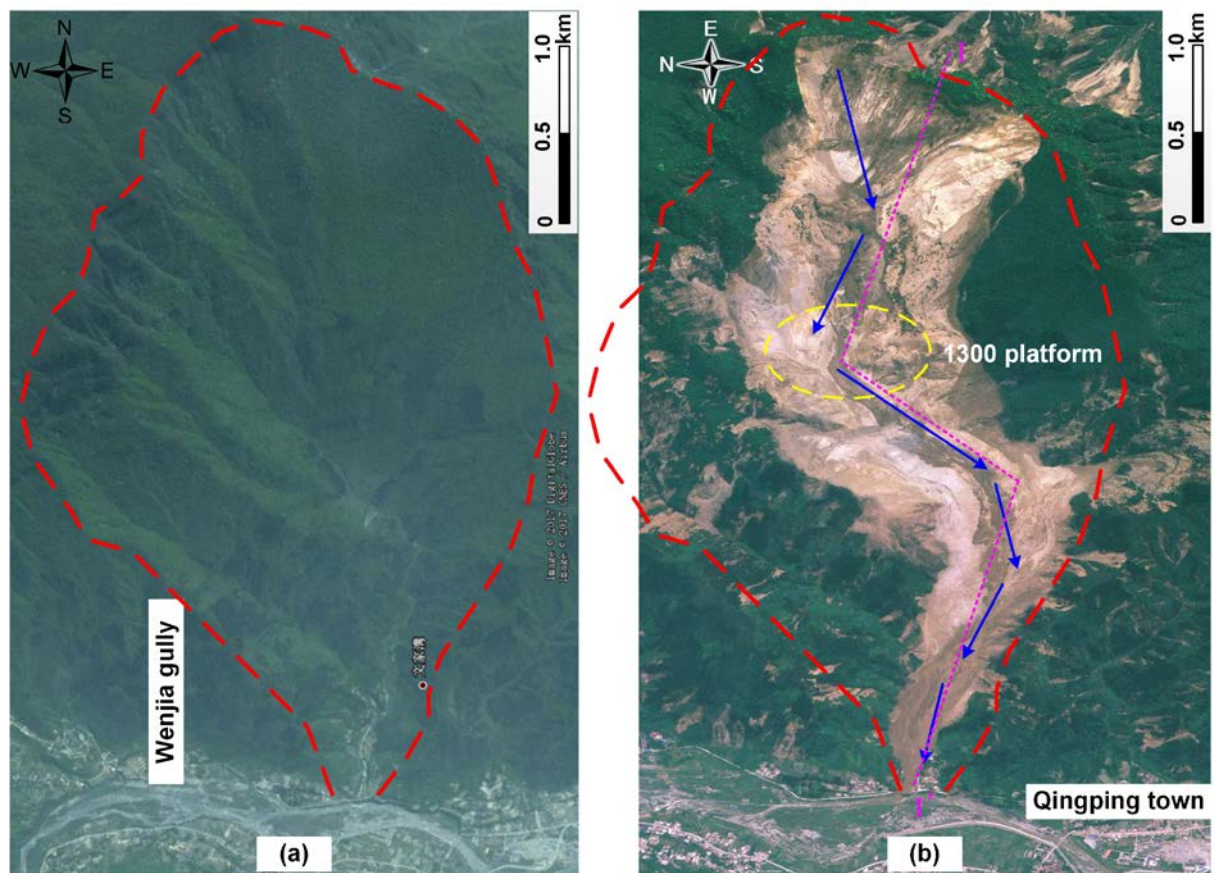
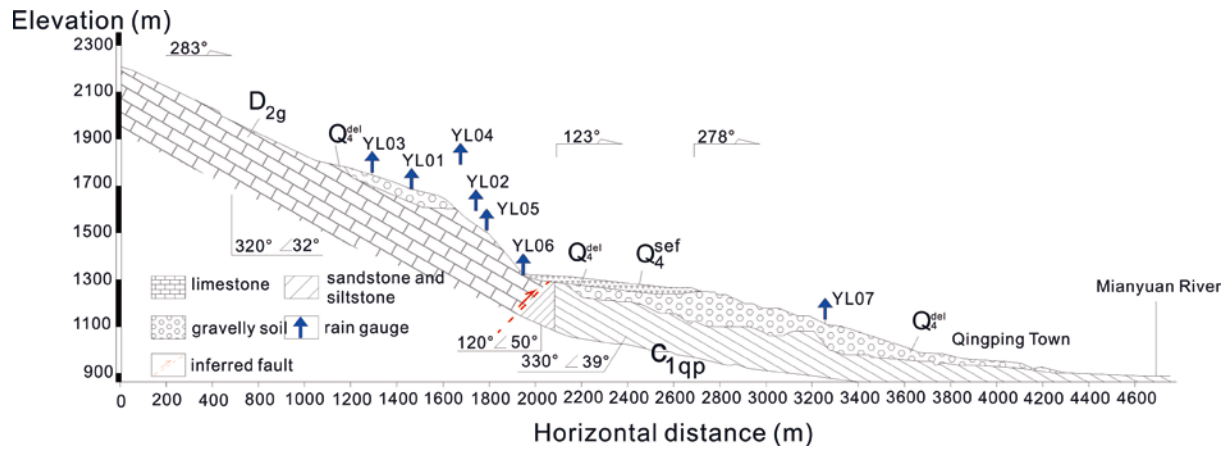



Fig. 3. Aerial image of Wenjia gully (a. image from Google Earth on Dec. 31, 2007; b. aerial photograph taken on May 18, 2008)

105

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

107   Fig. 4 is the geological profile of cross section Ⅰ-Ⅰ' in Wenjia gully (Fig. 3b). The exposure

108   strata are Guanwushan Group (upper devonian period) with limestone, and Qingping Group (cambrian

109   perod) with sandstone and siltstone. Field investigation also shows that the main loose deposits are

110   located at the 1300 platform (Fig 1 & 3). During heavy rains, the intense surface run-off may cause the

111   unstable slope collapse into the channel, maybe bed failure or run-off scouring of the loose deposited

112   material. This explains why there would be giant debris flow occurrence in this gully, e.g. the debris

113   flow event on August 13, 2010 above-mentioned.

114   **3.   Methodology**

115   According to Terzaghi theory in soil mechanics, the shear strength of material at a point within a

116   slope can be expressed as Eq. (1).

117 $$\tau = c + (\sigma - u)\tan\phi \tag{1}$$

118   where τ is the shear strength of the slope material, c is the effective cohesion of the material,

119   ϕ is the effective friction angle of the material, σ is the total stress normal to a potential slip

120   surface, and u is the pore pressure. Generally, the strength parameters (c, ϕ) of the slope material

121   mainly determined the stability of the slope and the potential position of the slip surface.

122   Rainfall infiltrates into a hillslope, always accumulating in a saturated zone above a permeability

123   barrier, and increases the pore pressures within the slope material. Based on the Terzaghi's work, the

124   increase in u would cause the effective overburden stress ($\sigma - u$) to decrease, and therefore the

125   decrease of the shear strength until the slope fails. A formula to calculate the critical level of the pore

126   pressure, for a highly idealized model of an infinite slope composed of cohesionless materials ($c = 0$)

127   has been presented by Keefer et al. (1987), assuming both slip surface and piezometric surface are

128   parallel to the ground surface. For all these assumptions, the critical pore pressure can be calculated by

129   Eq. (2).

130
$$u_C = Z \times \gamma_t \times \left(1 - \frac{\tan \theta}{\tan \phi} \right) \qquad (2)$$

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

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

133   Since the deposited material along the channel usually is loose and has a grain shape, it can be

134   regarded as an infinite slope composed of cohesionless materials. Therefore, the critical pore pressure

135   (Eq. 2) can be used to calculate the stability of the source area. Then pore pressure and rainfall

136   monitoring sensors were installed in the Wenjia gully to capture the real-time data and put forward a

137   comprehensive warning threshold for forecasting debris flow occurrence. The history events about

138   rainfall with debris flow occurrences and non-occurrences have been collected for this study from

139   2008 to 2018. Fortunately, three debris flow events with detailed rainfall and pore pressure monitoring

140   data have been recorded, which could be an important evidence to prove the presented methodology.

141   **4.   Results**

142   **4.1 Data analysis**

143   Data were collected from the literature about the occurrence of debris flows in the Wenjia gully

144   and from technical reports and documents presented by government agency. Since there is a large

145   difference in debris flow frequency before and after the Wenchuan earthquake, only the data after

146   quake were used for the analyses and set-up of an early warning system (Table 1). There were no

147   debris flow events after 2014, so the rainfall data are omitted in the table.

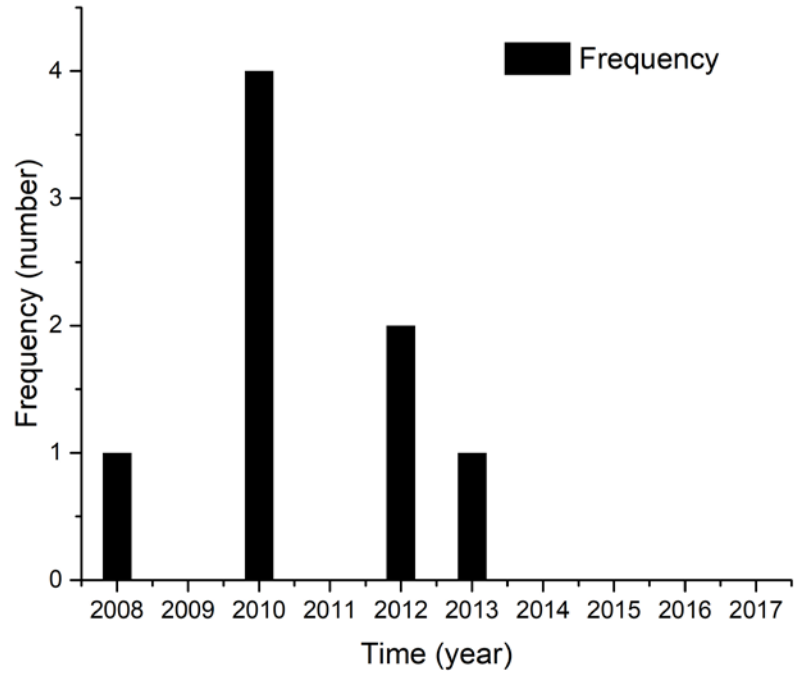
148   Table 1. Primary rainfall events in the catchment of Wenjia gully (2008-2018), added from Xu (2010)

149   & Yu et al. (2013b)

Time	Maximum hourly rainfall intensity (I_h: mm)	Accumulated precipitation (R_{dt}: mm)	Debris flow occurrence or not	Volume of debris flow (m³)
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	$1.0 \sim 2.0 \times 10^5$
Aug. 13, 2010	**70.6**	**185.0**	**Yes**	**4.5×10^6**
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	-
......	......	......	......	......

150   *note: The accumulated precipitation is a total sum of one rainfall event of which the beginning is defined as the moment

151   that the hourly rainfall amount is more than 4mm, and the end is when the hourly rainfall amount is less than 4mm, and this

152   should last for at least 6h (Huang et al. 2015b).

153
154   Fig. 5. The frequency of debris flow events in Wenjia gully from 2008 to 2017

155   Table 1 and Fig. 5 shows that the number of debris flows decreases with time. Several years after

156   the earthquake, however, giant debris flows still caused catastrophic losses, which alarmed the public

157   and government because of its huge destructive power and long-term impact. Particularly on Aug. 13,

158   2010, a great rainstorm lasting for 2 hours during midnight, triggered a giant debris flow, which buried

159   the Qingping town in the Mianyuan River floodplain. According to the inventory report, the maximum

160   deposition height was up to 6 m. Most of the check dams located in the downstream part of the Wenjia

161   gully collapsed and lost their effectiveness after passing of the debris flow. Meanwhile, it eroded the

162   channel bottom over a depth of about 13 m (Yu et al. 2012).

163   Pore pressure and rainfall monitoring sensors have been installed for understanding their

164   relationship, and the link with debris flow occurrence. The real-time monitoring system in the Wenjia

165   gully includes 7 automatic rain gauges and 5 pore pressure monitoring instruments. The installation

166   was finished by April 1, 2012 (see Table 2, Fig. 4 and Fig. 6). It can be seen that all rain gauges are

167 arranged in the upstream part of the Wenjia gully catchment, while pore pressure monitoring sensors

168 are distributed along the mainstream of the Wenjia gully, with a depth of 1 m below the ground

169 surface.

170   The 2012, heavy rainfall event on August 14, which triggered a debris flow has been caught totally

171 by the real-time monitoring system. During the rainstorm, monitoring sensors YL05, YL06 and SY02,

172 SY05 lost the connection with the monitoring center. The other monitoring sensors worked well, as

173 shown in Fig. 7 and Fig. 8. The figures show that the rainfall was almost concentrated in two hours

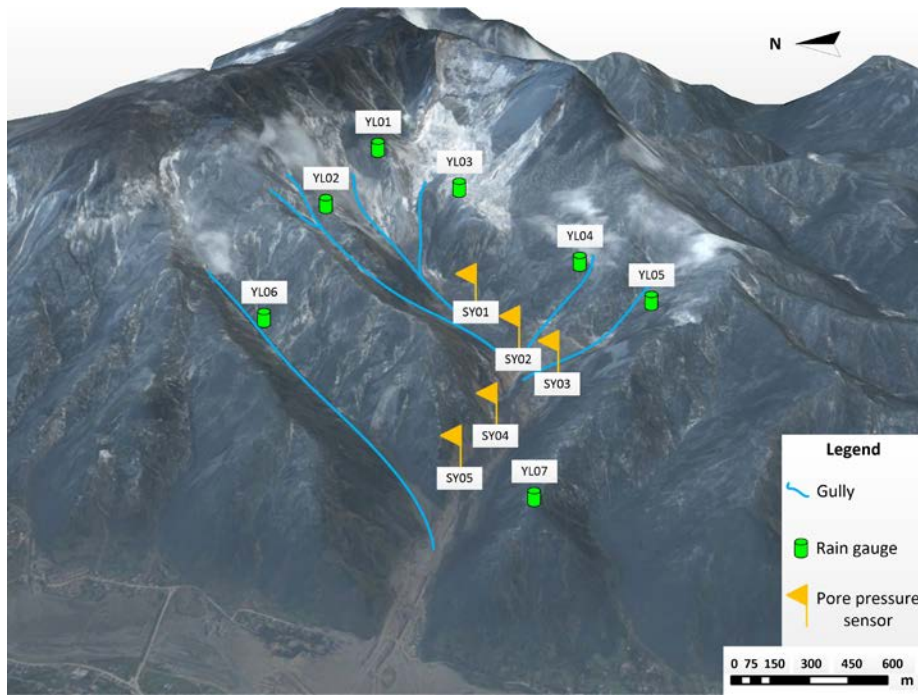
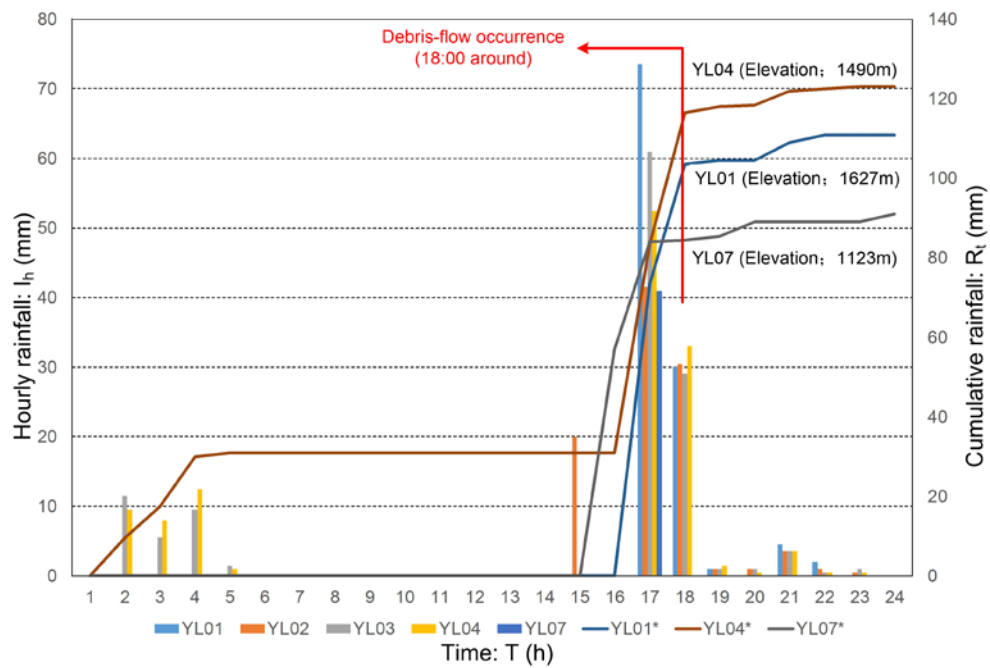
174 from 17:00 until 19:00. The amount of precipitation was highly variable along the channel of the

175 Wengjia gully. The maximum hourly rainfall intensity is 73.5 mm (YL01, 17:00), and the cumulative

176 maximum rainfall is 118 mm (YL04).

177

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	

178
179   Fig. 6. Layout map of the monitoring devices installed in the Wenjia gully (The base map is from Google Earth,
180   the date of background image is Dec. 18, 2010).

181
182   Fig. 7. The rainfall in Wenjia gully on Aug. 14, 2012 (the column graphs are hourly rainfall and the single line
183   curves are cumulative rainfall)
184

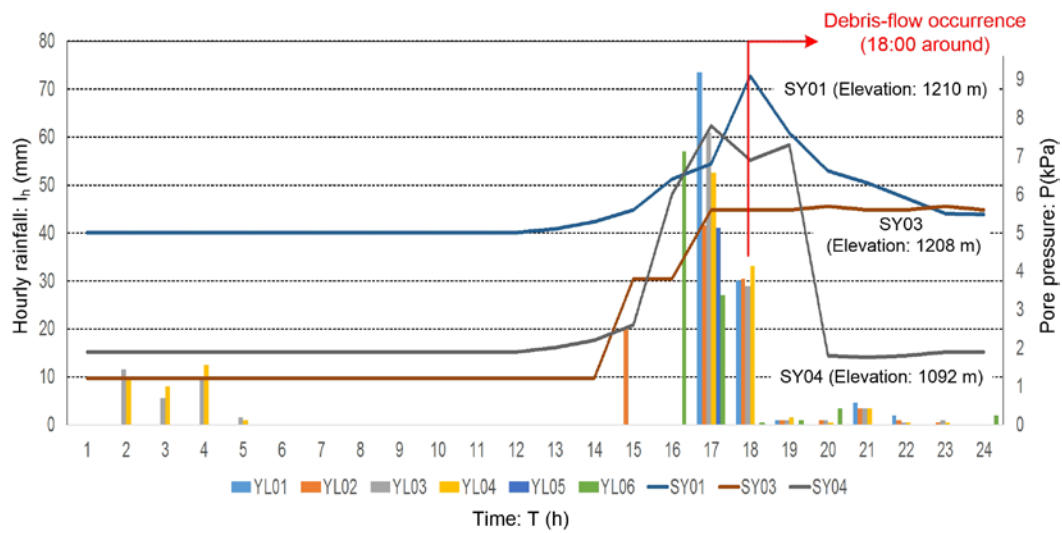



Fig. 8. The rainfall and pore pressure in Wenjia gully on Aug. 14, 2012 (the column graphs are hourly rainfall and the single line curves are pore pressure)

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. 8 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.

4.2 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

204 critical pore pressure of the deposited material can be calculated by Eq. (3).

205
$$u_C = (6.79 - 8.22) \times Z \qquad (3)$$

206   Obviously, it's a linear function, as shown in Fig. 9. According to the real-time monitoring system,

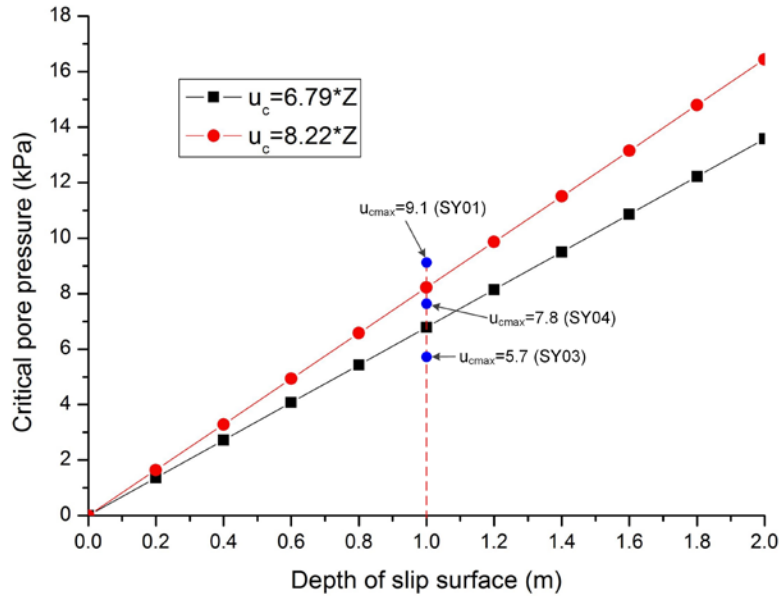
207 therefore, the critical pore pressure should be 6.79~8.22 kPa at the depth of 1 m below the ground

208 surface. According to Table 1, on Aug. 14, 2012, there was a debris flow with run-off volume of

209 3.2×10^4 m³, and before the debris flow event pore pressure monitoring data show its maximum value

210 was up to 9.1 kPa (SY01), 7.8 kPa (SY04) and 5.7 kPa (SY03). Obviously, SY01 has already

211 exceeded the upper threshold of critical pore pressure (8.22 kPa), which means that the critical pore

212 pressure might be an important factor in debris flow occurrence.

213
214   Fig. 9. The critical pore pressure with probable depth of slip surface in the Wenjia gully

215   Considering the acquired available data, the maximum hourly rainfall (I_h: mm) and cumulative

216 rainfall (R_t: mm) are selected as the basic triggering rainfall parameters for the rainfall threshold, and

217 the critical pore pressure (u_c) has been defined as a supporting factor in forecasting debris flow

218 occurrence. For each rainfall event with or without debris flow occurrence, R_t (Cumulative rainfall)

219 and I_h (Hourly intensity), can be plotted in a X-Y field, like the debris flow event on Aug. 13, 2010

220 (Fig. 10 Tag A). The red line drawn under the lowest rectangle points which represent debris flow

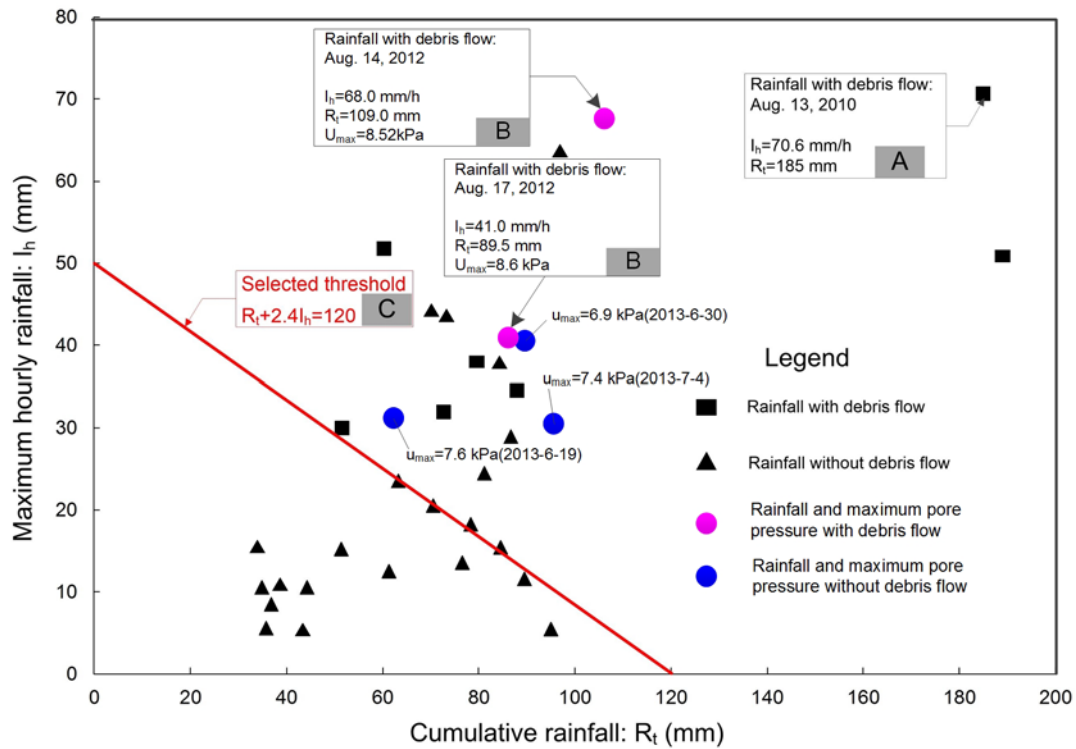
221 occurrences under such rainfall conditions. The area between the line and the x and y axes defines

222 combinations of R_t and I_h with a zero probability of debris flow occurrence. The gradient is an

223 uncertain parameter which can be determined by experts' experiences and historical data sets (Huang

224 et al. 2015b). Then, the rainfall threshold can be defined by Eq. (4) in Fig. 10 (Tag C).

$$R_t + 2.4I_h = 120 \qquad (4)$$

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

227
228 Fig. 10. Warning threshold combined with rainfall and pore pressure

229 While above the red line, the probability of debris flow occurrence is higher. But among these

230 points, there are 8 rectangular points with debris flow. The possibility of debris flow occurrence can be

231 predicted correctly up to 62% by rainfall threshold, which seems to be fine as a preliminary

232 assessment. If the pore pressure monitoring data has been considered, in Fig. 10, there are three blue

233 circular points without debris flow, but two magenta points show debris flow happened. The different

234 between them is that maximum pore pressure has exceeded the critical pore pressure line (8.22 kPa).

235 Therefore, the rainfall threshold and pore pressure threshold need to be combined during forecasting

236   debris flow occurrence, then there must be a much higher possibility of successful prediction. For a

237   given rainfall event, the starting point and its trend can be calculated and plotted in Fig. 10. In order to

238   verify in real time whether the trend line exceed the warning threshold. More detail information will

239   be discussed with an example as follow.

4.3 Example of application

241   In order to make a better use for the presented method, early warning criteria have to be

242   simplified to make a clear understanding for the study area. Therefore, a three-level early warning

243   system has been proposed for the Wenjia gully, as shown in Table 3. At level one there is low

244   possibility of debris flow occurrence. At level two there is a chance of debris flow occurrence in the

245   near future, and warning messages need to be sent to local authority and countermeasures need to be

246   discussed. At level three there is very likely to occur right now, therefore, local residents need to be

247   alerted and forbidden going to the threatened places.

248

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.

249   In order to explain how the presented method can be used in a real-time debris flow early warning

250   case, the rainfall on Jul. 8, 2013 has been selected as an application (Fig. 11). The small circular

251   magenta solid points connected by a magenta line shows the course of the real-time monitored data

252   during this rain storm, with the cumulative rainfall on the X axis and hourly rainfall intensity on the Y

253   axis. The Tag A in Fig. 11 shows the rainfall data at 17:00 on Jul. 8, 2013, with a pore pressure of 3.00

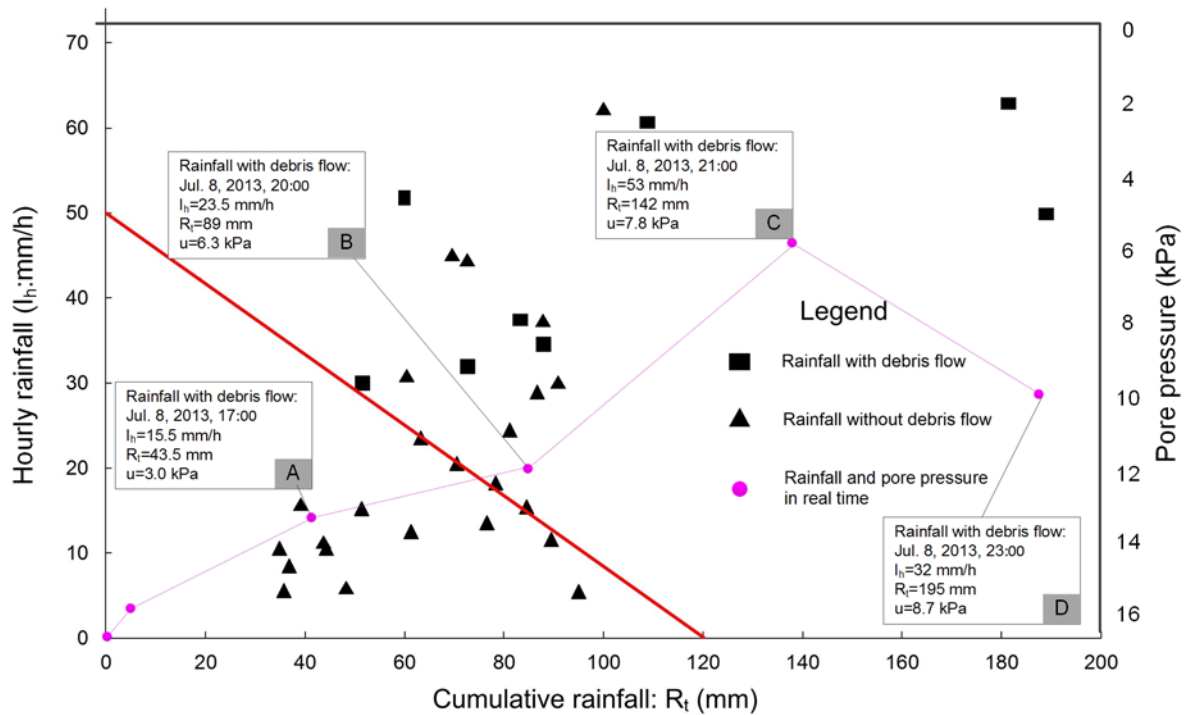
254   kPa at that time. Three hours later at 20:00 (Tag B), the real-time rainfall has exceeded the rainfall

255   threshold, but the pore pressure didn't exceed the critical pore pressure (6.3 kPa < 6.79 or 8.22 kPa)

256   indicating that the warning information stayed in level Ⅱ. One hour later at 21:00 (Tag C), the pore

257   pressure did exceed the lower critical pore pressure (7.8 kPa > 6.79 kPa) indicating that debris flow

258   had a much higher possibility to occur. Further, the pore pressure went up to 8.7 kPa over the upper

259   critical pore pressure (8.22 kPa), and triggered a debris flow occurrence finally (Tag D).

261   Fig. 11. Case application of the presented method in Wenjia gully (Jul. 8, 2013)

262   The case study shows that how to use this presented combined warning threshold in a real-time

263   way during a rain storm. In 2014, two heavy rainstorms (Table 1) both have exceeded the rainfall

264   threshold, but pore pressure did not cross the critical pore pressure during the whole course of the

265   rainfall. Therefore, a warning message has been sent to the local government with a median possibility

266   of debris flow occurrence. At last, fortunately no debris flow occurred during these rain storms.

267   Therefore, the presented comprehensive warning threshold can be used as a helpful tool for debris

268   flow prediction in mountainous area, especially in this earthquake area of Southwest China where a lot

269   of loose material is available.

270   **5. Discussion and conclusion**

271   Gully-type debris flow, usually triggered by high-intensity and short-duration rainstorms cause

272   serious harm to human lives and properties every year in the mountainous region of Southwest China.

273   Therefore, in order to prevent such natural disasters, there is an urgent requirement for an effective

274   method to predict debris flow occurrence. The combined warning threshold proposed and discussed in

275   this paper, not only use the common rainfall threshold, but also include the critical pore pressure

276   determined by a hydro mechanical stability model.

277   Two rainfall triggering factors: maximum hourly rainfall and cumulative rainfall, have been

278   selected to establish a simple rainfall threshold as a baseline for debris flow early warning. Critical

279   pore pressure can be used as a combined threshold to make the warning threshold better in practical

280   usage. The Wenjia gully was selected as a case study for a detailed explanation of the presented

281   method, for the great volume of deposited materials triggered by Wenchuan earthquake along the

282   channel. The results show that the combined threshold can play a great role in debris flow predicting,

283   at least reduce the mistaken alerts for debris flow occurrence compared to use of only a rainfall

284   threshold. However, such a combined warning threshold still has some restrictions. First, the critical

285   pore pressure is a linear function with the depth of a potential slip surface, which is difficult to

286   determine in an actual gully by the real time monitoring system. In this study, one-meter depth of the

287   slip surface was selected as a possible condition for this preliminary study. Second, the study area still

288   focused on the Wenjia gully, therefore the presented method can't be used in other gullies directly. But

289   in the near future, different gully-type debris flows will be researched, and more subsequent work

290   need to be carried on for a better understanding of debris flow prediction. Finally, the most complex

291   problem is the final determination whether to alert the local population, and whether some reactions

292   need to be done immediately, or later. Debris flow early warning is not an imminent hazard but is just

293   regarded as a potential danger. In spite of these limitations, the methodology presented in this paper

294   has reached the goal to establish a preliminary combined warning threshold for gully-type debris flow

295 prediction. In the future studies, the critical pore pressure threshold which are dependent on

296 topography, geology, and soil properties, can be determined by long-term field monitoring, and more

297 important by debris flow tests in laboratory with different slope angles, and depths of slip surface to

298 reduce the loss of properties and lives.

299

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