Experimental Identification on Thresholds for early warning of Rainfall-induced Failure on Fractured Slopes after Giant Earthquake
(Pengecaman Eksperimen Ambang untuk Amaran Awal Kegagalan Aruhan Hujan ke atas Cerun Retak selepas Gempa Bumi Besar)

Zong-Ji Yang*, Jian-Ping Qiao, Dong Huang, Taro Uchimura & Lin Wang

ABSTRACT

Prevention and mitigation of rainfall induced geological hazards after the Ms=8 Wenchuan earthquake on May 12th, 2008 were significant for rebuild of earthquake hit regions. After the Wenchuan earthquake, there were tens of thousands of fractured slopes which were broken and loosened by the ground shaking, they were very susceptible to heavy rainfall and change forms into potential debris flows. In order to carry out this disaster reduction and prediction effectively in Longmenshan region, careful real-time monitoring and pre-warning of mountain hazards in both regional and site-specific scales is reasonable as alternatives in Wenchuan earthquake regions. For pre-warning the failure of fractured slopes induced by rainfall, the threshold value or the critical value of the precipitation of hazards should be proposed. However, the identification of critical criterion and parameters to pre-warning is the most difficult issue in mountainous hazards monitoring and pre-warning system especially in the elusive and massive fractured slopes widespread in Wenchuan earthquake regions. In this study, a natural coseismic fractured landslide in the Taziping village, Hongkou County, Dujianyan City, was selected to conduct the field experimental test, in order to identify the threshold parameters and critical criterion of the fractured slopes of Taziping. After the field experimental test, the correlation of rainfall intensity, rainfall duration and accumulative rainfall was investigated. The field experimental test was capable of identifying the threshold factors for failure of rainfall-induced fractured slopes after the giant earthquake.

Keywords: Fractured slopes; giant earthquake; rainfall induced; threshold factors

ABSTRAK

Pencegahan dan mitigasi bencana geologi aruhan hujan selepas gempa bumi Ms = 8 di Wenchuan pada 12 Mei 2008 adalah penting untuk membina semula kawasan-kawasan yang terjejas. Selepas gempa bumi ini, terdapat ribuan cerun yang retak dan pecah kerana gegaran tanah telah terdedah kepada hujan lebat, berpotensi berubah menjadi aliran puing. Pengurangan serta ramalan bencana secara berkesan di rantau Longmenshan dapat dicapai dengan pemantauan masa nyata dan pra-amaran terhadap bencana gunung pada wilayah dan tapak skala spesifik. Bagi pra-amaran untuk kegagalan cerun retak aruhan hujan, nilai ambang atau kritikal bencana perlu dicadangkan. Walaubagaimanapun, pengenalpastian kriteria kritikal dan parameter untuk pra-amaran adalah isu yang paling sukar dalam pemantauan bancana pergunungan. Malahan sistem pra-amaran terutama di cerun yang retak sukar difahami serta meluas di kawasan gempa Wenchuan. Dalam kajian ini, tanah runtuh koseismos semula jadi di kampung Taziping, Wilayah Hongkou, Bandar Dujianyan, telah dipilih untuk ujian eksperimen lapangan. Hal ini bagi mengenal pasti parameter ambang dan kritikal pada cerun pecah Taziping. Selepas ujian eksperimen lapangan, hubung kait antara kekerapan dan tempoh hujan diselidiki. Ujian uji kaji lapangan ini mampu mengenal pasti faktor ambang untuk kegagalan cerun retak aruhan hujan selepas gempa bumi gergasi.

Kata kunci: Aruhan hujan; cerun retak; faktor ambang; gempa bumi besar

Introduction

After the Ms=8 Wenchuan earthquake on May 12th, 2008, the coseismic mountain hazards triggered by ground shaking in numbers and in scales this nation has never underwent before, caused extreme damage to the earthquake regions (Hayat et al. 2014; Huang & Yuin 2010; Huang et al. 2010; Lindang et al. 2017 & Qiao et al. 2009). Moreover, the post-earthquake effect of rainfall-induced slope failure as mountain hazards especially transformed into debris flows, became the most dangerous threat and caused extra massive damage to the Wenchuan Earthquake hit region in the Sichuan Province. Tens of thousands of fractured slopes which was broken and loosened by the ground shaking were very susceptible to heavy rainfall and changed form into potential debris flow after the Wenchuan earthquake. For example, on August 13th, 2010, as the 2nd

largest coseismic landslide Wenjiagou landslide, that was initiated by earthquake was triggered by rainstorms and transformed into debris flow in Qingping County, Mianzhu City and debris flows triggered by storms caused great damage initiated from landslide areas in Hongkou County, Chengdu City (Huang & Yuin 2010).

The fractured slope including some co-seismic landslides and unstable slopes were easily eroded into free surface by rain and running water in the groove on the edge of the slope (Huang et al. 2010). The enlarged free surface will lead to retrogressive failures caused by rainfall and gravity on the slope and the failure debris deposit in the gully can change into debris flow during the heavy rainfall (Figure 1). The volume of this kind of slope failure is known as the movable solid materials of potential debris flow from the total volume of solid materials in potential debris flow gullies including the all the deposit and material in the gully. The movable solid materials of potential debris flow are the effective object of the disaster, and identification of its threshold value of criteria is the most important key parameter to predict the hazards of debris flow.

FIGURE 1. Fractured slope was eroded and led to retrogressive failures caused by rainfall and gravity along the gullies in the erosion area in Yindongzi Gully, Dujiangyan County, Chengdu City

There is a lot of ways in mitigation and prevention of rainfall-induced mountain hazards including landslides and debris flows (Huang et al. 2010). Mechanical counter measures such as retaining walls and ground anchors have been widely used to prevent slope failures (Roslee et al. 2017; Tian et al. 2010; Towhata et al. 2011), However, they are expensive and it is not realistic to apply mechanical measures to every potentially risk slope and geohazard site because in Wenchuan earthquake region, mountain hazards existed everywhere with an innumerable number and most of them occured at extremely large scales. Therefore, careful real-time monitoring and pre-warning of mountain hazards

in both regional and site-specific scales are reasonable alternatives in Wenchuan earthquake regions (Yang et al. 2012). However, the identification of critical criterion and parameters for pre-warning is the most difficult issue in mountainous hazards monitoring and pre-warning system especially in the elusive and massive fractured slopes widespread in Wenchuan earthquake regions. In this study, a natural coseismic fractured landslide in the Taziping village, Hongkou County, Dujianyan City, was selected to conduct the field experimental test in order to identify the threshold criterion of the fractured slope (Huang et al. 2010). After the field experimental test, the correlation of rainfall intensity, rainfall duration and accumulative rainfall was obtained.

STUDY AREA

In order to carry out disaster mitigation and pre-warning effectively, the threshold value or the critical value of precipitation which is the primary triggering factor of the post-earthquake mountain hazards should be proposed.

An artificial rainfall test was conducted on a weathered andesitic deposit in order to observe its critical threshold value and correlation with pre-failure behaviours (Roslee et al. 2017). The experimental site is located on Taziping landslide slope in Dujiangyan County, which is located in the middle part of Sichuan Province (Figure 2). This area was hit by the Ms=8 great Wenchuan earthquake and huge damage was produced. The annual average precipitation is about 1234.8 mm, with the highest value being 1605.4 mm in average in 1978 (Qiao et al. 2019). Rainfall is mostly concentrated in the period between June and September. From a spatial distribution perspective, the study area shows a trend of decreasing precipitation from southeast to northwest, where the average precipitation in northwest mountainous region is up to 1800 mm. The landform of the area changes from high mountains, middle mountains, relatively hills and finally to flat Plain gradually.
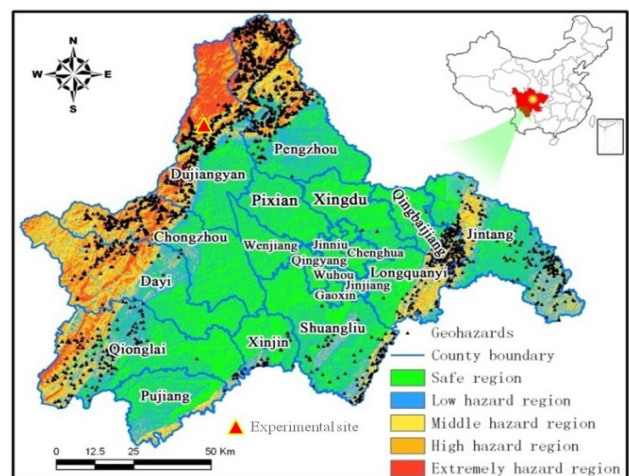

FIGURE 2. Location and spatial probability map of study area

Elevation in the study area ranges from the minimum of 387 m a.s.l. to the maximum of 5364 m a.s.l. with about 5000 m height difference. This area is drained by the Minjiang River and its branches. Geologically, this area is located along the transitional belt tectonically between the Chengdu plain and Longquanshan Mountains, which is a part of the Cathaysian structural system, and this region also belongs to the Yangtze para-platform and the Qinghai-Tibet quasi-geosynclinal area. There are three major pressure-shear faults with a northeast orientation crossing the area, which includes the Beichuan-Yinxiu faults, the Longquanshan faults and Guanxian faults (Tian et al. 2010). The study area is underlain by bedrock varying in age from the Quaternary to the Proterzoic. The average thickness of the crust is approximately 20000 m. The strata include sandstones, mudstones carbonates and carbonates intercalated with clastics, igneous rocks, metamorphic and shale as well as unconsolidated Quaternary deposits layer.
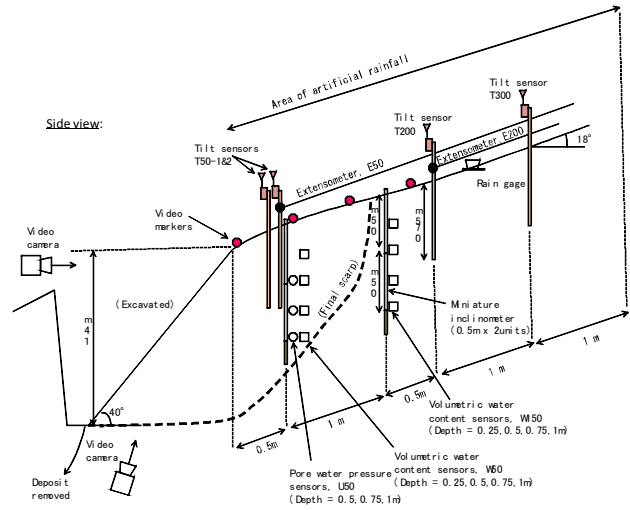

FIGURE 4. Cross-section of artificial rainfall test

Experimental fractured slope of Taziping

The experimental fractured slope of Taziping with some certain extent of sliding and pre-failure symptoms threatens the total rebuilt community residences of Hongse Village, Dujiangyan County (Figure 3). The slope failure was triggered by the Wenchuan earthquake, with about 500 m in length and 150 m width, a total volume of 120×10^4 m^3. The top of the fractured slope is 1370 m in altitude and the bottom of the slope is 1007 m in altitude (Towhata et al. 2011). The slope is composed of deeply weathered granite and andesite. 109 villagers as well as 45 houses will be in danger if the slope fails completely.

The slope consists of loose gravel and sand, whose blow counts by portable dynamic cone penetration tests are less than 10 for 10cm of penetration (Towhata et al. 2011). The slope angle is around 18° and its lower end was excavated down to a depth of 1.4 m with an angle of 40°. Figure 4 shows the cross-section and photo of the site together with the instruments are shown in Figure 5.

FIGURE 5. Photo of the site together with the instruments

FIGURE 3. Experimental test was conducted in a fractured slope of Taziping, to identify the Threshold value

Then, four artificial heavy rainfall were given to the fractured slope site and seven notable rainfall induced slope failure were onset during the tests (Uchimura et al. 2010). The process of artificial rainfall tests and rainfall parameters are shown in Figure 6 and the record of rainfall intensity of major deformations were between 29.4 mm and 54.2 mm/h and the average rainfall intensity was 48.1 mm/h (Zong-ji et al. 2013). Additionally, the water content was up to 0.2 at the failure point of the slope which can be defined as the threshold value of the failure of the slope (Roslee et al. 2017). Major deformation was observed and the slope failed progressively from the bottom with scarp angle of 40 to 50° which indicated the envelope of the gradient of the slope failure. The picture of final shape scarp after failures during the experiment is shown in Figure 7.
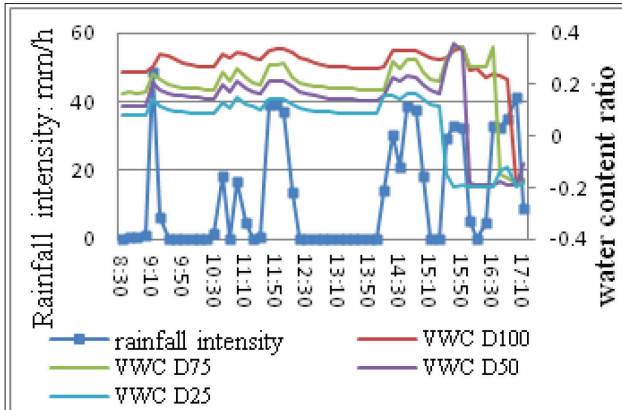
FIGURE 6. Total process and recorded rainfall and water content ratio of the site during the artificial rainfall test

FIGURE 7. The final shape of scarp and slope failed progressively in the test

The correlation of rainfall intensity and accumulative rainfall (*I-A*) was given as shown in Figure 8. The linear correlation of rainfall intensity and accumulative rainfall can be generalized as the following formula:

$$A=300-50*I,$$

where *I* is the rainfall intensity; and *A* is the accumulative rainfall. Early warning can be conducted when the monitoring rainfall data is shown above the linear formula which is the general model as the rainfall threshold for mountain hazards in China.

Figure 8 also shows the curve for *I-A* correlation which implies including more occurrences of data than the linear correlation, the curve is drawn by following formula:

$$A=23027*I^{-2.07}.$$

It is implied that the formula 2 emphasizes the importance of high rainfall intensities which is believed as the essential factor of mountain hazards which is especially the debris flows.
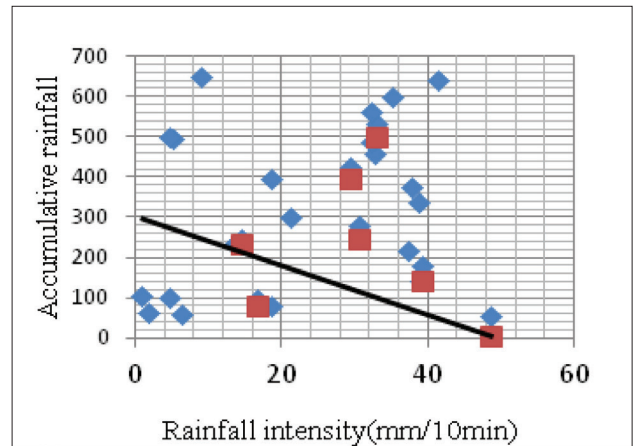

FIGURE 8. Comparison of various I– A thresholds in the test and historical data. The blue point in the chart is historical rainfall data collected by investigation in study area while red point is test artificial rainfall data obtained at the time of slope failure
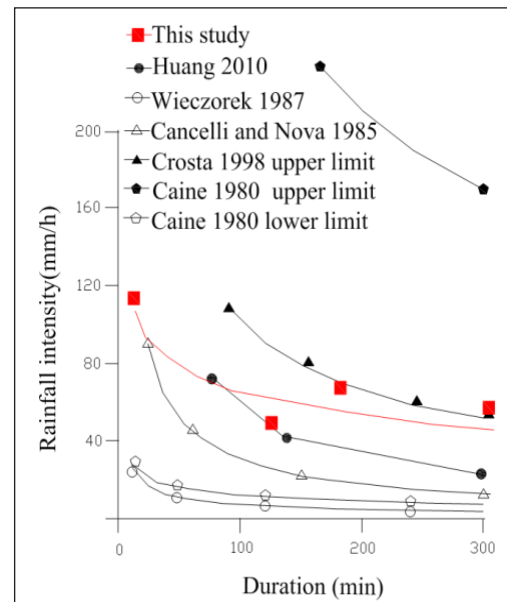

FIGURE 9. Comparisons of various I–D thresholds in present study

Figure 9 shows I-D plots for rainfall-induced mountain hazard threshold values that have been widely adopted in early warning slope failures. It indicates that these thresholds I-D relationships vary widely, suggesting that a high degree of uncertainty is always associated in using these empirical relationships (Uchimura et al. 2011). The comparison also suggests that these greatly varied thresholds may be a result of various geological and environmental conditions from the source area. Such variation has often been ignored in many studies of rainfall threshold identification. Therefore, it is believed that the field experimental tests of artificial rainfall induced slope failure in the natural fractured slope were supposed to obtain more accurate threshold criteria than statistics of

empirical data (Yang et al. 2010b). The rainfall intensities and duration (time) in four artificial rainfall tests were used to generate the I-D envelope of the test fractured slope. The correlation of rainfall intensity and rainfall duration (I-D plots) was given as shown in Figure 9. The I-D envelope can be summarized in the following formula by analysing experimental data:

$$I = 155.2D^{0.17},$$

where I is the rainfall intensity; and D is the rainfall duration. By the formula above, an envelope threshold curve for the early warning of Taziping landslide may give a guidance and approximate time for evacuation and preparation for potential landside by comparing monitoring rainfall intensities and its duration (Hayat et al. 2017; Lindang et al. 2017; Roslee et al. 2017).

Early warning can be applied by comparing the *I-A* and *I-D* with real-time monitoring rainfall data. if the monitoring rainfall intensity in Taziping landslide is about 45 mm/h which is very close to both the I-A and I-D envelope, local residents must be kept on caution because slope failure may occur in hours (about 5 h according to I-D envelope) while the situation should be quite urgent (about several minutes) if the monitoring rainfall intensity is up to 120 mm/h according to the *I-D* envelope in Taziping landslide (Yang et al. 2010a). For the critical value of water content (20% in this study), it is doubted that the water content value is used individually for disaster pre-warning because the slip surface where the water content should be measured is hard to identified before (Yang et al. 2012). As a result, monitoring water content data can be a reference in addition to the monitoring rainfall data so that the accuracy of the pre-warning can be enhanced.

Conclusion

The compound effect of earthquake and following rainfall triggered a mass of debris flows in the earthquake region. The early warning of rainfall-induced mountain hazards such as landslides and debris flows have high uncertainty and difficulties intrinsically. To improve the accuracy of mountain hazards pre-warning requires a better understanding of the internal-response-based slope failure mechanisms. This study proposed an experimental identification method for threshold on rainfall-induced mountain hazards. An artificial rainfall test was conducted on a natural fractured slope for identification of the threshold value on pre-warning. The *I-A* and *I-D* criterion proposed here will be useful for more accurate slope failure predictions. By the *I-A* and *I-D* formulas as well as the criteria values of water content ratio and the envelope slope gradient, an integrated threshold drove for the early warning of Taziping fractured slope were proposed which may give a guidance and approximate time for evacuation and preparation for potential landside by comparing monitoring rainfall intensities and its duration. Admittedly,

based on a limited experimental test with one fractured slope may not give good results in other place, and the water content has to be measured in the slip surface of the slope failure but locating the slip surface before failure is quite difficult. However, the method which based on detailed works of experimental tests and statistics on individual mountain hazard site is hoped to enhance the accuracy of threshold values for mountain hazards early warning according to continuously verifications. After the two giant earthquakes in Sichuan province, early warning and monitoring of debris flows and landslides should be pay more attention in the future.

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Zong-Ji Yang*, Jian-Ping Qiao & Dong Huang
Key Laboratory of Mountain hazards and Surface Process
Institute of Mountain hazards and Environment
Chinese Academy of Science
Chengdu 610041
China

Taro Uchimura
Department of Civil & Environmental Engineering
Saitama University, Saitama
Japan

Lin Wang
Chuo Kaihatsu Corporation
Tokyo

*Corresponding author; email: yzj@imde.ac.cn