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Experimental Study of Critical Rainfall of the Aizi Gully Baihetan Hydropower Station Near-Zone Area

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Abstract：

At dawn of 28 June 2012, a catastrophic debris flow occurred in Aizi gully near Baihetan hydropower station, resulting in 40 people dead or missing. In addition, the debris flow blocked the main transportation route of Baihetan hydropower station and severely affected the construction progress. After the catastrophic debris flow event, detailed field investigations were conducted. By means of the field investigation, the corresponding catchment parameters that prominently affected the process of debris flow formation were acquired, including the volume and distribution of loose solid materials in the source area, meteorological conditions, topography and landforms, etc. On the basis of field investigations, we predicted that Aizi gully still satisfies debris flows initiation conditions and poses a great possibility for debris flow breakout in the future. Therefore, sufficient accurate prediction and forecasting are the precondition for disaster mitigation and siting mitigation structures in Aizi gully. At present, critical rainfall plays a key role in debris flows prediction. Thus, the main objective of this paper is to obtain the critical rainfall of Aizi gully. An in-situ artificial rainfall experiments were conducted in Aizi gully catchment, and by means of analyzing the experimental results (rainfall, pore water pressure and moisture content) and comprehensively considering the local rainfall conditions, the critical rainfall and pore water pressure of Aizi gully is acquired. The critical rainfall is 32.92mm/24h (accumulative rainfall). On the basis of this threshold, an early warning system can be established in Aizi gully catchment. Thus in turn, the warning information can be released in a timely and accurate way and can reduce the threat caused by debris flow disasters. At the same time, the safety of the construction processes of Baihetan hydropower station can be guaranteed.

Keywords*：*Baihetan hydropower station, Aizi gully, Catastrophic debris flow, Artificial rainfall experiment, Critical rainfall

1 Introduction

Debris flows are an important process in landscape evolution[1] and pose significant hazards in mountain areas[2, 3]. In recent years in China, along with the construction of large-scale hydropower projects in mountainous areas, debris flows have caused heavier losses than before. Taking Sichuan Province as an example, from 2009 to 2012, about 41 debris flow events occurred in construction sites, accounting for merely 0.5% of the total geological disasters, but debris flows in the construction sites resulted in more than 281 people dead or missing, accounting for 57% of the total casualties. Thus, it can be noted that the percentage of casualties caused by debris flow disasters is very serious in construction sites. A variety of factors influenced the debris flows initiation processes. Moreover, the formation processes of a debris flow is extremely complex, which poses great difficulty in debris flow prediction[4]. Presently, the critical rainfall of a debris flow is the most effective way for disaster prediction and mitigation[5]. A number of approaches for the prediction of debris flows have been proposed[2, 6-9]. However, the accuracy of prediction ratio of debris flows cannot always maintain a stable and reliable level[10-13]. To verify the occurrence of debris flows, experts and researchers utilize topography, aerial photographs, satellite images and site investigations. It is a time-consuming and tedious work to monitor debris flows and collect data[14]. Therefore, the measurement for how to predict the occurrence of debris flows has become an important and challenging task[9, 15]. Many scientists have adopted different methods to calculate the critical rainfall for different areas and have acquired a variety of critical rainfall results, but due to the limitation of the research methods, there is no universal critical rainfall available. The critical rainfall for individual gullies rarely exists. In order to obtain the accurate critical rainfall for Aizi gully in the area near Baihetan hydropower station, an in-situ artificial rainfall experiment was conducted in the source area of Aizi gully, through which the prediction of critical rainfall could be obtained, which can be useful for future disaster prediction and mitigation.

2 Study area profiles

Aizi gully, with a catchment area of 65.55 km^2, is located on the left bank of Jinsha River within the Baihetan hydropower project area (15 million KW), which is the second largest hydropower station in China. On 28 June 2012, at 5:40am, a sudden catastrophic debris flow destroyed Yanzi village garden, which is located in the outlet of Aizi gully, leading to 40 people dead or missing. Aizi gully is located on the left bank of Jinsha River and the south slope of Daliangshan mountain, climatically falling into a subtropical monsoon climate zone with a distinct dry and wet season. Aizi gully watershed is composed of three confluence areas:

the confluence area of Aizi gully, the confluence area of Gualv gully and the confluence area of Niluohan gully. The west side is higher than the east in Aizi gully watershed, and the total length of Aizi gully is 21.96km. On both sides of the main gully, the tributary is narrow and deeply cut, and the mean gradient of the main gully is 155‰. In Aizi gully watershed, the maximum altitude is 3646m while the minimum is 604m, giving a maximum relief of 3042m. The vegetation in the watershed is prominently vertically distributed. The main superficial soil includes red soil, mountainous yellow soil, brown soil and meadow soil, among which red soil is the main soil type. The bedrock mainly includes Ordovician dolostone, limestone, sandstone, Cambrian dolomite, sandstone, Sinian system dolomite and Permian basalt.

2.1 Loose solid materials

The distribution of loose solid materials in Aizi Valley was mapped through the post-disaster field investigations and remote sensing interpretation (Fig. 1). From Fig. 1, it can be seen that the loose solid materials were mainly distributed at the upstream of Niluohan gully, most areas of Gualv gully and midstream of Aizi gully. Combined with field measurement and radar exploration (Fig. 2), we obtained the area and thickness of ancient debris flows deposits and landslide deposits by means of remote sensing and interpreted the measured the area of colluvial deposits. Previous research revealed the relationship between the area and the volume of loose solid materials after seismic activities, therefore the equation $V_L = 0.074 \times A_L^{1.45}$ [16] was employed here to calculate the volume of colluvial deposits. By means of field measurement and model calculations, we acquired the total volume of loose solid materials, its volume is 4812.54×10^4m^3, which includes 2388.1×10^4m^3 of residual sediments, 1158.34×10^4m^3 of colluvial deposits, 855.1×10^4m^3 of landslide deposits and 411×10^4m^3 of ancient debris flows deposits. Such abundant loose solid materials provided source conditions for a large-scale debris flows outbreak. In order to analyse the particle gradation, 20 soil samples were taken from the source area of Aizi gully. A sieve experiment followed to obtain the particle size distribution of the samples (Fig. 3).

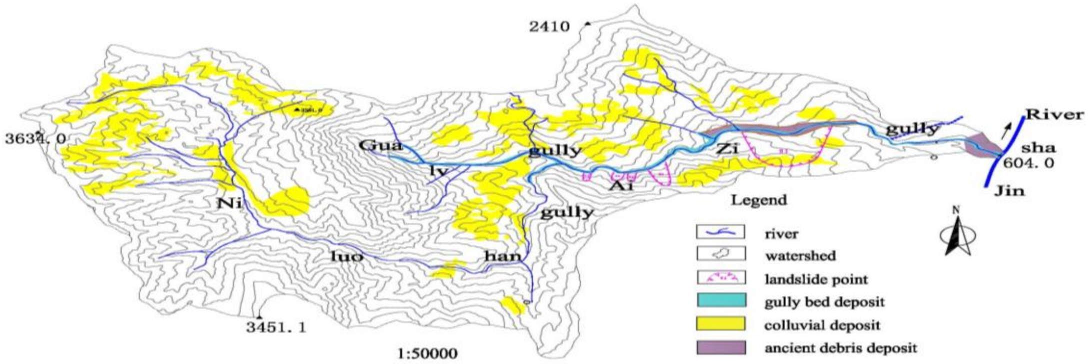


Fig. 1 Profile of loose solid material distribution in Aizi gully

a. Radar test (in some places of the gully where the pit test was hard to put into practice, we used a radar test to determine the thickness of the loose solid materials, and then calculating the volume of solid materials)

b. Field measurement (we carried out pit test to determine the thickness of solid materials, and this helped us to calculate the total volume of loose solid materials)

Fig. 2 Field measurement and radar test

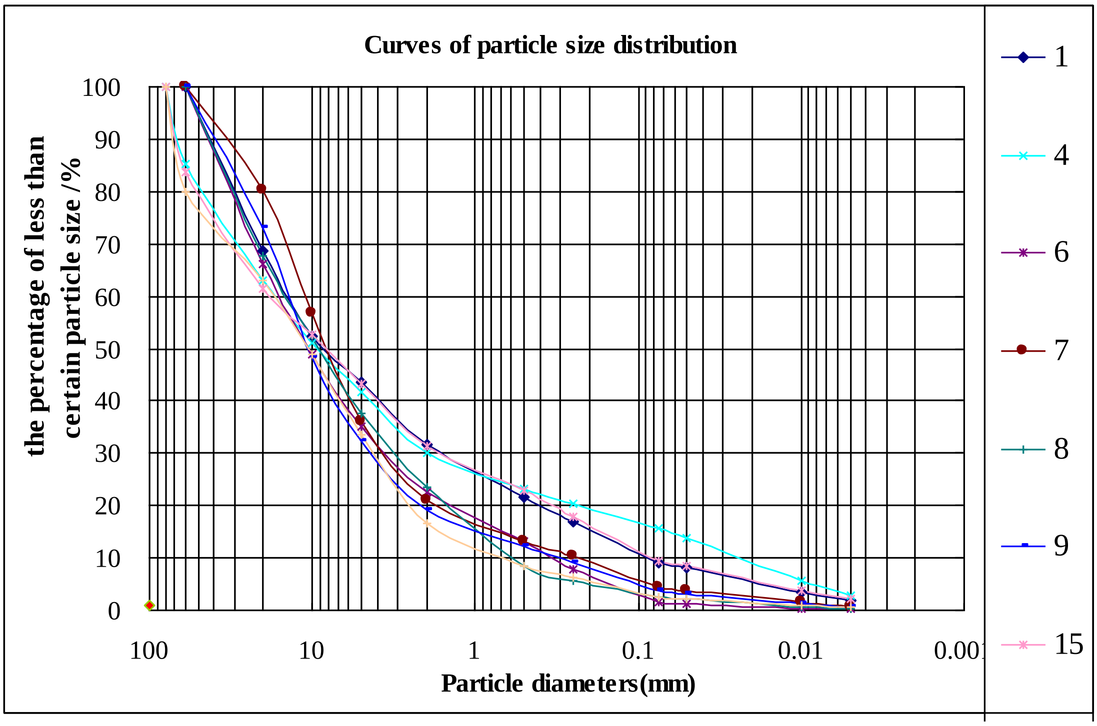


Fig. 3 Particle size distribution of part of the soil samples

2.2 Rainfall conditions

By means of collecting the rainfall data in Ningnan and Baihetan meteorological stations, the rainfall characteristics of the study area were obtained. The rainfall principally concentrated from May to October, the accumulative rainfall in this period accounting for about 90% of the total rainfall in one year (Fig. 4). The heaviest rainfall frequently occurred in June; after July, the rainfall lowered gradually, and after October, the rainfall reached the level of semiarid characteristics[17].

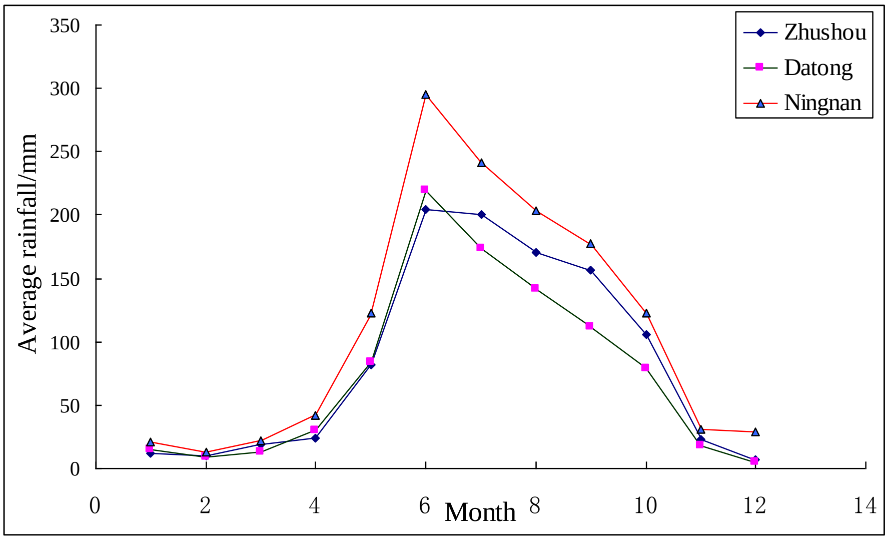


Fig. 4 Monthly average rainfall in three meteorological stations from 1986 to 2005

3 Methodology

The main objective of this paper is to obtain the rainfall threshold of Aizi gully watershed by means of in-situ artificial rainfall experiments, the equipments of the experiments mainly including an artificial rainfall system (pump, diversion box, sprayer, brackets, pipeline etc.), a pore water pressure acquisition system, a moisture content acquisition system, a rainfall acquisition system and a video camera. The experimental scheme is shown in Fig. 5. Through field investigations, the conditions of the whole basin was acquired. The inclination of the slope is mainly concentrated from 28° to 43°. In the experiments, the inclination of the slope is set to 35°. The size of the experiment slope is 1.5m×2.3m. The experiment was conducted in the source area of Aizi gully. The pore water pressure sensors and moisture content sensors were buried in the slope. The concrete location of the sensors is shown in the experimental scheme figure (Fig.5). With the purpose of acquiring accumulative rainfall at any time, the rainfall gauge was arranged on the slope. The video camera can record the position and scale of slope initiation. Combined with corresponding rainfall data, pore water pressure data and moisture content data can greatly helping us to better understand the formation process and comprehensively analysis the critical rainfall. Combined with the characteristics and patterns of rainfall in Aizi gully, the rainfall threshold was discussed under five different rainfall conditions, and the corresponding rainfalls are 52.1mm/h, 58.8mm/h, 73.2mm/h, 95.5mm/h and 109.8mm/h, respectively. The preparation and experiment process is shown in Fig. 6 and Fig. 7.

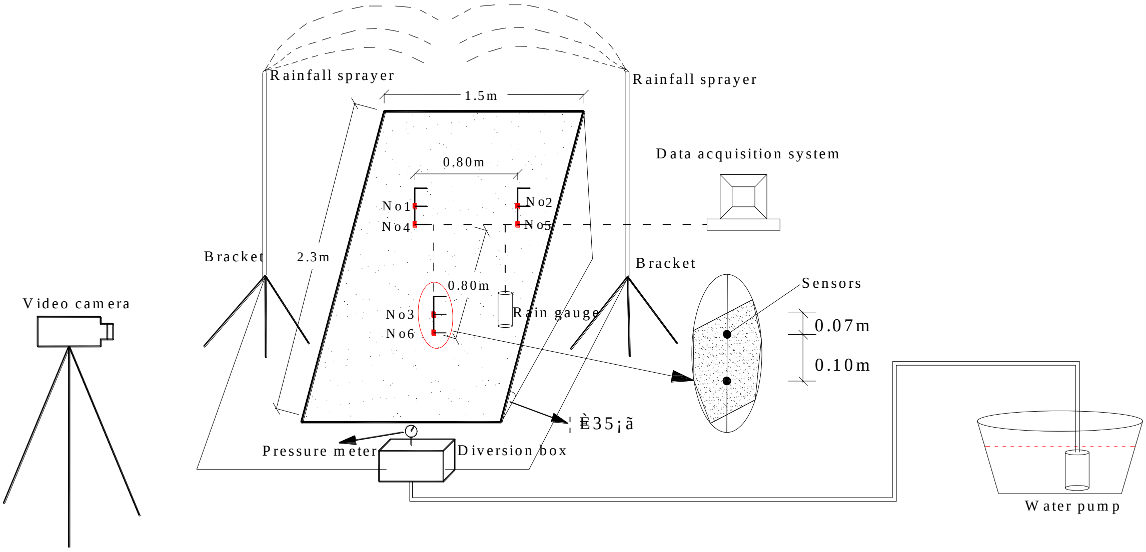


Fig. 5 Experimental scheme figure

a. Buried sensors b. Control slope parameters

Fig. 6 Experiment preparations

a. Rainfall process b. Data acquisition system

Fig.7 In-situ experiment progresses

4 Results and discussions

4.1 Results

Under five different rainfall conditions, the debris flow initiation time is 8′38″, 10′15″, 4′54″, 4′05″ and 3′32″ respectively. The corresponding accumulative rainfall is 7.5mm, 10mm, 6mm, 6.5mm and 6.5mm, respectively. By means of calculations, the 10mins critical rainfall under five rainfall conditions was obtained; the values are 8.7mm/10mins, 9.8mm/10mins, 12.2mm/10mins, 15.9mm/10mins and 18.3mm / 10 mins, respectively. Aizi gully is located within Ningnan county, Sichuan province. By referring to the 10min rainfall contour diagram, we know that 10mins of equivalent rainfall is 12mm, and the 10 minute rainfall variation coefficient is $C_v = 0.35$. Taking the 10min critical rainfall from the experiment, and dividing it by the 10min equivalent amount of rainfall and then referring to the Sichuan province small and medium-sized basin flood calculation manual, the rainfall frequency can be derived. Based on the rainfall frequency, by referring to 60min maximum rainfall isoline map of Sichuan province, the 60min point rainfall value is 30mm, and the 60min rainfall variation coefficient is $C_v = 0.4$. Combining this figure with the rainfall frequency and referring to the 60min maximum rainfall isoline map of Sichuan province, the rainfall coefficients can be calculated. The whole calculation process is shown in Table 1. By means of Table 1, the 60min accumulative rainfall under five rainfall conditions can be calculated, i.e., the 60min point rainfall value times the coefficients. The 60min critical rainfall (accumulative rainfall) under the five rainfall conditions is 20.3mm, 23.7mm, 30.54mm, 41.1mm and 47.94mm respectively.

Table. 1 60min critical rainfall calculation table

	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
Rainfall intensity (mm/h)	52.1	58.8	73.2	95.5	109.8
Debris flow initiation time	8′38″	10′15″	4′54″	4′05″	3′32″
10min accumulative rainfall (mm)	8.7	9.8	12.2	15.9	18.3
The ratio of experiment rainfall and actual rainfall	0.725	0.82	1.02	1.33	1.53
Rainfall frequency	78%	68%	46%	18%	8%
Calculated coefficients	0.678	0.79	1.018	1.37	1.598
60mins effective rainfall (accumulative Rainfall (mm)	20.3	23.7	30.54	41.1	47.94

After calculation, the correlation between rainfall intensity and 10min and 60min critical rainfall (accumulative rainfall) was analyzed. Through analysis, the correlation coefficients are 0.99660 and 0.99994, respectively, which means that the correlation is significant under the level $P < 0.01$. The fitting curves and corresponding equations are shown in Fig. 8, Fig. 9 and equations 1 and 2, respectively.

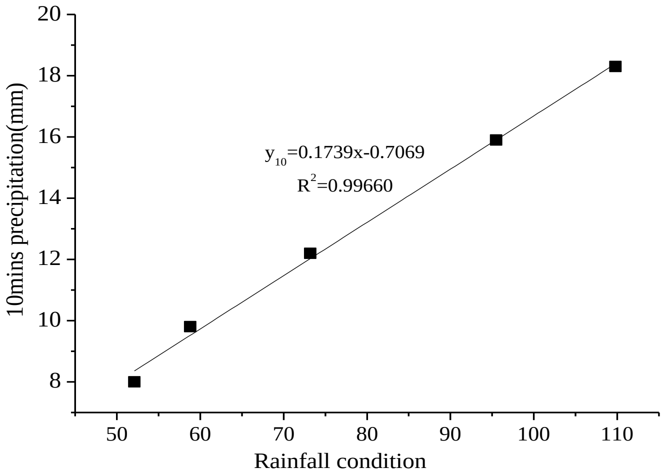


Fig. 8 Correlation curves between rainfall intensity and 60min critical rainfall (effective rainfall)

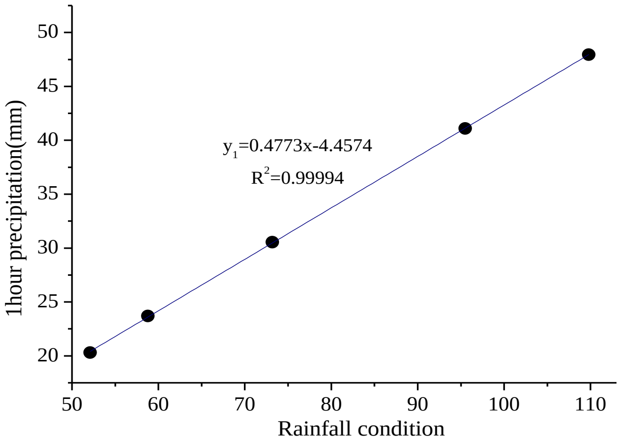


Fig. 9 Correlation curves between rainfall intensity and 10min critical rainfall (effective rainfall)

$$y_{10} = 0.17390x - 0.7069 \qquad R^2 = 0.99660 \tag{1}$$

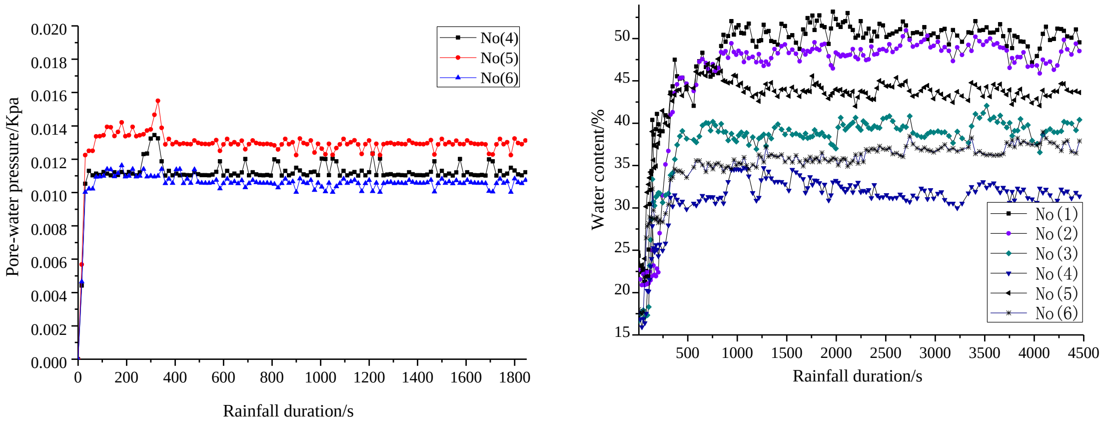
$$y_1 = 0.47730x - 4.4574 \qquad R^2 = 0.99994 \tag{2}$$

y_{10} and y_1 represents 10min and 60min effective rainfall respectively; x represents the actual rainfall intensity. The collected rainfall data in meteorological stations can be put into the formula, and 10min effective rainfall and 60min rainfall can be calculated.

After the 6·28 catastrophic debris flow, the rainfall data were collected. On June 28, 2012, the accumulative rainfall was 78mm. Input this rainfall value into equation 1 and equation 2 and the 10min and 60min critical rainfall can be calculated, which are 12.86mm and 32.77mm, respectively. Taking these two critical values as a disaster warning index, the early warning system can be established, and thus can greatly improve the accuracy of prediction.

4.2 Discussions

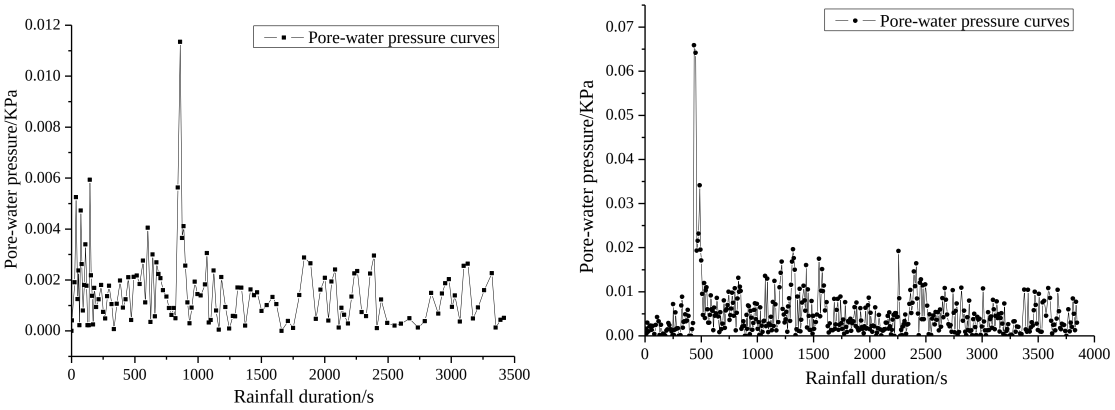
During the processes of the experiments, the initiation phenomena were recorded and observed meticulously. By observations some findings were found: the pore water pressure curves are different while the moisture content curves are almost identical. When rainfall intensity is lower (condition 1 and condition 2), longer rainfall duration is required for the pore water pressure and moisture content to reach the peak value, and the corresponding pore water pressure peak value is relatively low (Fig. 10). Under such circumstances, the soil experiences longer creep deformation, the depth of the initiated soil is shallow and the scale of debris flow is small. This is because the rainfall intensity is low, the scouring and entrainment capability of the surface runoff is limited and little soil participates in debris flows movement during the rainfall processes, so the scale and destructive power of debris flow are lower under this situation.



a. Pore-water pressure curves **b. Moisture content curves**

Fig. 10 Pore-water pressure curves and moisture content curves under conditions 1 and 2

When rainfall intensity increases, the internal flow and surface runoff increases simultaneously, and the drag forces increasing significantly. During heavy rainfall, pore water pressure increases sharply in a short time (Fig. 11). The heavier the rainfall intensity, the shorter the time it requires for a debris flow to be initiated. Under such conditions (conditions 3, 4 and 5) the scale and destructive forces of debris flows are significantly higher than those debris flows triggered under conditions 1 and 2. Based on these results and combined with the meteorological data from the nearby meteorological stations and the critical rainfall, the possibility and scale of a debris flow can be predicted, which in turn can reduce the disaster risk and at the same time improve the safety of local people and guarantee the construction progress of Baihetan hydropower station. Taking the critical rainfall as the warning index, comprehensively considered debris flow related parameters, such as the total volume of a debris flow, the velocity of a debris flow and impact loading and scale of a debris flow, can allow suitable countermeasures to be adopted. Therefore, on one hand, debris flows can be predicted accurately, and on the other hand prevention engineering can greatly reduce the effect of debris flows.



a. Pore water pressure curves under condition 3

b. Pore water pressure curves under condition 4

Fig. 11 Pore-water pressure under rainfall conditions 3, 4 and 5

5 Conclusions

By analyzing the debris flow formation conditions of Aizi gully, including the volume of loose solid materials, the slope inclination and the rainfall conditions, the following conclusions can be concluded: due to the large quantity of loose solid materials and steep slopes, a debris flow with a large scale still probable to be triggered by heavy rainfall. Moreover, Aizi gully is frequently influenced by strong earthquakes, and the integrity of the soil on the slope is destroyed by seismic activity. In recent years, extreme climate conditions frequently occurred, by statistical data we found that from 2009 to 2012, Aizi gully experienced three years of extreme drought. This situation coupled with abundant rainfall, can leading to a great debris flow disaster. In the future, under the combined effect of seismic activities, extreme climate conditions, human activities and heavy rainfall, a large scale debris flow may be triggered. Base on this research consequence and combined with the characteristics (particle gradation, slope inclination and rainfall condition) of Aizi gully watershed, an artificial rainfall experiments were conducted in the source area of Aizi gully. Through analysis of the experimental results, the critical rainfall of 10mins and 60mins was calculated, which is 12.86mm and 32.77mm, respectively. On the basis of these two critical rainfall indexes, an early warning system can be established in the future. Combined with the nearby meteorological data, the warning information can be released in a timely and accurate way; therefore, debris flow risk can be greatly reduced, and the safety of local people and of the construction's progress can be guaranteed.

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