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Prediction of Debris Flow Occurrence in Jiuzhui Gully Based on Field Investigation

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Abstract: Jiuzhui gully is located in the Jiexu hydropower station project area, where the debris flow in Jiuzhui gully poses a great threat not only to the construction process, but also to the future operation. With the aim of reducing the risk of disaster caused by debris flow in Jiuzhui gully watershed, we conducted a systematic field investigation to obtain the basic data of this basin. In addition, remote sensing interpretation was employed to identify the area and location of source materials. By means of field investigation, the fundamental data of the whole basin can be acquired, including the topography, angles of the slopes, rainfall conditions, vegetation coverage condition and seismic activity. Combining the field investigation with remote sensing interpretation, the amount of the loose deposits can be calculated, and debris flow initiation can be preliminarily analysed. Subsequently, the debris flow development trend in Jiuzhui gully watershed can be determined from different perspectives. Finally, on the basis of the obtained data, a comprehensive analysis can be conducted, and the conclusion can be drawn that the source materials, rainfall conditions and energy conditions can easily initiate debris flow. So, without engineering countermeasures or an early warning system, the debris flow in Jiuzhui gully may pose a great risk to the construction process and future operation of the hydropower station. In addition, the frequency and scale of the debris flow will be greatly magnified under the coupled effect of a strong earthquake and heavy rainfall.

Keywords: Development Trend, Debris Flow, Jiuzhui Gully, Field Investigation

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1. Introduction

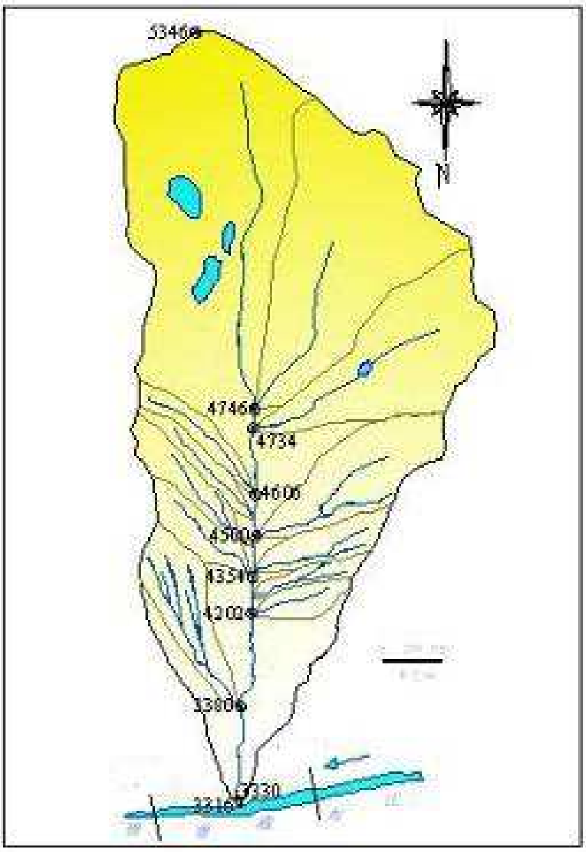
Debris flow is a common natural disaster in mountain areas. Due to its unexpectedly erupted attribution, the debris flow often causes serious casualties and property loss [1]. Debris flows cause damage mainly in three ways: deposition, entrainment, and direct impact [2]. Because these natural hazards can cause considerable damage and loss of lives and properties, they have been intensively investigated by many researchers over the past years [3-5]. Debris flow susceptibility is defined as a quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of debris flows which exist or potentially may occur in an area [6]. Debris flow susceptibility assessment is based upon suitable selection of factors which play a dominant role in slope stability. The evaluated input factors reflect geological, climatic and hydrologic conditions as well as morphometric characteristics of the relief, and actual landscape structure of the study area.

To mitigate and prevent hazards induced by debris flows and related risks, one must understand the formation of these in order to make reliable forecasts. Many factors are related to the occurrence of debris flows such as the basin gradient, the percentage of basin area with slopes greater than or equal to 30%, basin ruggedness, additional measures of gradient, slope aspect, rainfall intensity, and soil properties, including the clay percentage, the percentage of organic matter, the soil granulometry and sorting, and the soil liquid limit[7]. Other researchers stated that there are three groups of factors playing a major role in the formation of ordinary gully-type debris flows. They are related to topography, geology, and hydrology [8].

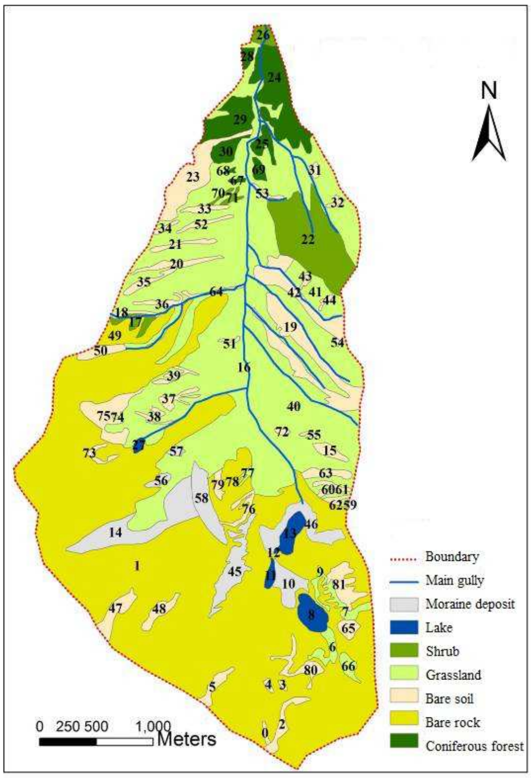
The objective of this paper is to explore the probability of debris flow occurring in Jiuzhui gully, and to facilitate disaster prediction and mitigation in the Jiuzhui gully area. With the aim of acquiring the fundamental data of the study area, a comprehensive field investigation was conducted. By combining the acquired data with local meteorological conditions, the occurrence and dynamic properties of debris flow in Jiuzhui gully can be evaluated.

2. Study Area

Jiexu hydropower station is located on the boundary between Sangri County and Jiacha County, Shannan District, Tibet Autonomous Region. In the hydropower station project area, four debris flow gullies were identified, which pose a great threat to the construction process and future operation. The debris flow gully that poses the most significant threat to the hydropower station is Jiuzhui gully. From field investigation, we found that, without engineering countermeasures or warning systems, the debris flow in this gully could be disastrous. With the aim of reducing the risk of economic loss and improving the security of construction workers, the relevant parameters of the debris flow in Jiuzhui gully need to be analysed comprehensively.



a. Water system of Jiuzhui gully



b. Soil types in Jiuzhui gully basin

Figure 1. *The profiles of the whole basin.*

Jiuzhui gully has a catchment area of 12.13 km^2, and is located on the right bank of the Brahmaputra River within the Jiexu hydropower project area, which is one of the most important hydropower stations in Tibet. In Jiuzhui gully watershed, the maximum altitude is 5766 m while the minimum is 3316 m, giving a maximum relief of 2456 m. The total length of Jiuzhui gully is 6.10 km, and the overall gradient is 346.48%. In addition, Jiuzhui gully has a confluence into the Brahmaputra River at the height of 3316 m.

The study area climatically falls into a plateau temperate monsoon semi-humid climate zone. Based on the recorded data from Jiacha meteorological station, the overall meteorological data from 1978 to 2005 can be acquired (Table 1). Analysing this, we found that the annual mean air pressure is 685.5hPa, the average annual temperature is 9.3°C, and the extreme maximum and minimum temperatures are 32.5°C and -16.6°C, respectively. The average annual precipitation is 527.4mm, while the maximum daily precipitation is 51.3mm and the average annual evaporation is 2084.1mm. The annual average relative humidity is 51%, and the annual average wind speed is 1.6m/s. The corresponding data are presented in Table 1. Jiuxu hydropower station is situated in the mid-stream of Brahmaputra River, and there are many hydrologic stations located in the tributaries, including Lazi, Nugesha, Yang village and Nuxia hydrologic station. In terms of the calculated runoff data from 1956 to 2009, we found that the mean annual discharge, mean annual runoff and mean annual runoff depth are 987 m^3/s, 31.15 billion m^3 and 203.3 mm, respectively.

Table 1. *Meteorological data from Jiacha meteorological station.*

Items	Jan	Feb	Mar	Apr	May	Jun	Jul
Mean annual temperature (°C)	0.3	2.9	6.5	9.7	13.3	16.4	16.6
Maximum annual temperature (°C)	10.6	12.4	15.7	18.5	21.9	24.7	24.4
Minimum annual temperature (°C)	-8.2	-5.6	-1.4	2.4	6.4	10.7	11.8
Extreme high temperature (°C)	23.4	24.0	32.0	28.8	30.8	31.8	32.5
Occurrence data	31/2001	1/2001	26/1992	24/2009	20/1995	19/2009	23/2009
Extreme low temperature (°C)	-16.6	-14.0	-10.0	-5.4	-3.3	2.0	4.4
Occurrence data	4/1983	2/2008	4/1986	2N/2Y	1/1989	10/1996	6/1978
Mean annual precipitation (mm)	1.2	2.6	10.3	19.7	44.2	87.7	148.5
Maximum annual rainfall (mm)	13	9	27.8	58.6	121.4	182.1	288.3
Occurrence year	1993	2009	1979	2004	2000	1979	2004
Minimum annual rainfall (mm)	0	0	0.4	0.6	4.6	24.5	62.6
Occurrence year			1981	1999	1986	1983	1992
Maximum daily precipitation (mm)	9.0	4.4	25.2	16.0	26.2	36.1	42.4
Occurrence data	12/1993	23/1990	27/2007	16/1989	22/2000	23/1979	18/1990
Mean evaporation (mm)	111.4	138.0	196.4	211.4	245.5	229.2	198.4
Mean relative humidity (%)	33	35	40	47	53	62	70

Table 1. *Continued.*

Items	Aug	Sep	Oct	Nov	Dec	year	Statistical years
Mean annual temperature (°C)	16.1	14.4	10.4	4.7	0.7	9.3	1978-2009
Maximum annual temperature (°C)	23.6	22.3	19.9	15.2	11.5	18.4	1978-2009
Minimum annual temperature (°C)	11.5	9.6	3.3	-3.1	-7.4	2.5	1978-2009
Extreme high temperature (°C)	30.3	29.2	27.1	24.8	21.0	32.5	1978-2009
Occurrence data	1/2005	5/2006	1/1994	15/2009	27/2007	2009.7.23	
Extreme low temperature (°C)	4.9	0.7	-5.4	-10.5	-14.7	-16.6	1978-2009
Occurrence data	19/2002	29/1983	30/2000	28/1984	29/1983	1/1983	
Mean annual precipitation (mm)	125.8	71.7	13.2	2.2	0.3	527.4	1978-2009
Maximum annual rainfall (mm)	286	142.7	35	18.7	5.9	748.4	1978-2009
Occurrence year	1998	1978	1986	1985	1979	2004	
Minimum annual rainfall (mm)	31	21.8	0	0	0	324.4	1978-2009
Occurrence year	2006	1992	1994			2009	
Maximum daily precipitation (mm)	51.3	37.7	21.4	8.7	2.2	51.3	1978-2009
Occurrence data	19/2002	4/1985	29/1996	12/1985	3 times in two years	2002.8.19	
Mean evaporation (mm)	181.8	164.9	179.5	130.8	96.9	2084.1	1978-2009
Mean relative humidity (%)	70	68	54	42	37	51	1978-2009

3. The Amount and Distribution of the Loose Deposits in Jiuzhui Gully Watershed

Three basic conditions must be satisfied for debris flow initiation, which include sufficient rainfall, energy conditions and abundant loose solid materials. The main object of this paper is to explore the probability of debris flow occurring in Jiuzhui gully watershed. To comprehensively analyse the formation conditions and predict future debris flow, a systematic field investigation was conducted. Based on field investigation, the amount and distribution of the loose solid material can be identified. The loose deposits mainly include four categories: gully deposits, colluvial deposits, landslide deposits and moraine deposits.

3.1. Gully Deposits

Through the field investigation, the thickness and the particle compositions of the deposits in the gully bed can be determined (Table 2). Therefore, the total volume of the gully deposits can be computed, and the corresponding value is 10.37×10^4 m^3. It was previously revealed that not all of the loose deposits participate in the debris flow movement, and the volume of the deposits which can mobilise into debris flow can be determined based on topography and rainfall conditions. Field investigation allows us to acquire the overall conditions of the gully bed: a few loose deposits were identified in the middle and lower stream, this being mainly due to the scouring capability of the runoff in the gully. Other researchers explored the depth of soil that can mobilise into debris flow through experimental models, finding that the depth ranges from 0.07 to 0.1 m, so the volume of the gully deposits can be calculated, and the amount is found to be 0.38×10^4 m^3.

Table 2. *Statistical table of the gully deposits in Jiuzhui gully.*

No	Length of the gully (m)	Width of the gully (m)	Thickness of the deposits (m)	Deposit area (m^2)	Volume of deposit (10^4 m^3)
0	113.5	3.2	3.5	363.2	0.13
1	173	7.1	4.6	1228.3	0.57
2	282.5	6.8	2.1	1921.0	0.40
3	290.3	7	3.2	2032.1	0.65
4	512.7	7.4	1.6	3794.0	0.61
5	476.24	8.5	3.2	4048.0	1.30
6	416.7	8.2	2.7	3416.9	0.92
7	177.4	6.1	3.6	1082.1	0.39
8	410	5.8	0.7	2378.0	0.17
9	404.6	7.5	2.3	3034.5	0.70
10	314.4	6.7	2.9	2106.5	0.61
11	372.8	5.8	2.1	2162.2	0.45
12	238.8	5.7	1.6	1361.2	0.22
13	340.8	5.4	1.5	1840.3	0.28
14	479	6.2	3.2	2969.8	0.95
15	396.8	6.8	2.4	2698.2	0.65
16	262.8	5.7	2.5	1498.0	0.37
Total volume				37934.4	10.37

3.2. Colluvial Deposits

Most of the colluvial deposits come from collapses. The collapses in the middle and lower stream of the watershed can be obtained by remote sensing interpretation. On the basis of statistical data, previous studies revealed a close relationship between the volume and area of the collapse [9], and the corresponding function is shown as follows:

$$V = 3.4573A^{1.2053} \quad R^2 = 0.7977$$

where V is the volume of the collapse, and A is the area of the collapse. This equation is more suitable for colluvial deposits whose area is less than 20×10^4 m^2. Combining the equation with the real conditions in Jiuzhui gully, the volume of the colluvial deposits can be calculated, and the concrete volume of each area is shown in Table 3. The total volume of colluvial deposits is 15.0×10^4 m^3.

Table 3. *Calculation table for colluvial deposits in Jiuzhui gully.*

No	Type of deposit	Area (m^2)	Thickness (m)	Volume (10^4 m^3)
1	Colluvial deposit	96339.08	0.5	4.82
49	Colluvial deposit	145297.94	0.7	10.17
78	Colluvial deposit	36.12	2.5	0.01
Total amount		241673.1		15

By means of field investigation, we found very little vegetation on the upper part of this area, but as the altitude becomes lower, the vegetation coverage becomes greater. We carried out a trial boring test in the basin, and found that the thickness of the unstable colluvial deposit ranges from 0.2 to 0.4 m. Therefore, the total amount of unstable colluvial deposit can be determined, and the volume is found to be 5.56 x 10^4 m^3. Experimental results proved that the unstable colluvial deposit cannot fully participate in debris flow movement, and the depth of the deposits which can mobilise into debris flow ranges from 0.07 m to 0.1 m. In addition, the area of the colluvial deposits can be drawn through remote sensing interpretation, so the volume of the colluvial deposit which probably can mobilise into debris flow is around 1.69 x 10^4 m^3.

3.3. Landslide Deposits

As can be seen from Figure 1b, four areas of landslide deposits were identified in Jiuzhui gully watershed, namely No 20, 21, 35 and 52, respectively. To better calculate their volume, we employed $h_l = \frac{L_p}{4\sin\theta_s}(\frac{0.0175\theta_s}{\sin\theta_s con\theta_s} - 1)$ to estimate the corresponding thickness (Figure 2). In this function, H is the maximum relief of the landslide, L_p is the horizontal distance between the front edge and back wall, θ_s is the angle of the slope (°), and h_l is the average thickness of the slide body.

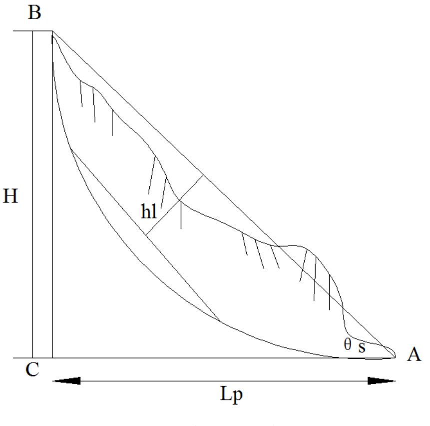


Figure 2. *Schematic diagram.*

Field investigation helped us acquire the length of the slide bodies. The corresponding values are 56, 34, 44 and 36, while the slope angles are 20, 22, 17 and 18°, respectively. Inputting these parameters into the above function, the volume of each landslide deposit can be computed, the values of which are 11.6×10^4, 4.89×10^4, 5.82×10^4 and 3.44×10^4 m^3. For all these landslide deposits, only part of them can mobilise into debris flow during rainfall or ice and snow melt, and the thickness of the slide bodies is determined by a trial boring test, while the area is obtained by remote sensing interpretation. Therefore, the volume of the landslide deposits that will probably participate in debris flow movement is 1.2×10^4 m^3.

3.4. Moraine Deposits

The moraine deposits are concentrated in the area with the altitude ranging from about 4500 to 5400 meters above sea level, especially in the middle of the valley where the gradient is relatively small. The thickness of the moraine deposits varies significantly in different regions, probably from several metres to hundreds of metres. For instance, the thickness of the moraine deposits in Hailuogou is around 120m [10, 11]. Some studies focused on the thickness of moraine deposits along Brahmaputra River, and revealed that the thickness varied from 8 to 40m [12, 13]. The highest altitude in Jiuzhui gully watershed is 5766 m, and combined with the meteorological conditions in this area, the thickness was determined as 10 m. The area of the moraine deposits is acquired by remote sensing interpretation. Thus, the total amount of moraine deposits is 441.8×10^4 m^3 (Table 4).

Table 4. *Calculation table of moraine deposits in Jiuzhui gully basin.*

No	Deposit type	Area (m^2)	Thickness (m)	Volume (10^4 m^3)
14	Moraine deposit	217007.82	10	217
45	Moraine deposit	106121.96	10	106.1
56	Moraine deposit	14613.47	10	14.6
57	Moraine deposit	9321.48	10	9.3
58	Moraine deposit	94763.82	10	94.88
Total amount		441828.6		441.8

Because most moraine deposits are situated in an area with a relatively high altitude, they have good stability. Moreover, these deposits are mainly concentrated on slopes with a lower gradient, so only a small portion of them can participate in debris flow mobilization [14-16]. According to glacial research findings, only the superficial surface can easily mobilise into debris flow, and the thickness is from 0.07 to 0.1 m. Therefore, the probable volume of moraine deposits that can participate in debris flow movement is 3.09×10^4 m^3.

4. Results and Discussion

The development of debris flow is influenced by a variety of factors, mainly including topography, geomorphology, rainfall conditions, seismic activity, arid climate, etc. To accurately evaluate the development trend of the debris flow in Jiuzhui gully, all of the above-mentioned parameters were obtained by field investigation and remote sensing interpretation. Therefore, a systematic and comprehensive analysis can be conducted. The results of the evaluation can greatly benefit local disaster prevention and mitigation and, at the same time, significantly reduce the potential risk posed by the debris flow in Jiuzhui gully watershed.

4.1. Evaluating the Development Trend Based on Activity History of Debris Flow

During the process of field investigation, we interviewed local residents in order to acquire some basic information about the debris flow in Jiuzhui gully. From these interviews, we learned that in the last one hundred years, no debris flow has occurred in this watershed. But some ancient debris flow deposits were identified in the gully bed and the outlet of this watershed. By analysing the deposits, we concluded that large-scale debris flow once occurred in this basin. Even though the debris flow is presently in an intermittent period, it still satisfies the required conditions of debris flow initiation.

4.2. Evaluating the Development Trend BASED on Topography

The energy accumulation process and debris flow development are greatly affected by the topography. The field investigation allows us to obtain the basic parameters of the whole basin, which include the average gradient of the gully bed, the maximum relief, the angle of the slopes and the vegetation coverage. With the aid of the aforementioned data, we concluded that Jiuzhui gully watershed has a fairly good condition for the formation of runoff, but the confluence condition is relatively unfavorable. The average gradient of the gully bed is 346%, the maximum relief is 2450 m, and most of the slopes in this area have angles greater than 30°. On the basis of these data, combined with the debris flow initiation conditions, we concluded that the topography characteristics in this basin can fully satisfy debris flow initiation conditions.

4.3. Evaluating the Development Trend Based on Loose Deposits

Through the calculation in section 3, we know that the total amount of loose deposits in the gully is 492.92×10^4 m^3. Through experiments and trial boring in the field, the probable amount of the deposits which can participate in debris flow movement is 6.36×10^4 m^3. The loose deposits in Jiuzhui gully watershed can fulfill the initiation conditions very well. Therefore, from the perspective of source materials, debris flow can be formed in Jiuzhui gully watershed.

4.4. Evaluating the Development Trend Based on Rainfall Conditions

Analysing the rainfall data from the local meteorological station, we can see that the mean annual precipitation is 527.4 mm, and the maximum daily rainfall in history is 51.3mm. The temperature varied significantly every year, which would cause the melting of ice and snow, which in turn provides the hydrodynamic conditions for debris flow initiation. Previous research indicated that the amount of rainfall in areas with altitude higher than 5000 m is greater than in lower areas. Therefore, the triggering condition for debris flow initiation can be satisfied well.

4.5. Evaluating the Development Trend Based on Seismic Conditions

The study area is located in the intersection area between the Himalayan seismic zone and the Tibetan seismic zone, and many seismic experts have predicted that earthquakes with magnitude 7 or 8 will probably happen here in the future. Some researchers revealed that after a strong earthquake, the frequency and scale of the debris flow will increase greatly (Table 5). And the critical rainfall level for debris flow initiation will reduce significantly.

Table 5. *Discharge of post-earthquake debris flow.*

Area	**Location**	**Occurrence time of earthquake**	**Occurrence time of debris flow**	**Debris flow discharge (m^3/s)**		**Amplification ratio**
				Before earthquake	**After earthquake**	
Tonggeding gully	Batang county	1989.4	1998	21.0 (torrent)	128.3 (debris flow)	6.0
Mantianxing gully	Pengzhou city	2008.5.12	2008.7.26	96.5 (debris flow)	355.9 (debris flow)	3.7
Huashiban gully	Beichuan county	2008.5.12	2008.9.24	23.2 (debris flow)	348.0 (debris flow)	15.0
Shenxi gully	Dujiangyan city	2008.5.12	2009.7.17	392.7 (torrent)	875.5 (debris flow)	2.2
Bayi gully	Dujiangyan city	2008.5.12	2010.8.13	256.3 (torrent)	1274.2 (debris flow)	5.0

It can be seen from Table 5 that the debris flow discharge is magnified 2.2 to 15 times after a strong earthquake. In addition, the seismic activity influenced the debris formation process for more than 20 years, and most large-scale debris flows occurred within 6 years after the occurrence of the earthquake.

5. Conclusions

The above analysis allows us to conclude that Jiuzhui gully is an ancient debris flow gully. Through field investigation and remote sensing interpretation, the basic conditions in this area can be drawn: the loose solid materials, amount of rainfall and energy conditions can satisfy the conditions for debris flow initiation. In the future, under the coupled effect of a strong earthquake and heavy rainfall, the frequency and scale of the debris flow will significantly increase. In order to reduce the losses caused by Jiuzhui gully debris flow, engineering countermeasures or early warning systems should be established beforehand.

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