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Evaluation of debris-flow activity in Bajiao gully on the basis of debris flow formation conditions[1]

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Abstract. Various types of flow or mass movement involving water and sediments occur on steep slopes in mountainous areas. Among them, debris flows are peculiar events during which a large volume of a highly concentrated viscous water–debris mixture flows through a stream channel. Around the world, these phenomena cause considerable damage but remain poorly understood, although a basic knowledge is already available concerning their recognition and propagation. To better analyse the debris flow development tendency, an effective method which can help us obtain the probability of debris flow occurrence is urgently needed. Bajiao gully watershed is located on the left bank of the Brahmaputra River within the Jiexu hydropower project area, which is one of the most important hydropower stations in Tibet. Geological disasters in this watershed have not only influenced the construction process, but also the future operation. With the aim of reducing the effect caused by Bajiao gully debris flow, a detailed field investigation was conducted, and the fundamental data with regard to Bajiao gully were acquired. On the basis of this data, a preliminary analysis was undertaken. Moreover, with the help of the fundamental data, a comprehensive analysis based on the weights of influencing factors can be performed, and the probability of debris flow occurring in Bajiao gully watershed can be determined. As a consequence, some disaster prevention and mitigation measures can be proposed, which can greatly facilitate the construction process.

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1. Introduction

A debris flow is a natural flow of liquefied geo-materials moving down a slope or a stream in mountainous regions [1]. The liquefied geo-materials are usually a mixture of water, soil and rock particles, with a high concentration of solid particles. The frequency and magnitudes of debris flows depend on the characteristics of catchments and local climate [2], [3]. Debris flows are found in a wide variety of environments worldwide. Main characteristics of these phenomena are the initial transformation from solid to flowing debris slurry which shows fluid-like macroscopic behaviour and the transport mechanism characterised by the interaction of solid and fluid forces [4], [5]. Debris flows generally occur during periods of intense rainfall or rapid snowmelt. They usually start on steep hillsides as shallow landslides. Initiation of debris flows requires loose rock and soil deposits, steep slope, and free flowing water from snowmelt or a rainstorm. Debris flows from many different sources can combine in channels where their destructive power may be greatly increased. They continue flowing down hills and through channels, growing in volume with the addition of water, sand, boulders, trees, and other materials. When the flows reach canyon mouths or flatter ground, the debris spreads over a broad area and the debris-flow fan forms [6], [7]. Because of their high mobility, velocity and density, debris flows can be very destructive and damaging when they encounter infrastructures such as buildings, roads, bridges, pipelines and hydropower facilities, and may lead to loss of human life [1]. Debris flow hazards and fatalities in wet seasons have often been reported in the mountainous regions of southwestern China [8]. Mitigation of such hazards is highly important, because many people live there.

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. Through detailed field investigation, we found that the Bajiao gully poses a great threat to the capacity of the reservoir, which will significantly influence the generating capacity.

Bajiao gully has a catchment area of $1.52\,\mathrm{km}^2$ and is located on the left bank of the Brahmaputra River within the Jiexu hydropower project area, which is one of the most important hydropower stations in Tibet. In Bajiao gully watershed, the maximum altitude is 4843 m while the minimum is 3317 m, giving a maximum relief of 1526 m. The total length of Bajiao gully is 2.40 km, and the overall gradient is 606.16 ‰. In addition, Bajiao gully has a confluence into the Brahmaputra River at a height of 3317 m.

3. Methods

On the basis of ancient debris flow traces and the formation conditions, the occurrence of debris flow can be preliminarily determined. For gullies with obvious debris flow traces, it can be easier to identify the probability of debris flow occurring, whereas, in the absence of debris flow traces, the occurrence of debris flow can only be determined through its formation conditions (Fig. 1).

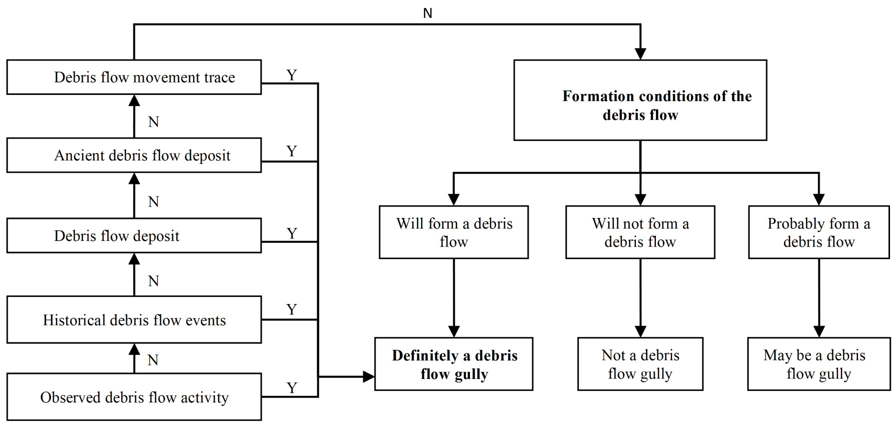

Fig. 1. Flow chart for judging debris flow gully.

A detailed field investigation was conducted in Bajiao gully with the aim of acquiring the debris flow activity data in this watershed. However, we did not spot any deposits and traces of ancient debris flow. As a consequence, whether Bajiao gully is a debris flow gully or not can only be determined on the basis of the debris flow formation conditions, which include sufficient loose solid materials in the debris flow source area, abundant rainfall and a steep slope. By means of field investigation, the fundamental data of this area are obtained, and the mean gradient of the gully bed is computed, the value of which is 606 ‰, which meets the requirement of debris flow initiation. Analysing the basic rainfall data from local meteorological stations, we found that the mean precipitation in Bajiao gully watershed is 524.77 mm, which satisfies the triggering conditions for debris flow initiation. We employed remote sensing interpretation and test pitting to explore the total amount of loose solid materials, and the amount per unit area can be calculated, the value of which is $0.193\,\mathrm{m}^3/\mathrm{m}^2$. Previous research revealed that the amount per unit area of the watershed determines the properties of the debris flow, and when the value ranges from about 0.1 to $0.3\,\mathrm{m}^3/\mathrm{m}^2$, the debris flow formed will probably be a dilute debris flow or flashflood. Hence, the debris flow that probably occurred in Bajiao gully can be determined as a dilute debris flow.

3.1. Loose materials in the source area

The loose solid materials in Bajiao gully watershed mainly fall into the following types, namely gully deposits and colluvial deposits, and these deposits can be calculated on the basis of field investigation, remote sensing interpretation and model calculation.

(1) Gully deposits

The length, width and the thickness of each gully deposit can be determined through a detailed field investigation (Table 1). Hence, the total amount of the gully deposits can be computed, the value of which is $0.17 \times 10^4\,\mathrm{m}^3$.

Table 1. The amount of each gully deposit in Bajiao gully watershed

No	**Length of the gully (m)**	**Width of the gully (m)**	**Thickness of the deposits (m)**	**Deposit area (m^2)**	**Volume of deposit ($10^4\,\mathrm{m}^3$)**
1	547.7	2.2	0.8	1204.9	0.10
2	124.8	1.9	0.3	237.1	0.01
3	182.4	2.0	0.6	364.8	0.02
4	162.6	2.4	0.3	390.2	0.01
5	136.1	1.8	0.4	245.0	0.01
6	149.4	1.4	0.3	209.2	0.01
7	186.2	2.5	0.3	465.5	0.01
Total volume				3116.7	0.17

Previous experiments indicated that the thickness of the gully deposits ranges from 0.07 to 0.1 m. In Bajiao gully watershed, owing to the influence of the perennial flow, very few deposits can mobilise into a debris flow, and the gully deposits which can participate are roughly $0.02 \times 10^4\,\mathrm{m}^3$.

(2) Colluvial deposits

The colluvial deposits in Bajiao gully watershed can be determined by means of a statistical model [9], and the corresponding function is $V = 3.4573A^{1.2053}$, where V is the volume of the sliding body ($10^4\,\mathrm{m}^3$), and A is the projected area of the sliding body ($10^4\,\mathrm{m}^2$). By comprehensively analysing the calculation results and the overall condition in Bajiao gully watershed, the total volume of colluvial deposits can be drawn, the volume of which is $29.13 \times 10^4\,\mathrm{m}^3$ (Table 2). The colluvial deposits that can mobilise into a debris flow are determined by remote sensing interpretation and field investigation, and the volume is $1.42 \times 10^4\,\mathrm{m}^3$.

By means of calculation, the total amount of the loose deposits in Bajiao gully watershed can be obtained, and the corresponding value is $29.3 \times 10^4\,\mathrm{m}^3$. Using

Table 2. Calculation results of the colluvial deposits in Bajiao gully watershed

No	**Loose deposit type**	**Area** (m^2)	**A**	**Volume of the deposit** ($10^4\,m^3$)
1	Colluvial deposit	1667.68	0.17	0.4
4	Colluvial deposit	2025.53	0.2	0.5
8	Colluvial deposit	3145.05	0.31	0.86
10	Colluvial deposit	17186	1.72	
12	Colluvial deposit	946.18	0.09	0.2
13	Colluvial deposit	1770.86	0.18	0.43
14	Colluvial deposit	3774.11	0.38	1.07
20	Colluvial deposit	1768.23	0.18	0.43
27	Colluvial deposit	73856.96	7.39	
28	Colluvial deposit	1397.66	0.14	0.32
33	Colluvial deposit	11.04	0	0
39	Colluvial deposit	303.39	0.03	0.05
41	Colluvial deposit	756.88	0.08	0.15
45	Colluvial deposit	7981.36	0.8	2.63
52	Colluvial deposit	8315.54	0.83	2.77
54	Colluvial deposit	1321.97	0.13	0.3
58	Colluvial deposit	5656.65	0.57	1.74
31	Colluvial deposit	3288.23	0.33	0.9
67	Colluvial deposit	4602.06	0.46	1.36
69	Colluvial deposit	12463.16	1.25	1.55
70	Colluvial deposit	5122.19	0.51	1.54
72	Colluvial deposit	888.25	0.09	0.19
74	Colluvial deposit	6596.2	0.66	2.09
77	Colluvial deposit	1236.53	0.12	0.28
79	Colluvial deposit	11149.11	1.11	3.94
80	Colluvial deposit	2911.11	0.29	0.78
95	Colluvial deposit	1647.06	0.16	0.39
106	Colluvial deposit	5850.84	0.59	1.81
107	Colluvial deposit	4676.85	0.47	1.38
109	Colluvial deposit	410.96	0.04	0.07
116	Colluvial deposit	3328.26	0.33	0.92
117	Colluvial deposit	3314.28	0.33	0.91
118	Colluvial deposit	2715.11	0.27	0.72
Total volume		111031.3		29.13

Table 3. Volume of the loose deposits in Bajiao gully watershed

Loose solid material type	**Area** (m^2)	**Total volume** ($10^4\,m^3$)	**Volume of the deposit that can mobilise into debris flow** ($10^4\,m^3$)	**Percentage of total** (%)
Gully deposit	3116.7	0.17	0.02	0.6
Colluvial deposit	111031.3	29.13	1.42	99.4
Total amount	114148	29.3	1.44	100

this number divided into the area of Bajiao gully, the volume per unit area is $0.193\,m^3/m^2$.

3.2. Rainfall conditions in Bajiao gully watershed

The study area climatically falls into a plateau temperate monsoon semi-humid climate zone. In terms of the recorded data from Jiacha meteorological station, the overall meteorological data from 1978 to 2005 can be acquired. By analysing the meteorological data, we found that the annual mean air pressure is 685.5 hPa, 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 527.4 mm, while the maximum daily precipitation is 51.3 mm and the average annual evaporation is 2084.1 mm. The annual average relative humidity is 51 %, and annual average wind speed is 1.6 m/s. 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.

3.3. Evaluation of debris flow occurrence in Bajiao gully

At present, determining the occurrence of a debris flow in a specific area usually uses a fuzzy mathematical evaluation method, which requires the fundamental data with regard to the whole watershed, including the formation conditions, dynamic features and deposit characteristics. There are many different methods that can be used to assess the probability of the occurrence of a debris flow, and in this paper we employed the method proposed by the Ministry of Land and Resources Industry Standard in China to evaluate the probability of the occurrence of a debris flow in the study area.

In the above-mentioned method, 15 factors are taken into consideration, considering their individual influence on debris flow initiation, each giving a different score. Therefore, the final decision can be concluded on the basis of the total score. The evaluation is shown in Table 4.

Table 4. Standardized table for quantitative and fuzzy evaluation

<table>
<tr><th colspan="5">Discriminant boundary value</th></tr>
<tr><td>Grade</td><td colspan="3">Yes</td><td>No</td></tr>
<tr><td>The scope of N</td><td colspan="3">44 130$(0.25\leq r\leq 1.0)$</td><td>15 43 $(r\leq 0.25)$</td></tr>
<tr><td>Upper and lower bounds of fuzzy boundary area 10% variation score range</td><td colspan="3">40, 130</td><td>15, 48</td></tr>
<tr><th colspan="5">Threshold of severity level</th></tr>
<tr><td>Grade</td><td>Occurrence is extremely easy</td><td>Occurrence is easy</td><td>Occurrence is mild</td><td>No occurrence</td></tr>
<tr><td>Self-judgment range of N according to the standard score</td><td>116, 130 $(r\leq 0.75)$</td><td>87, 115 $(0.5\leq r\leq 0.75)$</td><td>44, 86 $(0.25\leq r\leq 0.5)$</td><td>15, 43 $(r\leq 0.25)$</td></tr>
<tr><td>Self-judgment range according to the upper and lower bounds of fuzzy boundaries 10% deviation</td><td>114, 130</td><td>84, 118</td><td>40, 90</td><td>15, 48</td></tr>
</table>

With the help of Tables 4 and 6, and comparing the corresponding parameters in Bajiao gully to these tables, the final total score can be drawn, and the concrete value is shown in Table 7.

Analysing the result of Table 7, we concluded that the risk of debris flow occurrence in Bajiao gully watershed is mild.

4. Results and discussion

The risk of debris flow occurrence in Bajiao gully watershed is mild. However, its outlet is very close to the provincial road. In the absence of engineering measures, the debris flow in this watershed could have a great influence on local transportation and local economic development. With the aim of reducing the impact of the debris flow in Bajiao gully, we proposed to build a retaining wall at the outlet of the gully.

By analysing the frequency of the debris flow in Bajiao gully, we concluded that Bajiao gully is a low frequency gully. In order to decrease the risk caused by the debris flow in this watershed, some prevention and mitigation measures are proposed here.

More work needs to be done to preserve the water and soil in the upstream of this watershed. In addition, with the aim of preventing wild fire, a rigorous monitoring system should be established here. Through field investigation, it was found that some boulders are situated on the steep slopes in the upstream, and pose a great risk to the safe operation of the provincial road. Therefore, a warning sign should

Table 5. Quantitative scoring table for debris flow occurrence

No	Influential factors	Weight	Grading							
			The occurrence is extremely easy (A)	score	The occurrence is moderate (B)	score	The occurrence is mild (C)	score	No occurrence	score
1	Overall conditions of collapse, landslides, water and soil erosion	0.159	Severe landslides activity and collapse	21	Moderate landslides activity, and small gully developed	16	Few landslides and gully existing in the area	12	No landslides activity and the gullies are poorly developed	1
2	Supply of clay and sand along its movement path(%)	0.118	>60	16	60-30	12	30-10	8	<10	1
3	The deposit condition at the outlet of the gully	0.108	The main stream of the river is blocked and offset	14	The main stream of the river is slightly blocked	11	No blockage along the whole river	7	The river is not bent and not blocked	1
4	Gradient of the gully (°, %)	0.090	12 (213)	12	$12^\circ - 6^\circ$ (213–105)	9	$6^\circ - 3^\circ$ (105–52)	6	$<3^\circ$	1
5	Influence of regional tectonic activity	0.075	The magnitude of the earthquake is larger than grade 6	9	The magnitude of the earthquake ranges between 4 and 6	7	The magnitude of the earthquake is lower than 4	5	No tectonic activity	1
6	Forest coverage of the study area (%)	0.067	<10	9	10-30	7	30-60	5	>60	1
7	Fluctuation of the river bed (m)	0.062	2	8	2-1	6	1-0.2	4	0.2	1

Table 6. Quantitative scoring table for debris flow occurrence (continuation of table 5)

8	Influence of lithology	0.054	Soft rock and loess	6	Soft and hard alternated	5	Strong weathered and joints developed significantly	4	Hard rock	1
9	Distribution of loose solid material along the gully (10^4 m^3/km^2)	0.054	>10	6	10-5	5	5-1	4	<1	1
10	Slope angle (°, ‰)	0.045	>32° (625)	6	32° – 25° (625–466)	5	25° – 15° (466–286)	4	<15 (286)	1
11	Cross-section in sand production area	0.036	V-shaped, U-shaped	5	Wide U-shaped valley	4	Compound section	3	Flat type	1
12	Average thickness of loose deposits in the sediment-producing area (m)	0.036	>10	5	10-5	4	5-1	3	<1	1
13	Drainage area (km^2)	0.036	0.2-5	5	5-10	4	<0.2 or 10-100	3	>100	1
14	Altitude difference (m)	0.030	>500	4	500-300	3	300-100	2	<100	1
15	Degree of river blockage	0.030	Severe	4	Moderate	3	Slight	2	No	1

Table 7. Quantitative evaluation table for Bajiao gully debris flow occurrence

No	Influential factors	Weight	Bajiao gully watershed	
			Influential factors	score
1	Overall conditions of landslides and collapse	0.159	No collapse and landslides, gully not well developed	1
2	Solid material supplement along the main gully (%)	0.118	Solid material is supplemented in the middle and lower stream (8 %)	1
3	Debris flow activity in the outlet of the watershed	0.108	The river is smooth	1
4	Channel gradient (‰)	0.09	The gully gradient is 606 ‰	12
5	Influence of regional tectonics	0.075	Earthquake with magnitude larger than 6 occurred in this area	7
6	Forest coverage (%)	0.067	The forest coverage of Bajiao gully watershed is 26 %	7
7	Fluctuation of the river bed (m)	0.062	0.2	1
8	Influence of lithology	0.054	Hard rock	1
9	Solid material volume per unit area ($10^4\,m^3/km^2$)	0.054	<1	1
10	Slope angle (‰)	0.045	22 °	4
11	Cross-section in sand-producing area	0.036	Flat type	1
12	Average thickness of loose deposits in the sediment-producing area (m)	0.036	0.15 m	1
13	Drainage area (km^2)	0.036	1.52 km^2	5
14	Altitude difference (m)	0.03	300-100	2
15	Degree of river blockage	0.03	Mild	2
Total score				47
Evaluation result			Mild occurrence	

be erected, and a blocking wall should be set on the roadside.

To better and accurately predict the occurrence of the debris flow in this area, the fundamental data with regard to this watershed should be collected, and the data analysed to identify whether they satisfy the initiation conditions of debris flow or not; as a consequence, timely and accurate forecast signals can be released.

5. Conclusions

Bajiao gully watershed has a catchment area of 1.52 km^2, the relative height difference is roughly 1526 m, and the length of the main gully is 2.4 km. Through field investigation we found that the average channel gradient is 606.16 ‰. With the help of model calculation and remote sensing interpretation, the total amount of loose solid material can be explored, the value of which is $29.3 \times 10^4\,\mathrm{m}^3$. By further analysing the watershed conditions, the amount of loose solid material that can mobilise into debris flow can be determined, and the corresponding value is $1.44 \times 10^4\,\mathrm{m}^3$. On the basis of this data, we concluded that the source material can fully meet the requirement conditions of debris flow formation. In the study area, the mean annual precipitation is 527.4 mm, and the maximum historical daily rainfall is 51.5 mm. Moreover, the temperature varies a lot which results in the melting of snow, which significantly facilitate the confluence of the runoff in the watershed, and provides a basic condition for debris flow initiation.

Seismic activity plays a key role in the process of debris flow formation. Through a detailed field investigation, we obtained that the conditions required for debris flow formation can be fully satisfied. In particular, under the coupled effect of a strong earthquake and heavy rainfall, the frequency and scale of the debris flow occurring in this watershed will be greatly increased. We propose that a retaining wall should be built on the roadside, so that falling rocks can be blocked. Meanwhile, early warning information should be analysed meticulously, and once a strong earthquake or heavy rainfall occurs in this area, a timely forecast signal should be released. Thus the threat caused by the debris flow in Bajiao gully watershed can be reduced significantly.

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