DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

Proceedings
of the 5th International Conference

Tbilisi, Georgia, 1-5 October 2018

Editors
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Publishing House “Universal”
Tbilisi 2018

СЕЛЕВЫЕ ПОТОКИ: катастрофы, риск, прогноз, защита

Труды
5-й Международной конференции

Тбилиси, Грузия, 1-5 октября 2018 г.

Ответственные редакторы
С.С. Черноморец, Г.В. Гавардашвили

Издательство Универсал
Тбилиси 2018

ღვარცოფები: კატასტროფები, რისკი, პროგნოზი, დაცვა

მე–5 საერთაშორისო კონფერენციის მასალები

თბილისი, საქართველო, 1–5 ოქტომბერი, 2018

რედაქტორები
ს.ს. ჩერნომორეც, გ.ვ. გავარდაშვილი

გამომცემლობა "უნივერსალი"
თბილისი 2018

УДК 551.311.8
ББК 26.823

Селевые потоки: катастрофы, риск, прогноз, защита. Труды 5-й Международной конференции. Тбилиси, Грузия, 1-5 октября 2018 г. – Отв. ред. С.С. Черноморец, Г.В. Гавардашвили. – Тбилиси: Универсал, 2018, 671 с.

Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 5th International Conference. Tbilisi, Georgia, 1-5 October 2018. – Ed. by S.S. Chernomorets, G.V. Gavardashvili. – Tbilisi: Publishing House “Universal”, 2018, 671 p.

ღვარცოფები: კატასტროფები, რისკი, პროგნოზი, დაცვა. მე–5 საერთაშორისო კონფერენციის მასალები. თბილისი, საქართველო, 1–5 ოქტომბერი, 2018. გამომცემლობა "უნივერსალი", თბილისი 2018, 671 გვ. პასუხისმგებელი რედაქტორები ს.ს. ჩერნომორეც, გ.ვ. გავარდაშვილი.

Ответственные редакторы С.С. Черноморец, Г.В. Гавардашвили
Edited by S.S. Chernomorets, G.V. Gavardashvili

Верстка: С.С. Черноморец, К.С. Висхаджиева, Е.А. Савернюк
Page-proofs: S.S. Chernomorets, K.S. Viskhadzhieva, E.A. Savernyuk

При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).
Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

ISBN 978-9941-26-283-8

Conditions and mechanism for formation of glacial debris flows in Parlung Zangbo, SE Tibetan Plateau

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Alpine glaciers are vulnerable to climate changes, and their recession due to warming has already induced large number of geohazards closely related to glacial motion, such as debris flow. Strong coupling of the geology, geomorphology, climate and glacial action controls the type, size, development and frequency of debris flow in the Parlung River. The field investigation indicate that the northern bank is much bigger sizes and higher frequency of debris flows than the southern bank, the sharp contrast between the two banks is determined by their different formation conditions of debris flows, especially glaciers and geomorphology. The present paper examines the differences in the conditions for glacial debris flows to occur, through a combination of field investigation, interviews with local residents, and interpretation of remote sensing images. The mechanisms due to different formation conditions are analyzed. Based on the results, effective measures are proposed for mitigating the harm to roads and railways within this area done by this geohazard.

sharp contrast between two banks; formation mechanism; glacier recession; Sichuan-Tibet highway/railway

Условия и механизм формирования гляциальных селей в долине Парлун Цангпо, юго-восток Тибетского нагорья

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Высокогорные ледники уязвимы для изменения климата, и их сокращение из-за потепления уже вызвал большое количество геологических опасностей, тесно связанных с движением ледников, таких как селевые потоки. Сочетание геологического и геоморфологического строения, климата и динамики ледников влияет на тип, масштаб и частоту селей в долине реки Парлун. Полевое исследование показывает, что на северном борту долины селепроявления имеют гораздо большие масштабы и более высокую частоту, чем на южном борту. Резкий контраст между двумя бортами определяется различными условиями селеформирования, особенно в отношении оледенения и особенностей рельефа. В настоящей работе рассматриваются различия в условиях формирования гляциальных селей на основе сочетания результатов полевых исследований, опроса местных жителей и интерпретации материалов дистанционного зондирования. Анализируются механизмы, обусловленные различными условиями формирования. Исходя из результатов, предлагаются эффективные меры для смягчения ущерба от этого вида геологических опасностей для автомобильных и железных дорог в данном районе.

резкий контраст между двумя бортами долины; механизм формирования; сокращение оледенения; Сычуань-Тибетское шоссе и железная дорога

Introduction

Glacial debris flow is a natural geological phenomenon closely related to glacial motion, usually triggered by glacial meltwater or intense rainfall. Large glacial debris flows could also be caused by icefalls, avalanches or failure of dams across gullies [*Cruden and Hu, 1993; Kourp and Clague, 2009; McColl, 2012; Stoffel and Huggel, 2012; Fischer et al., 2012*]. Glacial debris flows are sudden, violent, and difficult to forecast, and tend to travel long distance at high speed. This kind of geo-hazard, which typically occurs in alpine regions, can cause severe damage to the villages, factories and mines, roads, railways, and towns along gullies or at their mouths, and thereby terrible loss of life and property [*Korup and Clague, 2009; Takahashi, 2014; Cui et al., 2015*].

Running across the substantially uplifted Tibetan Plateau, the Parlung Zangbo River (hereafter called “the Parlung River”) is among the world’s rivers with the highest elevation drops and greatest erosive forces. Due to this as well as the frequent earthquakes and abundant precipitation there, this river is one of the regions subjected to the largest-scale, most violent, and most hazardous debris flows in the world [*Shang et al., 2003; Ge et al., 2014*]. The Parlung River is home to the largest temperate glaciers of China [*Shi et al., 1964; Liu et al., 2013*]. The river basin has undergone active endogenic and exogenic geological processes, and has an extremely complex tectonic setting and high neotectonic activity [*IMHE and ITS, 1999*]. This, combined with the alpine-gorge terrain, high precipitation, and modern glacial activity, contributes to collapse, landslide, debris flow and other major geohazards in this region, among which glacial debris flow is the most destructive [*IMHE and ITS, 1999; Shang et al., 2005*].

Many large debris flows have taken place in the Parlung River in the history. The Sichuan-Tibet Highway, a section of China National Highway 318 [G318] on the northern bank of the Parlung River, has been blocked by many debris flows since it was built in the 1950s. For this reason, researchers have conducted a systematic series of research in this area since then. Glacial debris flows in this area were intensively studied during the comprehensive scientific investigation of the Tibetan Plateau in the 1970s [*IMHE and ITS, 1999; Du et al., 1985*]. Recent studies have looked at the deglaciation resulting from global warming in detail. Existing research has provided plenty of valuable data and insights into the characteristics of geohazards along the Sichuan-Tibet Highway and the conditions and mechanisms for their occurrence, and also proposed preventive measures [*Shang et al., 2005; Zeng et al., 2007; Zhang et al., 2017*].

Large glacial debris flows are considered a serious obstacle to regional economic development and a threat to major construction projects, such as the Sichuan-Tibet Railway [from Chengdu to Lhasa, Fig.1] which is planned to span the Parlung River. In order to ensure normal traffic on Sichuan-Tibet Highway and successful implementation of China’s Western Development Program, there is currently an urgent need to address glacial debris flows and ensuing environmental problems in the study area. The present paper examined the differences in the conditions for glacial debris flows to occur between the southern and northern banks of Parlung River, through a combination of field investigation, interviews with local residents, and interpretation of remote sensing images. The mechanisms for formation of glacial debris flows were analyzed. Based on the results, effective measures were proposed for mitigating the harm to roads and railways within this area done by this geohazard.

General settings

Geological conditions

The Parlung River is located in the northeastern part of the Eastern Himalayan Syntaxis, eastern end of Gangdise-Nyenchen Tanglha fault-fold belt. The area is mainly composed of gneiss of the Nyainqentanglha group and the Gangdise granite and Metamorphic rocks of Paleozoic system [Fig.1; *Ding et al., 1995; Xu et al., 2008; Zeitler et al., 2014; Zhang et al., 2016*], the neotectonics is characterized by fast regional crustal uplift with multiple faulting activities. The Tongmai-Zhongkang fault [TZF] and the Tongmai-Jingzhula [TJF] are two important active faults with an average dextral strike-slip rate of 4mm/a [Fig.1; *Ren et al., 2000; Tang et al., 2010*]. The syntaxis region is highly seismic with 124 earthquakes of ML 4.0 or greater from 1950 to 1996, including the Ms 8.5 Motuo Earthquake in 1950 [Fig.1; *GRGST, 1995; IMHE and ITS, 1999; Ren et al., 2000; Zeng, 2007*].

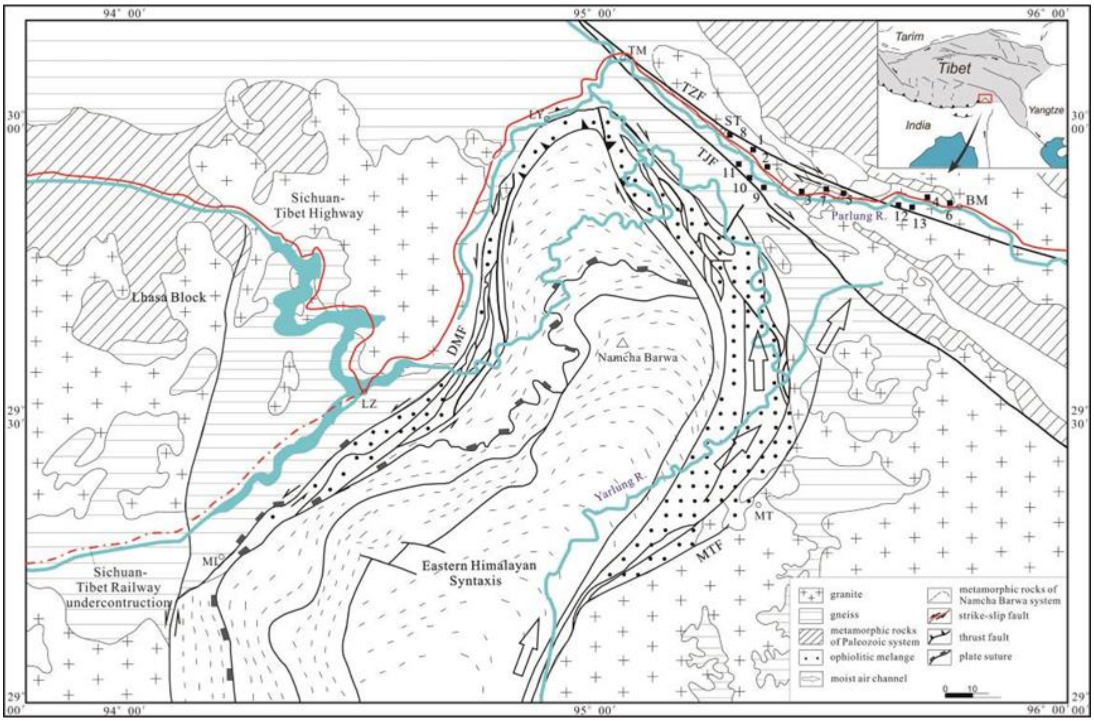

Fig. 1. Geological sketch map of the Eastern Himalayan Syntaxis [after Xu et al., 2008; Wei et al., 2017] (Abbreviations: Towns, BM-Bomi, ST-Suotong, TM-Tongmai, LY-Layue, LZ-Linzhi, ML-Milin, MT-Motuo. Faults, TZF-Tongmai Zhongkang fault; TJF-Tongmai Jinzhula fault; DMF-Dongjiu Milin fault; MTF-Motuo fault. Numbers: 1-Bitong debris flow; 2-Dada rock avalanche-debris flow; 3-Jiaolong debris flow; 4-Cangguo debris flow; 5-Zhataduo debris flow; 6-Naha debris flow; 7-Guxiang rock avalanche-debris flow; 8-Suotong debris flow; 9-Qiuzhu debris flow; 10-Chidan debris flow; 11-Songrao debris flow; 12-Michong debris flow; 13-Danka debris flow).

Climate and precipitation

Located in the southeastern Tibetan Plateau, the Parlung River is more sensitive to climate change than other parts of West China. It has a subtropical alpine climate affected by the Indian Monsoon. The Indian Monsoon carries moisture to the Tibetan Plateau, primarily along the valley of the Yarlung Zangbo River [hereafter called Yarlung River] on the west of the Parlung River and the Danlong and Chayu Rivers on the south, which are all open to the south [Fig. 1]. This leads to high precipitation in the plateau. For example, the average annual precipitation is as high as 1100-1400 mm/a in Tongmai and Bomi [Fig.1]. Due to the humid air and high elevations, the Parlung River has the largest expanses of temperate glaciers in China. A total of 1320 modern temperate glaciers are distributed in the Kangri Karpo Mountains on the river's southern bank, covering an area of 2655 km^2 [*Li et al., 1986; Mi et al., 2002; Yang et al., 2008*]. The high precipitation and temperature attributed to the warm moist air from the Bay of Bengal, plus global warming, keep the surface temperatures of the temperate glaciers in this area at around 0 ℃. Therefore, the glaciers undergo faster ablation than accumulation of ice and move actively. As a result, deglaciation occurs extensively and provides a lot of materials and water needed for formation of debris flows.

Geomorphology

The Parlung River extends on the northeast of the Eastern Himalayan Syntaxis. It is characterized by alpine gorges and deep-incised river valleys with extremely high erosion rates of > 5mm/a [*Zeitler et al., 2014*], and its elevation tends to decrease from east to west overall. The river flows through wide valleys in its upper reaches and narrow gorges in the lower reaches. It is bounded on the north by the southeastern branch of the Nyenchen Tanglha Mountains and on the south by the Kangri Karpo Mountains. The extensive development of glaciers and intense tectonic processes has created a wide variety of geomorphic features, such as glacial landforms, alpine gorges, and fluvial depositional landforms.

Geo-hazard history

Strong coupling of the above geology, geomorphology, climate and glacial action controls the type, size, development and frequency of debris flow in the Parlung River, Since 1950, the study area has been frequently hit by debris flows of different sizes, suffering huge loss of life and property [e.g. 1-13 in Fig.1; *IMHE and ITS, 1999*]. In particular, some debris flows were extremely tremendous and disastrous, such as the debris flow occurring in Guxiang area on September 29, 1953 [*Shi et al., 1964*].

According to the size classification, which is based on the total volume, peak discharge and inundated area, the size classes of the debris flows are given in Tabel 1, coinciding with the debris flow frequency based on the interview and previous study,

The debris flows in the study area were classified in terms of size using a size classification method based on total volume, peak discharge and inundated area (Table 1). The results are consistent with the data on debris flow frequency obtained from the interviews and previous study. In the region between Bomi and Suotong [Fig. 1], the southern and northern banks of the Parlung River differ greatly in occurrence of debris flows. Compared to the northern bank, the southern bank shows much smaller sizes and lower frequency of debris flows (Table 1). The sharp contrast between the two banks is determined by their different formation conditions of debris flows.

Analysis of the formation conditions of debris flow

Due to its unique geographic location and climate, debris flows in the Parlung River are closely associated with moisture distribution and glacial movement. The study found that they are a direct consequence of glaciers recession [*Zheng et al., 2014*].

Comparison of hydrology and glacier distribution between the two banks

The data from the field investigation and remote sensing images, together with the Second Glacier Inventory Dataset of China [*Liu et al., 2013*], suggest significant differences in glacier distribution between the northern and southern banks of the Parlung River. In terms of glacier type, valley glaciers are distributed only on the southern bank, while the northern bank is covered primarily by cirque glaciers and hanging glaciers. The snow line is generally higher in the east than in the west (Table 2).

In the region between Bomi and Suotong, northern bank of the river has 28 glaciers, which account for 32.56% of the region's total number of glaciers, 35.62% of glacier coverage, and 35.62% of ice reserves. The southern bank has 58 glaciers, which make up 67.44% of the region's total number of glaciers, 65.44% of glacier coverage, and 64.39% of ice reserves (Table 2). It is clear that the southern bank has more glaciers than the northern bank.

Table 1. Typical debris flows in the Palung River from Bomi to Suotong [e.g. 1-13 in Fig.1; *IMHE and ITS, 1999*]

No.	**Name**	**Date**	**Size class**	**Location**
1	Bitong gully	5 Sep. 2007	Middle	North bank
		5 Sep. 2016	Large	
2	Dada gully	4 Aug. 2013	Small	
		20 Jul. 2017	Middle	
3	Jiaolong gully	Sep. 1988	Middle	
		15 Aug. 1989	Large	
		5 Sep. 2016	Middle	
4	Cangguo gully	1975	Large	
		1996	Large	
5	Zhataduo gully	Jul. 1987	Large	
6	Naha gully	1968	Super-large	
		1978	Large	
7	Guxiang gully	29 Sep. 1953	Super-large	
		1954	Large	
		1963	Large	
		30 Jul. 2005	Large	
8	Suotong gully	26 Jul. 1991	Middle	
9	Qiuzhu gully	2014	Middle	South bank
		28 Aug. 2016	Middle	
10	Chidan gully	5 Sep. 2016	Middle	
11	Songrao gully	4 Sep. 2007	Large	
		25 Jul. 2010	Large	
12	Michong gully	Aug. 2015	Small	
13	Danka gully	Aug. 2015	Small	

Obviously, glaciers are more developed on the southern bank of the Parlung River than on the northern bank. Glaciers that fill gullies are called valley glaciers. The northern bank shows a snow line higher than that on the southern bank and basically has no valley glacier, indicating that the snow and ice on the northern bank are more active. Numerous large glaciers have formed on the Kangri Karpo Mountains because the mountains just stand in the way of the warm moist air brought by the southwest monsoon blowing from the great bend of the Yarlung River [Fig. 1], and thus become the wettest part of the Tibetan Plateau. After the moist air climbs over the Kangri Karpo Mountains and passes the Parlung River, it decreases in moisture content and thus supplies less moisture to the river's northern bank [the Nyenchen Tanglha Mountains]. Therefore, the northern bank is dominated by cirque and hanging glaciers.

Table 2. Glaciers in Palung River from Bomi to Suotong.

Location	Types of glacier	Number of glaciers and percentage		Area of glaciers [km^2] and percentage		Volume of glaciers [$\times10^6$m^3] and percentage		Average snow line [m]
Northern bank	Hanging glacial	18	20.93%	41.12	30.84%	2867.45	33.93	4040
	Cirque glacial	10	11.63%	4.96	3.72%	142.57	1.69%	
	Valley glacial	0	0%	0	0%	0	0%	
Southern bank	Hanging glacial	23	26.74%	31.18	23.38%	2058.01	24.35%	3429
	Cirque glacial	15	17.44%	5.82	4.36%	194.73	2.30%	
	Valley glacial	20	23.26%	50.27	37.70%	3188.54	37.73%	
Sum total	/	86	100%	133.35	100%	8451.3	100%	/

Moreover, the glaciers on the southern bank [the shady slope] melt at slow rates as they have lower surface temperatures due to low solar irradiation received. After a certain amount of snow has accumulated on a glacier, the glacier tends to move downward to valleys under gravity or pressure. This contributes to the higher probability of formation of valley glaciers on this bank. By contrast, glaciers on the northern bank [the sunny slope] show higher surface temperature due to greater solar irradiation and thus melt faster. For this reason, glaciers are unlikely to fill gullies and the dominant glacier types are cirque glaciers and hanging glaciers. Due to their differences in moisture supply and solar insolation, the northern bank has a snow line higher than that the southern bank's. The more active glacial motions and faster rate of melting on the northern bank are regarded as the preconditions for formation of glacial debris flow. For the melting of glacier provide it with enough water and the till in the glacier transform to the solid matter in the glacial debris flow.

Differences in geomorphology between northern and southern banks

Glacial debris flow nowadays is the result of the whole area's geomorphic evolution. From the Quaternary, during glacial period and interglacial period, as the the glacier scale of southern bank is much bigger than that of the northern, so as to the glacier erosion and transporting capacity. During Last Glacial Maximum, glacier filled the whole gully and reached the Parlung River. Therefore, under the effect of long-term structural erosion and glacier erosion, gullies in southern bank reflect higher grade of maturity. Its overall form takes the shape of oak leaf and cross section takes the shape of "u". While for the most gullies in northern bank, due to long time illumination, it is hard to form large scale glacier running through the whole gully and glacier remains mostly at the edge of gully at high altitude. Under the effect of freeze-thaw weathering and glacier erosion over the years, only mountains at high altitude suffer repeated erosion, thus to form wide top and narrow bottom. Its overall form takes the shape of funnel and cross section takes the shape of "v" at the lower part, which is favorable geography for debris flow [Fig. 2, Fig. 3]. Therefore, it is obvious the northern bank is more beneficial for the formation of glacial debris flow.

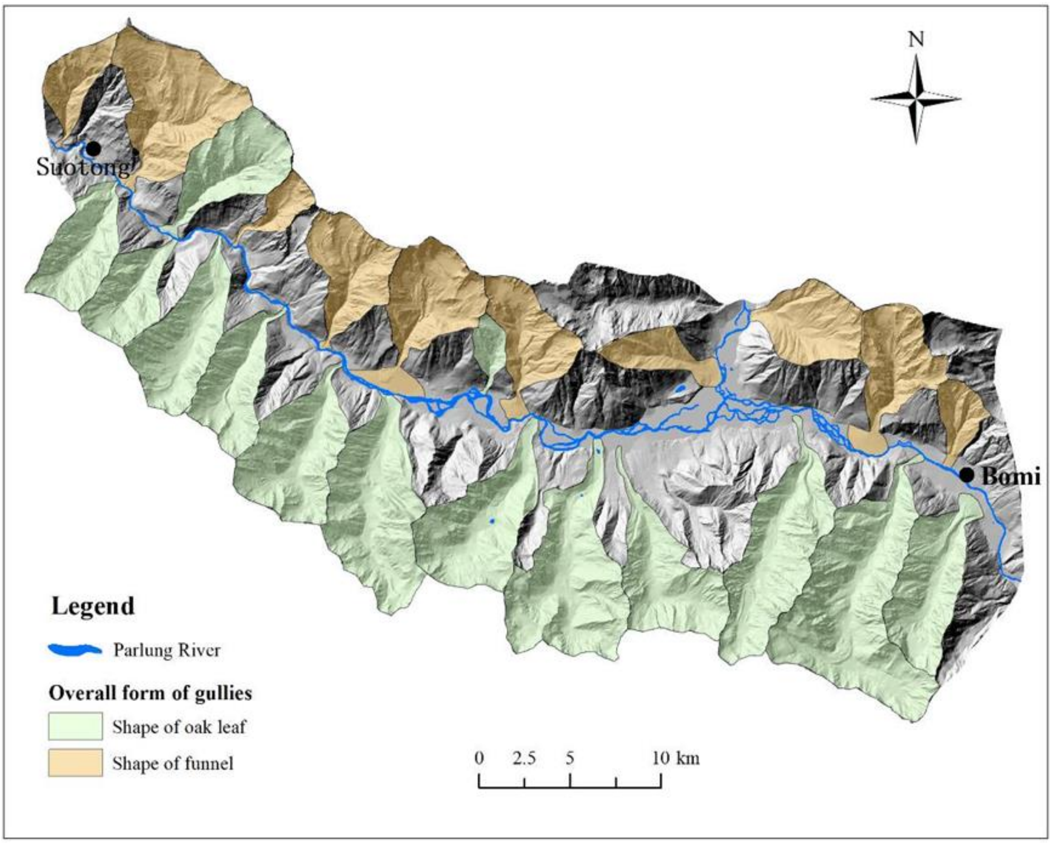

Fig. 2. Overall form of gullies in two banks between Bomi and Suotong (Fig. 1).

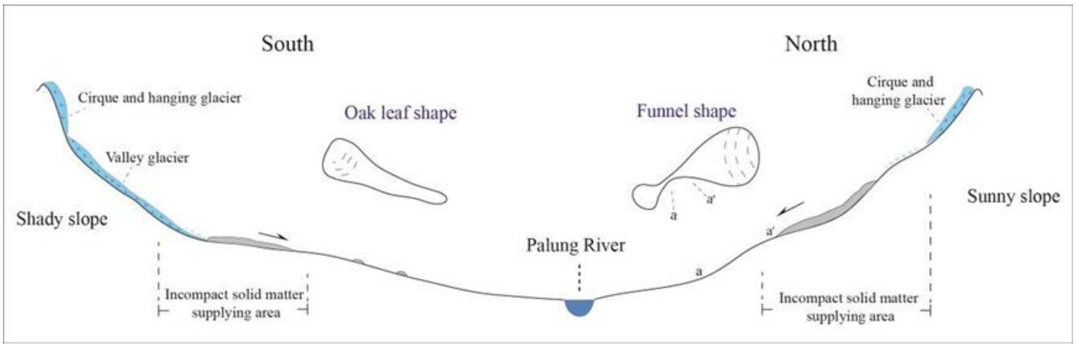

Fig. 3. Comparison of gullies geography in two banks.

Formation mechanism of debris flow in south and north of Parlung River

Occurrence of landslides, collapse, debris flows and other geohazards depends on a combination of internal and external conditions, including active tectonics, topography, climate, and hydrology. The field investigation and analysis show that glacial debris flows vary between the southern and northern banks despite their overall wide distribution across the region. According the previous research, the glacial debris flows on the two banks formed in significantly different conditions, and thus their formation mechanisms inevitably differed. [*Takahashi, 2014*] proposed three classical modes of debris flows: 1) falling debris mixes with water in a gully and transforms into a debris flow; 2) gully bed deposits are destabilized by surface runoff and then develop into a debris flow; 3) the collapse of a debris dam suddenly causes a debris flow. In fact, the formation of debris flows in the Parlung River can also be explained by these modes. However, the debris flows on the southern and northern banks occurred through different mechanisms due to different formation conditions.

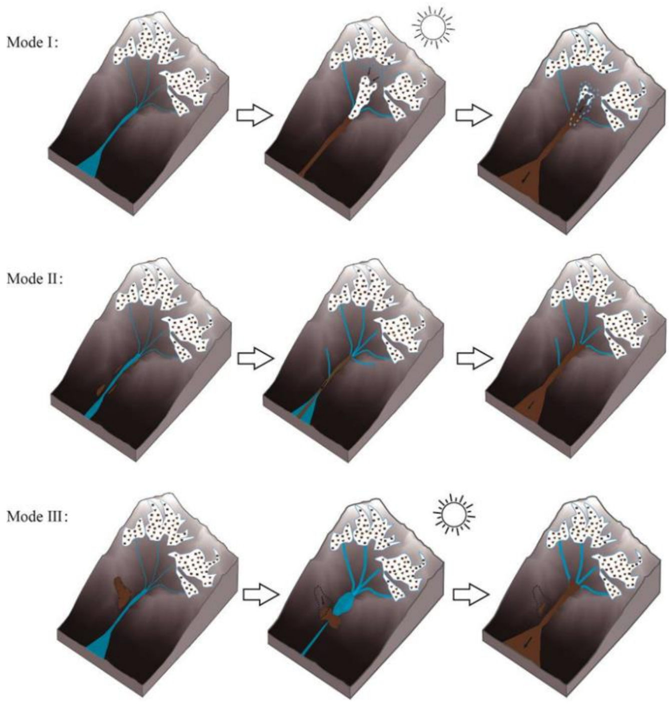

Fig. 4. Formation mechanisms of debris flow in the Parlung River

Mode I: During movement, a glacier tends to fracture during intense melt at its snouth. The glacial meltwater then moves into the glacial body along the resulting fractures and accumulate into runoff at the glacier base. Cavities form at the glacier snouth due to erosion by the runoff. As the fractures continue growing, the glacial till or rock masses deposited by the glacier tend to collapse, motivating the slow-moving glacier to move downward faster. During fall and breakage, ice will melt and the huge amounts of energy contained in meltwater runoff will destabilize the loose gully deposits, which then develop into a debris flow (Fig. 4, mode I).

Mode II: In the early stage, the small quantities of glacial meltwater and surface runoff generated by rainfall also provide materials for formation of a debris flow. When the ablation of glacier accelerates or a heavy rainfall occurs, the resulting water forms runoff, which will erode the glacial till and debris from landslides previously deposited in the gully and entrain the underlying sediments. The sediments will then be fluidized and move, forming a debris flow (Fig. 4, mode II).

In mode III, after gully slopes collapses, the materials from the slopes will accumulate in the middle part of the gully and form a dam. As a result, upstream rainfall and glacial meltwater will be blocked by the dam. After the water behind the dam reaches a certain amount, the dam will break and the water will be discharged rapidly. The discharged water then entrains the underlying sediments, resulting in a glacial debris flow (Fig. 4, mode III).

Discussion

The differences in climate, hydrology, geomorphology, glacier distribution and other conditions between the southern and northern banks of the Parlung River contribute to their differences in the size, frequency, and formation mechanism of debris flows. Data on previous debris flows suggests that debris flows on the northern bank were more active than those on the other bank. It is reasonable to predict that the debris flows will still occur more frequently on northern bank in the future.

The dominance of cirque and hanging glaciers on the upper part of gullies in the northern bank indicates greater potential energy carried by icefalls and avalanches. As the northern bank is the sunny slope, the glaciers there are more active and melt more intensely, increasing the probability of icefalls, avalanches, and rockfalls. Therefore, the mode of debris flow changes to mode I. Active glaciers will produce more meltwater and modern glacial till. The unique funnel shape of gullies not only facilitates confluence of water from different sources, but also increases the likelihood of blockage and dam break at the narrow part of a gully. Then mode III debris flow will occur. On the southern bank [the shady slope], the gullies are oak leaf-shaped and typically covered with valley glaciers. As the speeds of glacier motion and water catchment are slow, it will take a longer time for the materials produced by repeated freezing and thawing in the early stage and from a gully to develop into a debris flow. In this situation, a mode II Debris flow is more likely to occur. However, in extreme conditions, there is also possibility of a model III debris flow triggered by breakage of a dam, which is composed of the materials falling from both slopes of a gully. In conclusion, the debris flows on the northern banks primarily occur in modes I and III, while the southern banks are dominated by modes II and III debris flows.

Glacier is the controlling dynamic factor of debris flow in Parlung River. Warming is the root cause of the glacial recession, Mass meteorological data show that climate warming is significant in the Parlung River since the 1970s, the warming rate in Bomi is 0.23℃/10a [*Deng et al., 2017; Yang et al., 2010*]. It is speculated that the melting rate of glaciers will accelerate in the future, and the northern bank is more pronounce than the southern bank, for smaller glaciers are more sensitive than the larger ones and are easier to lose material.

The disappearance and recession of glaciers bring enough water and impact solid matter for glacier debris flows, no doubt debris flow in the region will increase gradually in the future [*IMHE and ITS, 1999; Shang et al., 2005; Cui et al., 2014; Gariano and Guzzetti, 2016; Wei et al., 2018*]. Strong earthquakes are bound to be the center of the centralized breaking out of glacier debris flows. In addition, the melting of the glacier will bring the moraine lakes, which are hidden danger for the subsequent debris flows caused by glacial-dammed lakes outburst.

The paper suggests that the major transport projects to be built in the Parlung River, such as the Sichuan-Tibet Expressway and Sichuan-Tibet Railway, should be located on its southern bank, in order to mitigate the influence of debris flows. To span gullies prone to debris flows, bridges and tunnels are proper solutions.

Conclusion

Study in the present paper indicate that, compared to the southern bank of the Parlung River, the northern bank shows much bigger sizes and higher frequency of debris flows. The sharp contrast between the two banks is determined by their different formation conditions of debris flows, especially glaciers and geomorphology. In fact, glaciers are more active on the northern bank of the Parlung River than on the southern bank, which means enough water and impact material for the debris flow. Overall form of gullies in northern bank mainly take the shape of funnel and cross section take the shape of "v" at the lower part, which is favorable geography for debris flow.

Three formation mechanisms are concluded, mode I: icefalls, avalanches and rockfalls mixes with water in a gully and transforms into a debris flow; mode II: gully bed deposits are destabilized by surface runoff and then develop into a debris flow; mode III: the break of a debris dam suddenly causes a debris flow. The glacial debris flows on the southern and northern banks occur through different mechanisms due to different formation conditions, the debris flows on the northern banks primarily occur in modes I and III, while the southern banks are dominated by modes II and III debris flows.

The disappearance and recession of glaciers bring enough water and impact solid matter for glacier debris flows, no doubt debris flow in the region will increase gradually in the future, and the northern bank is more pronounce than the southern bank. The paper suggests that the major transport projects to be built in the Parlung River, should be located on its southern bank, in order to mitigate the influence of debris flows. To span gullies prone to debris flows, bridges and tunnels are proper solutions.

Acknowledgements

The work is supported by geological survey project "Geo-hazards investigation in major towns and along main highways in SE Tibet", which is funded by China Geological Survey.

The authors thank sincerely to Dr. Dongxu Yang and Eng. Dong Yang for providing valuable discussions in the field.

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