Present situation and preliminary analysis of glacial lake in Naqu region

Z A Jiang¹², H Chen², W Cui¹ and H P Yan³

¹ School of Civil Engineering, Tianjin University, Tianjin, China.
² Sinohydro foundation board co., LTD, Tianjin, China.

tdjza@163.com

Abstract. The location of glacial lake is special and the results of previous researches are few. But it has caused a lot of geological disasters in its history, and been an urgent need to solve the engineering problems. Based on the historical data and a large number of field visits, the principle of the glacial lake disaster is analyzed, in combination with the first-hand data obtained from the site survey, the complexity of the glacial lake disaster mechanism is explained. It is believed that taking the glacier, glacial lake and the downstream rivers into consideration together is the key to solve the problem. This paper analyzes the possibility of glacial lake for hydropower generation, water diversion and water conservancy scenic area, and so on. On this basis, it proposes that the safety risk assessment is the basic work for disaster prevention and mitigation of glacial lake and their development and utilization.

1. Introduction

Glacial lake, as a special type of lake, is a valuable water and natural landscape, and is also many glacier breeding and birthplace. In the world, the glacial lake is mainly distributed in North America’s Rocky Mountains and Alaska Coastal Mountains, South America’s Andes, the European Iceland and the Alps, Asia, Central Asia and the Qinghai-Tibet Plateau region. Yao Xiaojun et al[1] have detailed on the glacial lake definition and classification, from the type of glacial lake, the glacial lake in Tibet belongs to the glacier end of moraine lake[2-5]. The remarkable feature of this glacial lake is that the moraine ridge has a low strength, poor stability, and is prone to collapse.

2. Overview of the glacial lake disaster in Tibet

2.1. Introduction to Glacial lake Disaster

Glacial lake disaster (or glacial lake flood) is one of the common natural disasters in the alpine glacier area. It refers to the floods caused by the glacial lake and the flood-caused mudflow, mountain collapse and landslides, etc that cause losses of the national economy and people’s life and property. Unlike the heavy rain or snow-melt floods, the glacial lake floods are characterized by being sudden, seasonal, with low frequency, high flood peak, sudden fluctuation of the flow quantity, destructive power, wide range of destruction and so on, often causes heavy damage to people’s lives and property and the infrastructure on the downstream areas.

According to the statistics of the relevant departments, the occurrence of glacial lake collapse in the 20th century has been more than 20times[1]. On July 16, 1954, a large scale glacial lake collapse happened. At that time, the source of the Nirvana in the southeast of the Gyagze County was at the
end of the mountain, due to the temperature went high, the snow and ice suddenly collapsed at night into Yu Sang Wang Lake, causing the lake soared, nearly 300 million m$^3$ of water running out of the glacial lake accompanied by mud into the Chu River, causing serious disaster in the Chu River Basin. According to statistics, in Kangma, Gyangze, Bai Lang areas, 170 villages of different sizes were destroyed, 3017 families, 16180 people were affected, 691 died (excluding Indian barracks and hospitals), 4321 hm$^2$ arable land drowned, 888 hm$^2$ arable land destroyed, 10074 houses collapsed, 8679 animals died. On July 14, 1988, in Bom County, Sichuan Province, in the middle section of the Sichuan-Tibet Highway, the upstream Guangxiecuo glacial lake collapsed, floods triggered a large debris flow, causing the river blockage, water level rose by more than 10m, and ran down along the river, it damaged the roadbed 42km long, of which 21km were all destroyed, some people and livestocks were missing, farmland was damaged, the only cement bridge to Jiali County was destroyed and the loss was estimated to be 270 million yuan.

Overall, due to the global warming, high altitude warming trend is more obvious, in such context, the glaciers generally retreat, glacier disaster events increases, especially the glacial lake disaster. As the environment of the glacier is changing, the glacial lake becomes unstable and the risk of collapse increases. On the other hand, due to the expansion of human activities to the mountainous areas, the glacial lake disaster area is expanding and the potential loss increases. In addition, the glacial lake disaster mostly occurred in the remote mountainous areas, generally the economic is underdevelopment, disaster prevention and mitigation capacity is limited, coupled with the presence of residents in the disaster area tending to resist "resettlement" and their psychological dependence on government and technology, making the glacial lake disaster is increasingly becoming a serious threat to human life and property safety.

### 2.2. Research Status of Glacial lake Disaster

Tibetan plateau alpine, where sparsely populated, and most of the glacial lakes are located in the inaccessible place, the research on the glacial lakes has not been started on a wide range, the understanding of the glacial lakes is still in the initial stage. At present, the research results show the following characteristics:

- Since the glacial lakes are in far location and difficult to reach, the wide range of research is based on satellite remote sensing technology, based on the Chinese Academy of Sciences Institute of Qinghai Tibet Plateau statistics for 2015 (http://news.xinhuanet.com/politics/2015-07/15/c_134414158.htm), the number of various types of glacial lakes has been more than 5000. For these glacial lakes, we only know the location and approximate area, however, their classification and naming cannot be finalized.
- The study of glacial lake mostly focuses on their influences on modern climate, the coupling relationship between glacier change and glacial lake evolution, and the identification of potential hazard glacial lake$^{[1]}$, and mostly by qualitative and semi-quantitative means.
- The specific glacial lake research is still in the passive form, i.e. the glacial lake which has caused disaster will become the object of study, there is still a long way to go for carrying out active research.
- The study of the glacial lake disaster itself is far more than the study of the glacial lake, and the study is mostly carried out by field investigating the mudflow - flood after the disaster and researching on the form, size and development characteristics of the disaster, to sum up experience, and learn lessons. For example, in the literature$^{[4]}$, the formation process and characteristics of the debris flow in the glacial lake of the Boqu River are analyzed and discussed, the suggestions for disaster prevention are also put forward, but no concrete method is involved. In the literature$^{[5]}$, the glacial lake disaster data were collected and the information
was accumulated for the later work. The literature \[6\] focused on the formation and process of the debris flow in the Tanghuolang glacial lake and the literature \[8\] summarizes the causes of glacial lake collapse in Jiali County.

3. Analysis on the Mechanism of Glacial lake Disaster

3.1. The Basic Characteristics of Glacial lake Disaster

The post-disaster study of the glacial lake has shown that the direct cause of the vast majority of glacial lake collapse is the large-scale collapse at the end of the glacial lake glacier \[2\]-\[6\]-\[8\], there are some researches show that seepage and piping are the causes of the final disaster \[4\]-\[5\], whatever direct cause it is, the ultimate incentive comes down to climate fluctuations \[3\]. Through the analysis of the climate characteristics before the collapse of the glacial lake, the following common features can be found before its collapse:

- One or a few years before the collapse of the glacial lake, there was abundant rainfall, low temperature, with wet and cold climate characteristics, which objectively increased the scale of glaciers, glacial lake;
- Before the collapse of glacial lake, there was a relatively long period of intensified precipitation process, which increased the glacial lake water quantity;
- Before the collapse of glacial lake, the high temperature of the glacial lake has aggravated the melting and activity of the glacial lake glaciers;
- The high temperature made part of the frozen soil in glacial lake bank area start to melt, intergranular cohesion disappeared or reduced, resulting in soil structure damage and strength reduction, which created the conditions for the collapse;
- The collapsed glacial lake is generally of blocked lake formed by modern moraine, closer to glaciers, and the glaciers are of larger scale and with strong activity.

It can be seen that the temperature and precipitation are the two important factors in violent activities of glaciers, glacial lake.

3.2. The mechanism of glacial lake collapse

Most of the glacial lakes in the Tibetan area are formed in the glacier retreat stage of the Little Ice Age. The potentially dangerous moraine obstruction lake is the product of the last glacier retreat stage in the past 100 years. It has deep lake basin and good closed Terrain, the final moraine ridge (embankment) is generally 60 ~ 120m high, and steep, some of the final moraine ridge (embankment) even buried dead ice. As the moraine particles are coarse, with poor sorting, large leakage, moraine ridge (embankment) is very unstable, and prone to collapse. The sudden flood mechanism of the glacial lake is as follows:

- **The end of the ice tongue collapse**

  In the case of strong ablation, the end of the ice tongue is mostly prone to collapse, in the event of ice collapse, a large number of ice falling into the lake, forming a huge surge, the resulting wave pressure will directly impact the moraine dam, together with the lake water level suddenly soaring caused by a large number of ice collapse, under the dual role of pressure imposed by the hydrostatic pressure and fluctuations, the water overflow the lake flood dam, the bank with weak cementing, poor mechanical properties will be destabilized and damaged.

- **The glacial lake collapse caused by overflowing or piping**

  In the year when the climate is changing from wet cold or dry cold to dry warm or wet warm, the temperature increases, the precipitation increases, the amount of glacier and snow melt increases, the runoff into the lake increases, and the water level rises. When the overflow port cut rate is greater than the glacial lake water level decline rate, the overflow flow rate increases, resulting in a stronger erosion under the cut, and subsequently the final moraine ridge instability. In addition, under the action of high osmotic pressure, the size of the piping under the embankment increases or the dead ice...
collapses, resulting in a considerable amount of molten water along the ice fissure infiltrates, increasing plasticity of ice, speeding ice movement, and finally results in large-scale slip.

4. Analysis of typical glacial lake

4.1. Glacial lake inspection results

After the occurrence of the glacial lake disaster in Jiali, many experts and scholars have systematically studied and analyzed the disaster. Through the comparison of the remote sensing image data and the analysis of the disaster scene, the reason of the disaster is speculated and the location of the glacial lake where the disaster occurred was confirmed. In order to obtain first-hand information and move glacial lake research forward, the author's research team also went to the scene, not only inspected the situation of the disaster glacial lake, also selected the other seven glacial lakes for investigation. Through the intermittent one-year work, some awareness of the status of the disaster glacial lake is summarized as the following:

- As to the understanding of glacial lakes, there is a great information asymmetry among the researchers, regional business managers, grassroots masses. Most of the researchers use the remote sensing data to understand the glacial lake, which has a great relationship not only with the ice environment of the glacial lake, but also with the researchers' research direction, research purposes; business management team does not have a clear work guide for the work, coupled with the limited number of manpower, its understanding of the glacial lake is passive, taken the 2013 glacial lake disaster as an example, before the incident there was no basic disaster glacial lake information, they did not know where it was, in what condition. Grassroots people do not know it is a dangerous source where they often graze, pick grasses. So in the specific level, even if the glacial lake broke down, the glacial lake even has several names. Researchers believe that the name of the glacial lake was Acha, and local business managers called the No. 8 glacial lake.

- The common point of the eight glacial lakes visited is the difficult geographical environment, the glacial lake with the easiest access takes 5 hours walk from the hillside, two of the other glacial lakes take about 30 hours walk to reach, and there is no way for walking, which basically dispel the feasibility of treating these glacial lakes with mechanical equipment operations.

- In the course of post-disaster assessment, most of the data ignores the environmental impact of the glacial lake disaster. Where mudflow passes, there is a large number of turf cut, leaving a variety of diameter sand gravel, which is the beginning of desertification of the plateau, since then these places cannot once again become the pasture.

- Not all the glacial lake with the possibility of failure are worthy of attention, living conditions at downstream of some glacial lakes are poor, there is no village and grazing grassland, so even if the debris flow - flood happens, it will not produce too much loss, so the study of glacial lake must be a combination of small watershed research of a holistic, systematic project.

4.2. Current situation of typical glacial lake

Bienongcuo glacial lake, located in the town of Jia Li County, will be taken as an example for introduction. Bienongcuo (glacial lake) is located in the Bielong ditch watershed source, Bielong ditch is the right tributary of Yigongzangbu River. The average elevation is more than 4400 m, the highest point is the Chula Hill, whose elevation is about 6600m. In addition, the Ayila Hill, Lugan La, Mount Gera, Gangba La, Bengxila Hill, etc, are yearly snow-capped mountains, the altitude is above 5500m, the role of ice margin is generally found in the mountains 4600 ~ 4800m above sea level. In some valleys or low-lying sections, there is the distribution of glacier deposits, typical micro-landforms are glacier lake, horn peaks, blade ridges, ice bucket and other ice erosions.

4.2.1. The basics situation of Bienongcuo. Three sides of the glacial lake are facing hills, the other side is the glacial lake earth dam (moraine dam) see figure 1. The glacial lake is up to about 2061m long, the maximum wide is about 720m, with an area of 1.1745 million m², see figure 2. Heavyhammer method is used to measure the depth of glacial lake water, the current ice surface elevation is measured
by RTK, the measured ice elevation is 4745.08m. According to the status quo of the glacial lake, this measurement arranged a total of 10 sounding holes, the depth of the pit can be seen in table 1. According to the water depth measurement data, the Civil3D software is used to draw the bottom contour line, and calculate the status quo of the glacial lake, the calculated volume of the glacial lake is about 92.7708 million m$^3$, the scale can be categorized as large (2) reservoir scale. The glacial lake storage curve is shown in figure 3.

![Figure 1. Overall view of Bienongcuo glacial lake](image1)

![Figure 2. Satellite imagery of Bienongcuo](image2)

4.2.2. Basic conditions of glaciers and catchment. According to the site survey, glacial lake glacier is located in the southeast of the glacial lake (see figure 4), south east 28 º. Glacier slope is about 25%, within the catchment area of glaciers, the maximum length is up to about 2400m, the maximum width is about 5600m, the area of the glaciers above the glacial lake is about 8.43km$^2$ (see figure 5), part of the glacier bedrock has been exposed on site, the nearest distance from the glacier ice tongue to glacial lake surface is about 15m. Bienongcuo (glacial lake) belongs to the moraine lake, the catchment area above the lake dam (embankment) is about 20.91km$^2$, of which glacier area is about 8.43km$^2$. According to the meteorological data of Jiali County, the average annual precipitation of the project area is 750mm, and the total annual rainfall in the lake is calculated as follows: $V = F \times H = 20.91 \times 106 \times 750 \times 10^{-3} = 15682500$ (m$^3$) =15.6825 (million m$^3$)

| Table 1. | data list of measured water depth |
|----------|----------------------------------|
|          |                                  |

length:2061m  
wide: 720m
### Table 1: Coordinates, Elevation, Depth, Ice Layer Inclination, and Ice Thickness

| No. | X      | Y      | Z      | Depth (ice layer incl.) | Ice thk (m) |
|-----|--------|--------|--------|-------------------------|-------------|
| 1   | 542215.01 | 3378904.26 | 4731.60 | 13.48                   | 0.65        |
| 2   | 542193.80 | 3378859.20 | 4719.10 | 25.98                   | 0.70        |
| 3   | 542249.40 | 3378752.47 | 4710.10 | 34.98                   | 0.70        |
| 4   | 542296.52 | 3378577.32 | 4679.10 | 65.98                   | 0.70        |
| 5   | 542438.00 | 3378249.90 | 4639.10 | 105.98                  | 0.70        |
| 6   | 542552.93 | 3378055.91 | 4602.08 | 143.00                  | 0.65        |
| 7   | 542630.25 | 3377839.98 | 4589.08 | 156.00                  | 0.60        |
| 8   | 542629.02 | 3377608.30 | 4646.08 | 99.00                   | 0.60        |
| 9   | 542765.73 | 3377553.44 | 4585.08 | 160.00                  | 0.60        |
| 10  | 542796.55 | 3377374.37 | 4640.08 | 105.00                  | 0.50        |

**Figure 3.** Storage curve of Bienongcuo

**Figure 4.** Current photo of glacier

**Figure 5.** Satellite image of glacier

### 4.2.3. Basic situation of moraine dam

The north bank of Bienongcuo is loose terminal moraine, with top width range at 10~30m, height at about 30m, upstream slope at about 40°, back water slope range at 25°~35° and embankment top 5~35m above the lake. The highest altitude of embankment top is 4780.88m, the lowest altitude at downstream is 4661.45m and the highest height of glacial lake embankment is 119.43m. Parent rock composition of moraine deposits focuses on conglomerate and granite, with different sizes of particles, from clay to big stones of meters. Roundness is poor. Deposit
is loose and mixed with poor stability. As the temperature for moraine deposit is low and chemical weathering effect is weak. After deposition, the experienced interglacial period is short. Without strong leaching and abrasion effect, organism does not grow. Therefore, moraine lacks organic matter (peat and humus etc); moreover, as the mineralization degree of melt ice water is extremely week, small matter can’t condense. The structure of moraine is loose, the water permeability is strong and the integrity and stability are very poor. There are only few herbs grown on the dam surface. On the top of moraine embankment, there is a naturally formed overflow tank with overflow width at 8~12m. Due to years of erosion, stones with diameter of 1~5m are scattered in the tank. Earth rockfill dam and current situation of overflow tank are shown in figure 6 and figure 7. The shooting time for figure 6 is beginning of May and there is no obvious water overflow at overflow tank. The shooting time for figure 7 is end of June and there is already water overflowed. As explained by local herdsmen, it will maintain this overflow state from middle June to end of August.

4.2.4. Basic conditions of the lower reaches of the river. 0.0~2.0km of downstream of Bienongcuo (glacial lake) is intermountain alluvial plain with small relief. The vegetation is grassland and the mountain on both sides is very stable. The erosion at 2.0~4.5km of downstream is very serious. Stones are exposed and river relief is big (as shown in figure 8). There is less vegetation and some shrubs. Mountain at two sides is relatively stable. At 3km of downstream, there are 3 families with about 160 yaks. At the section from 4.5km of downstream to Yigongzangbu, the river relief is small. There are roads along the river. There are four natural villages at two sides, with about 50 families and 1300 yaks.

Figure 6. Earth-rock dam status chart

Figure 7. Overflow tank status chart

Figure 8. 2.0~4.5km of downstream river status chart
5. Analysis of Engineering Treatment Measures

The main purpose of engineering circle studying glacial lake at the moment is preventing disaster and constructing initiative control system of disaster prevention and reduction. Through researches on numerous glacial lakes and based on disaster prevention experience of water conservancy project, following measures can be considered in the treatment of glacial lake.

5.1. Non-engineering measures

5.1.1. Monitoring and early warning system. As an important non-engineering measure, the glacial lake disaster early warning system is composed of the glacial lake disaster prevention and early warning system based on the information receiving and transmission platform and the anti-warning system of the glacial lake disaster. Glacial lake disaster prevention and monitoring system includes hydro-meteorological monitoring and geological environment monitoring. Flood-control headquarters at all levels and each professional monitoring system connect with each other through network and realize information sharing.

5.1.2. Resettlement. According to the actual situation of glacial lake disaster risk assessment, the division of dangerous areas and the development of disaster prevention and mitigation plans can be made. Disaster prevention measure of resettlement can be taken for lakes with small influence on downstream of dangerous glacial lake and lakes with construction difficulty for drainage engineering or glacial lake with big investment.

Characteristics of non-engineering measure are strong feasibility and small preliminary investment, but glacial lake monitoring requires a lot of professional staffs and the executive controllability of resettlement is poor.

5.2. Engineering measures

5.2.1. Excavate moraine dam to discharge water. The causal mechanism of sudden flood of glacial lake is very complicated; in addition, the sudden flood mechanisms of glacial lake with different genetic types are different. According to the investigation on glacial lakes in Tibet, excavation method has been adopted to discharge water and decrease water level, which can make water inflow and discharge reach balanced state in the shortest time, so that the risk of glacial lake burst can be decreased. For the glacial lake with big capacity, high water level, close to glacier and with certain risk of snow (glacier tongue) collapse as well as the glacial lake with weak dam body, it can construct drainage channel on blocked dam of glacial lake, so that the water level in the lake can be reduced to relatively safe water level and risk of glacial lake can be reduced. However, as the formation year of glacial lake is relatively long, it has formed relatively stable dependence relation with upstream glacier, surrounding mountains and downstream rivers etc. It is with specific environmental factor. The great decrease of water level will have adverse effect on the stability of upstream glacier, surrounding mountains and the bank as well as runoff regulation in lower reaches; it even induces glacier and mountain (bank) collapse and other secondary disasters, and then affects surrounding climate as well as changes of ecological environment. Therefore, sufficient argument has to be made for this measure.

5.2.2. Reinforcement of glacial lake dam foundation and surrounding bank. Dangerous dams should be reinforced to prevent leakage, piping and collapse. For glacial lakes with strong dependence on surrounding mountains, upstream glaciers and downstream rivers and so on and glacial lakes with construction conditions, the dam foundation of glacial lake and surrounding reservoir banks can be strengthened and the stability of dam foundation and surrounding reservoir banks can be increased through grouting, masonry retaining wall, slope cutting treatment and other engineering measures, which not only decrease the possibility of collapse, but also protect glacial lake and its environment.
5.2.3. **The construction of storage, detention project.** At the downstream channel of glacial lake without strengthening conditions, flood control dam and flood detention area can be constructed. On the one hand can block the dam to bring the mud and the flood, on the other hand can delay the dam floods, reduce flood losses.

5.3. **Analysis on the feasibility of glacial lake development**

Most of above engineering measures take disaster prevention and reduction as the main purpose. In recent years, some experts have proposed to govern and develop glacial lake depending on big reservoir capacity and clean water quality, so that it can play greater social efficacy. Combining characteristics of 8 glacial lakes of frontline survey, following analysis has been made:

5.3.1. **Used for water diversion.**

- Focus on glacier melting and the water quality is good.
- Single water storage capacity of glacial lake is considerable, for example, the water storage capacity of Bienongcuo is about 100 million m³.
- Catchment area is small and water amount can be developed is limited.
- Distance between glacial lakes is big and joint water supply is difficult.
- Engineering construction is with great difficulty.

Compared with other water resource in Tibet, the cost performance of taking glacial lake as source of water diversion is low and it is not suggested.

5.3.2. **Used for water power generation.**

- Natural water level drop is big
- Catchment area is small and water supply is with strong seasonal feature. From September to April of coming year, the glacial lake is basically in frozen state and the water amount for development is limited.
- Whether it is to strengthen the moraine dam or to carry out the diversion tunnel construction, it is very difficult and may affect the glacier and the surrounding ecology.
- The promotion speed for power grid construction in Tibet is fast. The power supply for very few areas without grid has been guaranteed basically through wind, solar complemented power station and other project constructions. The dependence of residents near glacial lake on small and medium sized hydropower station is decreasing gradually.

Combining with the great investment of engineer construction and power transmission cost, the cost performance of taking glacial lake as small hydropower development is extremely low and it is not suggested.

In summary, the water capacity and water energy of glacial lake are difficult to develop and utilize, but there is no doubt that the extremely beautiful natural scenery of glacial lake is precious natural resource. During the field investigation made by scientific research team, we met adventure lovers for glacial lake. Therefore, for glacial lake with convenient transportation and good natural conditions, it is a possible choice to develop tourism to some extent under the principle of ensuring safety and maintaining natural environment. Characteristic water conservancy scenic spot can be established with combination of unique local national culture, diet habit and local customs and practices etc, which provides another choice for local economic development and targeted poverty alleviation.

6. **Conclusions and suggestions**

- Due to the huge quantity and harsh natural environment, most of researches on glacial lake take remote sensing technology as the main method. Through site survey and visit, it is believed that single research method is not comprehensive and should not be taken as the main technical means.
- Researches on glacial lake at current stage have taken shape and formed a series of results. It should summarize these scattered research results, combine them with practical project and apply them to initiative reality of disaster prevention and reduction.
• Most of previous researches focus on the relationship between glacial lake and glacier, relationship between glacial lake and climate; but in fact, the ecological condition at upstream and downstream plays a very important role in glacial lake system and it is also an important field of glacial lake research.

• Glacial lake is a precious freshwater resource and is also the special feature unit at plateau area, which plays an important role in plateau ecology and even the ecological environment of the whole country. It is also of great importance in the construction of plateau water tower construction. The governance work of glacial lake should be governed in protection firstly.

• The relationship between glacial lake and local microecology is not specific, but it is clear that there is important relationship between them and it is an important direction in following research work, which is crucial for protecting and restoring plateau ecology.

• Current cognition of scientific circle and engineering circle for glacial lake is very limited and it is worthwhile to try to construct reservoir for glacial lake and make archival management. With this, it is possible to make risk classification and safety risk assessment for glacial lake and it also provides reliable data support for the following protection and governance.

• Extensive interview is a necessary work to make data management for glacial lake. The prevention of glacial lake disaster include engineering measures and non-engineering measures, in which non-engineering measures are easy to take and with small difficulty; engineering measures need to measure the feasibility based on specific conditions of glacial lake. The selection of measures should be based on risk assessment results and feasibility of project construction.

• The development and utilization of glacial lake should consider about economic efficiency and feasibility of project construction comprehensively, should be measured from perspectives of water capacity, water energy, geological location, environment and local demand etc, should not be taken as small hydropower and water diversion source for development. Glacial lakes with conditions can be developed properly as water conservancy scenic spot on the basis of full assessing the balance between safety risk and ecological environment.

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