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Stability of Moraine Dam of Tsho Rolpa Glacial Lake

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Abstract
This abstract summarizes a study focused on assessing the vulnerability of Tsho rolpa Glacial Lake's moraine dam located in the lap of Himalayas. Tsorolpa Glacier Lake lies among the rough himalayan mountains that hides an impending threat i.e. moraine dam instability. This research looks into the multidimensional dynamics of moraine dam instability in the setting of Tsorolpa Glacier Lake, with a particular emphasis on the contributory elements of seepage and slope failure. This study project aims to understand the complexities of dam instability using a combination of particular field surveys such as Topographical surveys, Bathymetric survey and GPR survey also by use of numerical modeling. It explores the geological, hydrological, and geotechnical factors that affect the moraine dam's structural integrity. The study evaluates the propensity of seepage through the moraine and sheds light on its potential effects for dam stability by closely examining the hydrogeological conditions and using sophisticated seepage modeling. In order to assess the slope stability of the dam, the geotechnical characteristics of the materials made of moraine are rigorously evaluated. To clarify the vulnerabilities associated with the moraine dam, particularly in the context of slope failure, advanced slope stability calculations are used. The analysis also takes into account complex interactions between glacier dynamics, climate change, and seismic activity that enhance the instability of the dam. Importantly, this study adds to our understanding of the combined impact of seepage and slope failure on the moraine dam of Tsorolpa Glacier Lake. It defines major failure scenarios and analyzes the associated hazards, promoting a thorough understanding of the potential for glacial lake outburst floods (GLOFs). Such findings are critical for developing effective monitoring and mitigation strategies that protect downstream communities, ecosystems, and infrastructure. As a result, this work makes a significant contribution to the field of assessing the hazards associated with glacial lakes by providing insightful information about the complex interactions between seepage and slope failure in the context of Tsorolpa Glacier Lake

Keywords
Moraine dam Instability, Slope Failure, Seepage, moraine dam

1. Introduction

Glacial lakes are essential elements of high-altitude regions, and they hold a crucial role in shaping the physical landscape and supporting local ecosystems. One such glacier lake of significant importance is the Tsho Rolpa Glacial Lake. Tsho Rolpa Glacial Lake stands as a prime example of the intricate interplay between glacial processes, climate dynamics, and environmental concerns. Tsho Rolpa Glacial Lake is situated in the heart of the Himalayan mountain range, a region renowned for its towering peaks, extensive glaciers, and diverse ecosystems. The lake finds its abode within the rugged topography of a valley carved by the relentless movement of glaciers over millennia. The lake's location is characterized by its high altitude, making it vulnerable to the influences of quickly changing climate patterns and glacial retreat. As glaciers advance and retreat, they often leave behind depressions that eventually fill with melt water from the ice and surrounding snowfields. The lake's water originates from the melting ice and snow from the surrounding glaciers, and its size and volume can fluctuate seasonally in response to temperature variations.

A moraine dam, also referred to as a glacial moraine dam or terminal moraine dam, is created naturally when a glacier deposits sediment, including gravel, sand, and rocks, at its endpoint . Moraine dams are relatively prevalent in regions with active glaciers, and they can remain in place for extended periods, even after the glacier has retreated further. They have a substantial impact on shaping the landscape, affecting local hydrology and, in some cases, presenting flood risks if they break or rupture. As a glacier advances and flows downhill, it gathers and carries a substantial amount of debris from the surrounding area. When the glacier either reaches its maximum reach or begins to recede, the ice laden with debris starts to melt or stall at the glacier's terminus. As the ice melts, it deposits the sediment it carried, shaping a mound or ridge-like structure. Over time, this sediment accumulation acts as a natural barrier across the valley where the glacier ends. These dams can differ in size and appearance, and they may hold back water from the glacier's melting, resulting in the creation of a lake or pond, often referred to as a moraine-dammed lake or tarn.

Moraine dams that hold back lakes pose a significant disaster risk due to several factors. These dams are relatively young and are situated at high altitudes where regular vegetation growth is hindered by cold temperatures, preventing the stabilization of their slopes [1]. Additional reasons for their risk include the steepness of the dam faces, with downstream faces being relatively stable at around a 35-degree slope while upstream faces can be much steeper, depending on the time elapsed since deglaciation. Additionally, the existence of an ice core within the dam can lead to thermal degradation or melting [2]. Additionally, when comparing moraine dams to landslide dams, it's important to note that moraine dams typically have a narrower height to width ratio, which increases their susceptibility to failure. This is due to the fact that the geometry of the dam's cross-section is very important in determining how frequently dams may breach. Various dynamic forces, including the movement of ice, snow, rocks, or landslide avalanches [3, 4], glacier retreating, wave surges, the melting of glacier ice buried underneath the sediments [5], atmospheric events like heavy rainfall and melting of snow, as well as earthquakes [6], are the typical factors that initiate moraine dam failure mechanisms [1]. Moraine dam failure can result from a variety of factors, including overtopping, incision, piping, seepage, the gradual degradation of the moraine structure, and the occurrence of flood waves originating from the upper lake within the catchment area. Overtopping failure and pipeline failure are the most often seen failure mechanisms among these systems. Among these processes, the failure mechanisms most commonly observed are overtopping and piping failures. [2].

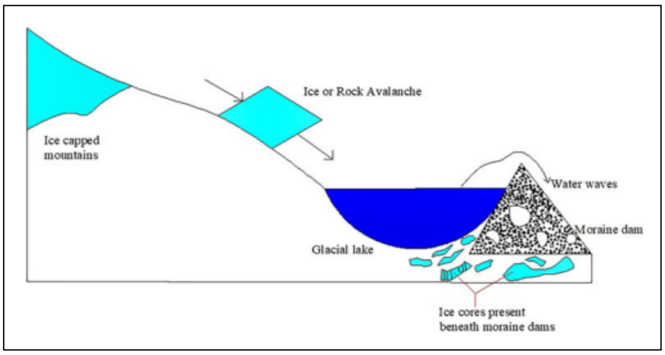

Figure 1: : Wave overtopping mechanism (Source : Robin Neupane, Huayong Chen & Chunran Cao 2019)

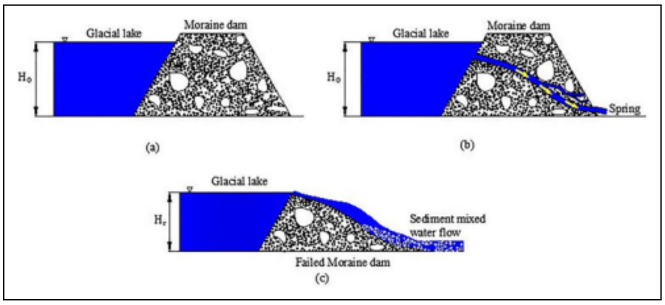

Figure 2: Piping outburst mechanism (a) Pre- failure, (b) The piping process and (c) Post- failure (H0 represents initial water level, and Hr indicated reduced water level after failure)(Source: Robin Neupane, Huayong Chen & Chunran Cao 2019)

Tsho Rolpa Glacier Lake is more than just a beautiful body of water also extremely has great importance for the surrounding ecosystem and downstream settlements. Global climate change has resulted in faster glacial retreat and higher melt water intake into the lake. This continuous rise in water level concerns about the stability of the lake's moraine dams, which can be at great risk of breaching which ultimately trigger glacial lake outburst floods (GLOFs).Many research had been conducted on the Tsho Rolpa glacial lakes as it possess potential threat to downstream areas. To reduce this threat lake is lowered by 3m so that rate at which retreating glacier that feeds the lake possess less impact on the moraine dam. This study mainly focuses on stability of end moraine of Tsho Rolpa glacial lake. Further, this study also focus on seepage analysis through the end moraine Tsho Rolpa glacial lake.

2. Area of Study

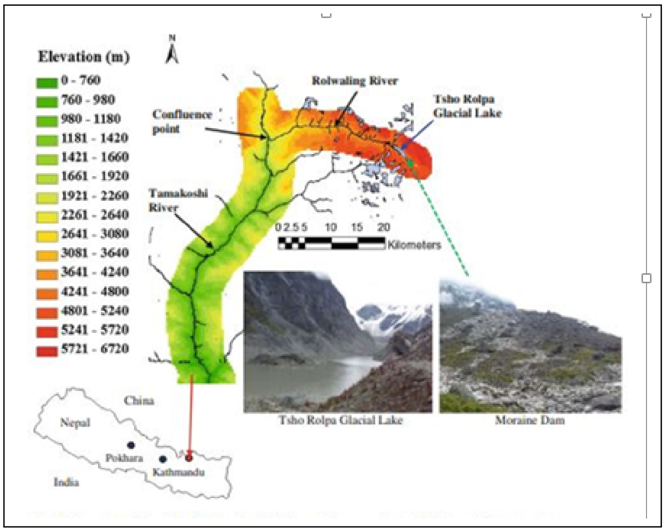

Figure 3: Area of Study (Source: Survey Department of Nepal in 2002)

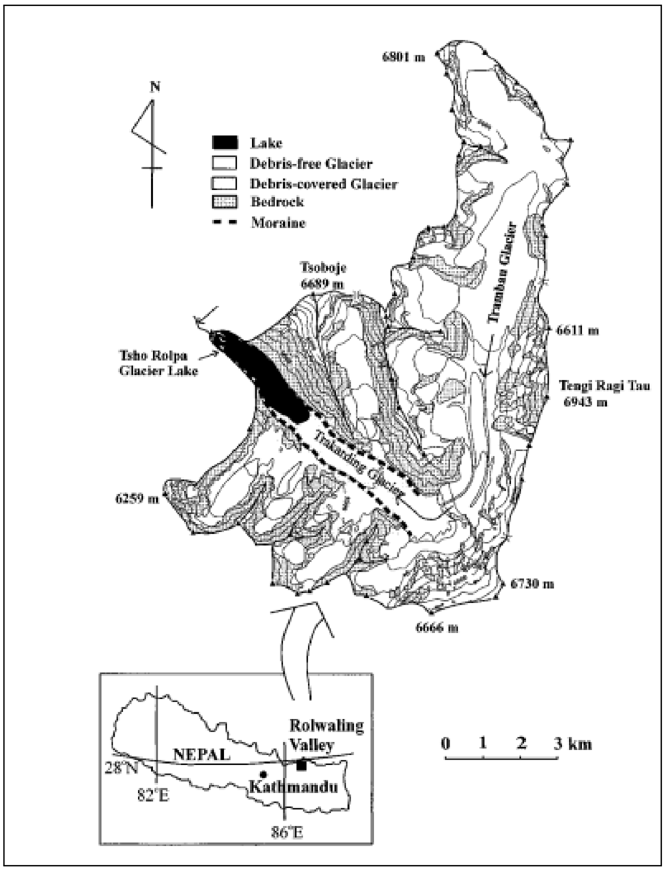

Figure 4: Drainage basin of Tsho-rolpa Glacial Lake, Rolwaling Valley and its Location in Nepal (Source: modified Schneider's topographic map; Schneider 1981)

The Tsho Rolpa glacial lake (27 510 N, 86 290 E) is the largest potentially dangerous glacial lakes in Nepal. The lake is located at altitude of 4,555 m in the Rolwaling Valley and lies in the Gauri Shankar Village Development Committee (VDC), Dolakha District, Nepal. Over the past 55 years, the lake has come into existence due to the accelerated melting of the glacier that feeds it, as documented by Bajracharya in 2008 [7]. The Trakarding Glacier, located on the upstream of the lake, has been melting at a rapid pace of 20 meters annually, attributed to the escalating temperatures. At present, the lake spans approximately 3.45 kilometers in length and 0.5 kilometers in width. Encompassing a surface area of 1.537 square kilometers, the lake holds a substantial water volume of 85.94 million cubic meters. The entire drainage area, inclusive of the lake surface, covers an expanse of 77.6 square kilometers. Within this expanse, glaciers account for approximately 71.8% of the coverage. Among these glaciers, 55.3% belong to the debris-free Upper Trambau Glacier, while the remaining 16.5% are characterized by the presence of debris, making them the Trakarding Glacier [8]. Remarkably, Tsho Rolpa lake has displayed exponential growth over time. Its surface area expanded from 0.23 square kilometers in 1957-59 to 1.27 square kilometers in 1988-90, and further increased to 1.54 square kilometers by 2009. This growth occurred despite efforts to lower its water level by 3 meters through the establisment of an open channel outlet in 2000. [9, 10, 11, 12].

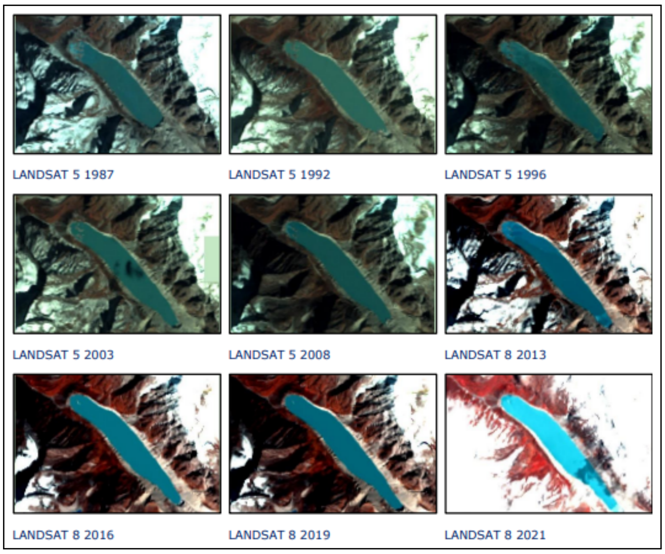

Figure 5: : Landsat images of Tsho Rolpa Lake since 1987 to 2021 (Source: Department of hydrology and meteorology)

3. Methodology

The research work is carried out initially through desk study. The desk study involves study of various journals related to moraine dam in Himalayas. After the outline of research is concluded then required data that needed for research works are collected from Department of Hydrology and Meteorology (DHM).The survey was carried out on 2022 that includes Topogrpahic, Bathymetric & GPR(Ground Penetrating Radar) survey.Further works is carried by using commercial software Plaxis 2D Version V20. The analysis is carried using the soil parameters from different papers and geometry of dam is taken from recently survey topographical map that is provided by DHM. The general outline of the research methodology is as follows:

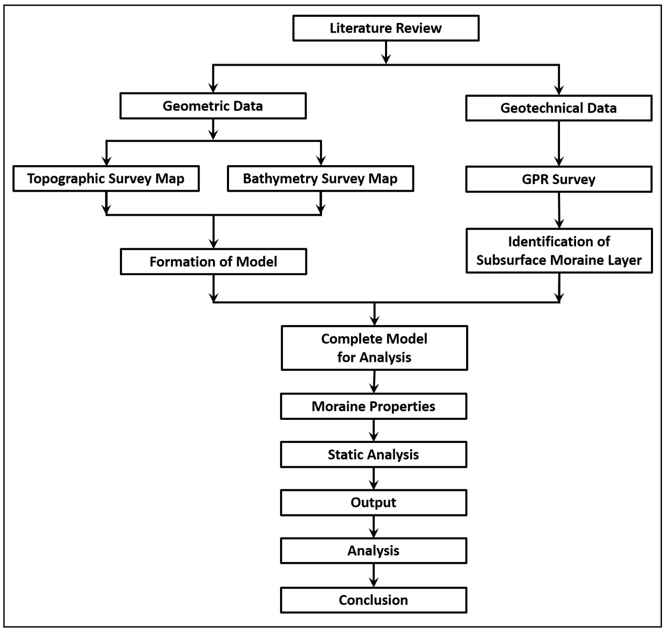

Figure 6: Flowchart of Methodology

3.1 Soil Properties and Materials

Material needed for numerical analysis are collected from Department of Hydrology and Meteorology (DHM). The required material are topography, bathymetric and GPR surveyed data of glacial lake. The soil parameters are taken from different articles that resembles with the moraine parameters of Tsho Rolpa glacial lake.

3.1.1 Subsurface Complex of Terminal Moraine

The geophysical test i.e GPR is conducted on the site to study the subsurface information of moraine dam. The subsurface formation of the moraine complex of Tsho Rolpa glacial lake are Block Ice & Frozen moraine .The Geotechnical parameters of these layers are as follows:

Table 1: Shear strength property of dead ice [13]

S.N	Parameter	Value
1	Cohesion (c)	99.4 kPa
2	Friction Angle (ϕ)	30.2°
3	Young's modulus of elasticity (E)	44.23 MPa
4	Specific Weight(γ)	23 kPa

Table 2: Shear strength property of Frozen Moraine [13]

S.N	Parameter	Value
1	Cohesion (c)	65.6 kPa
2	Friction Angle (ϕ)	30.5°
3	Young's modulus of elasticity (E)	13.4 MPa
4	Specific Weight(γ)	21 kPa

4. Results and Discussions

The dam was found to be primarily composed of Frozen moraine and block ice, with varying degrees of cohesion and internal friction. The study conducted seepage analysis to evaluate the potential for water seeping through the moraine dam. Results showed that there is a possibility of seepage through the dam due to its porous nature. Seepage can weaken the dam structure over time and pose a risk to its stability.

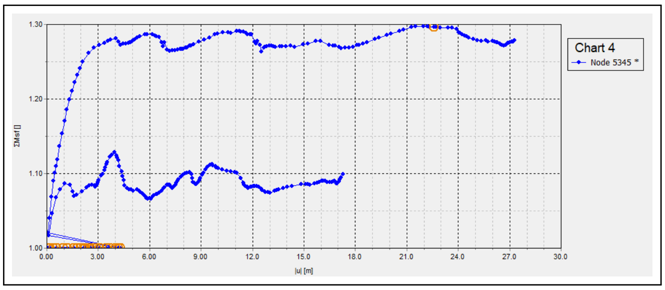

Figure 7: Deformation Vs FOS under static condition

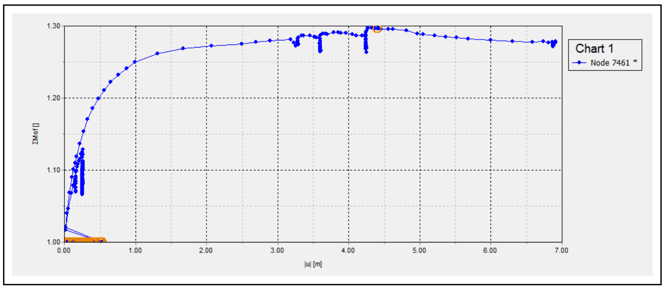

Figure 8: Deformation Vs FOS under static condition

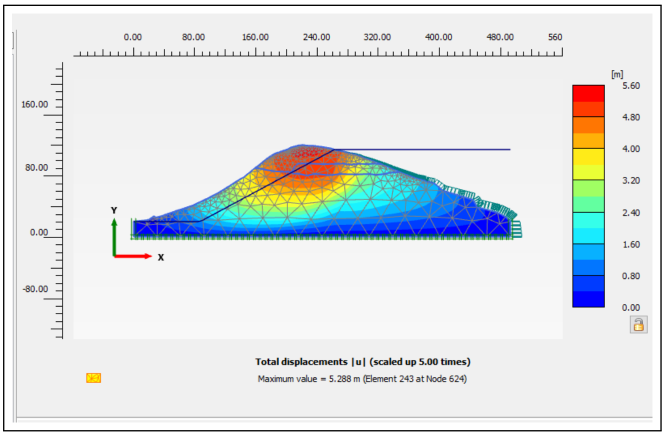

Figure 9: Displacement of moraine dam body at plastic deformation stage

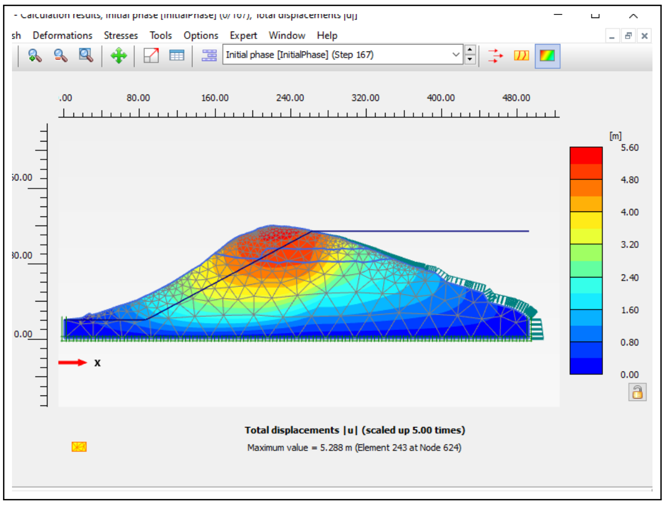

Figure 10: Displacement of moraine dam body at initial stress condition

Slope stability analysis was a critical component of the study, assessing the likelihood of slope failure in the moraine dam. The results suggest that the dam's slopes are generally less stable under current conditions. However, the presence of glacial melt water can increase pore water pressures within the dam, potentially reducing its stability during periods of increased inflow.The results from the study on the stability of the moraine dam of Tshorolpa glacial lake shows important information into the structural integrity and potential risks associated with the moraine dam. The geotechnical analysis indicates factors such as slope stability, soil composition, and structural integrity should be thoroughly examined & indentify the specific areas that may require improvements in to increase the overall stability of moraine dam. The monitoring and early warning systems has been on the service as a crucial component to mitigate potential risks. Effective early warning systems combined with real-time monitoring of dam conditions can improve readiness and response times.

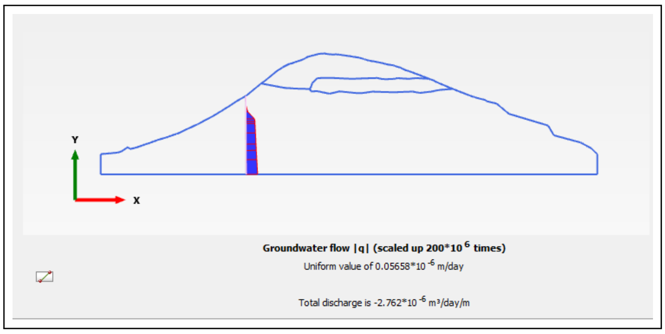

Figure 11: Seepage discharge at Front of moraine dam

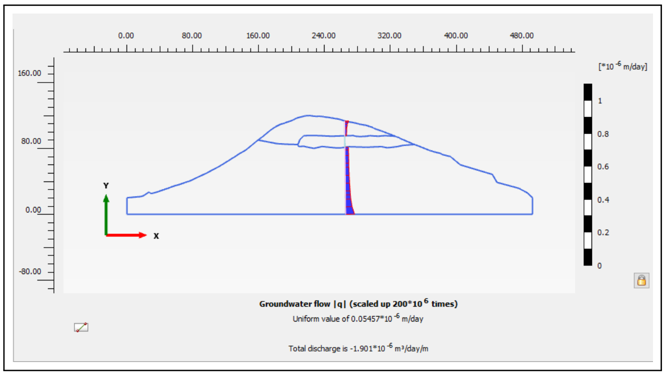

Figure 12: Seepage discharge at mid section of moraine dam

5. Conclusions and Recommendations

The stability analysis of the moraine dam at Tsho Rolpa Glacial Lake provides essential understandings into the current condition and potential risks associated with this critical structure.The stability of the moraine dam at Tshorolpa glacial lake demands immediate attention and proactive measures.

The moraine dam at Tsho Rolpa Glacial Lake demonstrates a reasonable level of stability under existing conditions i.e. FOS for extising condition lies between 1.3 to 1.4. Geotechnical assessments and slope stability analyses indicate that the dam is currently able to slightly withstand the forces imposed by the glacial lake. The presence of seepage through the dam's porous materials is a notable concern as seepage through dam is at front & mid-section is 2.762 * 10-6 m3/day/m & 1.901 * 10-6 m3/day/m . While the dam's current seepage rates may not pose an immediate threat, they require continuous monitoring and potential mitigation measures to prevent long-term erosion and weakening of the dam structure. Eventually in order to the guarantee the dam stability over long run it is suggested that observed stability difficulties should be addressed via the application of geotechnical treatments & dam conditions should be tracked using ongoing monitoring methods, including as regular inspections and real-time data collecting.

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