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Assessing Moraine Dam Stability of Imja Glacial Lake

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Abstract
This study presents a comprehensive study centered on the stability analysis of Imja Glacial Lake. The primary objective is to conduct a comprehensive stability and seepage analysis of terminal moraine of the Imja Glacial Lake. Assessing the factor of safety for moraine dam is crucial to ensure the overall safety of the dam under various scenarios. This study focuses on employing 2-D Finite Element Modeling using the Plaxis 2D to simulate the combined effects of seepage and stability of terminal moraine dam. The analysis involves determining the phreatic seepage surface, seepage discharge through the dam and stability of dam. Steady state seepage analysis is done to model the seepage flow through the dam. The steady state seepage analysis and stability analysis of terminal moraine is studied under different water level condition. The lake water level is varied from present water level to 2m, 5m and 10m down to study the effect of lake water level lowering in the terminal moraine. As per the result of simulation the average rate of seepage through the terminal moraine is $4.978 \times 10^{-6} m^3/s/m$ at existing water level condition. As the lake water level is lowered the seepage discharge is also decreased respectively. Similarly, the safety factor of moraine dam is analyzed using Finite element. In all water level condition the safety factor of moraine dam comes greater than 3. Hence for existing condition under static load the moraine dam seems to be stable. The obtained results provide valuable insights into the behavior of dam.

Keywords
Slope stability, Seepage, Moraine dam

1. Introduction

Glacial lakes are conspicuous elements within high-altitude mountain landscapes, forming as a result of glacier retreat driven by global climate change. These lakes function as indicators of the ongoing environmental shifts transpiring in delicate alpine ecosystems. Due to the global warming from the last century the Himalayan glaciers have found to be melted so rapidly. This melting of the glaciers forms the lake, whose water will be either held back of the terminal moraine (Proglacial Lake) or the water will be held within the glacier (Supraglacial Lake). As the temperature of the earth surface is increasing the rate of melting of the glaciers are also increasing from few meters to the several tens of meter per year [1]. Hence the size of the pre-formed glacial lake is also increasing, causing the increase in hydrostatic pressure at the terminal moraine of the lake. This can ultimately lead to the failure of the moraine.

The area of study centers around the Imja glacial lake which lies in the Solukhumbu district of Nepal within the Everest region (Co-ordinates: 27.95°N, 86.85°E). Imja Lake has lateral moraines on its northern and southern sides, ice encased within the moraine constituting its western boundary, and the Imja glacier surrounding it on its eastern side. According to Hambrey et al. (2008) [2], these lateral moraine troughs serve as conduits that gather silt and debris from rockfalls, snow avalanches, and river transport. A series of outlet lakes allows water to leave the lake [3, 4]. Bajracharya, et al. (2007) [1] and Watanabe et al. (1994) [3] documented swift melting of ice concealed by debris and substantial alterations in the outlet location of Imja Lake. Measurement done in Imja Lake in 2002 showed that the size of lake had grown to 41.6m with maximum depth of 90.5 m [5]. Similarly, by 2007 the size of lake was about 2000 m long, 650 m wide with an area of about 1.01 km^2 [6].

The stability analysis of moraine dam of glacial lake is complex process as the stability and seepage flow through the dam is highly dependent on the properties, location and the size of the dead ice. Previous research on Imja Glacier Lake has primarily focused on hydrodynamic, glaciological, and subsurface aspects, with a particular emphasis on downstream inundation models and breach hydrographs. However, there has been a notable gap in evaluating both seepage and slope instability concurrently. This study aims to address this critical research need with the help of previous researches done on Imja glacial lake.

Watanabe et al. (1994) [3] examined the growth of Imja glacial lake through the analysis of various maps and photographs from diverse sources. Similarly, Shrestha et al. (2010) [7] investigated moraine dam failure mechanisms, considering both overtopping and seepage, employing both numerical and experimental analyses. The experimental aspect involved flume experiments. Takenaka et al. (2010) [8] employed electrical resistive tomography (ERT) testing to delve into the internal structure of the moraine dam of Imja glacial lake. They used ERT data to estimate the spatial distribution of dead ice within the dam, demonstrating its effective role in damming the lake water. Somos-Valenzuela et al. (2014) [9] conducted a comprehensive study on the hazards and risks associated with Imja glacial lake. They performed a bathymetric survey to determine the lake's depth, and a ground-penetrating radar survey at the terminal moraine to ascertain the presence of dead ice and the distribution of moraine materials.

Dahal et al. (2018)[10] focused on investigating the distribution of dead ice within the terminal moraine using ERT testing. Their study also involved examining and evaluating the properties of the surface moraine material, which included estimating the quantity of concealed ice, identifying seepage channels, and mapping the distribution of permafrost material.

The primary objective of this research is to evaluate the stability condition of terminal moraine of Imja glacial lake by conducting coupled seepage and stability analysis using Plaxis 2D. Along with the stability the study also focuses to analyze the seepage characteristics of moraine to understand potential seepage pathways and zone of excessive seepage. The variation of safety factor of terminal moraine with the variation in lake water level is also tried to studied by integrating seepage and slope stability analysis.

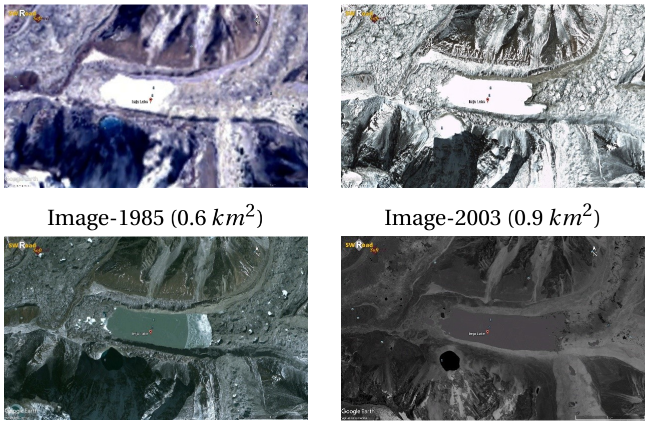

Image-1985 (0.6 km^2) Image-2003 (0.9 km^2)

Image-2009 (1.01 km^2) Image-2015 (1.31 km^2)

Figure 2: Areal expansion of Imja Glacial Lake from 1985-2015, before gate construction (Source: Google Earth)

2. Study Area

Situated within the Nepalese Himalayan region, approximately 9 kilometers to the south of Mount Everest, lies Imja Lake, which is also referred as Imja Tsho. Over the past five decades, the lake has undergone substantial expansion both in terms of its surface area and volume [6].

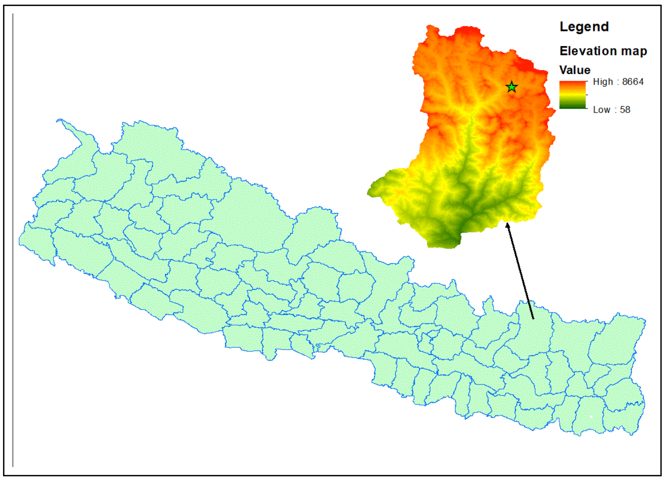

Figure 1: Location of Imja Glacial lake

This rapid growth of lake has increase the potential occurrence of a devastating glacial lake outburst flood (GLOF). The ramifications of such an event extend to neighboring villages downstream, including Dingboche, positioned around 8 kilometers away from the lake's terminal moraine.The flow generated from Imja lake forms the Imja river, which is one of the tributary of Dudhkoshi river. Imja Lake has predominantly expanded during the past 50 years as a result of the glacier's eastern terminus breaking off [2]. According to Watanabe et al. in 2009 [6], the growth toward the eastern side has showed no symptoms of slowing down whereas the expansion toward the western, downstream direction has recently become rather stable. The area of lake has developed rapidly from 1950s to 2007 [4]. The growth of Imja glacial lake can also be justified from google earth.

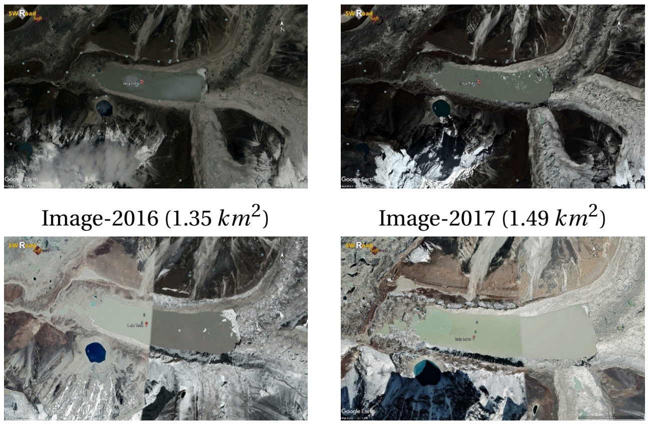

Image-2016 (1.35 km^2) Image-2017 (1.49 km^2)

Image-2019 (1.51 km^2) Image-2021 (1.58 km^2)

Figure 3: Areal expansion of Imja Glacial Lake from 2016-2021, after gate construction (Source: Google Earth)

3. Materials and Methodology

3.1 Topographic map

The cross section of the moraine dam is determined from the topographic map. The topographic map is drawn by digitizing the topographic map found in literature. The complete topographic map of the study area is drawn by combining the topographic map around the terminal moraine and bathymetry map of the lake.

The topographic map of end moraine is drawn by digitizing the topographic survey map from report "Detailed Geophysical-ERT Investigation for Structural Design of Imja Lake Lowering" prepared by United Nations Development Programme (UNDP).

Similarly, the glacial lake water level and bed level of lake is determined from bathymetry map done by ADAPT-Nepal in 2014.

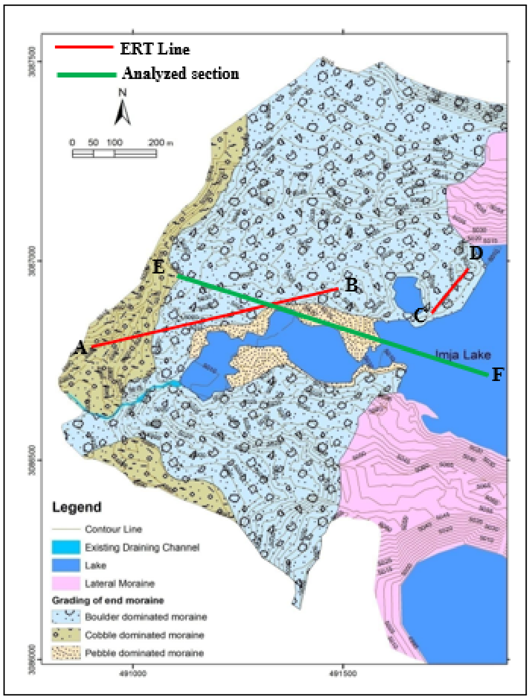

Figure 4: Topographic map around terminal moraine of Imja Glacial lake (Source: UNDP 2014)

Table 1: Assigned Resistivity Value for Interpretation (After dahal et al. 2018 [10])

S.no	Materials	Resistivity (Ωm)
1.	Saturated Moraine Materials	< 5000
2.	Frozen Moraine	5000 – 20000
3.	Dead Ice	> 20000
4.	Lake Water	200

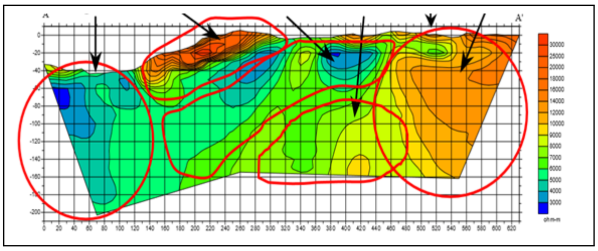

Figure 6: Inverse resistivity profile along section A-B [8]

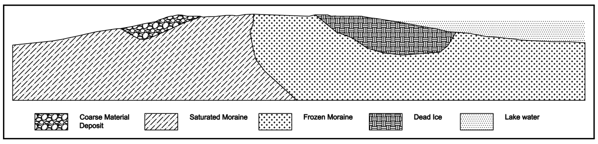

Figure 7: Interpreted cross section from inversion profile

3.2 Subsurface Study of Terminal Moraine

The subsurface complex around terminal moraine of imja glacial lake has determined by various researchers and organizations using geophysical test [10, 9, 8].

The ERT test done by Takenaka et al.(2010) [8], is used as a reference to determine the internal structure of terminal moraine, as it study the variation of moraine complex up to a greater depth as compared to the remaining. The inverse resistivity profile along line A-B and C-D (see Figure 4) is used and the resistivity value is interpreted based on the other literature.

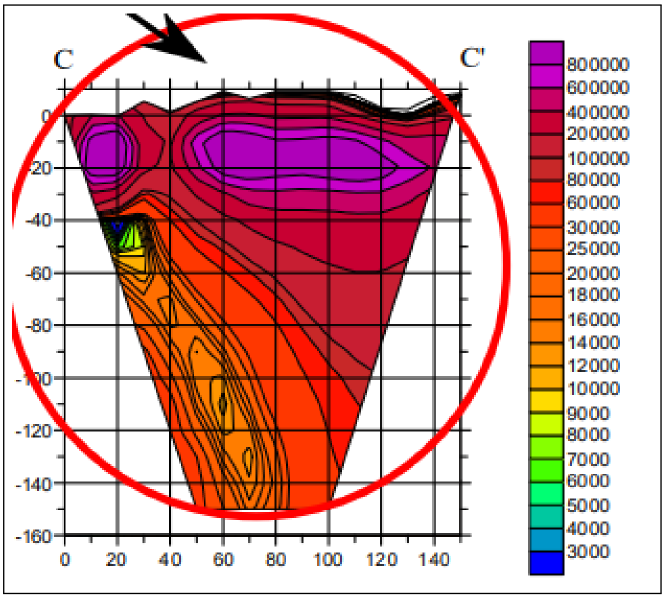

Figure 5: Inverse resistivity profile along section C-D [8]

3.3 Moraine Materials Properties

Moraine materials can consist of mix of rocks, gravel, silt and clay. The composition of the rocks and sediments it includes, as well as the processes that generated it, can have a significant impact on the qualities of moraine material. Based on the ERT inverse resistivity profile the moraine mass is divided in four category i.e. coarse grained material, saturated moraine, frozen moraine and dead ice.

The properties of moraine mass is determined with the help of different literature reviewed.

- **Coarse grained material**

  Akita (2003) [11], investigated the Imja glacial lake as a part of risk assessment. Grain size analysis, triaxial test and direct shear test is conducted to determine the shear strength property of the moraine mass collected from the site.

- **Frozen Moraine and Dead ice**

  Li et al.(2022) [12], examines the ice rich moraine soil of Tianmo valley through triaxial constant strain rate and coupled thermo-mechanical test comparing crushed ice and block ice. Direct shear test and triaxial test are conducted to determine the property of crushed ice and block ice moraine. The property of crushed ice moraine is used in the study as a frozen moraine, while the property of block ice moraine is used as a dead ice.

- **Saturated moraine**

  Yin Xiansong et al. (2018) [13], analyzes moraine deposits, focusing on morphology, distribution, material composition, and structure. It summarizes the engineering properties of moraine and explores its potential utilization.

Table 2: Properties of moraine materials

S.no	Material	Cohesion (Kpa)	Friction Angle	Young's modulus of Elasticity (Mpa)	Specific Weight (Kpa)
1.	Coarse grained material	2	38	15.7	21
2.	Saturated moraine	60	30	12.6	21
3.	Frozen Moraine	65.6	30.5	13.4	21
4.	Dead Ice	99.4	30.2	44.2	23

3.4 Numerical Modeling

In this work, a 2D model simulating a 3D situation is used to evaluate the stability of an earth dam using PLAXIS software (version 20).

3.4.1 Problem Configuration

In Plaxis the scenario is reduced into a two-dimensional plane strain system for the analysis, which is particularly useful for geological materials with large cross-sections. This suggests that the strain in the thickness (z direction) is minimal in the 2D model.

3.4.2 Project geometry and Boundary condition

The model is first drawn in AutoCAD with the four region assigned and then imported in the analysis tool Plaxis 2D using import geometry tab. The material properties of the four region are assigned as mentioned in the moraine material properties.

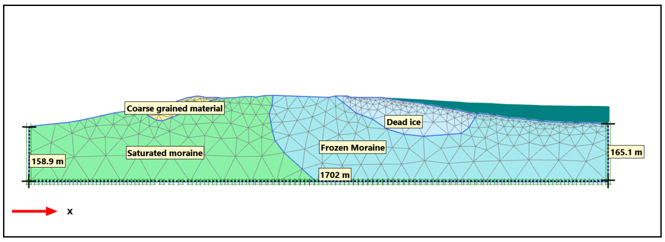

Figure 8: Project Geometry

Boundary condition is applied at the edges of the model to simulate the actual deformation. At the two edges of the model boundary condition are applied by normally fixing the vertical boundary and making the lateral displacement to zero. While at the bottom the boundary is fully fixed making both horizontal and vertical displacement to zero. The top portion of the model is fully free and can displace in both horizontal and vertical direction.

3.4.3 Generation of Mesh

In Plaxis, the act of breaking down a complicated geological or geotechnical model into discrete elements—typically triangles or quadrilaterals in 2D and tetrahedral or hexahedra in 3D—is referred to as mesh generation. A 15-node element triangle is used to represent the moraine dam in the model in Plaxis. The mesh generated for this study is shown in above Figure 4.8. The mesh consists of 734 elements and 6329 no of nodes.

3.4.4 Analysis

Stability condition and seepage discharge through the terminal moraine is calculated by using Finite element software Plaxis 2D. Along with the present water level condition the stability and seepage condition is analyzed in lowered water level condition of 2m, 5m and 10m.

4. Result and Discussion

This section discuss the effect of combined seepage and slope stability of Moraine dam of Imja glacial lake. Main results includes factor of safety, pore water pressure, flow pattern through dam body etc.

4.1 Analysis of Terminal Moraine at Present Condition

4.1.1 Stability Analysis

The stability condition of moraine dam is checked under static condition. Figure 9 shows that at existing situation the terminal moraine dam seems to be safe with factor of safety of 3.181. The maximum displacement that occurs at the downstream slope of the moraine dams is 1.91mm, which lies in safe limit.

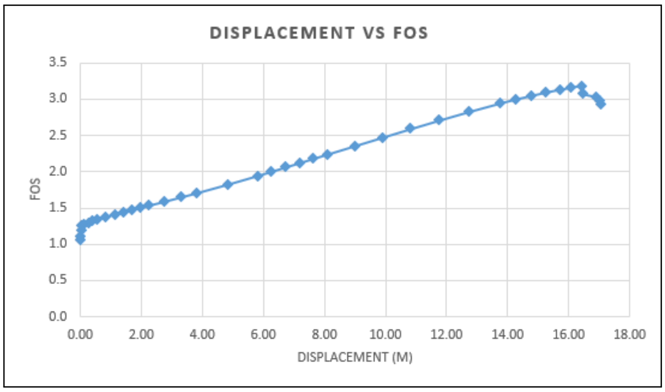

Figure 9: Deformation Vs FOS at existing water level condition

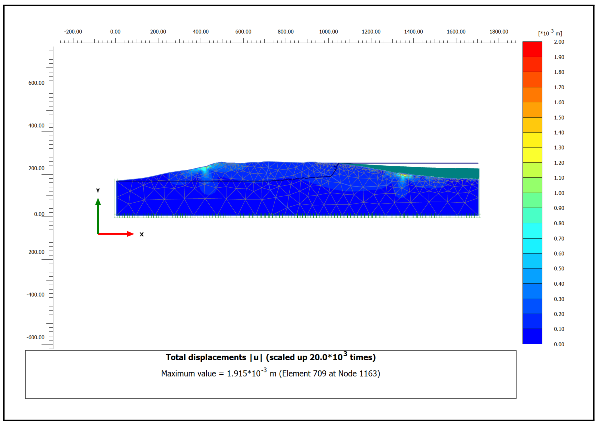

Figure 10: Displacement contour at existing water level condition

4.1.2 Seepage analysis

The seepage analysis is done in steady state condition. The seepage discharge, seepage velocity and the phreatic surface is computed with the help of finite element method. At the existing lake level condition the seepage discharge is calculated as $4.978 \times 10^{-6} m^3/s$ per meter length of the dam as shown in Figure 11. The total average seepage discharge occurs through the length of the dam is $0.003 m^3/s$.

Somos Valenzuela et al. (2015) [14] studied the seepage discharge through the moraine of the Imja glacial lake using a tape measure and a portable velocity meter. From the study the seepage discharge is calculated as $0.005 m^3/s$. The seepage calculated from the analysis comes close to the field measured.

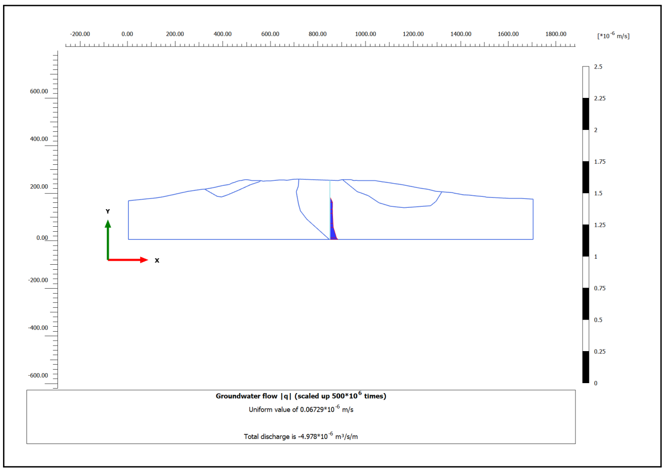

Figure 11: Seepage discharge through moraine dam body

The presence of dead ice inside the moraine dam plays great role in the moraine stability and seepage flow through the moraine. The presence of dead ice act as a seepage cutoff layer and blocks the seepage flow through the moraine dam.

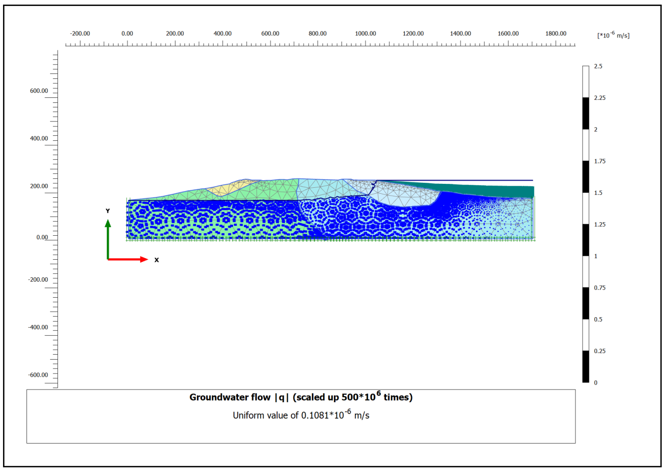

Figure 12: Seepage flow through the terminal moraine

Figure 12 shows that the presence of ice, blocks the seepage of water through the moraine body and allows the flow below the dead ice. The presence of dead ice in the moraine dam functions same as core in earth fill dam. Hence reduction in the size of dead ice can increase the seepage velocity and flow through the moraine making the moraine less stable.

4.2 Lake water lowering scenario

Imja glacial lake is one of the most studied glacial lakes of Nepal. Many no. of researcher has studied the risks of outburst of Imja glacial lake. Some researcher has said Imja glacial lake as safe while some has categorized it to be high potential to outburst. Department of hydrology and meteorology had conducted a project in 2016 to lower the lake water level by 3.4 m so, as to reduce the risk of outburst.

Hence to analyze how the stability and seepage flow through the moraine changes as the lake water level is lowered, Lake water level lowering scenario is done. Apart from existing lake water level condition, three more i.e 2m down, 5m down and 10m down condition is analyzed.

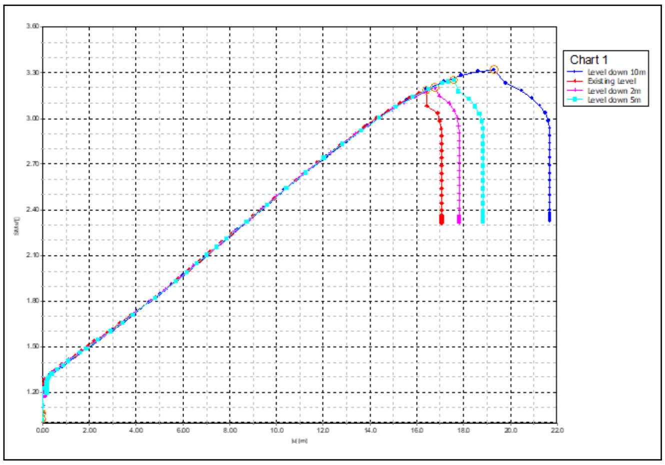

Figure 13: Deformation Vs FOS at different water level condition

As the water level of the glacial lake is decreased the factor of safety of the terminal moraine is increasing. At existing water level condition the factor of safety of moraine dam is 3.181, while as the lake water level is dropped by 10m the factor of safety comes to be 3.317 (Figure 14). From the analysis it is obtained that the dropping of Lake water level by 10m only increases the factor of safety of moraine dam by 4.27%.

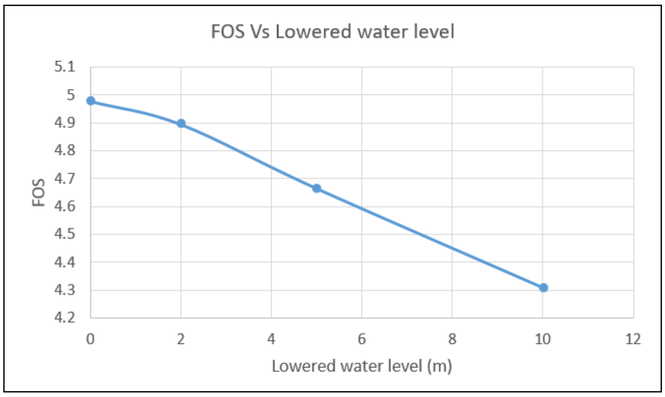

Figure 14: FOS Vs Lowered Water Level

Similarly, the seepage condition is also analyzed for lake water level lowering scenario. As the water level is dropped the seepage discharge through the moraine dam is also decreased (Figure 15). At existing water level condition the seepage through the moraine dam is $4.978 \times 10^{-6}\ m^3/s/m$, while at

10m water level dropped condition the seepage discharge is found to be $4.309 \times 10^{-6}\ m^3/s/m$.

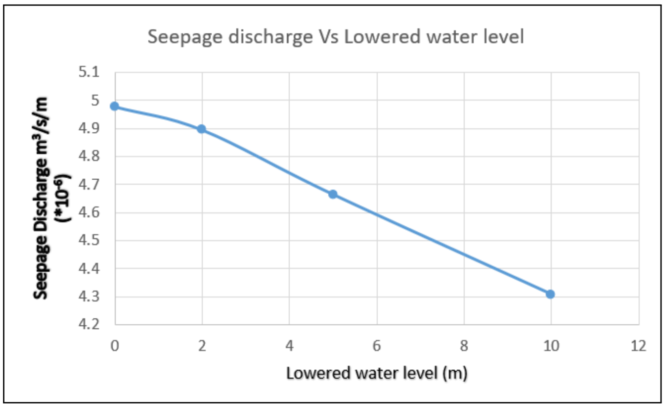

Figure 15: Seepage discharge vs lowered water level

5. Conclusion

In the study the evaluation of stability and seepage discharge through the moraine dam of Imja glacial lake is analyzed. The analysis is done in different lake lowering scenarios along with the existing water level condition.

In every condition the factor of safety of moraine dam comes greater than 3 and deformation also comes with in the acceptable range. The analysis shows that factor of safety increases as the lake water level is lowered up to 10m i.e $3.181 < 3.198 < 3.247 < 3.318$ respectively. Similarly, the analysis result showed that the decreasing the lake water level by 10m reduces the seepage discharge by significant amount. By decreasing the water level from existing level to 10m down the seepage through the moraine also decreases from $4.978 \times 10^{-6} m^3/s/m$ to $4.309 \times 10{-}6 m^3/s/m$. The presence of dead ice inside the moraine dam plays great role for the flow path of seepage discharge. Due to low permeability the ice blocks act as a seepage cutoff and reduce the seepage discharge through the moraine. Although the factor of safety of moraine dam is found to be increased as the water level is decreased but the increase in safety factor isn't significant within 5m depth of water level lowering. Hence to gain significant safety factor the water level should be dropped by more than 10m.

References

[1] S. R. Bajracharya, P. K. Mool, and B. R. Shrestha. *Impact of climate change on Himalayan glaciers and glacial lakes: case studies on GLOF and associated hazards in Nepal and Bhutan.* International Centre for Integrated Mountain Development (ICIMOD), 2007.

[2] M. J. Hambrey, D. J. Quincey, N. F. Glasser, J. M. Reynolds, S. J. Richardson, and S. Clemmens. Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, mount everest (sagarmatha) region, nepal. *Quaternary Science Reviews*, 27(25-26):2361–2389, 2008.

[3] T. Watanabe, J. D. Ives, and J. E. Hammond. Rapid growth of a glacial lake in khumbu himal, himalaya: prospects for a catastrophic flood. *Mountain Research and Development*, pages 329–340, 1994.

[4] T. Watanabe, S. Kameyama, and T. Sato. Imja glacier dead-ice melt rates and changes in a supra-glacial lake, 1989-1994, khumbu himal, nepal: Danger of lake drainage. *Mountain Research and Development*, pages 293–300, 1995.

[5] A. Sakai, T. Yamada, and K. Fujita. Volume change of imja glacial lake in the nepal himalayas. In *International Symposium on Disaster Mitigation & Basin Wide Water Management*, volume 556561, 2003.

[6] T. Watanabe, D. Lamsal, and J. D. Ives. Evaluating the growth characteristics of a glacial lake and its degree of danger of outburst flooding: Imja glacier, khumbu himal, nepal. *Norsk Geografisk Tidsskrift-Norwegian Journal of Geography*, 63(4):255–267, 2009.

[7] B. B. Shrestha, H. Nakagawa, K. Kawaike, Y. Baba, and H. Zhang. Glacial lake outburst due to moraine dam failure by seepage and overtopping with impact of climate change. *the Annuals of the Disaster Prevention Research Institute*, 53(B):569–582, 2010.

[8] S. Takenaka, T. Yabuta, and H. Fukui. Estimation of distribution of dead ice on imja glacier lake embankment bodyin khumbu region of nepal by 2 dimensinal resistivity survey. *Journal of the Japanese Society of Snow and Ice*, 1(72):3–12, 2010.

[9] M.A. Somos-Valenzuela, D. C. McKinney, D. R. Rounce, and A.C. Byers. Changes in imja tsho in the mount everest region of nepal. *The Cryosphere*, 8(5):1661–1671, 2014.

[10] P. R. Dahal, K. R. Paudyal, and S. Rajaure. Geophysical study on moraine dam of imja glacial lake in eastern nepal using electrical resistivity tomography method. *Journal of Nepal Geological Society*, 55(1):15–22, 2018.

[11] Akita. Physical and mechanical properties of the moraine of imja glacier lake located in nepal. *Nihon University College of Engineering*, 2003.

[12] C. Li, R. Wang, D. Gu, J. Wang, X. Chen, J. Zhou, and Z. Liu. Temperature and ice form effects on mechanical behaviors of ice-richmoraine soil of tianmo valley nearby the sichuan-tibet railway. *Engineering Geology*, 305:106713, 2022.

[13] X. Yin. Iop conf. ser. : Earth environ. *Sci. 128 012040*, 2018.

[14] M.A. Somos-Valenzuela, D.C. McKinney, A.C. Byers, D.R. Rounce, C. Portocarrero, and D. Lamsal. Assessing downstream flood impacts due to a potential glof from imja tsho in nepal. *Hydrology and Earth System Sciences*, 19(3):1401–1412, 2015.