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Hazard assessment of the Tsho Rolpa Glacier Lake and ongoing remediation measures

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ABSTRACT

The Tsho Rolpa Glacier Lake stores about 100x10^6 m^3 of water behind an unconsolidated moraine dam in the Rolwaling Valley of central Nepal. The 150 m high terminal moraine has been deteriorating rapidly since the last 4–5 years, as buried dead-ice is being exposed. Displacement waves formed by the calving of the Trakarding Glacier terminus into the Tsho Rolpa are increasing in magnitude. Seepage from springs on the distal flank of the end moraine some 50 m below the dam crest and shallow slumps were also observed, and all of these phenomena indicate deterioration of the moraine dam. The majority of past studies suggested lowering the lake level to prevent a glacier lake outburst flood. Engineering work to lower the lake level down to 3 m by constructing an open channel on the terminal moraine began in May 1999 and ended successfully in July 2000. Several studies, including the ground penetrating radar survey, were conducted in association with the construction work. They provided the detailed information on subsurface conditions of the lake area. The construction of the open channel reduced the volume of water available to form a potential glacier lake outburst flood by about 20%. This work demonstrated for the first time in Nepal that such remediation of a glacier lake outburst is quite effective.

INTRODUCTION

In recent decades, a general retreat of the world's glaciers is observed, including the glaciers of the Himalayas. While it has caused problems of diverse nature globally, in the Himalayas it has led to the formation of many lakes in the space once occupied by these glaciers. Almost all the glacier lakes in the Nepal Himalayas are dammed by lateral and end moraines formed during the last advancing stage in the neo-glaciation period between the 15th and 19th centuries (Yamada et al. 1998). These natural moraine dams are composed of unconsolidated sediments consisting of boulders, gravel, sand, and silt. These dams are structurally weak and unstable, and undergo constant changes due to erosion and slope failures. Hence, they are prone to catastrophic collapse, causing glacier lake outburst flood (GLOF). Principally, a moraine dam may break by the action of some external trigger or self-destruction. A huge displacement wave generated by rockslide or snow/ice avalanche from glacier terminus into the lake may cause the water to overtop the moraines, create a large breach, and eventually cause the dam failure (Ives 1986). An earthquake may also be one of the factors triggering dam break depending upon its magnitude, location, and characteristics. Self-destruction is caused by the failure of the dam slope and seepage from the natural drainage within the dam.

A GLOF is characterised by a sudden release of a huge amount of lake water, which in turn rushes down the stream channel in the form of dangerous flood waves. These flood waves comprise water mixed with morainic materials and cause devastating consequences for downstream riparian communities, hydropower stations, and other infrastructure. The severity of flood wave depends upon the amount of water released, debris load, and on the basin characteristics of the watershed. Discharge rates of such floods are typically in the order of several thousand cubic metres per second.

The record of the past disastrous GLOFs in Nepal is shown in Table 1. Although the GLOF is not new in Nepal, it

Table 1: List of GLOF events recorded in Nepal (modified after Yamada 1998)

Date	River basin	Name of lake
450 years ago	Seti Khola	Machhapuchhare
Aug-35	Arun	Taraco
21-Sep-64	Sun Koshi	Gelhaipu Co
1964	Trishuli	Zhangzangbo
1964	Arun	Longda
1968	Arun	Ayaco
1969	Arun	Ayaco
1970	Dudh Koshi	Ayaco
3-Sep-77	Tamur	Nare
1980	Aun	Puncham
11-Jul-81	Sun Koshi	Zhangzangbo
27-Aug-82	Arun	Jinco
4-Aug-85	Dudh Koshi	Dig Tsho
12-Jul-91	Tama Koshi	Chubung
3-Sep-98	Dudh Koshi	Sabai Tsho

attracted the attention of the scientific community and government only when a disastrous GLOF occurred at Dig Tsho Glacier Lake on 4 August 1985 in the Langmoche Valley of the Khumbu region in eastern Nepal (Galay 1985; Ives 1986; Yamada 1991, 1993, 1996, 1998). It caused serious damage to the nearly completed Namche Hydropower Project, washed away a wide area of cultivated land, several bridges, and many houses (including livestock and inhabitants) along its path downstream. The flood waves lasting for about 4 hours released about 6 to 10 million cubic metres of water (Ives 1986). Since then, His Majesty's Government of Nepal (HMGN) has considered the GLOF as a threat to the development of water resources of the country, and has given priority to its study and mitigation.

The GLOF research programme of the Water and Energy Commission Secretariat (WECS) started in September 1990 under the assistance of the Japan International Cooperation Agency (JICA), which conducted several researches on glacier lakes and made preliminary inventory of glaciers of the Nepal Himalayas. Based on these investigations and a joint study by the Department of Hydrology and Meteorology (DHM) and Reynolds Geoscience Limited (RGSL), UK in 1997, the Tsho Rolpa Glacier Lake in the Rolwaling Valley of central Nepal was identified as one of the most dangerous glacier lakes in the Nepal Himalayas (Reynolds 1997; Yamada 1998). An accelerated growth of the lake, rapid degradation of terminal and lateral moraines holding lake water, melting of fossil ice inside the moraine, seepage of lake water from the end moraine, and rapid ice calving from the glacier terminus were responsible for the high GLOF hazard at the Tsho Rolpa Lake.

This paper provides a review of studies on the Tsho Rolpa Glacier Lake and describes the mitigation measures undertaken for controlling its GLOF hazard.

TSHO ROLPA GLACIER LAKE

The Tsho Rolpa Glacier Lake is located about 110 km northeast of Kathmandu in the Rolwaling Valley (Fig. 1). It is located in Ward No. 1 of the Gauri Shankar Village Development Committee in the Dolakha District of Nepal, and takes about 7 days of walk from Dolakha. The Tsho Rolpa Glacier Lake is the largest moraine-dammed proglacial lake in the Nepal Himalayas. It is located at an altitude of 4,580 m.

Preliminary studies of the Tsho Rolpa began in 1992 after the Chubung GLOF in 1991 (Thomson 1992). Damen (1992) prepared the first detailed report on the Tsho Rolpa and recommended lowering the lake level by several metres using siphons over the southwestern side of the end moraine. Further, he recommended carrying out flood mitigation works and monitoring the lake level fluctuation and the discharge of the Rolwaling Khola.

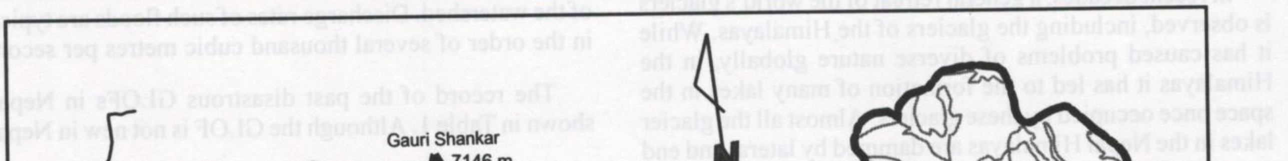

Fig. 1: Location map of the Tsho Rolpa Glacier Lake

In 1993, more detailed qualitative and quantitative works were carried out by WECS (Mool et al. 1993). The authors studied the growth pattern and the size of the lake, and carried out the bathymetric survey and topographical survey of the downstream villages and prepared the river cross-sections. WECS continued to carry out the studies on glacier lakes and prepared a series of interim reports (Yamada 1993).

Fujiwara (1995) and Reynolds (1994) carried out the hazard assessment due to GLOF in the Rolwaling Valley. Distribution of buried ice in the end moraine was evaluated in 1995 using electrical resistivity exploration at the end moraine of the Tsho Rolpa. This study suggested that the ice masses are present in the vicinity of the islands.

Modder and Olden (1995) conducted the geotechnical hazard analysis of the lake. They conclude that on the engineering timescale (50–100 years) the dam is considered stable if no large-scale events like earthquakes occur. But on the geomorphological timescale (>100 years), moraine dam failure will eventually take place if no mitigation measures are taken.

Rupke and Modder (1996) conducted further works on geomorphology and geotechnical study. Reynolds (1996, 1997) proposed the lowering of the lake level and also assessed the status of the lake.

A study conducted under the joint glaciological research programme of the DHM and Glaciological Expedition in Nepal (GEN) showed that the sediment-laden underflows are traceable down to 110 m indicating that the Trakarding Glacier is grounded (Chikita et al. 1997).

Mool et al. (1993) and Yamada (1998) reconstructed the development of the Tsho Rolpa (Fig. 2). The lake is about 3,300 m long and about 500 m wide with a total surface area of about 1.65 km². The maximum depth measured in 1994 was 132 m with estimated average depth of about 55 m (Yamada 1998). The lake is undergoing constant growth due to the intensive calving of the Trakarding Glacier terminus. The total volume of water at present is estimated at 100 million cubic metres. The total catchment area of the lake is 77.6 km², of which 55.3 % is the debris-free glacier and 16.1 % is the debris-covered glacier.

GLOF HAZARD

There are some steep hanging glaciers on the northern flank of the Tsho Rolpa Glacier Lake. However, they do not pose an immediate threat of ice avalanching, as there are cascades of rocky platforms between the glacier snout and the lake water.

Many meltwater channels from the surrounding glacier drain into the Trakarding Glacier making the lake level rise during the monsoon period. Increased melting can cause a fast rise in the lake level, which in turn might result in the overtopping of the dam.

The glaciers on the southern side of the lake do not pose threat to the lake, as there is a depression between the mountains containing these glaciers and the southern lateral moraine. The snow and ice avalanche from the eastern side always gets contained in the 5 km long Trakarding Glacier and no threat can be expected from them.

Observations of the end moraine have shown that the northwestern portion is the most dynamic one. This area of the moraine is characterised by several tension cracks, depressions, sinkholes, and slope failures. An extensive area of exposed dead ice (i.e. melt feature) was observed in 1997 in this region. It is therefore considered that this area is vulnerable to failure due to hydrostatic pressure of the lake water on the ice or catastrophic degradation of the moraine owing to fast melting of the cored ice.

Large displacement waves due to calving of the ice front at the Trakarding Glacier terminus can be another GLOF triggering mechanism. The Trakarding Glacier terminus is changing from year to year. The ice cliff can be up to 50 m high. The ice calving when there is no ice or debris apron in front of the cliff (e.g. in 1997) can cause huge waves (Plate 1).

The amount of water released by the Dig Tsho GLOF was about 6 to 10 million m³ (Ives 1986). If GLOF occurs at the Tsho Rolpa, the amount of water released would be around 30 million m³; an amount much larger than that

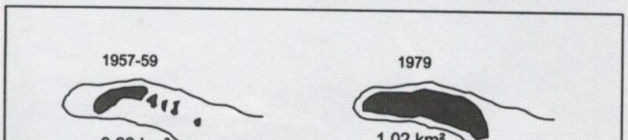

Fig. 2: Development of the Tsho Rolpa Lake

released by the Dig Tsho and naturally, the destruction would be much more. It would cause a potential threat to the lives of 10,000 people and infrastructure. A dam break model was run to simulate the flood generated by the Tsho Rolpa Glacier Lake (DHM 2000). The worst scenario estimates the peak discharge of about 7,000 m^3/s and the downstream impact up to 100 km (Fig. 3). According to the model, the peak height would reach 17 m at the narrow places such as Beding and Manthale. The gradient of the Rolwaling Khola is very steep between Beding and Chet Chet. This reach is also heavily forested. Chances of temporary damming are very high in this reach, which might result in land inundation and destruction of infrastructure. It could also cause adverse impacts on the Khimti Hydropower – a 60 MW complex located about 80 km below the Tsho Rolpa Lake.

GLOF MITIGATION PROGRAMMES

The majority of the studies carried out until 1995 recommended lowering the lake level. The mitigation programme conducted in the Tsho Rolpa Lake and the impact area can be listed broadly as: installation of test siphons; installation of the GLOF early warning system; and construction of an open channel to lower the water level. Each of these is briefly discussed below.

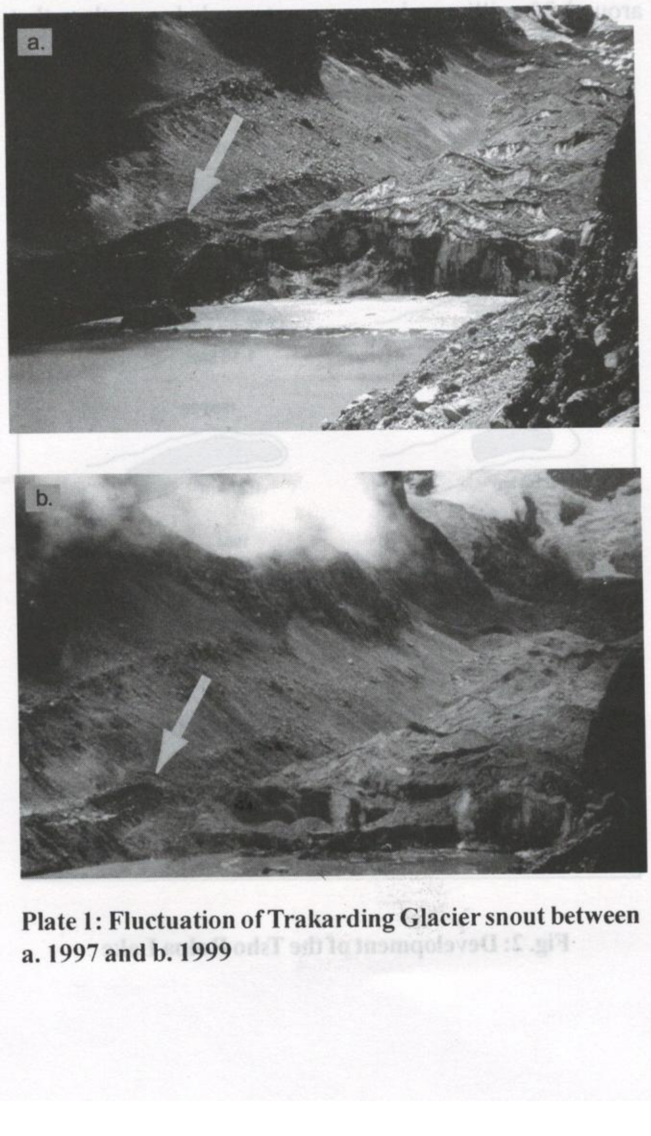

Plate 1: Fluctuation of Trakarding Glacier snout between a. 1997 and b. 1999

Installation of test siphons

Since there was no dedicated fund for the lake level lowering, the remediation had to be conducted on a piecemeal basis, without the possibility of a large-scale construction work. In May 1995, test siphons were installed in the southwestern part of the end moraine, after WAVIN Overseas BV donated the specially designed siphon pipes and couplers. The work was undertaken through the Nepal-Netherlands friendship associations. By the summer of 1997, the Tsho Rolpa GLOF hazard received a widespread acceptance and the government was committed to work against it. Nevertheless, a dedicated fund was still lacking. Therefore, the limited mitigation work was canalised through the Natural Disaster Fund of the Ministry of Home. Further work to lower the lake level continued in the monsoon of 1997, by installing five other sets of locally manufactured siphon pipes.

The purpose of installing siphon pipes was to test their performance in the high altitude environment with freezing conditions in winter. The test siphons worked satisfactorily with some maintenance and showed that if funds are available, siphoning out the lake water could be an option to lower the water. However, the siphon option was later dropped out due to the need of a large number of pipes, the

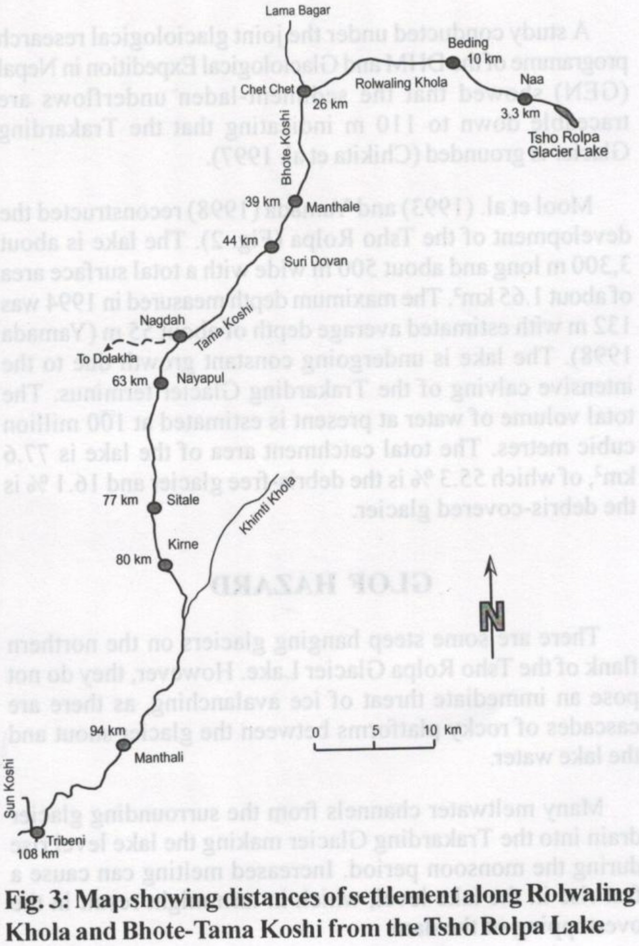

Fig. 3: Map showing distances of settlement along Rolwaling Khola and Bhote-Tama Koshi from the Tsho Rolpa Lake

lack of space to install them, and the maintenance requirements.

GLOF early warning system

While test siphons were operating, a temporary Nepalese Army post and a number of police posts were established at the lake and the lower reaches of it, respectively. These posts were equipped with satellite phones and radios so that an event of GLOF could be timely informed to the inhabitants of the downstream locations. A year later (before monsoon of 1998), the DHM established the meteor burst-type early warning system to provide the inhabitants of the Rolwaling and Bhote–Tama Kosi Valleys early information about a GLOF event, thereby allowing for the time to access to a safe location. This system consists of a GLOF sensing system located just downstream of the end moraine. A GLOF event is sensed by these sensors and is relayed to 19 stations located downstream, equipped with audible alarms. The early warning system is working satisfactorily to date.

Construction of an open channel

In August 1997, a formulation team visited the lake and recommended to lower the lake level by 3 m by cutting an open channel in the end moraine (DHM 1997). The Government of the Netherlands funded the Tsho Rolpa GLOF Risk Reduction Project (TRGRRP) in August 1998. This GLOF risk reduction system consists of a lined channel constructed through the western end moraine (DHM 1998). About 90% of the work was complete when the construction was halted for the winter shutdown in October 2000 (DHM 2000). The construction work began again in April 2000 and was completed in the middle of July 2000. The project comprises the following components.

The channel passes through what was a depression in the moraine commonly referred to as the Horseshoe Lake (Fig. 4 and Plate 2). The channel is 6.4 m wide at the bottom and the bottom elevation at the gate structure is 4.43 m below datum. The channel bottom is flat upstream of the gate structure, and has a grade of 0.3% downstream of the gate. The channel sides are sloped at 2H:1V (where H = horizontal distance and V = vertical distance). A gate structure is located in the channel (Fig. 5 a-c) to regulate the flow if necessary, comprising three gates, each of 2 m wide and capable of being opened 1.5 m above the channel bottom. The 20 m of the channel upstream of the gates are lined with gabion mattresses extending 1.0 m above the datum. The gabion mattresses are underlain by a geotextile, a 100 mm thick sand layer, a geomembrane, a geotextile, and another 100 mm thick sand layer, respectively (Fig. 5b and 5c). The channel is intended to cater for the design flood flow of 14.6 cubic metres per second (cumecs) and the extreme flood flow of 30 cumecs.

Ongoing research work

The TRGRRP has a provision of a Physical Monitoring Task Group (PMTG) comprising five specialists (i.e. glaciologist, meteorologist, civil engineer, geologist, and surveyor). The PMTG is responsible for conducting different kinds of research work during the first two years of the project as well as to monitor the physiography of the lake area during the construction period. The PMTG established an automatic weather station (AWS) in June 1999, which collects the hourly records of various meteorological parameters (i.e. air temperature, relative humidity, net radiation, precipitation snow depth, and lake level

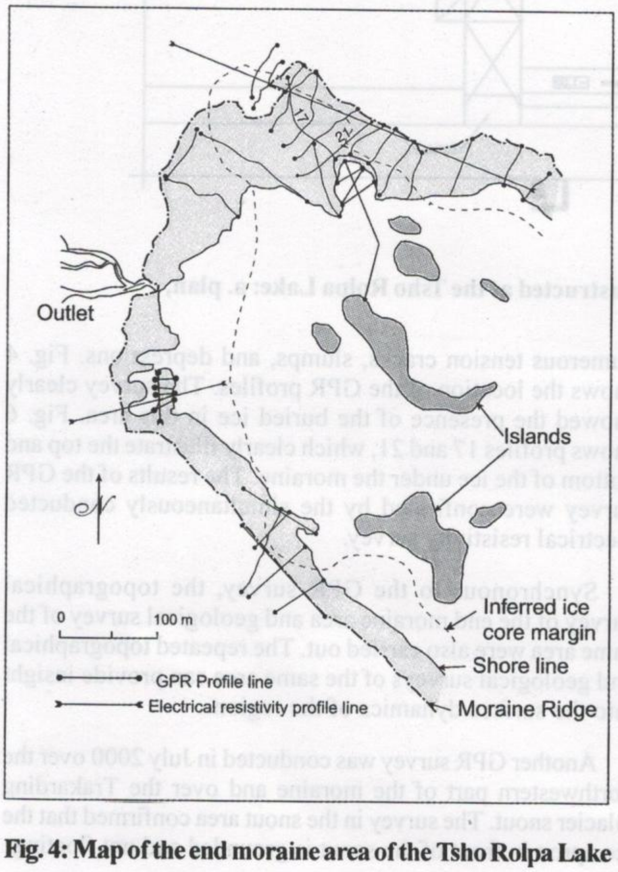

Fig. 4: Map of the end moraine area of the Tsho Rolpa Lake

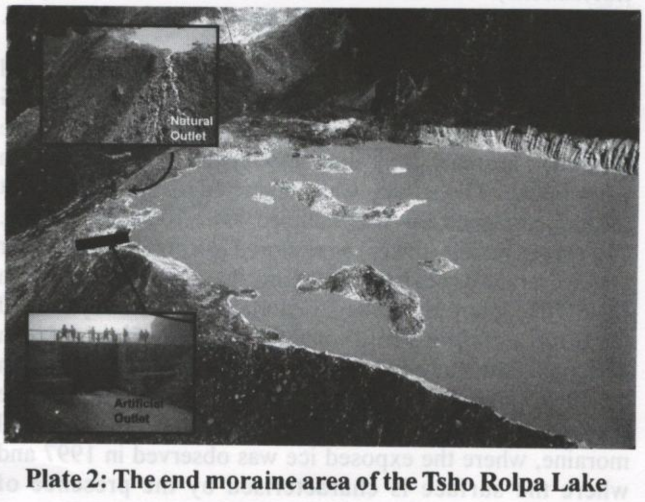

Plate 2: The end moraine area of the Tsho Rolpa Lake

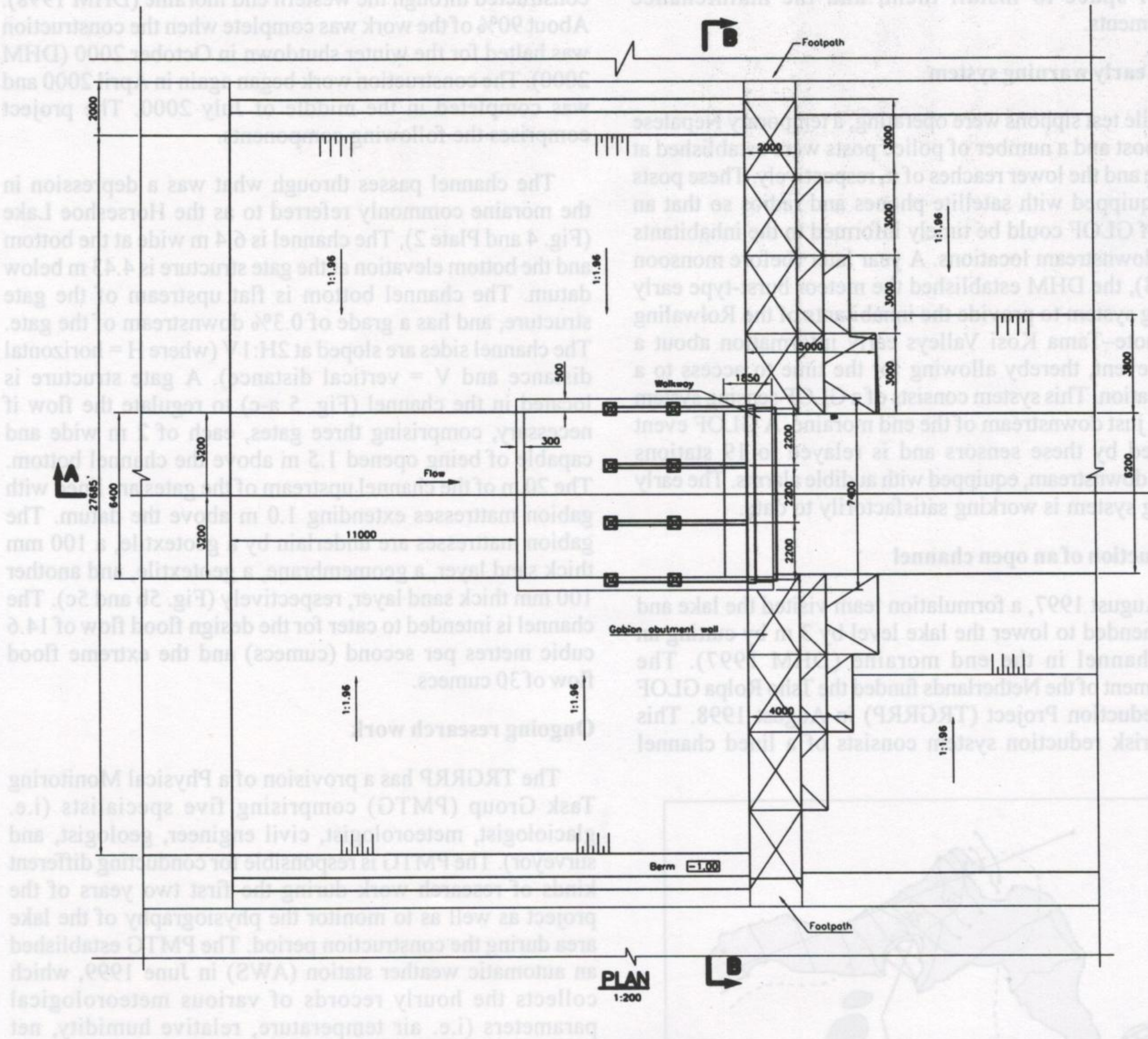

Fig. 5: Drawings of the engineering structures constructed at the Tsho Rolpa Lake: a. plan,

fluctuations). The lake level fluctuation data are analysed regularly to detect the formation of any displacement waves.

The TRGRRP also has a provision of an International Technical Advisor (ITA), in liaison with whom the PMTG conducted a ground penetrating radar (GPR) survey of the construction area in May–June 1999, before the construction work began. The survey was conducted using a GPR Unit (Mala Geoscience, Sweden) coupled with a 100 MHz antenna. The survey results (traces) were stored in a portable computer and were analysed later by using the computer program GRADIX (Interplex limited, Colorado). The survey around the construction area confirmed the absence of buried ice in the immediate vicinity of the excavation area up to a depth of 48 m. The GPR survey was also conducted in the northwestern part of the end moraine and the northern lateral moraine, where the exposed ice was observed in 1997 and where the surface is characterised by the presence of numerous tension cracks, slumps, and depressions. Fig. 4 shows the location of the GPR profiles. The survey clearly showed the presence of the buried ice in this area. Fig. 6 shows profiles 17 and 21, which clearly illustrate the top and bottom of the ice under the moraine. The results of the GPR survey were confirmed by the simultaneously conducted electrical resistivity survey.

Synchronous to the GPR survey, the topographical survey of the end moraine area and geological survey of the same area were also carried out. The repeated topographical and geological surveys of the same area can provide insight into the surface dynamics of the region.

Another GPR survey was conducted in July 2000 over the northwestern part of the moraine and over the Trakarding Glacier snout. The survey in the snout area confirmed that the ice apron in front of the snout is grounded and not floating.

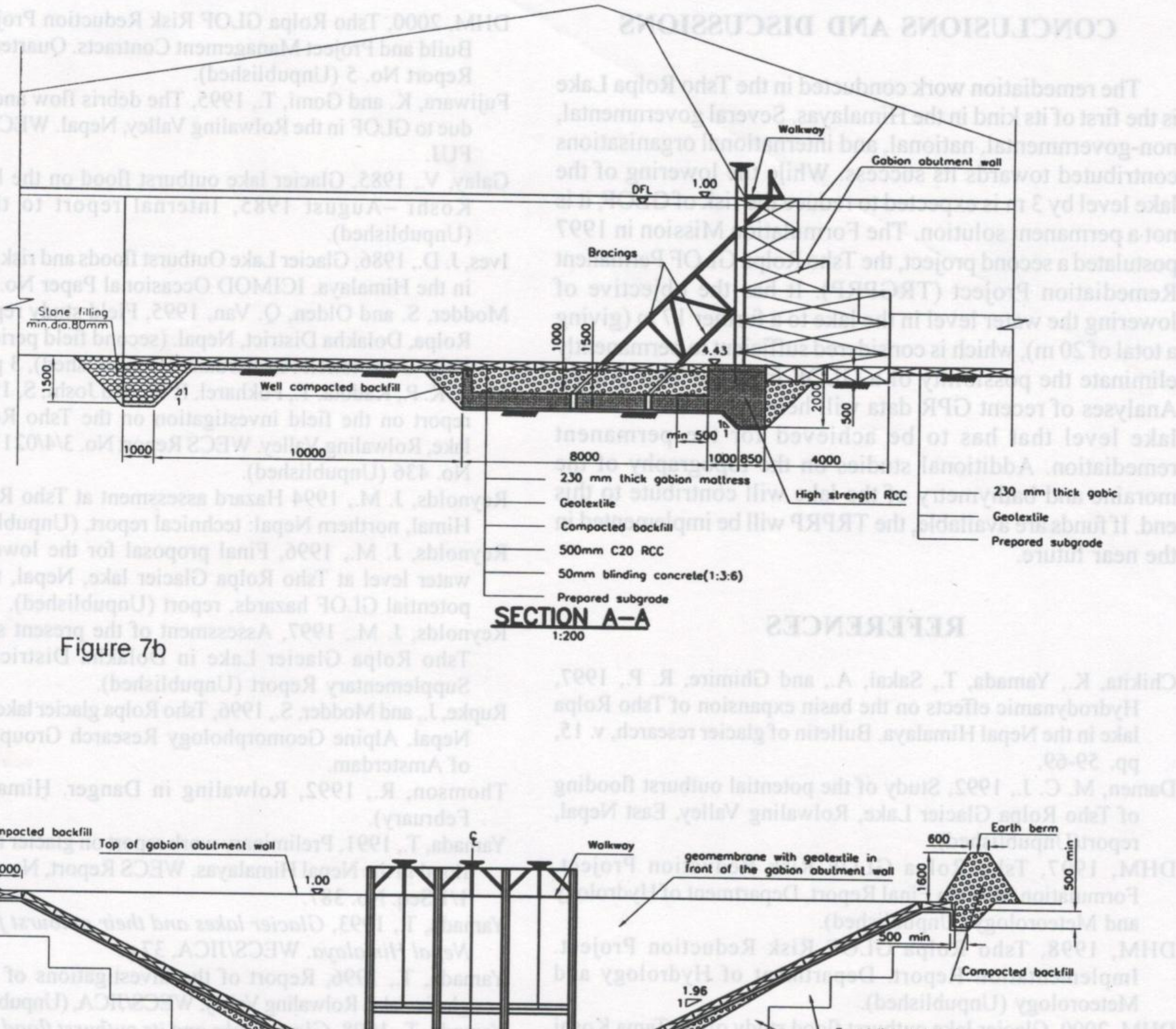

Fig. 5: b. longitudinal section, and c. cross-section.

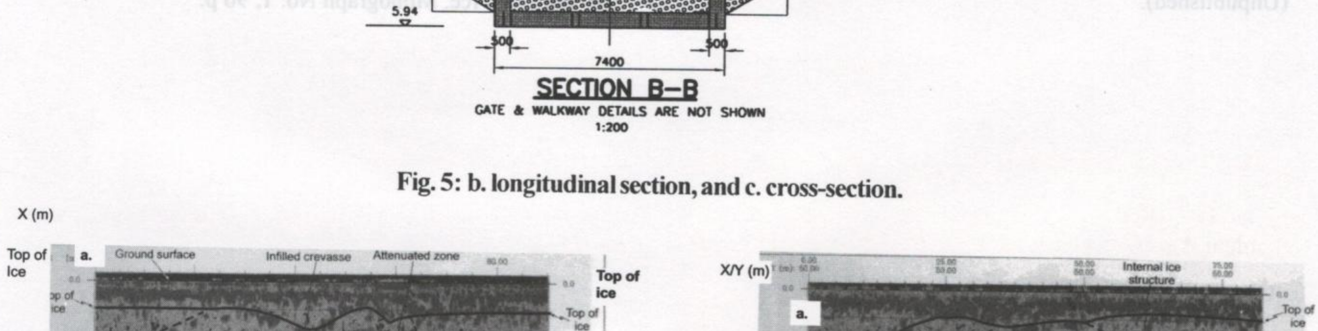

Fig. 6: Instantaneous amplitudes of the GPR profiles: a. 17 and b. 21

CONCLUSIONS AND DISCUSSIONS

The remediation work conducted in the Tsho Rolpa Lake is the first of its kind in the Himalayas. Several governmental, non-governmental, national, and international organisations contributed towards its success. While the lowering of the lake level by 3 m is expected to reduce the risk of GLOF, it is not a permanent solution. The Formulation Mission in 1997 postulated a second project, the Tsho Rolpa GLOF Permanent Remediation Project (TRGPRP). It has the objective of lowering the water level in the lake to a further 17 m (giving a total of 20 m), which is considered sufficient to permanently eliminate the possibility of a GLOF from the Tsho Rolpa. Analyses of recent GPR data will help establish the actual lake level that has to be achieved for the permanent remediation. Additional studies on the topography of the moraine and bathymetry of the lake will contribute to this end. If funds are available, the TRPRP will be implemented in the near future.

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