Degradation of ice-cored moraine dams: implications for hazard development

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Abstract Field and geophysical studies have allowed us to identify processes leading to ice-cored moraine degradation for three natural dams investigated in Peru and Nepal. As potentially hazardous lakes form on the snouts of debris-covered glaciers they may separate a stagnant ice body from the upper reaches of the glacier to form an ice-cored end-moraine complex. The ice-cored moraines appear to degrade through ablation beneath the debris cover, by localized thermokarst development, and by associated mass movement. Relict glacier structures serve as a focal point for the onset of accelerated thermokarst degradation. Once exposed, the ice core then undergoes accelerated wastage through the combined affects of solar radiation and mechanical failure due to the rheological response of the ice to deepening kettle forms. Continuing degradation reduces the lake freeboard, weakens the moraine dam, and can lead to its catastrophic failure.

INTRODUCTION

Outburst floods from moraine-dammed glacial lakes represent significant natural hazards in many glaciated regions (Lliboutry et al., 1977; Clague & Evans, 1994; Richardson & Reynolds, 2000). Moraine-dammed glacial lakes are commonly associated with periods of glacier wasting and recession, particularly by debris-covered glaciers. During periods of ice wastage, ice at the glacier margins in the ablation zone may be preferentially insulated by the thick debris cover and can become incorporated within terminal and lateral moraines to form substantial ice cores. Wasting of stagnant ice within ice-cored moraine dams by a variety of thermokarst processes (Clayton, 1964; Healy, 1975) can affect the development and stability of potentially hazardous glacial lakes.

We have investigated several moraine dams during assessments of potentially dangerous glacial lakes in the Himalayas and the Andes. Three examples are presented here from Nepal and Peru where buried ice has played an important role in affecting moraine dam stability. Our studies consisted of topographical surveying, geomorphological mapping of moraine landforms and glacial structures, sedimentological characterization, photography of key features, Ground Penetrating Radar (GPR) and electrical resistivity studies of moraine structure, and interpretation of oblique and vertical aerial photographs.

HUALCÁN, PERU

A Neoglacial end-moraine complex near Hualcán, Cordillera Blanca, Peru (Fig. 1), was studied during a successful hazard assessment and mitigation programme.
undertaken between 1988 and 1993 (Reynolds et al., 1998). "Lake 513" developed on a composite glacier that flowed westwards from Nevado Hualcán (6122 m a.s.l.) into an elongated bedrock basin. Aerial photographs show that between 1948 and 1962 the debris-covered glacier snout was losing mass by downwasting rather than by retreat. Small ponds up to c. 100 m across began to form on the glacier snout between 1962 and 1970. By 1988 individual ponds had coalesced to form a single lake separating an ice-core end-moraine complex from the upper reaches of the glacier (Fig. 1). By 1993 the lowermost part of the glacier had ablated completely and the glacier had retreated to form a highly unstable ice tongue on the steep slope descending into the basin.

**Fig. 1** The hazard threat from "Lake 513", Hualcán, Peru, and sketch maps showing the growth of the lake between 1962 and 1988. Map of the potential flood route from Reynolds et al. (1998).
Melting of the glacier and formation of the lake left a prominent end-moraine ridge with steep inner flanks at the former position of the glacier terminus (Fig. 2). Electrical resistivity was used to investigate the internal structure of the moraine ridge to assist the design of a suitable hazard remediation programme. It was confirmed that the moraine was cored with stagnant glacier ice up to c. 8 m thick, directly overlying bedrock. The ice core was overlain by at least 0.5 m of diamict containing angular and sub-angular boulders. Detailed topographical levelling showed that the moraine surface had subsided by 4 m across much of the end-moraine complex between 1985 and 1988. This was interpreted as melting of the ice core beneath the debris cover, lowering at an average rate of about 11 cm per month (Reynolds, 1992). Water from the lake was flowing over the ice core and draining via two springs on the distal side of the moraine.

Lowering of the moraine’s ice core reduced the lake freeboard to less than 1 m in 1988, leaving the moraine vulnerable to overtopping by displacement waves. It was thought that if nothing had been done to mitigate the situation, the moraine might have failed in 1989, possibly destroying Carhuaz and part of Hualcán with the loss of many thousands of lives. An emergency remediation programme was initiated in 1988–1989, employing siphons and an engineered tunnel to successfully lower the lake level (Reynolds, 1992; Reynolds et al., 1998).

![Fig. 2 Composition of the moraine dam at Lake "513", Hualcán, clearly showing the angular and blocky nature of sediment indicative of supraglacial transport.](image)

**TSHO ROLPA, ROLWALING HIMAL, CENTRAL NEPAL**

Tsho Rolpa glacier lake lies at the head of the Rolwaling Valley in northern Central Nepal and, with a length of 3.2 km and volume of c. $10^8$ m$^3$, it is the country's largest
The lake formed by the coalescence of supraglacial ponds on the debris-covered Trakarding Glacier (Mool, 1995) and is dammed by a 150 m high moraine ridge complex. The potential for the lake to burst catastrophically from behind its moraine dam prompted a detailed hazard assessment (Reynolds, 1998) and a remediation scheme to lower the lake level through an engineered channel (Rana et al., 1999).

Morphological and geophysical studies of the end-moraine between 1994 and 1999 provide evidence for degradation processes and rates. Degradation has been greatest in the terminal area where two lobate ridges of angular supraglacial debris mark the extent of the last Neoglacial advance (Fig. 3). Between the lobate ridges and the lake shoreline, on the inner flank of the end-moraine complex, is an area of hummocky moraine. Steep gullies and scarps up to 2 m deep bound the hummocky moraine. Comparison of photographs taken between 1994 and 1999 indicates that the scarps and gullies are deepening and that the hummocky moraine is subsiding relative to the lobate end-moraine ridges. Also in this area are two well-developed sinkholes, each up to 45 m across (indicated “M” and “S”, Fig. 3). Sinkhole formation plays an important role in moraine surface lowering. Between 1996 and 1999 the moraine surface subsided by 19.5 m into one sinkhole (Fig. 4). At least 13 m of this subsidence occurred between October 1996 and
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Fig. 4 Cross-section through the inner flank of the Tsho Rolpa end-moraine highlighting variable degradation rates, 1995–1999. The location of sinkhole “M” is indicated on Fig. 3.

May 1997, equating to a maximum lowering rate of 22.3 m year\(^{-1}\). Adjacent to the sinkhole the surface lowering rates over the same period were up to 1.05 m year\(^{-1}\). Further evidence for moraine degradation is provided by rotational failures on the inner flank of the end-moraine ridge (Fig. 3). Each backscarp is up to 40 m long and 3 m high. Geophysical profiles through the rotational failures show that the moraine is not ice-cored at this location. The failures are interpreted as relating to an adjacent supporting ice mass beneath the lake, with slippage occurring as the ice gradually melts.

Degradation landforms on the Tsho Rolpa end-moraine, including subsiding hummocky moraine, kettle-form sinkholes and rotational failures, are coincident with the extent of buried ice as mapped geophysically. The internal structure of the moraine beneath a developing sinkhole (indicated “D”, Fig. 3) has been studied using GPR and electrical resistivity to determine possible controls on degradation (Fig. 5). At 61 m along the shown GPR radargram, there is a depression in the interpreted top of ice at a depth of c. 4.5 m below moraine surface (circled, Fig. 5(a)). A flat prominent bright reflection above the cusp coupled with a strongly attenuated zone beneath suggests that this depression is water-filled but penetrates into the ice mass below. The same feature is imaged in the electrical resistivity tomogram as an inclined low resistivity zone that dips towards the lake separating two highly resistive bodies to a depth of 15–20 m (Fig. 5(b)). The higher resistivity values observed (reaching 100 000 $\Omega$ m\(^{-1}\)) are clearly indicative of buried ice. It is clear that there is a significant discontinuity in the buried ice mass that is consistent with this zone being a debris and/or water filled crevasse that reaches to the base of ice. Correlation of a newly developing sinkhole in the moraine surface above a water and debris filled crevasse in the underlying ice core suggests that relict ice structures may act as foci for moraine degradation.

The role of relict ice structures in facilitating moraine degradation was observed in 1997 when an exposed block of ice >100 m\(^3\) gradually became detached along the line of a former crevasse. The ice block had been exposed in the side wall of a sinkhole into which the lake had encroached. Undercutting of the ice cliff at the water line was aiding calving and causing the ice block to rotate into the lake, failing along well developed crevasses (Fig. 6). In the process of calving, flakes of ice were spalling from
the undercut ice cliff. Sub-aqueous calving was also observed involving ice blocks of up to 4 m$^3$. Behind the rim of the sinkhole a series of sub-parallel gullies in the moraine surface were becoming activated. These were interpreted as crevasses being reactivated in response to the creep of ice towards the developing sinkhole. Sub-horizontal debris filled conduits exposed in the face of the ice cliff periodically issued pulses of saturated sediment. Connectivity of the conduits with the crevasses behind the sinkhole was inferred, allowing water and debris to drain from the widening crevasses.

**THULAGI, CENTRAL NEPAL**

Thulagi Glacier lake in Manaslu Himal, Nepal, is 2.2 km long and has a volume of c. 32 million m$^3$. At the downstream end of the lake is a complex of ridges and hummocky sand and gravel through which the main outlet river drains (Fig. 7). Exposures in the ridges show predominantly silt grade material overlain by angular to sub-rounded gravels and cobbles. They have been interpreted as erosional remnants of a former lake bed (Hanisch et al., 1998). GPR and electrical resistivity measurements over the area indicate the presence of a major ice body below 10–35 m of sediment (Hanisch et al., 1998). The ice is approximately 100 m thick, at least 550 m long and extends for 500 m across the entire valley. This stagnant ice and overlying veneer of silts, sands and gravels forms a dam that is at least 550 m wide.

![Geophysical data showing internal structures of the Tsho Rolpa end-moraine. (a) is a GPR profile, and (b) is an electrical resistivity tomogram. The profile location is indicated on Fig. 3.](image-url)
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Fig. 6 Stagnant glacier ice exposed within the Tsho Rolpa terminal moraine in May 1997. Note (a) the undercut ice cliff, (b) active crevasse behind calving ice block, and (c) debris filled conduit within the ice core.

Fig. 7 The ice-cored dam complex at Thulagi, Nepal, showing (a) hummocky sands and gravels, and (b) erosional ridges of silts and sands. The field of view is c. 700 m wide.
Evidence for degradation of the dam complex is restricted to the flanks of the ridges adjacent to the hummocky sand and gravel. Small slope failures within the finer silts and sands are evident where vegetation has not stabilized the ridge slopes. Within the hummocky area itself there are several depressions up to 8–10 m across containing concentrations of larger boulders. These have been interpreted as sinkhole drainage centres, although these features are relatively immature (cf. Clayton, 1964). The ice is not exposed and there is no morphological evidence to indicate that rapid ablation is occurring. Calculations of theoretical geothermal heat flow indicate that the average melting rate at the top of the ice has probably increased during the last 50–60 years but remains low at a maximum value of c. 2.4 cm year\(^{-1}\) (Hanisch et al., 1999).

The dam at Thulagi is considered relatively stable due to the large size of the ice body and the insulating properties of the overlying thick sediment cover. The 500 m wide dam is less vulnerable to overtopping by displacement waves than a narrow end-moraine dam. Breaching is only likely through accelerated widespread ablation or through external factors such as seismic activity. It is unlikely that the immature thermokarst development and low general ablation rates at Thulagi will have a negative impact on such an extensive ice mass in the foreseeable future.

**DISCUSSION**

**Processes of moraine degradation**

In the examples presented here, the ice-cored moraine dams were formed during stagnation of debris-covered glaciers. During periods of wastage, ice at the glacier margins may be insulated by the thick debris and can become incorporated within end-moraines to form substantial ice cores. Degradation of the moraine dam may then occur by ablation of the ice body beneath the debris cover, by localized thermokarst development within the buried ice and by slope failure in the moraine sediments.

Widespread lowering of the moraine surfaces at Hualcán and Tsho Rolpa is attributed to ablation of buried ice beneath the supraglacial debris. The resulting subsidence of the moraine surface produces characteristic hummocky topography that may be bounded by active scarps and gullies. Measured subsidence rates are of the order of 1–2 m year\(^{-1}\). These rates are consistent with published values of ablation on debris-covered stagnating glacier ice elsewhere (e.g. Watanabe et al., 1995). It is known that debris thickness and lithology type can influence ablation rate (Inoue & Yoshida, 1980; Nakawo & Young, 1981; Nakawo et al., 1999), but the variation in rates does not appear significant in terms of hazard development.

The development of thermokarst features such as sinkholes helps to accelerate moraine degradation. Proto-thermokarst features are expressed as linear and circular depressions in the moraine surface (Fig. 8(a)). These occur over water- and debris-filled crevasses as interpreted from geophysical investigations. The crevasses may act as meltwater conduits that aid differential melting of the sinkholes and lead to exposure of the ice core. Once the ice is exposed to solar radiation the melting accelerates and the backwasting ice slope steepens to form a cliff (Fig. 8(b)). If ponding occurs in the sinkhole, undercutting of the ice cliff may lead to Reeh-type calving (Reeh, 1968) (Fig. 8(c)). Water from icemelt and snowmelt may also collect in
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Fig. 8 Model of sinkhole formation within an ice-cored moraine dam. See text for discussion.

Sub-moraine supraglacial ponds and may pass through crevasses exacerbating the degradation (Fig. 8(d)). In time, the rotating ice block fails leaving a lower angle slope that may be insulated by debris (Fig. 8(e)). Backwasting may then continue until the next set of structures within the ice is exploited mechanically. Exposed ice may disintegrate as rapidly as 22 m year\(^{-1}\) as witnessed at Tsho Rolpa. Similar degradation rates were observed at Donjek Glacier, Canada, where Johnson (1971) reported erosion of exposed ice by an average of 0.6 m per week.

Slope failures on the inner slope of a moraine dam have been observed at Tsho Rolpa adjacent to the buried ice body. It is thought that the buried ice mass beneath the lake may support the toe of sediments in the moraine ridge. As the ice mass melts, this support is removed and the moraine sediments are able to slide. Rates of movement have been inferred from time series photographs and are of the order of centimetres per year. A similar process also occurs in moraines adjacent to active glaciers (MacDonald, 1989).

Role of degradation processes in hazard development

Moraine ridges containing ice cores are potentially unstable, leading to unstable moraine-dammed lakes. Degradation causes moraine subsidence and reduces the
structural integrity of the dam. Subsidence of relatively narrow end-moraine dams (e.g. Hualcán and Tsho Rolpa) leaves the dam vulnerable to overtopping by displacement waves from ice avalanches or by rising lake waters. Overtopping is one of the most common causes of historical outburst floods from moraine-dammed glacial lakes (Richardson & Reynolds, 2000). Relict glacier structures may fragment ice cores and reduce the cryostatic and lithostatic strength of the dam relative to the hydrostatic pressure of the lake. Structures within the ice core also provide possible conduits for lake water to percolate deep into the moraine core leading to the steepening of hydrostatic gradients thereby effectively reducing the width of the dam.

Dams containing thick and extensive bodies of debris-covered ice (e.g. Thulagi) are generally more stable than well-defined narrow end-moraine dams. Extensive ice bodies are less likely to be breached rapidly by the hydrostatic pressure of the lake or by erosion from displacement waves or rivers flowing over the ice and debris surface. Where ice is exposed by meltwater any downcutting will be gradual and lowering of the lake will be in a controlled manner.

CONCLUSIONS

Supraglacial lake formation on downwasting debris-covered glaciers may lead to the separation of a stagnant ice mass from the upper reaches of the glacier to form an ice-cored moraine dam. Moraine dams may subsequently degrade by: (a) ablation beneath a debris cover occurring at rates of a few centimetres to a few metres per year, (b) thermokarst development resulting in localized formation of kettle forms with subsidence rates of tens of metres per year, and (c) mass movement of the moraine sediments related to the wasting ice core and due to the saturation of sediment at the ice–moraine interface.

Relict glacier structures probably play a vital role in moraine degradation. Proto-thermokarst features may start as air- and water-filled voids at the ice–debris interface above old structures, which act as conduits for meltwater and lead to differential melting and exposure of the ice core. Degradation accelerates once the ice core has been exposed through the combined effects of solar radiation and mechanical failure due to the rheological response of the ice to deepening kettle forms.

Moraine dams containing ice cores are potentially unstable, leading to unstable moraine-dammed lakes. Degradation of the ice core causes moraine subsidence and lowers the lake freeboard, leaving narrow dams vulnerable to displacement waves from ice and/or rock avalanches into the lake. Structures within ice cores may also provide conduits for lake water to percolate deep into the moraine thereby threatening its structural integrity.

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