The construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru

J. M. Reynolds,1 A. Dolecki2 & C. Portocarrero3

1 Reynolds Geo-Sciences Ltd, The Stables, Waen Farm, Nercwys, Mold, Flintshire CH7 4EW, UK
2 Rust Environmental, 29 Cathedral Road, Cardiff, South Glamorgan CF1 9HA, UK
3 Unidad de Glaciología y Recursos Hídricos, Huaraz, Ancash, Peru

Abstract. At Hualcán in the Cordillera Blanca is a high-altitude glacier lake dammed by a moraine. Local glaciers regularly produce ice avalanches. In 1988 it was confirmed that the moraine was ice-cored. The rate of melting of the ice was sufficiently fast that, unless mitigation measures had been undertaken rapidly, the moraine would have collapsed. This would have resulted in the inundation downstream of Carhuazu, a town with a population of 25,000 people. Following the successful installation of siphons in 1988–89 to reduce the water level by 8 m, it was decided to undertake more permanent engineering works to ensure that the lake could never again pose a threat. It was proposed to construct a 2-m diameter tunnel, 155 m long beneath a rock bar below the moraine dam, to lower the lake level by a further 20 m. This would create sufficient freeboard to contain possible displacement waves.

Work on the tunnel was started in May 1993 using compressed air drilling and blasting with hand excavation. The initial tunnel design consisted of a single tunnel drive 135 m long plus a 20-m inclined drive under the lake. A second, near-vertical shaft was constructed for ventilation and access. Had the proposed method of breakthrough from the tunnel to the lake been carried out, it would have resulted in a rockburst leading to the catastrophic discharge of the lake. The tunnel design was changed on site to include three additional inclined drives from the main shaft, reaching the lake at vertical intervals of 5 m. Using this method, the lake level was lowered 20 m safely.

The objective of this paper is to describe in detail the geotechnical engineering aspects of the tunnel construction, the reasons for the change in its design, and the results of the mitigation work.

Introduction

On 13 December 1941, the town of Huaraz in the Callejón de Huaylas, Cordillera Blanca, was severely damaged by a catastrophic flood/debris flow caused by the rupture of lakes Palcacocha and Acoshecocha to the east. Over five thousand people were killed and considerable damage was caused to the town. Although this was far from being the first known disaster of its kind in the Cordillera Blanca (the earliest known in historical times occurred in 1702), it hit at the very heart of the Ancash Department, the town of Huaraz. Consequently, Corporación Peruana del Santa (CPS) was established in order to evaluate the safety of mountain lakes and to utilize the naturally stored water in the generation of hydroelectric power. CPS later became known as ElectroPerú in which the Unidad de Glaciología y Recursos Hídricos was established in 1966. One of the products of this work was the first glacier inventory of the Cordillera Blanca (Ames 1988), and some 40 hazard assessment and mitigation projects have been undertaken by ElectroPerú throughout the country. The problems of these catastrophic floods have been reviewed in detail by Lliboutry et al. (1977) and by Reynolds (1990, 1992, 1993).

The Cordillera Blanca is the largest glacier-covered area in the tropics, with some 722 glaciers covering a total area of 723 km² (Kaser et al. 1990). It is now well established that glaciers have been receding throughout the last 50 years (Hastenrath & Ames 1995), although reduced rates of recession and minor re-advances have occurred between 1974–79 and 1985–86. As the ice fronts retreat up-valley, lakes tend to form behind the moraines that marked the furthest advance positions of the ice tongues. Some of these moraine dams are ice-cored and are thus vulnerable to catastrophic collapse, releasing many thousands of cubic metres of water in very short time periods, typically several hours only. These catastrophic floods are known in South America as 'aluviones' (singular 'aluvión').

There are four main factors which, when combined, may lead to the eventual collapse of a natural moraine dam with significant impact on the local community.

- the volume of water within the lake;
- the presence of hanging glaciers (sources of ice avalanches);

• the structure and characteristics of the moraine dam; and
• the morphology of the land downstream, coupled with the presence of vulnerable communities and infrastructure.

For a lake to be considered to form a significant risk, there has to be a sufficient volume of water within it which, if released catastrophically, would have the capacity to cause major damage downstream.

Hanging glaciers either act as a source of ice avalanches or may themselves actually slide down the mountainside into the lake. The displacement waves arising from the impact of the falling ice create seiche or standing waves within the lake. Depending on the amplitude of the seiche wave, the local moraine dam may be over-topped and the overflow may cause erosion on the distal side so compromising the integrity of the dam. If the first seiche wave damages the dam, successive waves may aggravate the weakness until the moraine fails.

Moraines are complex masses of heterogeneous materials formed by many processes: deposition, thrusting, slumping, ablation of material, downwasting by

waterflow, fluvio-glacial processes, slope instabilities, etc. Some moraines are affected by piping whereby water is able to permeate through the moraine through conduits from which fine material is removed. Continued attrition of material from within the moraine weakens it until failure occurs. Furthermore, inherent weaknesses within a moraine can be exacerbated by earthquakes. If an ice core is present, formed by the burial of stagnant glacier ice, its melting results in the gradual lowering of the moraine dam until the freeboard is reduced to nothing and the lake overtops the moraine.

If the above phenomena occur in a remote area, potential breaches through the moraine may have only a limited effect on the immediate locality and there may be little risk to communities. However, with increasing populations causing growing communities particularly at the confluences of rivers which offer good development sites in otherwise very steep mountainous regions, a growing number of people are at risk from inundation from aluviones. Also, vital infrastructure (roads, railways, bridges, etc.) may be at risk, and in some cases, hydroelectric power installations may be vulnerable. Should such structures be severely damaged or totally destroyed the consequential economic loss may be very

Fig. 1. Location of Lake 513 and the area threatened by a potential aluvión.
substantial, not only in the immediate aftermath of a disaster, but for periods in excess of decades (Reynolds 1992). The total economic losses can easily mount to billions of dollars. For developing countries such as Peru, such huge financial losses could have a very significant impact on the entire financial state of the country over many years.

As a means of reducing the potential risk to communities vulnerable to possible alluviones, hazard assessment has been and is being undertaken. Once a glacier lake has been identified as being potentially dangerous, and for what reasons, a mitigation strategy is devised. In Peru, four different approaches have been taken to alleviate the dangers of catastrophic floods.

- excavation of open cuts in the moraine dam to lower the lake's water level;
- construction of siphons;
- tunnelling through bedrock into the lake to drain it; and,
- construction or restitution of the natural dam.

Aspects of moraine structures and methods of remediation have been discussed in detail by Lliboutry et al. (1977) and by Reynolds (1992). Open cuts in a moraine can be excavated during the dry season when a lake's water level is lower than that during the wet season. Such a method is risky as any displacement wave arising from an ice avalanche can rip through the cut and breach the moraine. This should only be attempted where there is no risk of avalanches into the lake.

Siphons are attractive in that they are readily transportable, relatively easy to install, and can be very effective, as will be described later. They are used as a first-stage method of reducing water level prior to undertaking more substantive measures.

Tunnelling can only be carried out through competent rock beneath or beside a moraine dam. The costs of such a method are such that tunnelling is only undertaken where the expense can be justified. Unfortunately, not all moraine dams are suitable for tunnelling as the local materials may be inappropriate for such a technique.

Reconstitution of a moraine dam can be achieved by making a cut into the freeboard, placing a substantial culvert and recovering it to restore the freeboard. This exposes the moraine to the risks from avalanches, but if the work can be carried out quickly, the method can be very effective.

One aspect of hazard mitigation which is often overlooked but which is absolutely vital to the safe remediation of any glacial lake is that the whole glacier/lake system should be monitored carefully throughout the mitigation work. This permits the possible detection of any potential problems arising in the local catchment.

While this paper concentrates on describing a specific example of glacial hazard mitigation in Peru, catastrophic floods are known to occur elsewhere, such as in the Alps (Tufnell 1984; Dutto et al. 1991), the Himalayas (Ives 1986; Reynolds 1995, 1998), and in North America (Mt Rainier, Washington State (O'Connor & Costa 1993); Canadian Cordillera (Clague & Evans 1994); Yukon (Clarke 1982)), amongst many others.

**Background to Hualcán**

**Physical and geological setting**

In August 1988 a field visit was arranged to an unnamed lake, referred to as Lake 513, at the head of a river valley approximately 12 km NE of Carhuaz (Fig. 1). This town has a population of c. 25,000, and lies within the Callejón de Huayas, some 30 km NW of Huaraz. ElectroPerú had previously investigated this lake in 1985 and again in 1988. Over this time interval the ice-cored moraine damming the lake had lowered by about 4 m at an average rate of 11 cm per month. At the time of the authors' (J.M.R. and C.P.) visit in August 1988, water from the lake was already filtering over the ice core within the moraine (Fig. 2) and draining via two springs on the down-valley side. There was less than 1 m of freeboard. It was thought that if nothing had been done to mitigate the situation, the moraine would have failed within two months, probably destroying Carhuaz with the loss of many thousands of lives.

**History of hazard assessment and initial mitigation**

In August 1988, it was concluded that the immediate course of action was to install a siphon to lower the lake level by at least 8 m and preferably 12 m to below the level of a natural bedrock rim beneath the moraine. By the end of October 1988, one siphon had been constructed and was discharging at a rate of 1901 s⁻¹. However, by Christmas, the water level had not changed even though about 1 million m³ had been discharged. Fortunately, funding for a further siphon was arranged and installation was completed by the end of January 1989. The combined rate of discharge was 5001 s⁻¹. By 31 March, the water level had fallen 2 m and fell a further 2 m by June 1989. By June 1990, the water level had been lowered by a total of 5 m and it was considered safe to excavate a channel through the moraine to ensure that the lake level could not rise above this level. More details of the hazard mitigation phases have been given by Reynolds (1990, 1992).

In 1991, a significant ice avalanche occurred causing displacement waves up to 2 m high which overtopped the moraine through the excavated channel causing regressive erosion of the moraine and an aluvión ensued. This resulted in a channel some 20–25 m deep being eroded through the outer moraine. Fortunately, deposition of flood debris was contained locally within a flat-lying infilled lake downstream of Lake 513. Flood water and
some debris caused damage to bridges several kilometres downstream but no lives were lost. The occurrence of this aluvión was a stark reminder of the potential power of such floods. It demonstrated that there was still a real risk of a more substantial aluvión occurring should a larger ice avalanche take place. Consequently, it was decided to construct a 2-m diameter tunnel, 155 m long, through the rock bar to 20 m below the then water level in order to drain the lake still further. The basic design of the tunnel is shown in Fig. 3.
**The tunnel**

**Engineering geology**
Surface geological mapping by geologists from Electro-Perú provided initial information on rock characteristics and the nature of discontinuities. No intrusive investigation or laboratory analysis was undertaken. Electro-Perú had decided to drive the 2-m diameter drainage tunnel using drill-and-blast techniques with hand excavation. The majority of the tunnel was likely to be constructed through the granodiorite bedrock, with the final rock ‘plug’ masked by morainic debris on the floor and sides of the lake. Engineering geological mapping of the initial discharge portal area of the tunnel confirmed the strength of the rock mass and anticipated support requirements for the tunnel.

The conditions exposed light grey, coarse-grained massive and fresh, very strong granodiorite rock with generally widely spaced joints. The rock mass was intersected by a number of low-angle normal faults and numerous randomly orientated, generally tight, low persistence, generally rough but planar joints. At several locations within the tunnel, significant water inflows were encountered, generally emanating through open, vertical and mineralized joints (probably leakage through interconnection with the lake floor). These flows did not affect the overall stability within the tunnel.

Rock mass classification systems were employed to confirm tunnelling condition and to predict support. Joint orientation can affect blasting, span widths, roof support and groundwater flows, and it was vital that this information was collected and assessed as tunnelling progressed. The Peruvian geologists were introduced for the first time to the Norwegian Geotechnical Institute (NGI) system of Barton *et al.* (1974, 1992). On the basis of an evaluation of a large number of case histories of underground excavation stability, Barton *et al.* (1992) proposed an index for the determination of a tunnelling quality of a rock mass. The Tunnelling Quality Index, $Q$, is based on an assessment of six parameters relevant to the consideration of the rock discontinuity fabric, groundwater conditions and stress regime. The numerical value of this index $Q$ is given by:

$$Q = \frac{(RQD)}{J_n} \times (J_i/J_a) \times (J_w)/SRF$$  \hspace{1cm} (1)

where $RQD =$ rock quality designation; $J_n =$ joint set number; $J_i =$ joint roughness number; $J_a =$ joint alteration number; $J_w =$ joint water reduction factor; and SRF =$=$ stress reduction factor.

The $Q$ system can be used to predict behaviour and support requirements by the use of an additional parameter, $D_e$, equivalent dimension, where:

$$D_e = \frac{\text{span, diameter or height of excavation (m)}}{\text{excavation support ratio (ESR)}}$$  \hspace{1cm} (2)

where the excavation support ratio is related to the use for which the excavation is intended and the extent to which some degree of instability is acceptable. $Q$ values in excess of 10, representing good quality rock, were generally encountered along the tunnel route. For the majority of the Lake 513 tunnel, the equivalent dimension was taken as 2 m/1.6 = 1.25 m.

Hence, given the tunnel width/excavation span and function of the tunnel, the assessment confirmed that the tunnel was unlikely to require support for the construction duration time and full service life. Particular areas required special consideration, but no remedial measures

<table>
<thead>
<tr>
<th>CHAINAGE</th>
<th>40m</th>
<th>GRANODIORITE</th>
<th>50m</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRACTURES</td>
<td>F5 - M2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER</td>
<td>0.011/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q/SUPPORT</td>
<td>2-(D)POOR</td>
<td>10 - (CLASS B) GOOD ROCK - UNSUPPORTED</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 4.** Example of a tunnel log at Lake 513.
were needed in practice. An example log of the engineering geology of the tunnel is presented in Fig. 4.

**Construction**

Excavation of the tunnel using hand-held compressed-air drilling equipment, blasting of explosives and 'mucking out' by hand was a slow process, but was the only available technique given the extreme site conditions (altitude, remoteness and equipment availability in relation to site access).

The typical blasting pattern and sequence, shown in Fig. 5 provided the optimum rock breakage and debris pile formation for the particular rock type, strength and cross-sectional area of the tunnel.

A charge of approximately 5 kg m\(^{-3}\) per 1.3 m depth of tunnel round using burn cut with a total of 38 holes per round and half a second delay period was used for most of the length of the tunnel. Ventilation was by compressed air blown through tubes to the tunnel face area, with clearance subsequently travelling throughout the entire tunnel length.

On return to the face, visual inspection and scaling of loose rock was carried out prior to 'mucking out' with shovel and wheelbarrow. The rate of advance with one to two rounds per day was typically between 10 m and 13 m per week.

Breakdowns were very common due to prevailing conditions, particularly the thin air at altitudes of 4500 m. No support or permanent lining was utilized. The downstream tunnel portal is shown in Fig. 6. The view is towards Lake 513. The shaft gantry above the ventilation shaft is arrowed. The smooth bedrock was exposed by the 1991 aluvión.

**Breakthrough into the lake**

It was originally intended by ElectroPerú that the breakthrough from the tunnel into the lake should be achieved by a single explosive blast at a level 20 m below the then water level. Had this procedure been followed, it was estimated that the static water pressure alone within the tunnel would have exceeded the local overburden pressure; the dynamic pressure effect of the water driving through the tunnel immediately after the explosion would have added to the local in-tunnel pressure. The combined effect would have undoubtedly resulted in a rock burst at the discharge portal. This would have led to an uncontrolled discharge of the lake, with potentially catastrophic consequences downstream.

During the visit to the site by all three authors in October 1993, an alternative design was devised which required only additional explosives. All other potential options were either far too costly or were considered impractical under the prevalent field conditions. It was decided that a series of three additional sub-horizontal drives (Fig. 3) should be constructed using the same excavation techniques as for the rest of the tunnel. The work was undertaken between October 1993 and May 1994. In October 1993, ElectroPerú engineering geologists and engineers were given brief but necessary training in new techniques of tunnel construction and safety (e.g. that of Barton et al. 1992).

Each additional drive terminated within bedrock several metres from the estimated base of the lake and at approximately 5 m vertical increments. The uppermost tunnel was connected with the lake by a small explosive charge producing a 0.9 m diameter portal into the lake. The lake discharged through this until the water level reached the lower lip of the portal. The second tunnel was then connected to the lake by the same process and the lake drained a further 5 m. Problems occurred with the charges within the end of the third additional tunnel and this was abandoned. The lake-side portal of the main tunnel was exploded through under 10 m head of water. Using this staged approach, the structural integrity of the bedrock bar was retained, and the dynamic pressures within the tunnel during drainage were reduced relative to those anticipated had the original plan been followed. Furthermore, the rates of water flow and the peak volumes were all within the tolerances within the existing river system downstream, thereby minimizing damage to the river bed during the controlled drainage. By May 1994, the lake level had been lowered safely by 20 m.

An additional benefit of this design is that, should the lowermost tunnel become blocked, and the lake level...
rise again, the discharge portals at higher elevations would still be able to provide safe discharge of the lake. Maintenance of the higher portals was possible once the lake achieved its reduced level. This also increased the freeboard of the rock bar against any possible displacement waves arising from large-scale ice or rock avalanches.

**Final discussion and conclusions**

The present case history has demonstrated the successful implementation of both short-term and long-term mitigation measures following appropriate glacial hazard assessment. Installation of two siphons provided almost immediate relief, allowing time to implement a larger-scale engineered solution, namely the tunnel. The two greatest risks throughout the project were a potential lack of finance for the mitigation measures within an appropriate time scale, and the possible occurrence of a significant ice or rock avalanche into the lake during the construction of mitigation measures.

The original tunnel design was demonstrated to be potentially hazardous but alternative solutions were adopted that resulted in the lowering of the lake level by 20 m safely. Revised training of local geological and engineering staff has raised their awareness of new tunnel construction and safety techniques.

From initial awareness of there being a problem at Lake 513 through to the completion of safety works took 9 years. Had the initial siphons not been installed when they were, there would have undoubtedly been a major aluvion with the loss of thousands of lives.

For glacier hazard mitigation to be successful, there has to be a monitoring programme in place that facilitates the recognition of potentially dangerous lakes. There then has to be the political and financial support on a short enough time scale for the implementation of immediate mitigation measures. At the same time, plans can be developed for the long-term mitigation work leading to the final completion of lake remediation.

There are thought to be in excess of 600 potentially dangerous lakes within the Peruvian Andes alone. To cope with what is a growing problem, given the continuation of glacier recession and lake development through global warming, there is an urgent need for a national government strategy for glacier hazard assessment and mitigation. This project has demonstrated
that, given the timely intervention and appropriate mitigation measures, dangerous lakes can be made safe relatively inexpensively. The costs of mitigation are a fraction of those of disaster relief. Donor countries, who typically spend vast sums of money on relief programmes following disasters, could contribute money more effectively by supporting mitigation programmes in order to reduce the risk of potential disasters. This approach is better for both the donor country and the recipient nations. It is perhaps appropriate that this fact is emphasized at the mid-way point in the International Decade for Natural Disaster Reduction.

Acknowledgements. J.M.R. and A.D. are both grateful to the Emergency Aid Department of the Overseas Development Administration for funding the visit in November 1993. ElectroPerú has provided excellent facilities, hospitality and logistical support throughout this work.

References


