The Attabad landslide crisis in Hunza, Pakistan – lessons for the management of valley blocking landslides

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ABSTRACT
On 4th January 2010, a rockslide blocked the Hunza valley at Attabad in Pakistan. The landslide, which had a volume of c.45 million m^3, generated a natural dam c.120 metres high and 1.5 km long. Subsequently, a 22 km long lake developed behind the barrier, reaching a maximum volume of >500 million m^3. This paper outlines the development of the landslide failure event, the filling of the barrier lake, and the overtopping event, and examines the major challenges that the landslide presented. This analysis is used to highlight lessons that can be learnt the management of large valley blocking landslides.

RÉSUMÉ
Le 4 Janvier 2010, un éboulement a bloqué la grande vallée de l'Indus à Attabad au nord-ouest Pakistan. Le glissement de terrain, qui avait un volume de c. 45 millions m^3, a généré un barrage naturel à quelque 120 mètres de haut et 2,5 km de longueur. Par la suite, un lac 25 km de long au point derrière la barrière, pour atteindre un volume maximal de plus de 500 millions m^3. Ce document décrit l'évolution du glissement de terrain et l'événement le déversement, et examine les défis majeurs que le glissement de terrain a présenté. Cette analyse est utilisée pour mettre en lumière les leçons qui peuvent être tirés de la gestion des glissements de terrain grande vallée de blocage.
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1 INTRODUCTION

The 2010 Attabad landslide disaster of Hunza in northern Pakistan is one of the most significant landslide events to have occurred in the last two decades, affecting over 100,000 people for a period of more than a year to date. At the time of writing the chronic hazard remains unresolved, with large numbers of people displaced or severely compromised; road access between Pakistan and Tibet impeded; and a very high level of residual risk remaining in the landscape. This paper seeks first to outline the nature of occurrence of, and the sequence of events associated with, the Attabad landslide; and second to describe and discuss possible lessons learnt from the management of the crisis that unfurled at the site. The paper does not seek to apportion blame to any party in any respect in the management of this most difficult crisis.

2 THE ATTABAD LANDSLIDE SITE

The Attabad landslide occurred within the valley of the Hunza River in northern Pakistan (Fig. 1). The Hunza flows in a generally southward direction from its source on the Tibetan Plateau into northern Pakistan, where it joins the Indus River. The Indus then drains southwards through the remainder of the mountain chain, and then across the deserts of Pakistan to drain into the Arabian Gulf. As such the Hunza drains a substantial area of the Karakoram mountain chain. The Hunza river valley is perhaps best known as the route of the northern component of the Karakoram Highway, a strategically-important but comparatively poorly-maintained mountain road linking Tibet with Pakistan. This road is of great strategic importance as it provides a key connection between western China and the Pakistani sea ports on the Arabian Sea. As such it is potentially important route in terms of the economic development of the far west of China, meaning that the loss of the highway has economic, social and political implications that pass well beyond the borders of Pakistan.

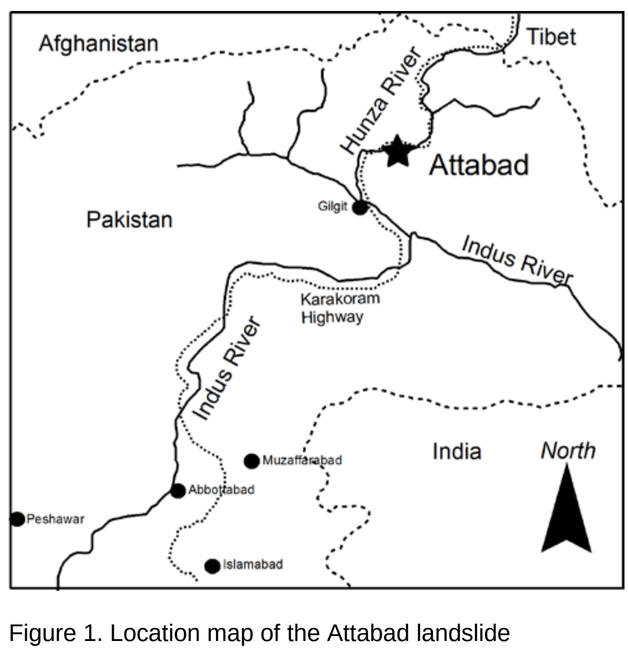

Figure 1. Location map of the Attabad landslide

The Hunza valley has a long history of landslides, as witnessed by the valley walls, which are marked by large numbers of very large landslide scars, and mass movement deposits are found widely on the valley floors and on the lower part of the valley walls. On a smaller scale, during the construction of the Karakoram Highway in the 1970's and 1980's almost 900 workers lost their lives, with the primary cause being landslides and rockfalls. Mass movements remain a daily occurrence on the highway, causing extensive disruption and frequent loss of life. It should also be noted that the area has also been assessed as being associated with high levels of seismic hazard, exacerbated by the likely location of a large seismic gap (Thingbaijam *et al.* 2009 for example).

It is clear that the ancient mass movements have frequently led to blockages of the valley, evidenced by the numerous fragmentary remains of both landslide deposits and upstream sediments from barrier lakes. More recently, a large, valley-blocking landslide is known to have occurred at Salmanabad in Hunza in 1858, damming the Hunza river valley for over six months and generating a lake over 30 km in length. The landslide dam breached catastrophically, probably as a result of landslide-generated waves. The location of this breach-generating landslide was close to the upstream end of the lake. The resultant flood caused extensive damage along a >400 km length of the Hunza and Indus river valleys, including substantial loss of life.

2.1 The landslide

The village of Attabad was located in Gilgit-Baltistan Province, approximately 130 km upstream of the town of Gilgit (Fig. 1), which marks the confluence of the Hunza and Indus rivers. The village was located on the western wall of the Hunza Valley, about 600 m above the bed of the river. The climate in this part of Pakistan is essentially arid, with high (25 to 30°C) summer temperatures but sub-zero temperatures in the winter. The village was home to a few hundred people who mostly made a living through subsistence agriculture, supplemented by day wage work and some work-related migration.

The geology of the Attabad area is complex due to the intense tectonism that has affected this region (Hussain and Awan 2009). The site is underlain by deformed and sheared Precambrian orthogneisses and paragneisses of the Baltit Group. These rocks are extensively affected by very large-scale veins. Some local faulting is evident. Overlying the bedrock are extensive, thick deposits of Holocene colluvium and fluvio-glacial deposits, mostly consisting of gravels, cobbles and boulders with a sandy matrix. Some evidence of shearing is seen in these deposits.

In 2002 a series of large cracks developed in the slope, running through the village and surrounding farmland. Local reports suggest that these cracks first developed during the 20th November 2002 M_w = 6.3 earthquake (Hussain and Awan 2009), the epicentre of which was located approximately 75 km to the south of Attabad. This earthquake was responsible for 23 deaths and some landslides across northern Pakistan, including a small number of mass movements in the Gilgit-Baltistan area. Over the succeeding six years the cracks in the slope at Attabad progressively lengthened and widened. Significant movement events were recorded in 2004 and again in 2005 during shaking associated with the 2005 M_w = 7.6 Kashmir earthquake (Hussain and Awan 2009).

By 2009, the cracks had extended over several hundreds of metres. Hussain and Awan (2009) reported three main crack systems, with maximum displacements of over 5 metres. At this stage 12 houses had been seriously damaged by the deformation. Hussain and Awan (2009) recommended that the actively deforming component of the slope should be evacuated; this was implemented by an NGO, Focus Humanitarian Assistance in late 2009.

On 4th January 2010 the slope at Attabad failed catastrophically, without any reported precursors or warning signs. There was no apparent trigger for the landslide, which occurred in the middle of winter when the atmospheric conditions were both dry and cold. Two days earlier, on 2nd January 2010, an earthquake of magnitude M_w = 5.1 had occurred in Central Asia, but as the epicentre was about 450 km to the northwest of Attabad it is improbable that this event was responsible for the final collapse.

Although the landslide involved a total mass of about 45 million m^3, eye-witness reports and some photographic and even video evidence suggest that it occurred in a series of probably retrogressive collapses extending over more than 24 hours. However, the initial failure event was undoubtedly both large and highly dynamic, although of unknown volume.

The landslide has a maximum vertical extent of c. 1,175 m from the present crown of the landslide scar to the river bed, and the maximum horizontal displacement was about 1,300 metres (Fig. 2). The landslide body blocked the Hunza valley to a depth of about 200 m at the highest point and 120 m at the saddle. The resulting deposit was highly asymmetric, with the highest point being located on the far side of the valley from the landslide scar (Fig. 2). The across valley length of the main deposit is about 300 metres, and it is about 1.5 km in length along the axis of the valley.

The landslide process appears to have been complex, consisting of at least two different landslide mechanisms, controlled by the local geological conditions. The main failure event was a rockslide / rock avalanche consisting of a combination of bedrock and superficial deposits. The resultant deposit is chaotic, but is divided into distinct zones. For example, the upstream portion of the landslide deposit consists mostly of chaotically-organised large boulders with no matrix, whereas other parts consist of a mix of boulders and superficial deposits. This may reflect a multiphase failure process.

The second landslide event is associated with the superficial deposits in the valley. At Attabad the floor of the Hunza Valley comprised recent river sediments sitting over a reasonably thick, silty-clay lake bed deposit. This deposit was probably laid down in the lake that formed behind the 1858 valley-blocking landslide at Salmanabad, the site of which was located just 3 km downstream of Attabad. The first, presumably large, phase of the Attabad landslide event was rapidly emplaced onto this saturated lake-bed deposit. It appears that the emplacement induced liquefaction, presumably through an extreme undrained loading process, causing catastrophic mobilisation of the mass (Fig. 3).

Figure 2. Photograph of the Attabad landslide looking from downstream of the dam. The source area is on the left, and the main landslide mass is on the right side, piled up on the opposite valley wall. The dark mass is the silty-clay mantling the landslide body. The saddle is clearly visible in the centre–right of the photograph.

Figure 3. Photograph of the secondary mudflow that travelled downstream from the Attabad landslide, killing 19 people. The image was taken from the main landslide body. Note the flow structures and the water ponded on the surface of the mass. The fresh material in the lower right corner is spoil excavated from the spillway.

The lake bed deposit formed three separate, simultaneous flow-type landslides. The first reportedly flowed about 1.5 km in an upstream direction along the Hunza Valley, although this flow has been difficult to verify as it was inundated by the lake within a few days of the failure event. The second flowed across the valley and was then pushed up the opposite valley wall, before flowing back across the main landslide mass to be emplaced on top of it (Fig 4). The third, largest, flow travelled downstream along the Hunza valley for about 3 km, terminating at the remains of the 1858 landslide dam. This flow was reported to have travelled rapidly along the valley, and there is ample evidence from the valley walls in the form of disturbed vegetation and splash marks to support this report. In the path of the flow was Sarat, a small hamlet located on a riverside terrace, surrounded by small fields on the surface of adjacent river terraces. The downstream flow struck Sarat directly, killing 19 people; these were the only direct fatalities from the landslide event. However, in total the homes of 1,652 people were destroyed or rendered unsafe by the landslides.

Figure 4. Photograph of the sharp contact between the silty-clay and the underlying landslide deposit. The width of the section shown is about 50 cm.

2.2 The landslide dam

The rockslide deposit formed a natural dam that blocked the Hunza valley, totally impeding flow and allowing the development of what is now known as Gojal Lake. Within two days of the landslide this lake was being monitored by a team of geologists from Focus Humanitarian Assistance. Although this monitoring was undertaken using rudimentary (but effective) surveying techniques, the resultant dataset of the lake level against time is excellent (Fig. 5). The filling curve for the lake is complex, reflecting an unusual hydro-meteorological regime (Petley *et al.* 2010). Unfortunately though there are no gauging stations for the Hunza River upstream of the landslide. The river is primarily fed by melt water from seasonal snow and from glacial melt in the high mountain areas. Thus, at the time of the landslide (winter) the river discharge was low, and it remained in such a state for the first four months after the landslide emplacement. Inflow increased during the late Spring, fed primarily by snowmelt and the release of water from glaciers, driven by the higher summer temperatures. Occasional higher discharge events occurred, generally associated with small glacial lake outburst floods (GLOFs) and subglacial drainage events. Concern remained high that a sudden, larger GLOF event could occur, especially in the latter stages of filling, that could trigger a breach event, but no monitoring was in place for such an event. Fortunately this risk has to date been unrealised.

2.3 Dam performance forecasting

From very early on in the crisis concern was raised about the possible future performance of the natural dam. Concern centred on two key aspects:

a. The potential for the dam to fail during or after overtopping, with the resultant possibility of a high magnitude flood;
b. The potential for the dam to remain intact after overtopping, with the result that the hazard would remain in the landscape and the Karakoram Highway would remain blocked indefinitely.

Both scenarios represented real cause for concern, albeit potentially affecting different groups of people. The former scenario, if the breach were to be rapid, generated a situation in which the population downstream was substantially imperilled. The latter scenario produced a chronic hazard for the upstream community, numbering about 25,000 people.

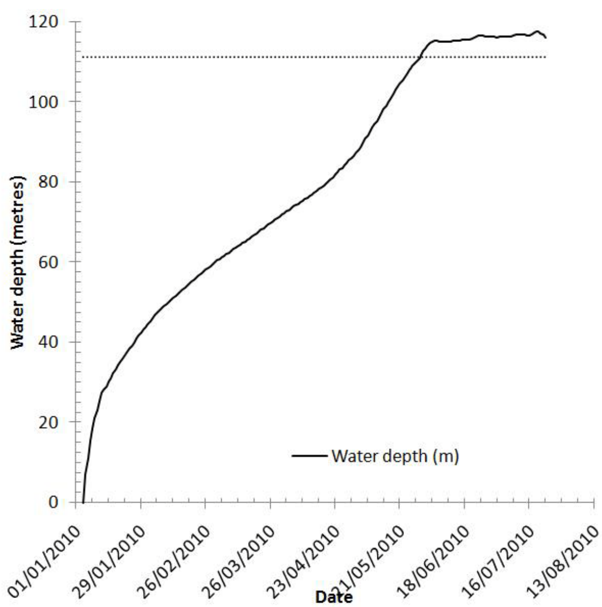

Figure 5. Focus Humanitarian Assistance data of the water level in Gojal Lake from the point at which filling commenced (after Petley *et al.* 2010).

However, there was considerable uncertainty about which of these two scenarios might play out, primarily as a result of a distinct paucity of information about the internal structure of the rockslide deposit. The surface layers of the landslide consisted of two materials. On the upstream face of the landslide mass the deposit mostly consisted of large (metre to tens of metres long exes lengths), chaotically-organised boulders, with very little matrix. However, the landslide saddle and the downstream face was mantled by the river-bed silty-clay, which potentially had low resistance to erosion. It was unclear as to whether the structure beneath the silty-clay consisted of fine or coarse materials. Inference from the lack of through dam seepage during the early stages of filling suggested that it must be reasonably fine-grained, but a lack of boreholes or geophysical surveys meant that this could not be determined. Despite recommendations to so do, the authorities were not able to organise any exploratory drilling to investigate the internal structure.

The lack of information on this aspect meant that the potential performance of the dam had to be inferred from the known behaviour of previous examples. These suggested that the level of hazard of a rapid breach event was unacceptably high. For example, previous known large-scale landslide barriers on the Hunza River had shown rapid breaching. Indeed, despite the multiple landslide scars mantling the walls of the Hunza valley, no barrier lakes remain present in the landscape, and there is little evidence that previous barriers have been completely filled by sediment. Secondly, the source materials of the landslide included substantial amounts of comparatively fine-grained colluvium and glacial deposits, suggesting that the core of the dam could be fine-grained. Thirdly, the silty-clay deposit mantling the top of the dam was also potentially erodible. Mitigating the threat of a rapid breach event was the relatively low-angled downstream face of the landslide deposit, and the potential for a coarse-grained core to the landslide as per the upstream face.

The key response to the threat by the Pakistani National Disaster Management Agency (NDMA) was to implement the construction of a spillway across the saddle of the landslide. The aims of the spillway were to reduce the peak volume of the lake at the time of overtopping and to control the flow. The original intention of the agency was to construct a channel 30 metres deep. No plans were in place to armour the base or the downstream face of the spillway, although it was anticipated that the excavation would remove the erodible silty-clay deposit. However, excavation of the silty-clay proved to be exceptionally challenging. During drying the surface of the silty-clay formed a slightly plastic crust that effectively reduced the rate of water loss from the underlying, plastic materials. Tracked machinery quickly broke through this crust and then often became bogged down in the wet sediments below. As a result, despite the presence of several backhoes and bulldozers, the maximum spillway depth at the time of overtopping was about 15 m, and the bed of the spillway remained mostly within the silty-clay deposit. It should be noted that these excavations exposed the operators to high levels of risk. Large-scale rockfalls occurred on a daily basis. Unfortunately one bulldozer operator and one local man were killed by rockfalls during the excavation operations.

Close to the time of overtopping the NDMA organised the evacuation of the population from the valley floor downstream of the barrier over a distance of about 100 km, and ordered the preparation of evacuation plans for the remainder of the population along the Hunza and Indus rivers from Attabad to the Tarbela Dam close to Islamabad. Mostly of the relocated population were moved onto the valley sides away from the flood level, with the safe level being considered to be 50 m above the valley floor.

Generating scenarios for behaviour during overtopping proved to be very difficult given the lack of data for the area affected. Regression-type analyses for a breach event (e.g. using for example the equations of Costa and Schuster 1991) suggested that the peak discharge for a rapid breach could range from about 5,000 to 50,000 cumecs. Flood modelling, undertaken by several groups, suggested peak water depths of over 30 metres for reasonable breach scenarios (See Leonard *et al.* 2010). Previous landslide dam floods and GLOF events suggested that little attenuation of the flood wave along the river valley was likely, primarily because of the very narrow topography of the valley system, resulting in high levels of risk along the length of the Hunza and Indus rivers as far as the dam at Tarbela, some 400 km downstream from Attabad. It was clear however that, contrary to some local reports, the capacity of both the reservoir and the spillways at Tarbela were sufficient to deal with any reasonable breach scenario.

2.4 Local impacts

During the early part of 2010 the key impact of the landslide on the local population was the loss of the Karakoram Highway. Initially the blockage was just for the 1.5 km stretch of the landslide mass itself. However, the road is located on a platform cut into the valley wall within 50 m of the valley floor, such that as the lake filled the highway upstream of the blockage was progressively inundated. At the time road had been undergoing large-scale upgrading works, including carriageway widening and the construction of new culverts and bridges. The loss of the road rendered the upstream population, numbering about 25,000 people, cut off from the outside world until the high pass to the north reopened in the late spring. This population lost their major sources of income, which were passing trade on the road and the export of agricultural products, and access to basic needs such as health care and electricity was also severely impacted. For example, there were no medical professionals located on the north side of the barrier. At the time of overtopping the maximum length of the lake was about 22 km, meaning that in excess of 25 km of road was buried or inundated. Some mitigation for this was provided by the provision of a helicopter service in the early days after the landslide emplacement, replaced by a rudimentary and expensive ferry service later on.

3 LAKE FILLING

For the following reasons forecasting the time of overtopping proved to be very difficult:

a. The Hunza River has a very strongly seasonal discharge, controlled primarily by melt in the high mountains. Thus, the rate of in-flow was expected to increase substantially in the late Spring. However, as this is temperature controlled, the timing of the increasing discharge proved difficult to estimate. In fact the mountainous areas of northern Pakistan suffered an unusually cold winter, meaning that the increase in discharge occurred later than had been anticipated, such that the overtopping event was rather later than some estimates had indicated.
b. Good quality topographic data were not available, meaning that determining the potential lake storage volume proved to be difficult. Various iterations of DEMs generated from SRTM and ASTER data were tested by groups from the USA and Canada (Leonard *et al.* 2010); none of these approaches proved to be entirely satisfactory in forecasting the time of overtopping;
c. The time of overtopping was also controlled by the rate of excavation of the spillway. Clearly a more rapid construction process (and thus a deeper spillway) would have led to an earlier overtopping event. As the spillway excavation was slower than expected, overtopping occurred later;
d. Unexpectedly, the floor of the spillway underwent heave as the lake level rose, probably in response to both increased water content in the silt and creep of the channel wall materials. In the later stages of excavation some of the extracted materials were dumped closed to the edge of the channel. This may have generated a surcharge load that may have exacerbated deformation of the channel walls and bed.

A consequence of this uncertainty a series of premature estimates of the overtopping date were made by a range of agencies and announced to the media, generating mistrust amongst the already discomforted local population. Rumour and speculation were rife. In an attempt to mitigate the uncertainty associated with the overtopping date, the author, working with Focus Humanitarian Assistance, started to produce daily graphs of measured lake level and the spillway bed level. These were posted online on a dedicated website by the combined FHA and Durham teams, providing a simple display of the freeboard on a daily basis, accompanied by a simple commentary to explain how and why this was changing. These graphs were widely used in Pakistan, and provided an independent source of information to planners, NGOs and potential victims of a flood. However, this approach was criticised in some quarters, who expressed the view that information should be provided only by the relevant agencies. Some parties expressed the view that the provision of this information rendered the work of the relevant government agencies more difficult, although to date no concrete evidence of this has been provided. The author recognises that this is an open question that requires further research, and has sought information to support these suggestions.

However, it is true to say that the difficulties in monitoring the situation on the ground using an ad hoc, if highly able and dedicated, team, especially in the later stages of the lake filling, meant that the heave of the channel base was not anticipated and the effects were under-estimated. As a result, the overtopping event occurred a few days later than had been reported. However, when it was identified that this heave was occurring this information was posted on the website with an explanation.

Initial analysis of the potential failure modes of the dam identified two additional possible mechanisms. The first was a catastrophic breach triggered by either a landslide into the lake or an earthquake. This was considered possible but unlikely. The second, more likely, scenario was considered to be piping (seepage) failure. The morphology of the dam, and in particular the low-angled downstream face of the landslide mass, and the presence of the lower permeability lake deposit mantling this surface, were considered to reduce but not eliminate the likelihood of this mechanism of failure. However, the lack of knowledge about the internal structure of the dam meant that it was hard to estimate the likelihood.

Seepage first developed on the downstream face of the dam about two months after landslide emplacement, and thereafter steadily increased with the rising lake level rose (Fig. 6). Over time seepage developed in six separate locations on the downstream face of the dam, with the rate of flow increasing non-linearly with time (Fig. 6). Whilst for a time the rapid increase in the seepage rate caused concern, it did not induce failure of the dam prior to overtopping as had been feared. However, downstream of each seepage point substantial volumes of the silty-clay were quickly eroded away by the flow, indicating that this material had very little resistance to erosion.

4 OVERTOPPING

Flow through the spillway started during the night of 28th-29th May 2010, at which point the spillway elevation was 111.41 metres above the valley floor. By the time overtopping started the deformation of the walls of the spillway had meant that it had reduced to a basal width of about 1 m. The estimated lake volume was 520-640 million m^3 (Leonard *et al.* 2010). The lake had inundated a total of 171 residential properties in several small villages. At the time of overtopping the spillway capacity was substantially lower than the inflow discharge, such that the lake level continued to increase at a rate of 0.5 metres per day for several days (Fig. 5). This caused substantial confusion amongst the local community, who had thought that continued increases in lake level would not occur. Several further properties were lost during this time.

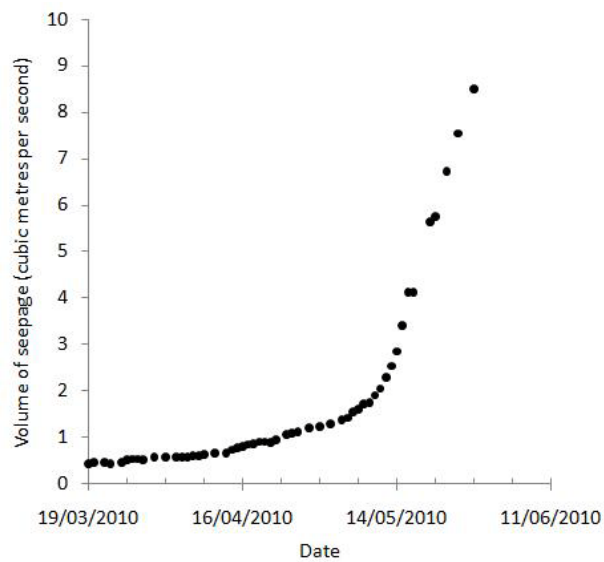

Figure 6. Focus Humanitarian Assistance data of the measured seepage rate at Attabad Dam (after Petley *et al.* 2010). Measurement of seepage ceased soon after overtopping.

The initial erosion effects of the overtopping were primarily associated with headward erosion of the gully formed by the flow. As discharge increased this headward erosion accelerated notably, increasing the perceived likelihood of failure through this mechanism. Some widening of the channel through undercutting and collapse also occurred, but these small scale failures were not sufficiently large to block the channel. However, downcutting of the bed of the spillway itself remained surprisingly limited. It took about six days (i.e. until 5th June 2010) for the outflow to equilibrate with the inflow, by which time the lake level had risen by a further 3.81 m (fig. 5). Thereafter the lake level rose and fell by about 2 metres according to changes in inflow rate. The rapid headward erosion ceased close to the saddle, and downcutting remained limited. It is assumed that this indicates that the base of the spillway became armoured by large boulders sitting below the silty-clay. A small number of very large boulders also that emerged during the initial lateral erosion of the channel also served to prevent the channel from widening further, such that the spillway rapidly achieved a remarkably stable state

Unfortunately, the quantitative data for the dam ceased in late July 2010 as a consequence of the exceptional monsoon rainfall event that occurred across northern Pakistan at that time. Whilst this rainfall did not extend north as far as Attabad (meaning by good fortune that the dam was unaffected), the monitoring teams were redeployed to assist with other aspects of the disasters unfolding across Pakistan.

The spillway remained intact, with slow rates of evolution, throughout the summer high flow period. In the autumn as the melt season in the high mountains ended the inflow reduced. This caused the lake level to decline by about 2 metres, allowing some inundated properties to re-emerge from the water. During the winter NDMA started a programme of works to deepen the spillway, although at the time of writing the progress on this was unclear.

The high lake level has continued to impose serious challenges on the local population. In particular, during the winter of 2010-11 the lake surface froze, preventing the use of boats. For a while local people walked across the ice, but this was (rightly) outlawed by the government on safety grounds. The lack of transportation for a prolonged period caused very real problems, exacerbated by a continued reported lack of medical personnel on the north side of the barrier.

5 MANAGEMENT LESSONS

The Attabad landslide of course raises a series of management issues, most of which were essentially intractable. In this discussion these issues are divided into the pre-failure, the immediate post-failure (i.e. Summer 2010) and the long term periods.

5.1 Pre-failure

The Attabad landslide was identified as being a site undergoing progressive slope failure some years in advance of the final collapse event. This identification was initially made by the NGO Focus Humanitarian Assistance. It is well-known that such collapses do not require a final trigger event (Petley *et al.* 2005), such that the collapse should not be seen as being surprising. Prior to the collapse the local population was safely evacuated, meaning that no lives were lost in Attabad village itself. This was a substantial success, showing the value of proactive slope hazard management in less developed countries.

On the other hand, the loss of 19 people in the valley below was clearly deeply regrettable. Given the information available it was to all intents and purposes impossible to foresee this particular secondary landslide mechanism, such that protecting the population in Sarat was not considered. However, where similar progressive failures develop on the walls of the Hunza Valley (and similar valley systems) it may be important to determine whether similar lake bed sediments are present on the valley floor.

5.2 Immediate post-failure

The period between the failure occurring and the end of the summer, when river flows declined, was one of great controversy in Pakistan. In the media the National Disaster Management Agency was widely criticised for what was perceived to be an unacceptably slow response to the disaster in terms of mitigating the hazard posed by the lake and in providing support to the affected communities.

The response of the NDMA in the months following the slope failure was primarily focussed on the construction of a spillway. Such structures are a sensible response to valley blocking landslides, and of course in the event the spillway proved to be sufficiently effective to mitigate the hazard during this period. The construction process proved to be slow and difficult due to the materials involved.

The principal difficulties in terms of the management of a potential flood during this phase were associated with the lack of knowledge of the internal structure of the dam and the difficulties associated with good quality flood modelling. These problems would have been greatly reduced with the availability of borehole data for the dam itself, and LIDAR data for the valley both upstream and downstream of the blockage. In terms of the former, a small number of c. 30 metre deep boreholes along the line of the saddle could have been drilled at comparatively low cost and using technologies widely available in Pakistan. These boreholes would probably have identified the presence of a large boulder layer within the core of the dam, meaning that judgements of the likelihood of a breach would have been more reliable. Flood modelling relied upon the availability of SRTM data, which has low resolution, meaning that there was considerable uncertainty in estimates of both the volume of water impounded in the lake and the magnitude of a flood wave as it moved downstream. A LIDAR campaign early in the crisis would have mitigated these problems, albeit at high cost, It should be remembered though that the LIDAR data would have been useful beyond just the management of this accident.

Two major social issues also emerged during the crisis. The first was the perceived comparatively slow response to the hardship faced by upstream communities. The poor quality and relatively expensive boat service undoubtedly led to great hardship. In future similar disasters organising a proper emergency transportation infrastructure must be a priority. The second issue revolves around the communication of information to the local community. The quality information distributed by the various agencies and organisations, including the media, was generally quite poor, with for example misleading statements about the likely date of overtopping, poor information about progress with the spillway, contradictory statements about the lake level, and a lack of information about management plans. This dearth of quality information undoubtedly led to increased levels of apprehension amongst the local population. A number of other agencies, including the author of this paper, sought to plug this information gap. However, this was also inadequate and at times may have not been entirely successful. This is clearly an issue that needs further consideration.

Frustration with the lack of information was most clearly demonstrated by an attempt to widen the spillway by hand by local people over a few days at the peak of the crisis. Despite a huge physical effort there is little evidence that this had a tangible effect, although it placed the people concerned at considerable risk.

Finally, a very substantial challenge to the disaster management agencies at Attabad lay in how to determine when the “all clear” could be sounded. This is a very substantial problem that in future crises would be best managed by: i) the establishment of clear criteria before overtopping (and the communication of these criteria to the public); ii) the formation of an expert advisory panel to guide decision-making, formed from a range of international and domestic specialists in this topic; and iii) the establishment of monitoring and warning systems such that early decisions can be made. The aim should be to allow the population to return to areas considered to be at acceptable levels of risk as soon as is possible. Needless to say transparency and openness greatly assist in the development of trust in this process.

5.3 Long term management

There is little doubt that the long term management of the Attabad landslide site is a substantial challenge for an impoverished country. Whilst the magnitude of the hazard reduced as the inflow levels fell at the end of Summer 2010, the danger posed by the lake did not cease. In particular the threat posed by either a large seismic event or a further landslide into the lake remains high. Either scenario could lead to a rapid breach event. Furthermore, as detailed previously the upstream community has suffered substantially during winter 2010/11 due to the loss of the boat service for long periods of time. Current reported plans of the NDMA are to lower progressively the lake level by 30 metres and to construct a new section of Karakoram Highway, at a reported estimated cost of up to US$250 million (although this value may well be substantially inflated). Whilst this will reduce the hazard considerably, it will not remove the threat completely, such that serious consideration should be given for a long term monitoring and warning system.

Finally, it is likely that similar failures will occur in the future in Pakistan and in other high mountain areas. Indeed there is clear evidence that similar large-scale progressive failure is developing at other sites in northern Pakistan, such as at Thoi in Yasin Tehsil in Ghizer District, and at Gupis village, also in Ghizer . The major lesson of the Attabad landslide must be that there is need for a major contingency plan to reduce the impact of such an event.

6 CONCLUSIONS

The Attabad landslide represented a major crisis in northern Pakistan during 2010. Fortunately, in this case the range of the most serious potential scenarios were not realised. This does not mean that a rapid breach event is precluded from either this landslide site, or from other future valley-blocking landslides. Unless mitigated, Attabad will still represent a substantial threat in the event of a rare, high magnitude inflow event (such as a large GLOF), a large earthquake, or a further landslide from the lake walls. The landslide teaches important lessons about hazard assessment, disaster management and, most importantly, public communication during ongoing crises.

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