Geological Prerequisites for Landslide Dams' Disaster Assessment and Mitigation in Central Asia

Alexander Strom

Abstract Landslide dams' hazard assessment aimed to disaster mitigation requires knowledge of the origin of hazardous phenomena, its triggering factors, magnitude, spatial distribution, recurrence, as well as characteristics of their possible secondary and tertiary effects. These hazards identification and quantification can be derived from detail geological and geomorphic study of the present and past river-damming landslides and related phenomena such as evidence of outburst floods. Several historical catastrophes that occurred in the Central Asian region due to formation and/or breach of landslide dams are described briefly and case studies demonstrating various manifestations of landslide damming in the Central Asia region are discussed with special emphasis on those topics, which still remain unsolved or controversial. These are: (1) the landslide versus moraine interpretation of the Pamirs' natural blockages origin, (2) the relationship between formation of large-scale bedrock landslides and seismicity, which is critically important for both landslide and seismic hazard assessment, (3) morphological and structural peculiarities of large-scale bedrock landslides—the main type of river-blocking slope failures that predetermine magnitude of river damming, its longevity and character and rate of dams' breach. The importance of the detailed study of the past breached dams, as the analogues of the existing and future hazardous blockages is discussed in the conclusive remarks.

Keywords Landslide dam · Inundation · Dam breach · Outburst flood · Landslide hazard assessment

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1 Introduction

A "disaster" is defined as "a sudden calamitous event bringing great damage, loss, or destruction" (Merriam-Webster's 11 Collegiate Dictionary). Those, classified as "Geo-disaster", are of natural origin, mainly, and their mitigation must be considered as an important task of the mankind and, at the first place, of the geo-hazard scientific community. The disaster mitigation requires correct identification of type, location, magnitude, timing (recurrence), primary and secondary effects of the natural phenomena that can be considered as being potentially disastrous. Based on these data, measures aimed to prevent or predict such phenomena can be elaborated. The prevention is preferable, however, if it is impossible from technical or economical reasons, timely prediction via site monitoring and early warning must be arranged.

Large-scale landslides and, especially, those that cause river damming are among the most disastrous natural phenomena in mountainous regions all over the world (Schuster and Costa 1986; Costa and Schuster 1988, 1991; Evans et al. 2011). The Central Asia region that includes the Pamirs and the Tien Shan Mountains (Fig. 1) is not the exclusion (Delaney and Evans 2011; Strom 2010b).

Various aspects of identification and quantification of hazards related to landslide dams' formation and evolution are described and discussed hereafter with special emphasis on those topics, which still remain unsolved or controversial. After brief description of some historical catastrophes that occurred in the Central Asian region due to formation and/or breach of landslide dams I will dwell on the controversial interpretation of the Pamirs' natural blockages origin (landslide vs. moraine), which determines at a great extent possibility of future disasters. Another problem is the relationship between formation of large-scale bedrock landslides, those that cause rivers' damming in particular, and seismicity, which is critically important for both landslide and seismic hazard assessment.

High emphasis is placed on the morphological and structural peculiarities of large-scale bedrock landslides (rockslides and rock avalanches)—the main type of river-blocking slope failures (Hermanns et al. 2011; Fan et al. 2012). These characteristics predetermine magnitude of river damming, its longevity and character and rate of dams' breach. Besides, analysis of rockslides morphology and internal structure allows assumptions on their motion mechanism(s) (Strom 2006, 2010a). The importance of the detailed study of the past breached dams, as the analogues of the existing and future hazardous blockages will be discussed in the conclusive remarks.

2 Brief Overview of the Historical Disasters Associated with Landslide Dams in the Central Asia Region

Several catastrophes associated with large-scale slope failures and breach of landslide-dammed lakes occurred in the Pamirs and the Tien Shan in the twentieth Century exemplifying basic primary and secondary effects of these hazardous natural phenomena.

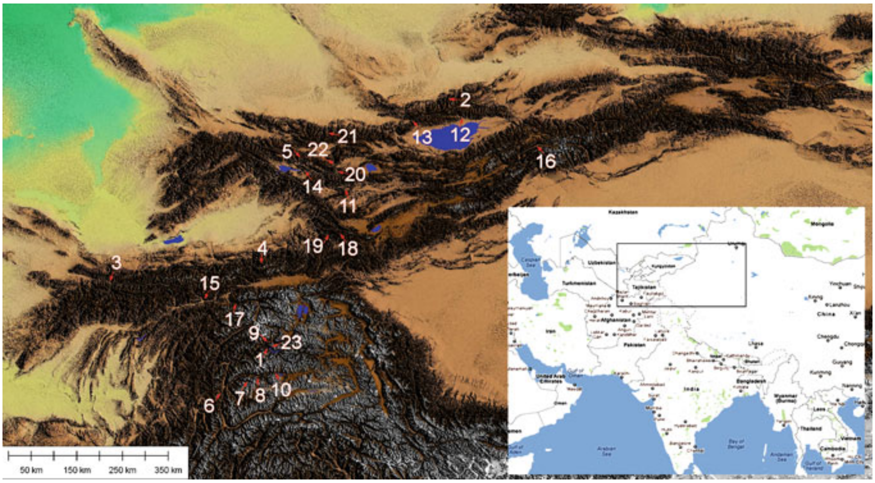


Fig. 1 General map of Central Asia with location of all features mentioned in this chapter (*Red arrows*). The study region is marked on the inset. *1* the 1911 Usoi landslide and Sarez Lake; *2* the 1963 Issyk outburst flood; *3* the 1964 Aini landslide and its prehistoric predecessor; *4* the 1966 Yashinkul outburst flood; *5* the 1992 Belaldy landslide and 1993 debris flow; *6* the Shiva dam and Lake; *7* the Rivakkul dam and Lake; *8* the Imom rockslide; *9* the Kudara-Pasor landslide; *10* the Yashilkul dam and Lake; *11* the Beshkiol landslide; *12* the 1911 Ananievo landslide; *13* the 1911 Kaindy landslide; *14* the Djuzumdybulak rock avalanches; *15* the 1949 Khait rock avalanche; *16* the Upper-Inylchek landslide cluster; *17* the Muksu landslide cluster; *18* the Kulun landslide-dammed lake; *19* the Kulun mouth silted landslide-dammed lake; *20* the Lower Aral landslide; *21* the Aksu landslide; *22* the Kokomeren landslide; *23* the Murgab assumed landslide

2.1 Usoi Dam and Sarez Lake

The most known case study is the formation of the Usoi landslide and the Sarez Lake in Central Pamirs. The world largest historical non-volcanic landslide originated on February 18, 1911, when large earthquake with $M_w = 7.7 \pm 0.2$, according to the recent analysis of the macroseismic and instrumental data performed by Ambraseys and Bilham (2012), caused catastrophic wedge-like failure of about 2.2 km^3 ($\sim$6 billion tons) of rocks (Fig. 2) and formation of the 567-m high Usoi natural dam named after the small Usoi village that was buried with 54 inhabitants. Only three men who spent that night in the Sarez village survived (Luknitskiy 1955). This should be considered as a primary disastrous effect of the landslide.

The 5-km long (across the valley) and 3.75-km wide dam (Fig. 3) have blocked the Murgab River valley at 38°16.5′ N, 72°36′ E (1 on Fig. 1). Despite the remoteness and inaccessibility of the site, Russian researchers performed first studies of this unique feature soon after the event (Bukinich 1913; Shpilko 1915; Preobrajensky 1920). Its regular studies started in sixtieth of the twentieth Century (Scheko and Lekhatinov 1970; Gaziev 1984; Agakhanjanz 1989).

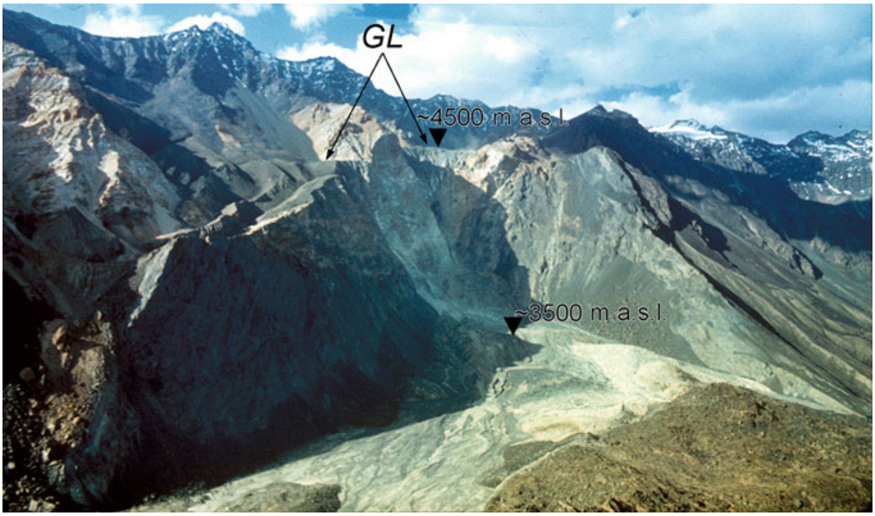


Fig. 2 The Usoi rockslide headscarp. *GL*—glacial valleys remaining above the headscarp

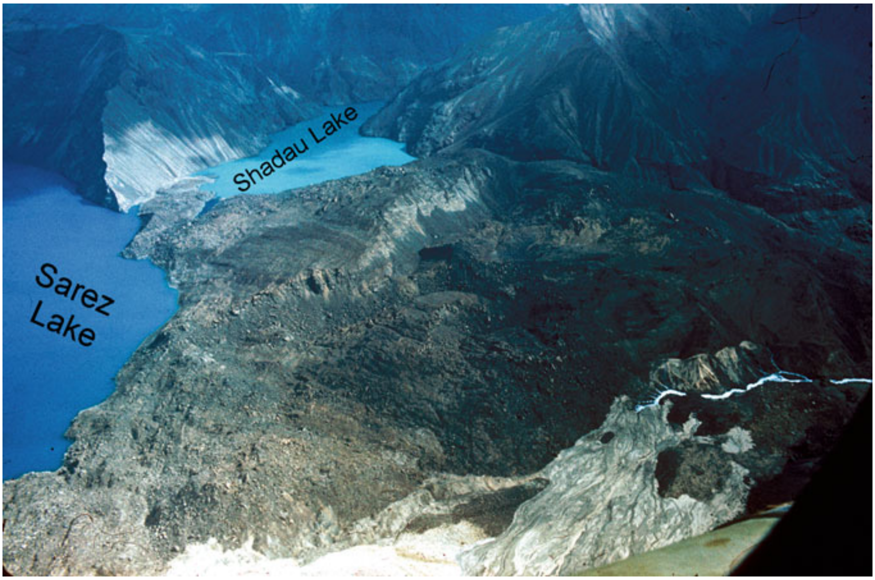


Fig. 3 The Usoi natural dam. Helicopter view from north. Giant block retaining original structure is visible on top of the dam in front of the Shadau Lake. Seeping water forms springs at the left bank of the erosion canyon. Whitish flat area above the canyon—deposits of debris flows that came in this direction before their diversion towards the Lake in 1947. Steep scarp that crosses the dam body indicate its transverse spreading likely due to impact over the steep opposite slope of the Murgab River valley

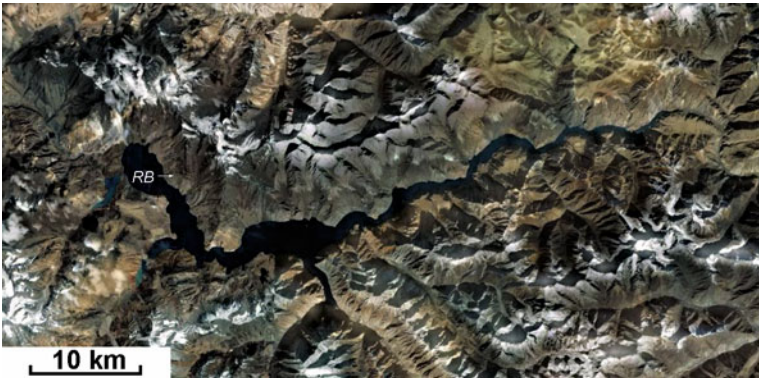


Fig. 4 The Sarez Lake. Google Earth space image. *RB*—location of the assumed Right-Bank landslide

The 500-m deep and 60-km long lake containing almost 17 km^3 of water (Fig. 4) was named after the Sarez village that was submerged along with several other minor settlements. Such inundation represents secondary disastrous effect of landslide river damming, which, though being not sudden and, thus, *sensu stricto*, not "catastrophic", produced complete damage not only of the local people property, but of the entire inhabited environment, forcing people to resettle to other kishlaks (villages) in the Bartang River valley and in the Gunt River valley, passing south from the Rushan Range. In high mountains economic and social losses due to such secondary effects could be much higher than that of the landslide itself. All these however, are negligible in comparison with what could happen if the Usoi dam will be breached and water stored in the lake released.

Fortunately, the enormous size of the blockage, especially of its upper permeable part (seepage takes place through the uppermost ~140 m of the dam only with most permeable zones within the uppermost 50–70 m, while the dams body bellow is practically impermeable) provides nearly balanced values of the mean inflow and outflow. However, according to regular observations, lake level increases gradually (up to 20 cm/year) and is now 3261 m a.s.l., only 38 m below the lowermost part of the blockage (at maximal water level) (Ischuk 2011). Significant filtration through the dam started around 1925. Present day estimates of mean discharge passing through the dam range from 45.8 to 47 m^3/s (State Water Inventory 1964–1981; Hanisch and Söder 2000). During the flood period water rises for about 5 m above the mean annual level, but, simultaneously, filtration increases up to 84 m^3/s (Hanisch and Söder 2000). Present state of the dam is considered as safe. There are, however, several factors that do not ensure the stability of the Usoi dam "forever". Besides the above-mentioned gradual rise of water level, the seeping water forms powerful springs ~140 m below the lake level in the canyon cutting the downstream slope of the blockage (see Fig. 3). Its head erodes both the dam body and sediments left by debris flows fed by the streams from glacier valleys remaining above the headscarp. After 1947, when a rockfall from the headscarp wall blocked the channel and diverted these debris flows towards the lake (Paramonov 1969), intensive growth of the canyon stopped but, anyhow, filtering water erodes it. Recently several new powerful springs were identified in the canyon (Anatoly Ischuk, personal communication).

Downstream slope of the blockage is crossed by steep bow-shape scarps (see Fig. 3) indicating some transverse (down-valley) spreading of the landslide body (Paramonov 1969). Largest of them could originate when rapidly moving rockslide collided with the opposite bank of the Murgab River valley (Strom 2010a). It can be assumed that such secondary deformations decrease the overall stability of the dam, producing potential sliding surfaces. Along with the gradual development of the canyon it is difficult to predict how the stability of the downstream slope of the blockage will evolve in decades and centuries.

In 1960s it was hypothesized that large-scale slope failure might occur on the lakes' right bank, 4–5 km from the blockage (RB on Fig. 4), which would cause the huge displacement wave that can gash over the dam at its lowermost section resulting in the dam's partial or complete breach (Sheko 1968; Sheko and Lekhatinov 1970; Fedorenko 1988), as it occurred, for example, in the Las Conchas valley (Argentina) in the prehistoric times (Hermanns et al. 2004). Different researchers estimated volume of this "Right-bank landslide" from 0.3 to 2.0 km^3. However, possibility of such a large-scale failure, its volume and rate estimates are still controversial and require more studies (Alford and Schuster 2000; Ischuk 2011; Strom 2012c). Additional uncertainty of the Lake banks stability assessment is associated with high seismic activity of Central Pamirs. It should be mentioned that none of several gigantic past rockslides that had blocked the Murgab River valley close to the Usoi dam (Fedorenko 1988) remain intact, proving the assumption that long-term stability of the dam and lake can not be guaranteed without special security arrangements.

Recently the early warning system have been installed within the frames of the World Bank Project, aimed to record various indicators of the dams' instability (seismic strong motion, rapid increase of water level in the Lake, etc.) and to allow people living downstream to escape to special shelters arranged above the endangered level. It should mitigate the disastrous consequences if dams breach would occur (Zaninetti 2000).

Since the potential risk of the blockage breach and of the devastating outburst flood exists, special measures should be undertaken to ensure long-tem safety of the Lake Sarez regardless of any dynamic effects such as strong earthquake or impact of the displacement wave caused by large-scale failure in the lake. Possible solutions, which are under discussion, envisage not only risk reduction measures, but also use the Lake Sarez water for irrigation and power production. Construction of a spillway tunnel through the left bank bedrock massif from the small Shadau Lake formed in the tributary valley (visible at the background on Fig. 3) seems to be the most reliable variant (the Sarez Lake could be linked with the Shadau by a channel) that allows not only lowering of the Sarez Lake up to the safe level (i.e. outburst flood disaster prevention) but also the integration of a powerhouse (Strom 2012c).

2.2 Outburst Floods Caused by Landslide Dams' Breach

The most disastrous effect of landslide river damming is an outburst flood caused by dams' breach. Numerous case studies from the Alps, Karakorum, Himalayas, Central American and Argentinean Ands, Tibet and Longmanshan mountains are described, for example, in various chapters of the book "Natural and Artificial Rockslide dams" (Evans et al. 2011a, b).

Three outburst floods caused by rockslide dams breach had occurred in Central Asia in 1960s (Pushkarenko and Nikitin 1988; Strom 2010b) and two of them were really devastating. One more disastrous breach occurred in 1993.

On July 7, 1963 the catastrophic breach of the Issyk Lake (43°15.3′ N, 77°28.9′ E) occurred east from the former capital of Kazarhstan, the Almaty City (2 on Fig. 1). Evidence of a devastating debris flow that passed through the Issyk valley could be visible till now, almost 50 years after the disaster.

The prehistoric landslide dam about 0.6 km^2 in size and up to 200 m high (about 50 Mm^3 in volume), composed of diorite blocks (on top) and same rock crushed at a high extent in the dams' interior (Eugen Gaspirovich, personal communication), was breached by overtopping caused by debris flow that originated in the upper reaches of the catchment due to the Jarsai glacial lake breach. Up to 6–7 million m^3 of debris was brought into the Issyk Lake within 3–4 h resulting in rapid increase of the lake level and creation of waves that destroyed the upper part of the blockage. Water stored in the lake rushed downstream eroding the dam body as well as river banks and valley bottom (Gerasimov 1965). Peak discharge recorded about 10 km downstream, close to the Issyk town, was 745 m^3/s, while mean discharge of the river at this site is 4, 96 m^3/s (from (State Water Inventory 1964–1981). Only small remnant lake has remained after the disaster. Later on an artificial dike was built in the eroded canyon to protect downstream valley and the Issyk town from new debris flows and to renew this beautiful touristic site (Fig. 5).

Next year, on April 24, 1964, 20 Mm^3 of rock debris blocked the Zeravshan River valley in Tajikistan close to the junction of the Zeravshan and Fandaria Rivers just upstream from the Aini town (39°23′ N, 68°32.5′ E) (3 on Fig. 1). The dam was up to 150 m high (maximal height, the effective one was much lower, about 50–60 m) and 1.3 km along the stream. Dammed lake fed by both rivers with cumulative discharge of about 90 m^3/s (in April–May, 1964; mean annual discharge at this gauge is 147 m^3/s, according to (State Water Inventory 1964–1981) could store up to 126×10^6 m^3 of water, which release would devastate lower part of the Zeravshan River valley with the historical Samarkand City. To take the situation under control the 865-m long and up to 23 m deep trench across the dams' crest was excavated by directed blasts. On May 6 water started passing through this artificial channel and 2 days later the discharge exceeded the inflow. The peak discharge of 1,200 m^3/s was recorded on May 31. Lake was almost emptied at June 20, when its level dropped for 325 m. 3 millions cubic meters of debris was eroded from the dam resulting in significant aggradation of the

Fig. 5 The Issuk dam and Lake after restoration of the dam. The rockslide headscarp is on the left. Large alluvial fan was formed by debris flow that caused the dam's breach in 1963. 3D Google Earth view

Zeravshan River channel downstream (Neshikhovskiy 1988; Strom 2010b). This case study is one of the first examples of the successful prevention of the rockslide dam breach disaster.

I want to point out that there are evidence of both past and future slope failures at this site. First, it is clearly seen that the 1964 rockslide occurred within the headscarp of a much larger prehistoric rockslide (Fedorenko 1988). Second, an arcuate scarp above the headscarp of ancient rockslide (marked by small red arrow on Fig. 6) and upslope-facing scarps at the upper part of the opposite—south-facing slope of the watershed indicate possibility of the formation of new large rockslides at this site.

One more catastrophic outburst flood caused by the rockslide dam breach occurred on June 18, 1966 in the Isfairamsay River basin in Kyrgyzstan (4 on Fig. 1). The rockslide dam 20–30 Mm^3 in volume (the entire rockslide volume was about two times larger, but almost half of it rests within the headscarp—see Fig. 7) originated about 300 years ago, likely being triggered by an earthquake, and formed a dam about 100 m high that had blocked the Tegermach River valley (right tributary of the Isfairamsay River) at 39°55.6′ N, 72°18′ E (Rezvoi and Rezvoi 1969; Rezvoi et al. 1971; Reizvikh et al. 1971; Strom 2010b). The dam of the Yashinkul Lake was overtopped due to continuous raining. Outburst flood lasted for about 7 h with peak discharge of 5000 m^3/s and caused significant damage not only in Kyrgyzstan but also in Uzbekistan farther downstream. The breach canyon is up to 90 m deep, 50–60 m wide at its bottom and 280–340 m wide at the dams' crest level (Neshikhovskiy 1988) (measurements on the Google

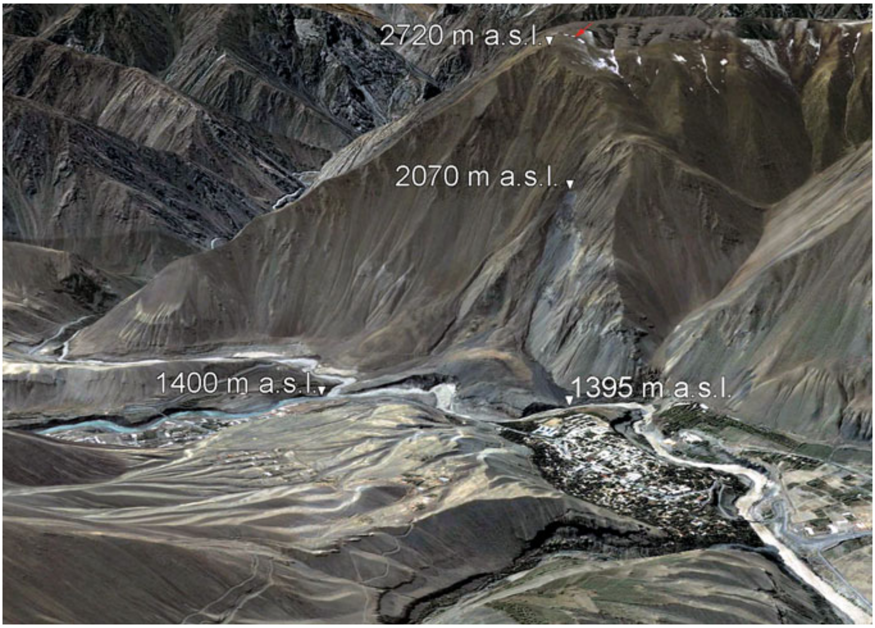


Fig. 6 Remnant of the 1964 rockslide dam at the Aini town (Tajikistan) immediately downstream from the junction of the Zeravshan river (coming from the left with clear blue water) and the Fandarya River (with muddy water, coming from the gorge at the background). *Red arrow marks* an arcuate scarp indicating possibility of slope failure at this site in future. 3D Google Earth view

Earth image returns width value up to 370 m). Thus, about 10×10^6 m^3 of debris (much more than in the Aini and Issyk cases) was removed from the dams' body causing significant aggradation downstream.

The most recent disaster associated with landslide river damming in Central Asia region occurred in the Belaldy River valley—small right-bank tributary of the Naryn River than now falls in the Toktogul reservoir (5 on Fig. 1). The M7.3 Suusamyr earthquake triggered rockslide about 40 Mm^3 in volume on August 19, 1992. Its debris formed $\sim$500 m wide and 1000 m long body that filled steep but wide glacial valley bottom forming blockage about 100 m high (Fig. 8). Rockslide killed few people who tended a herd in the upper reaches of the valley. Unlike other case studies described above where large water bodies had been impounded, this rockslide dam formed two minor lakes up to 200–300 m^2 in size only. Nevertheless, 10 months later, in June 1993, likely after intensive snowmelt at elevations exceeding 3000 m a.s.l., these lakes burst out producing powerful debris flow that partially devastated the Belaldy village 17 km downstream and the Torkent village 30 km downstream from the dam site (Korjenkov et al. 2004).

This case study demonstrates that rockslide-damming phenomena causing small-size impoundment could have, nevertheless, quite severe tertiary consequences (considering upstream valley inundation as secondary effect).

Fig. 7 The Yashinkul dam breached in 1966. Note large difference of the benchmarks elevations upstream and downstream from the dam resulting from the significant sedimentation of the 300-years old lake (compare with the Aini landslide dam on Fig. 6). Just downstream from the dam evidence of valley aggradation are still visible. 3D Google Earth view

3 Origin of Natural Blockages

Correct determination of the river-damming feature origin plays a critically important role in the entire process of the related hazards and risks assessment. Several basic problems must be solved. First, is the blockage(s) in question a landslide dam(s) or drainage disturbance was caused by any other process (glaciation, tectonics)? The correct solution would foreordain most of further analysis and practical actions aimed to study the feature and to elaborate disaster mitigation measures if necessary. If features in question are glacial landforms, they would not have any relation to seismic events. If landslide origin of the dam(s) is substantiated, next question arises—what is the cause/trigger of such event(s). Here possibility of their seismic origin must be taken into consideration and either proved or disproved in each particular case (see, e.g. Strom and Stepanchikova 2008; Strom 2012b).

If rockslides are caused/triggered by earthquakes, then, due to unpredictability of large earthquakes, prediction of future slope failures place and time could be performed, most likely, at a regional scale based on probabilistic approach rather than at a local scale using site-specific deterministic analysis. If, in contrast, slope failures result from gradually developing processes, site-specific landslide prediction and, possibly, prevention, seems to be more realistic. The following sections address to these problems.

Fig. 8 1992 rockslide at the upper reaches of the Belaldy River—source of the powerful debris flow of June 1993. 3D Google Earth view

3.1 Landslides Versus Moraines

Genesis of natural blockages in mountain valleys has been a debatable topic for a long time. Two main processes are considered as being responsible for their formation—glaciation (either retreat of large along-valley glaciers leaving end moraines as barriers, or such a glaciation-related phenomena as rock glaciers—see e.g. Owen and England 1998; Burger et al. 1999), and large-scale slope failures. It was discussed in details for the Karakoram region where rockslide nature of such barriers was proved by Hewitt (1998, 2002, 2006). However, recently the problem was raised again, this time for the Pamirs, in publications of Nikolai Ischuk (2008, 2011a, b) who considers almost all of them, including well-known features such as the existing dams of the Yashinkul and Shiva Lakes and the breached Kudara-Pasor blockage as being formed by end moraines. His main argument in favor of such assumption is the presence of large amounts of moraine material in these dams.

Correct solution of the contradictory interpretation of dams' landslide versus moraine origin provides the basis for hazard assessment of such phenomena. If most of the Pamirs natural blockages, both intact and breached were formed by end moraines—no hazard of large rivers' blocking is anticipated in the near future, since present day glaciation degradation makes the formation of new similar features in the main river valleys impossible and only small lakes in the glaciated tributary valleys may originate with ongoing glaciers' retreat or being dammed by gradually moving rock glaciers. If the opposite—rockslide—origin of these features is true, then, in contrast, no general restrictions of river damming at any time in future exist and related risks should be much higher.

Fig. 9 Rockslide dam of the Shiva Lake in the Afghan Badahshan at 37°23′ N, 71°24′ E (6 on Fig. 1). It is clearly visible that the headscarp is a unique feature which relief is much younger than that of other parts of the valley slope. 3D Google Earth view

Several reasons do not allow me to agree with interpreting valley barriers either as end moraines or as a combination of end moraines as main river-damming features accompanied by subordinate rock slope failures as proposed by Ischuk (2011a, b). First, all (!) natural dams are associated with the concave lowering on the valley slopes just above these bodies, which are distinctly younger than the adjacent slopes and are nothing else than the rockslide headscarps (Figs. 9, 10). I cannot accept so high probability of association of end moraine and subsequent rockslides—there is no reason to interconnect these totally different phenomena. Moreover, in most of cases nothing similar to such a spoon-shape lowering could be found on the adjacent slopes. Ischuk (2011a, b) interpreted these features as being formed by small cirque (niche) glaciers or "pre-glacial" nivation hollows. But glaciation that forms such geomorphic features is a climate-driven process that depends (at a valley scale) on elevation and slope aspect. Thus, if niche glacier or nivation hollow exits on a slope at one site, similar and same age topographic features *must* exist on the adjacent similarly-facing slopes at the same elevation. However, as mentioned above, nothing similar can be found and headscarps from where rockslides originated are unique for the particular segments of river valleys (see Figs. 9, 10). It excludes interpreting these geomorphic features as being left by niche glaciers or nivation phenomena.

Presence of large amount of moraine material in the dams' bodies can be explained as follows. Since most of the Pamirs valleys had been intensively glaciated in the past, lower parts of their slopes are covered by the material from the lateral and/or bottom moraines of these past glaciers. When large-scale slope failure occurs, moving bedrock material bulldozes moraine material and often overrun and overlay it (Strom 1994, 2006). Additional possibility of the appearance of rounded and semi-rounded boulders in the damming barriers can be exemplified by the Usoi rockslide that involved some material from the modern glacier valleys above the headscarp crest (see Fig. 2).

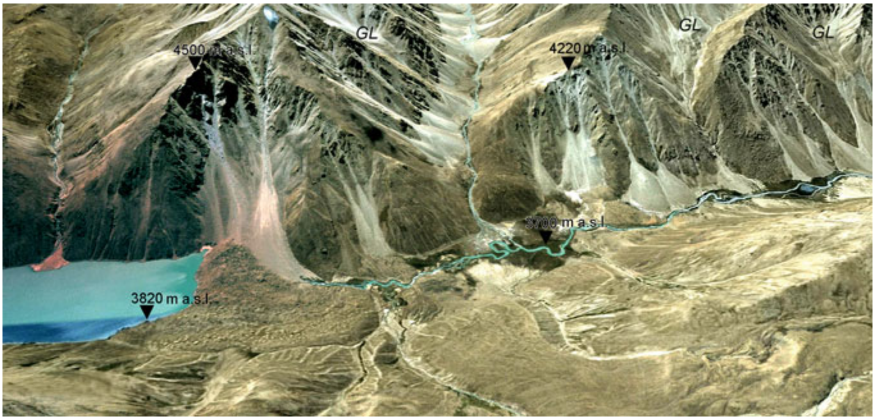


Fig. 10 The Rivakkul Lake dam in the Gunt River basin at 37°37′ N, 72°03.5′ E (7 on Fig. 1). One more smaller blockage can be seen immediately downstream from the dam and one more—downstream from the small green plane at 3700 m a.s.l., which is the bottom of the small emptied lake. *GL*—modern glacier deposits contemporary with the damming features develop much higher than rockslides that blocked the valley. 3D Google Earth view

This mechanism—pushing-out of old moraine material resting at the feet of valley slopes in front of moving rockslide debris can be seen very clearly at the Imom rock avalanche in the Gunt River valley (31°41.5′ N, 72°19.6′ E, 8 on Fig. 1, Fig. 11). This 2.5 km long and 20–30 Mm^3 in volume rockslide caved from the 700 m high slope composed of Precambrian crystalline rocks. The inner part of its body is composed of angular blocks and rubble of crystalline rocks while the frontal 300 m and 50–100 m wide 'stripes' bounding the main body from both sides are composed of typical moraine material—rounded and semi-rounded boulders with sandy-rubbly matrix. This material originated from the remnants of lateral moraine that rest on the slope and, partially, of the alluvial fan that is now overlaid by rockslide body, but originally was formed at the slopes' foot.

In several cases distinct zoning of the deposits in question clearly indicates that their motion was directed across the valley, not along it, as at the Kudara-Pasor dam at 38°24′ N, 72°34.3′ E (9 on Fig. 1, Fig. 12), which also contradicts glacier hypothesis but is in line with the rockslide one.

One more case study, mentioned by Ischuk (2011b) that allows alternative interpretation is the Yashinkul dam and Lake—the source of the Gunt River (37°47′ N, 72°44′ E, 10 on Fig. 1). Here about 50 Mm^3 of gneiss caved from the 1 km high slope, hit the spoor at the opposite bank of the river and spread up- and downstream for about 4 km in total (Fig. 13). Moving gneiss debris scraped up large amount of moraine material from the slope foot, but, unlike the Imom case, did not just pushed it in front as a bulldozer, but overrun and overlaid it (Strom 1994, 2006). So, it looks as if the river channel is filled by moraine material just blanked by rock avalanche debris. But in fact the entire blockage was formed by rock avalanche that involved large amount of moraine material. Moreover, some

Fig. 11 The Imom rockslide at the left bank of the Gunt River valley. Frontal and flank parts of its body are composed of moraine material resting at the slope base that had been bulldozed by moving rockslide debris. 3D Google Earth view

part of the latter spread outside the limits of the blocky gneiss zone forming microrelief that differs significantly from the intact terrain outside (Figs. 13, 14). Besides, here we can also see that the headscarp is a unique feature at this slope within its elevations range, which indicate non-climatic cause of its origin.

Case studies described above demonstrate that presence of moraine material in the river-damming barriers does not exclude their rockslide origin. Combination of blockages and headscarps just above them proves that most of large natural barriers in the Pamirs river valleys, both existing and breached have been formed by rockslides, not by end moraines.

I should note that in much less elevated Tien Shan, which have not experience so strong glaciation either at present or in the past (except its central highest segment with Victory and Khan Tengri peaks), some rockslide and rock avalanche deposits were also mapped as "moraines", on State geological maps compiled in 1960s–1970s in particular. Argumentation refuting such interpretation is the same as discussed above.

One more controversial issue is the possibility of long-term and large-scale river damming due to active tectonics. Diversion or temporary damming of streams by local anticlines and surface ruptures has been described after several earthquakes (Florensov and Solonenko 1963, 1965; King and Vita-Finzi 1981; King and Stein 1983; Meghraoui and Doumaz 1996). However, since largest terrestrial single-event

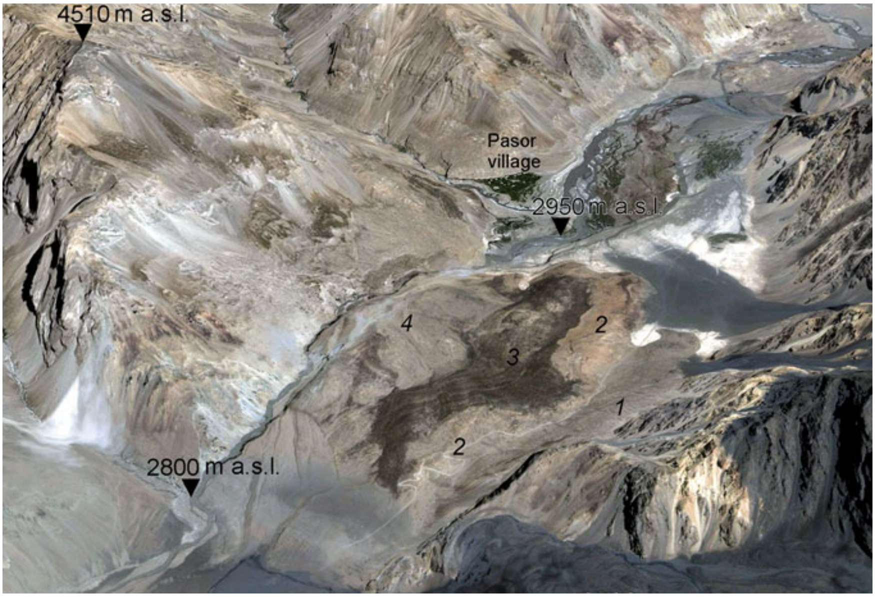


Fig. 12 Breached dam in the Kudara River valley downstream from the Pasor village (9 on Fig. 1). Numbers *1–4* mark various lithologies in the dam's body, which position clearly indicates that material moved across the valley from the headscarp with top mark 4510 m a.s.l. 3D Google Earth view

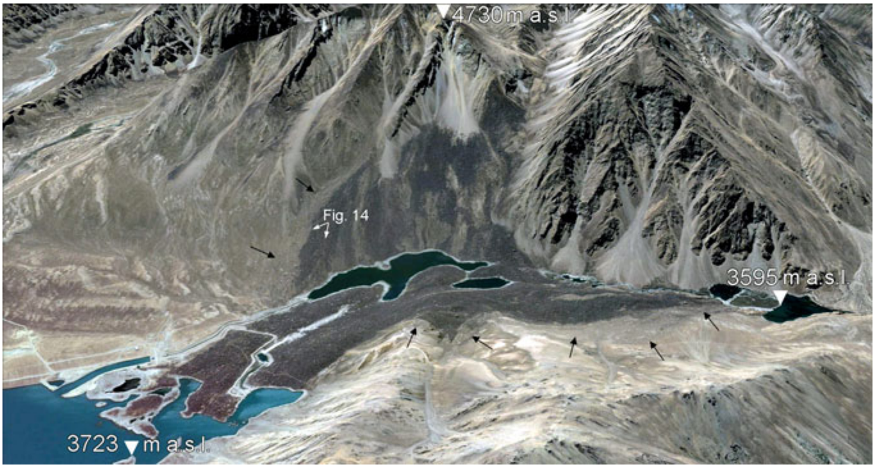


Fig. 13 Yashilkul rockslide dam. Dammed lake is the source of the Gunt River. Gneiss rock avalanche debris is *dark brown*; *black arrows* mark the outer limit of light-brown moraine material spread in front and sidewise from gneiss debris and being part of rock avalanche; *white arrows mark* the site from where photograph shown on Fig. 14 was made. 3D Google Earth view

Fig. 14 Wide thin stripe of moraine material bounding central part of the Yashilkul rock avalanche debris composed of gneiss blocks. Its microrelief differs significantly from old moraine material (outer limit of rock avalanche is marked by *arrows*). Photograph was made in 1980s before the construction of the spillway visible on Fig. 13

vertical offsets associated with earthquakes do not exceed ca. 10 m (Wells and Coppersmith 1994; Strom and Nikonov 1997) such phenomena do not provide same hazard as landslide river damming. In particular, the assumption that large-scale disturbance of the Naryn River at the Alabuga River mouth resulting in accumulation of thick lacustrine succession could be caused by continuous, long-term, and relatively rapid faulting (Makarov 1977) appeared to be erroneous, since long-term blocking that lasted for about 3000 years was caused, in fact, by a gigantic Beshkiol landslide about 10 km^3 in volume that had blocked the valley at 41°26.5′ N, 74°30′ E (11 on Fig. 1), about 15 km downstream from the site where active fault crosses the Naryn River (Korup et al. 2006; Strom and Korup 2006).

3.2 Possible Triggering Factors: Seismic Versus Aseismic

Large-scale bedrock slope failures in rugged terrain could be a culmination of a continuous deformation process driven by gravity force and sometimes accelerated by an abnormal rainstorm, snowmelt, permafrost degradation or human activity (McColl 2012). On the other hand they could be triggered or even caused by an "external" force—earthquake strong motion. It should be mentioned that slowly moving landslides generally do not cause river damming being eroded gradually by a stream, thus just catastrophic events produce features that are the topic of this paper. One more important point is that most of large-scale seismically triggered catastrophic slope failures were associated with large earthquakes, not with small or medium ones.

Large earthquakes triggered most (but not all) of the large historical rockslides in the Pamirs and the Tien Shan Mountains. Besides the Usoi and Belaldy rockslides described above they accompanied the 1887 Verniy earthquake (Mushketov 1890), the 1911 Kemin earthquake (Bogdanovich et al. 1914; Delvaux et al. 2001), the 1946 Chatkal earthquake (Leonov 1970), the 1949 Khait earthquake (Leonov 1960; Evans et al. 2009b). Same occurred in many other regions—in the USA where the 1959 M7.1 Hebgen Lake earthquake in Montana triggered the Madison Canyon landslide (Hadley 1964), in Alaska in 1964 and 2002 when earthquakes with M9.4 and M7.9 triggered spectacular rock avalanches (McSaveney 1978; Jibson et al. 2006), in Peru where the 1970 M8.0 Ankash earthquake produced the Huaskaran ice-rock avalanche (Plafker and Eriksen 1978), in China during the 2008 M8.0 Wenchuan earthquake that triggered the giant Daguangbao rockslide 0.75–1.1 km^3 in volume and numerous smaller landslides and rockslides (Wu et al. 2010; Yin et al. 2011). The list can be expanded. Such a distinct association led to the situation when presence of large and/or long runout prehistoric rockslide is often equalized with an evidence of strong past earthquake without providing any additional reasons in favor of such assumption—just due to enormous size and expressiveness of these features.

However, numerous large bedrock landslides had occurred without seismic triggering—the 1903 Frank rockslide 30 Mm^3 in volume in Canada (Krahn and Morgenstern 1976), the above mentioned 1964 Aini landslide $\sim$20 Mm^3 in volume in Tajikistan (Fedorenko 1988) (Prof. Zolotariov—one of the leading landslide experts in the Soviet Union, who studied the Aini rockslide, said in late 1970s that if he would not know that this slope failure was not triggered by a strong earthquake, he would, likely, considered it as seismically induced feature), the 1962 Huaskaran ice-rock avalanche—the aseismic predecessor of the larger 1970 event (Evans et al. 2009a), the 1974 Mayumarka rockslide 1.6 billion cubic meters in volume in Peru (Hutchinson and Kojan 1975), the 1987 Val Pola rock avalanche $\sim$40 Mm^3 in volume in Italy (Crosta et al. 2011), the 2000 Yigong landslide 300 Mm^3 in volume and about 10 km long in Tibet, China (Shang et al. 2003), etc. Thus, neither size nor runout of landslide can prove its seismic origin itself. It is confirmed by data, presented by McColl (2012) that numerous large bedrock landslides all over the world have occurred not only without earthquakes, but without any observable triggering.

I must point out that if the assumption of a particular landslide or group of landslides seismic origin is erroneous, it would cause not only an overestimation of seismic hazard, but, also, underestimation of an overall landslide hazard. Direct linking of large-scale rock slope failures' formation with large earthquakes only, which are relatively rare events with typical recurrence intervals at a particular causative fault varying from several hundred to several thousands of years, means that large bedrock landslides should occur with more or less the same recurrence.

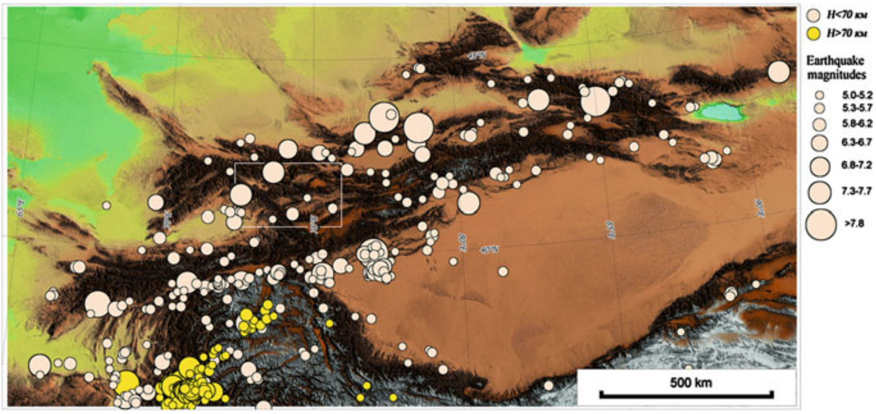


Fig. 15 Seismicity of the Tien Shan Region. Notice lack of earthquakes in the Central Tien Shan (75°–79° E, 40.5°–42° N), in the Zeravshan River basin (67°–70° E, 38.5°–40° N) and in some other parts of this mountain system with high concentration of large-scale landslides (outlined area is shown on Fig. 16)

However, other natural phenomena that can trigger such slope failure (e.g. rainstorms, hurricanes, abnormal snowmelt, etc.—see McCall 2012 for the detailed review) are much more frequent. For example, 3 typhoons hit Taiwan annually on average (Jan and Chen 2005) while large earthquake occur at this island several times per century only (Hung 2000; Cheng et al. 2007). In the area where the 1999 M7.6 Chi–Chi earthquake had triggered large Tsao-Ling landslide, 5 large-scale slope failures occurred since 1862, but only three of them—in 1862, 1941, and 1999—were triggered by earthquakes. Two others—in 1942 and in 1979 were rain-induced phenomena (Hung 2000).

No doubts that seismicity, strong earthquakes in the first place, is one of the main factors leading to slopes' instability. But such origin of large-scale bedrock landslides should be not just postulated, but substantiated somehow. It is especially important in the Central Asia region where historical data on various natural phenomena are available for a short time, generally, less than for 200 years, much shorter than the recurrence period of large earthquakes at a particular causative fault.

Distinguishing of seismic and aseismic rockslides and rockslide dams is a critical problem in the internal parts of the Tien Shan mountains, occupied by the Naryn, Zeravshan and Sarydzhaz River basins. Unlike northern and southern limits of this mountainous system and the Ferghana depression rim where numerous large earthquakes have been recorded in the historical times (Ignatiev 1886; Mushketov 1890; Bogdanovich et al. 1914) and, later on, instrumentally (Fig. 15), no similar large earthquakes are known in the inner parts of the Tien Shan. Thus, its seismic hazard assessment is based, at a large extent, on the paleoseismological data (Korjenkov 2006; Abdrakhmatov et al. 2007). Those include analysis of both surface ruptures and bedrock landslides, which are as widespread in the inner parts of the region as in its boundary zones with high modern seismic activity. Some

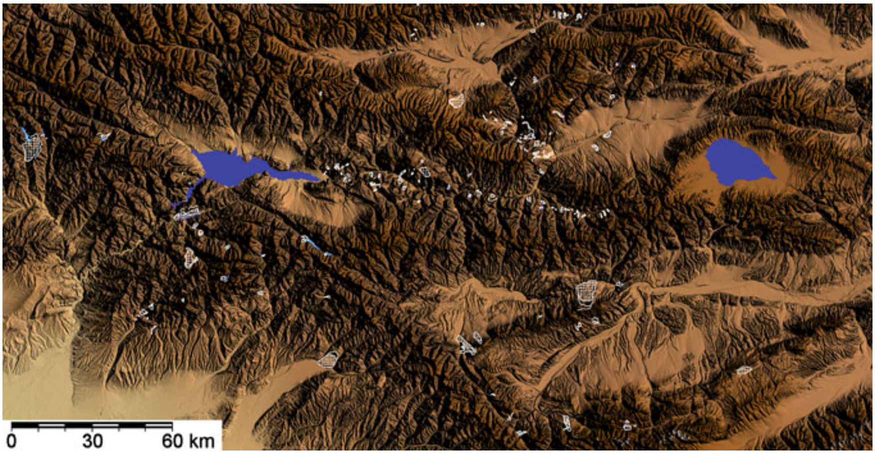


Fig. 16 Spatial distribution of large-scale bedrock landslides (*white-colored* features) in the central part of the Naryn Ricer basin. This region is characterized by low seismic activity during last ca. 200 years. *Dark blue*—the Toktogul reservoir and the Sonkul Lake impounding central part of the neotectonic depression. *Light blue*—largest landslide-dammed lakes visible at this scale

zones of the inner Tien Shan, such as those stretching along the Zeravshan River valley (Fedorenko 1988) or along the Naryn—Lower Kokomeren—Minkush River valleys (Strom 2012a) feature abnormally high concentration of large-scale rockslides and rock avalanches (Fig. 16).

The most unequivocal evidence in favor of seismic origin of a particular rockslide dam is a direct spatial and temporal coincidence of slope failure on the one hand and of the surface rupture on the other hand. Such historical coincidence could be exemplified by the 1911 Kemin earthquake when the Ananievo (12 on Fig. 1) and Kaindy (13 on Fig. 1) rockslides occurred on slopes directly undercut by surface ruptures (Bogdanovich et al. 1914; Delvaux et al. 2001). Spatial closeness and, likely, simultaneity of the prehistoric surface ruptures and of rockslide dams was found at the Talas-Feghana fault zone and in the western part of the Naryn-Sonkul fault zone (Fig. 17a) (Belousov et al. 1994; Korjenkov 2006; Abdrakhmatov and Strom 2006).

However, quite often large rockslides originate far from the surface rupture, like, for example, the above mentioned Belaldy rockslide triggered by the 1992 Suusamyr earthquake. No direct data on the location and even on the formation of surface ruptures are available for the well known 1911 Sarez (Ambraseys and Billham 2012) and the 1949 Khait (Leonov 1960; Evans et al. 2009b) earthquakes in Central Asian accompanied by large landslides—the Usoi rockslide dam and the Khait 7.3 km long rock avalanche (15 on Fig. 1).

Therefore in most cases sound conclusions on a particular landslide(s) seismic origin could be derived from the set of indirect evidence mainly (Fedorenko 1988; Strom and Stepanchikova 2008; Strom 2012b). One of such evidence is the close ages of several large rockslides distributed over more or less large area, especially

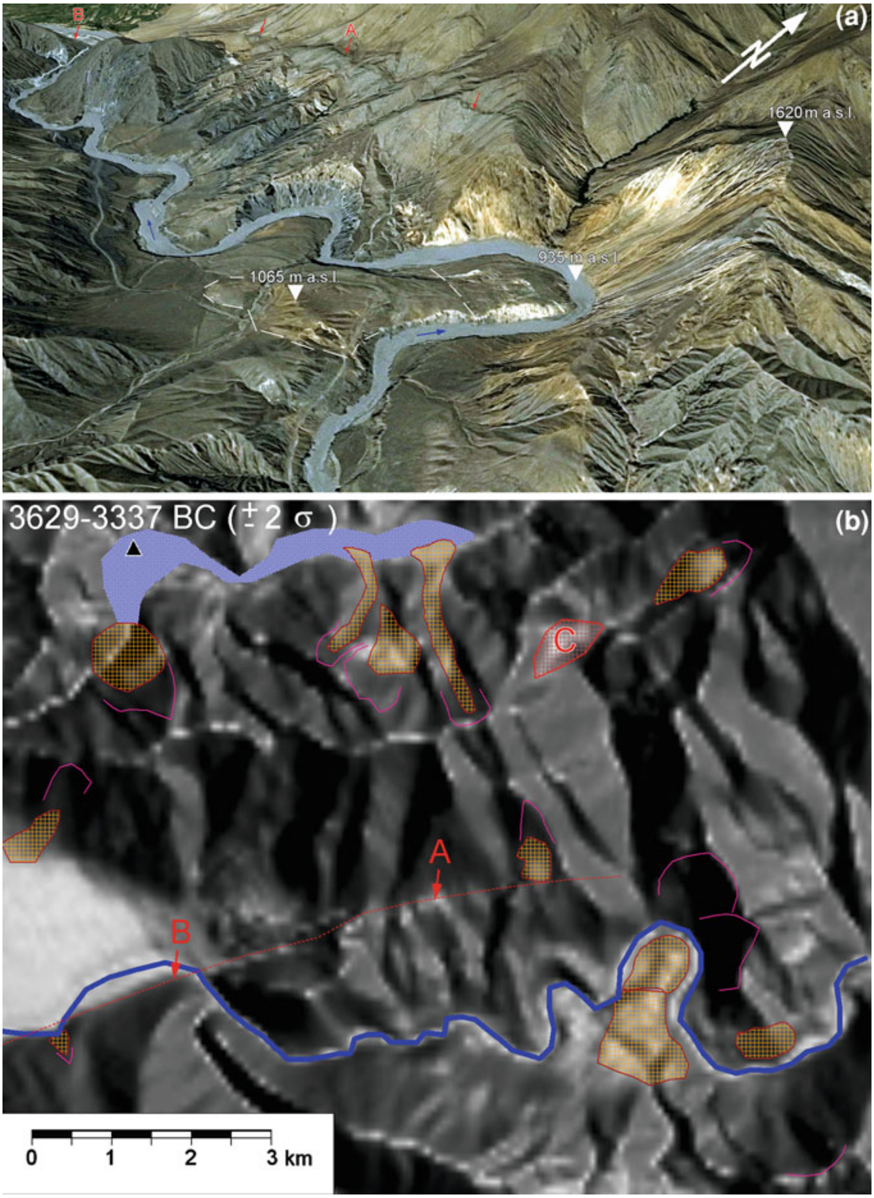
Fig. 17 **a** The Djuzumdy rock avalanche site (14 on Fig. 1, 41°47′ N, 73°24′ E) in the Naryn River valley, east from the Ketmen-Tiube depression. 3D Google Earth view. Large-scale slope failures from the headscarp on the *right* (bellow point at 1620 m a.s.l.) had occurred twice. Approximate frontal edges of these rock avalanche deposits are marked by dashed lines. According to lichenometric studies the younger body was formed more than 1000 years ago, which does not contradict to the age of the latest rupturing event along the adjacent active fault (marked by *red arrows*), that had happened roughly from 105 BC to 238 AD (2σ range). Trenching was performed at the site marked as (**A**). Evidence of recurrent surface faulting were found at the site marked as (**B**). **b** Sketch of landslides and active fault developed at this area. Three rockslides about 3 km north from the Naryn River, at the opposite side of the ridge, affected by the Djuzumdy rock avalanches and surface rupture, rest on the deposits of the older landslide dam. The charcoal sample collected from these deposits returned age of 3629-3337 BC (2σ range). Thus, they should be younger than ~5000 years. Calibration of radiocarbon ages was performed by Calib 5.0 (Stuiver and Reimer 1993). "C" marks the Djuzumdy caldera-like cavity (Strom and Groshev 2009) ▶

if they are located close to a large active fault (Crozier 1992; Belousov et al. 1994; Bull 1996). Strictly speaking the above Naryn-Sonkul fault zone case exemplified by the Djusumdybulak landslides (see Fig. 17a) also represents indirect evidence of various features simultaneity—landslide ages determinations just bound the age of faulting with better precision (Fig. 17b).

We must consider also that, according to Malamud et al. (2004), strong earthquakes and other energetic triggering phenomena like typhoons usually produce one or few large and extra-large landslides along with numerous medium and minor features. Indeed, many earthquakes were accompanied by only one extremely large slope failure without anything else comparable (Ischuk 2011; Owen et al. 2008), or by few large landslides located at a significant distance from each other (Bogdanovich et al. 1914; Wu et al. 2010; Yin et al. 2009, 2011; Huang and Li 2009). It is evident that hundreds and thousand years after the event it would be difficult to proof large-scale slope failures simultaneity, even if we would be able to date them directly, considering accuracy of sampling and precision of dating methods that can be used for such studies (Walker 2005).

Additional (though, of course not the alternative) approach is based on thorough analysis of the basal units of lacustrine sediments in the drained landslide-dammed lakes where one can find features closely timed to master events (Strom 2012b). Simultaneity of large-scale slope failure and of other slope failures or liquefaction phenomena that occur at a rather large distance provides sound reasons to considering all these phenomena, each of which could be caused by ground shaking, to be triggered by strong earthquake that had affected large area.

At present relations of most of the prehistoric river-damming bedrock landslides in the Pamirs and the Tien Shan with large earthquakes are still unknown. Solution of this problem requires extensive and regular studies of such features including their dating, detailed analysis of their relationships with nearby active faults and reconstruction of the pre-slide slope morphology and internal structure that could be used for retrospective numerical modeling of slope stability. The latter is a powerful tool for revealing real nature of the phenomena in question, but its reliability strongly depends on the input parameters accuracy and reliability.



4 Spatial Distribution of River-Damming Landslides

The first step of the landslide hazard assessment in general and of hazard assessment related to landslide river damming, in particular, is regular mapping of landslides and compilation of their representative inventories. The preliminary studies carried out in the Central Asian region revealed significant unevenness of landslide distribution throughout these mountainous systems—zones of their extreme concentration alternate with areas with similarly rugged terrain but lacking such features (see Fig. 16).

Most of zones featuring high concentration of bedrock slope failures coincide with large fault zones, with some exceptions, however. For example, east–west trending belt with numerous landslides stretching along the Naryn, Lower Kokomeren and Minkush River valleys visible on Fig. 16 follows the Naryn-Sonkul fault zone. However, numerous landslides in the upper part of the Kokomeren River valley (Strom and Abdrakhmatov 2009) do not follow any regional fault zone though some of them are close to local active faults.

Areas where deep river valleys follow large fault zones seems to be the most susceptible for the formation of large landslide dams due to combination of several factors: (A) presence of high steep slopes formed due to the powerful streams' incision; (B) wide distribution of rocks weakened by faulting and fracturing typical of large fault zones; (C) complex groundwater conditions supported by differently oriented aquifers and aquicludes. All these factors favor formation of very large landslide dams and landslide-dammed lakes. Seismicity, which is, often, associated with same fault zones, is an important, but not obligatory factor. Thus, as discussed above, while active fault zone with known high seismic activity should be definitely considered as a landslide-prone area, opposite conclusion, i.e. consideration of a fault zone with high concentration of landslides as being seismically active requires additional argumentation.

Sometimes, landslide distribution within fault zones is uneven too and distinct clustering could be observed along their strike (Strom and Abdrakhmatov 2004; Abdrakhmatov and Strom 2006). While numerous multiple-aged landslides could be found within such clusters, nothing similar exists between them, despite similarly rugged topography, presence of active faults with surface ruptures, and complex geological structure. It can be exemplified by the Inylchek River valley blocked by large successive rock avalanches that collapsed from both slopes of the valley at 42°09.5′ N, 79°27.5′ E, about 17 km downstream from the present day terminus of the Southern Inylchek glacier (16 on Fig. 1, Fig. 18). Both geology and topography of the valley just at this section and outside, where no similar slope failures have occurred, look similar (Fig. 19). Absence of any recognizable geological and geomorphic anomalies at those sections of the river valleys following along large fault zones were recurrent large-scale rockslides occur allows assumption that an abnormally high slopes' instability is caused by an "external" factor, notably by increased strong motion effect governed by some peculiarity of source rupturing process. It follows thence that these sites should be considered as most hazardous during future large earthquakes.

Even if these speculations about role of seismicity in landslide clustering is wrong, and real causes of any particular slope failure and of their concentration at this site are not fully understood, areas featuring recurrent large-scale slope failures are characterized by an abnormally high landslide hazard level and should be, thus, the first priority sites for hazard assessment and monitoring. It can be exemplified by the Aini

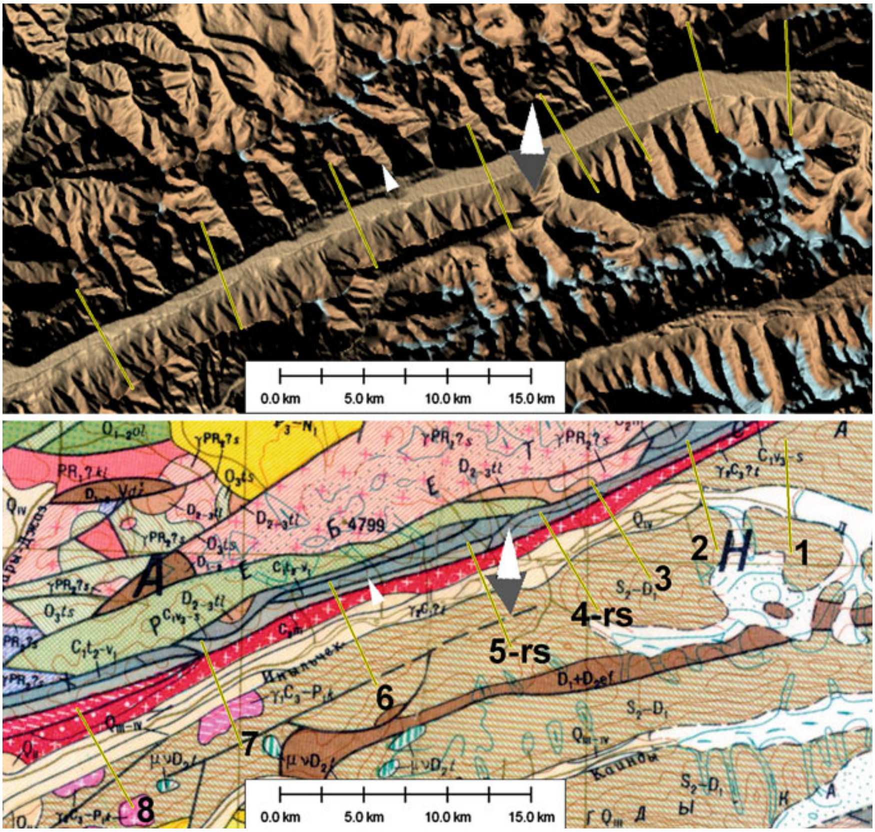


Fig. 18 SRTM DEM (*above*) and fragment of 1:500,000 geological map of the Inylchek River valley. Triangles show the position of large rockslides identified in the valley. Rockslide from the right bank (*larger white triangle*) is younger than that from the *left* bank (*grey triangle*). *Numbered yellow lines* profiles shown on Fig. 19

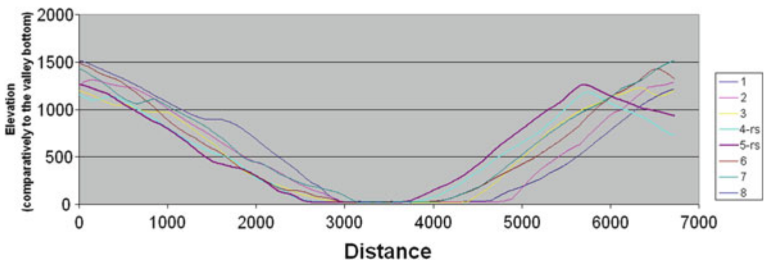


Fig. 19 Superposed cross-sections of the Inylchek River valley (see their location on Fig. 18). Profiles 5-rs and 6-rs cross the valley close to the landslide dam formed by *right-bank* rockslide that overlaid the *left-bank* one. Note that slopes' steepness is almost the same all over the valley

town area in the Zeravshan River valley in Tajikistan, described above (see Fig. 6). The 1964 river-damming landslide was preceded by much larger prehistoric one and indications of future instabilities are evident on the left-bank watershed.

Similar clusters could be identified not only in the Tien Shan, but in the Pamirs as well. One of the largest of them includes the Usoi dam—the most recent river-damming feature, the preceding giant Murgab landslide (23 on Fig. 1), the Kudara breached dam in the adjacent river valley (9 on Fig. 1) and several smaller breached dams nearby. Such an abnormal concentration increases probability of the new large landslides within this area, including the Sarez Lake banks, though it is unlikely that we can quantify this hazard with reasonable substantiation. Landslide dams' distribution in other parts of the Western Pamirs is more even, in general, while the plateau-like Eastern Pamirs almost lacks such features.

Ambraseys and Bilham (2012) noted that almost all large-scale slope failures in the vicinity of the Usoi dam have occurred on south-facing slopes and linked this effect with stronger weathering depending on slope aspect. This assumption is opposed, however, by inverse orientation of slopes most affected by large rock-slides in the upper part of the parallel Gunt River valley and its tributaries. Here many large-scale slope failures including river-damming features took place on the north-facing slopes. Among them are the Yashinkul (see Fig. 13), the Rivakkul (see Fig. 10), the Imom (see Fig. 11) rockslides and several others that could not be described herein due to paper length limitations. In contrast, westward, in the downstream part of the Gunt valley and in the lower reaches of its largest tributary—the Shakhdara River valley, most of bedrock slope failures affected south-facing slopes—similar to the Murgab-Kudara (Usoi) cluster.

Such differentiation allows assumption, though just speculative at present, that slope failures orientation could be governed by directivity of seismic shaking, rather than by the influence of any exogenous processes (weathering, nivation phenomena, etc.). In case of the Murgab-Kudara (Usoi) cluster this hypothesis is in line with the assumption that the source zone of the 1911 Sares earthquake was located somewhere west from the Usoi landslide site (Ambraseys and Bilham 2012, their Fig. 4), likely within the fault zone that stretches in the NE direction towards the Karakul Lake tectonic depression. If so, just right (south-facing) slopes of the river valleys would be "lighted" by seismic waves spreading from their foci.

Voluminous outburst floods could provide especially high risk for the hydraulic schemes located downstream. Thus, identification of sites with increased possibility of future river damming within the catchment should be performed within the frames of corresponding engineering surveys. In the Central Asia region such analysis was carried out for the Rogun Dam in Tajikistan (Besstrashnov et al. 2011; Zhirkevich et al. 2011). Cluster of several past rockslide dams and evidence of the potential future failures was identified in the central part of the Muksu River valley in the northern Pamirs at 39°08′ N, 71°45′ E (17 on Fig. 1,) and rough estimates of the volume of possible landslide-dammed lake and of the outburst flood parameters were obtained. It was shown that, due to significant distance from this site to the Rogun reservoir and the dam site, even worst scenario would not pose a real threat for the dam. Nevertheless, considering centuries-long life-time of most of hydraulics structures, such analysis must be obligatory for hydraulics engineering and should be included in the national and international guidelines and regulations (Besstrashnov et al. 2011; Zhirkevich et al. 2011).

5 Effects of Bedrock Landslide Dams' Morphology and Internal Structure on Their Hazard Assessment

Geological conditions discussed above determine formation of large-scale bedrock landslides which is the main type of slope failures in mountainous regions of Central Asia responsible for river damming. However, as mentioned above, effects of valley inundation and of subsequent outburst floods are, in most cases, much more disastrous than direct effects of slope failure itself. As soon as landslide occurs and blocks the valley, further evolution of the blockage depends on hydrological characteristics of the stream on the one side and on dimensions, shape and internal structure of the blockage on the other side (Hermanns et al. 2011; Dunning and Armitage 2011). Though most of such dams have been breached rather soon (Schuster and Costa 1986; Costa and Schuster 1988; Schuster and Evans 2011; Evans et al. 2011a, b), many of them exist for decades, centuries and millennia. At the same time, even centuries-long survival of a landslide-dammed lake does not ensure its further stability that was exemplified tragically in the region in question by the above mentioned Issyk and Yashinkul disasters.

5.1 Critical Morphological Peculiarities

In the overview of the Central Asian landslide dams (Strom 2010b) it was shown that most of them behave as predicted according to the DBI value (Ermini and Casagli 2003). However, several landslide dams demonstrate inverse behavior. Some of features that have large DBI values indicating their instability have existed for a very long time, and, likely, will be stable in future, while some other with low DBI (i.e. within the stability domain) have been breached soon after formation. Analysis of such abnormal behavior reveals several additional factors and parameters (besides landslide dam volume and height, and stream discharge described in terms of catchment area), which must be considered as prerequisites for landslide dams' disaster assessment and mitigation.

An important factor influencing a landslide-dammed lake lifetime and risk of an outburst flood is the presence of another dam upstream. Such cascade location can either decrease risk or increase it significantly. The first scenario can be exemplified by the Kulun River that had been dammed twice—in its upper reaches at 40°32′ N, 74°17.2′ E, where the 90-m deep Kulun Lake still exist (18 on Fig. 1) and at 40° 27.6′

N, 74° 04.2′ E, just upstream from its mouth where 70-m high rockslide dam formed by rockslide from the upper part of its right bank composed of Paleozoic limestone (19 on Fig. 1), created 6.5-km long lake. The dam was overtopped but not breached and the lake have been silted completely (Strom 2010b). Here the stable upstream dam forms the lake large enough to cut off seasonal floods that reduces possibility of a downstream lake outburst significantly.

In contrast, breach of even rather small upstream lake of any origin (landslide, moraine, etc.), especially if it causes a debris flow, could have a dramatic effect on the downstream water body and its damming feature, resulting sometimes in the outburst flood much more powerful than the initial one. Just such chain catastrophe occurred in 1963 in the Issyk River basin (see Sect. 1.2).

One of landslide dams' characteristics quite important for assessing their longevity and style of breach is the cross-valley profile of the dam (Hermanns et al. 2011; Korchevskiy et al. 2011), which, in turn, depends at a large extent on rockslide motion mechanism (Strom 2006). Perhaps the main mechanism of dams breach is their erosion due to overtopping, which starts at a lowermost part of the dams crest. Under otherwise equal conditions landslide dams formed in relatively narrow valleys by rock avalanches of the primary type (Strom 2006) with distinct proximal lowering are more subjected to catastrophic breach than those with distal lowering (formed by rock avalanches of the secondary and jumping types, ibid). While in the first case erosion would cut through landslide body composed of crushed debris and this process can be quite rapid and catastrophic, in the second case it is much more likely that stream incision will start at the frontal edge of the landslide body and will affect the bedrock of the opposite slope. Thus, the outlet channel will develop gradually, like it happened in case of the Beshkiol (Korup et al. 2006) and Kokomeren (Hartvich et al. 2008) landslides. In the latter case the gigantic ($\sim$1.5 km^3 in volume) Late Pleistocene Kokomeren rockslide (41°55.5′ N, 74°13.5′ E, 22 on Fig. 1) likely experienced dual style of breaching—upper part of the dam composed of rockslide debris could fail catastrophically while its lower part several tens meters high was eroded gradually being protected by the bedrock spur at the upstream edge of the blockage (Fig. 20).

Slower breach of the dams with distal lowering is not obligatory, however, it strongly depends on the shape of the buried valley. For example, the Holocene Lower Aral landslide that had blocked the Kokomeren River valley at 41°47.9′ N, 74°17.3′ E (20 on Fig. 1) by the 70-m high dam with distal lowering was, nevertheless, breached catastrophically, producing powerful debris flow with peak discharge about 28,000–30,000 m^3/s (calculations were performed by A. Zhirkevich) that left large boulders on top of a 10-m high cliff $\sim$2 km downstream from the dam (Fig. 21). In this case the landslide had filled just the lowermost box-shape part of the river gorge with very steep slopes. In any case this factor—the across-valley dam profile—should be taken into consideration when predicting blockage evolution and elaboration of possible disaster mitigation measures.

One more important morphological characteristic of landslide dams is the along-valley debris distribution (Hermanns et al. 2011; Strom 2010a). Dams' stability and its possibility to sustain erosion dew to overtopping and/or internal

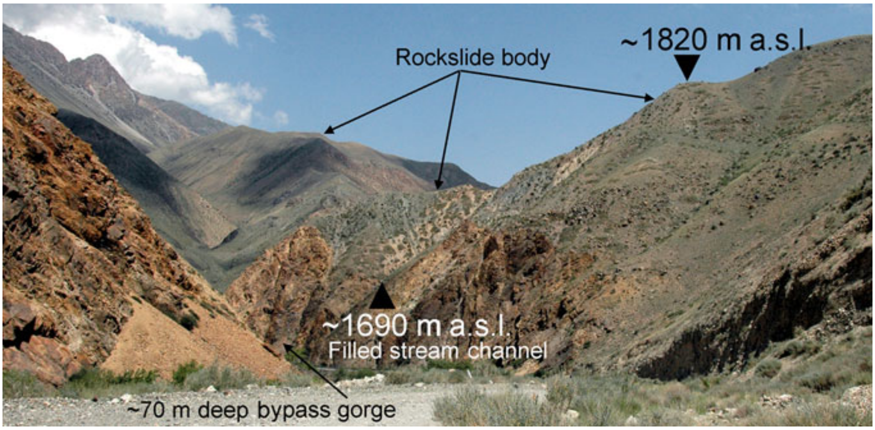


Fig. 20 Bypass gorge eroded through the bedrock at the upstream limit of the Late Pleistocene Kokomeren rockslide dam

piping strongly depend on its compactness. It can be well exemplified by two extreme case studies—the Yashinkul dammed Lake in Pamirs described above (10 on Fig. 1) and the Aksu breached dam in the Tien Shan (42°32.5′ N, 74° E, 21 on Fig. 1). Both of them demonstrate behavior, opposite to that expected according to the DBI of features in question (Strom 2010a). The fist one (see Fig. 13), with DBI = 3.71, much more than 3.08—the lower bound of the instability domain (Ermini and Casagli 2003) is, nevertheless, quite safe and stable feature. Its debris collided with rocky spur at the opposite bank of the river and spread for 3.7 km up and downstream the valley, which decreased dams' height significantly—up to ~50 m maximum. Difference between the lake level and the downstream tip of rock avalanche is about 130 m that returns water table gradient of 0.035, which corresponds to its inclination angle of about 2° only. Such a weak flow is unable to erode blocky carapace that covers the dam body (see Fig. 14), thus there is no possibility for this dam to be breached in any reasonable time.

The giant Aksu dam more than 400 m high (it is a minimal—effective dams' height) and about 1.5 km^3 in volume (Fig. 22) that had blocked rather small river demonstrates opposite behavior. With DBI = 1.94 this feature should be in the stability domain, which upper limit is 2.75 (Ermini and Casagli 2003). Nevertheless the dam was breached and, judging from the absence of lake sediments in the valley upstream, soon after its formation. Most likely that after overtopping rapid turbulent flow at the downstream slope of this very compact dam with along-stream length of 2.5 km only (compare with ~4 km long Usoi and ~3.5 km long Shiva dams of the same order of size) had eroded its proximal lower part very fast.

Analysis of dams' morphology allows optimization of the disaster mitigation measures. For example, if the crest level of the newly formed dam at its distal and proximal parts would be more or less equal, it would be more reasonable to excavate an artificial outlet channel at the distal edge of the blockage, rather than at

Fig. 21 Debris left by outburst flood after breach of the Lower Aral Holocene landslide dam on the isolated ~10 m high cliff about 2 km downstream from the breached dam. *Dark blue arrow* shows river flow direction. *Left* inset—large angular blocks of granite up to 1 m in size carried by the fist, most powerful surge of the debris flow formed by outburst and deposited immediately downstream from the cliff in its ‘shadow’. This material was, likely, eroded from the dams’ outer part. *Right* inset—cliff is covered by stony angular granite debris left by the following part of the debris flow enriched by smaller fragments, likely from the internal part of the dams’ body. Orientation of flattened fragments clearly indicates direction of debris flow motion (*brown arrows*). Note that debris flow was thick enough to leave about 2-m thick debris 10 m above the river level

its central or proximal parts. In this case we can expect slower incision prevented by the bedrock of the valley opposite slope, and, thus, lower peak discharge of the outburst flood (of course, not in the case of the U-shape or box-shape valley).

5.2 *Basic Characteristics of the Landslide Dams’ Internal Structure*

The majority of bedrock landslide deposits that form large natural dams both in the Central Asia region and all over the World are characterized by dual internal structure—their lower/internal parts are composed by intensively comminuted and compactly embedded debris that forms giant low permeable blockage core overlaid by

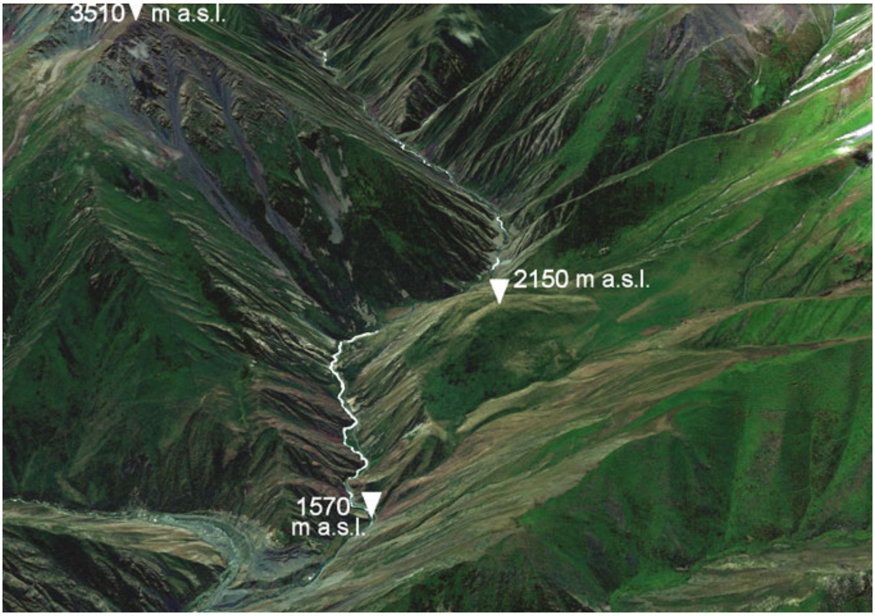


Fig. 22 Breached Aksu dam in the Aksu River valley at the northern slope of the Kyrgyz Range. Remaining part of the dam's body is the smooth hill with top mark at 2150 m a.s.l. 3D Google Earth view

coarse blocky carapace or, sometimes, by huge intact bedrock massifs (McSaveney and Davies 2006; Poschinger et al. 2006; Poschinger 2011; Dunning and Armitage 2011; Hewitt 2006, 2011; Abdrakhmatov and Strom 2006; Strom 1994, 2006, 2010b; Crosta et al. 2011; Davies and McSaveney 2011; Weidinger 2011).

Such internal structure predetermines water filtration pattern and, in favorite cases, possibility of the dam to sustain the superficial and internal erosion. Coarse blocky carapace with large void space supports filtration, while intensively crushed and densely compacted angular fragments of the internal core could form almost impermeable body. Permeable blocky carapace, along with significant up- and downstream debris spreading ensure long-term stability of the above mentioned Yashinkul dam in Pamirs. In general, higher the dam is, wider its upper filtering zone would be and, at favorite conditions, its dimensions could be large enough, so that filtration can compensate the inflow as in the Usoi case (Ischuk 2011). It can explain longevity of some giant dams in Nepal Himalaya (Weidinger 2011), Karakoram (Hewitt 1998, 2006, 2010, 2011) and Argentina (Hermanns et al. 2011) that had blocked rivers with rather large discharge. In such case the higher dam could be much safer than the lower one.

If, however, outer coarse blanket is removed naturally or by excavation and powerful turbulent flow affects the internal comminuted debris directly, dam fails catastrophically, unless the outflow channel incises the bedrock (as on Fig. 20). Such catastrophic breach occurred, in particular, in 1963 at the Issyk Lake (see

Fig. 5) where waves generated by debris flow entering in the lake removed blocky carapace armoring the blockage surface. Subsequent dams breach was quite rapid (Gerasimov 1965). Presence of large amount of intensively fragmented bedrock debris, which is entrained in the water flow leads to its immediate transformation in the rapidly moving debris flow, which was observed during the 1985 Bairaman dam breach in Papua New Guinea (King et al. 1989) and was described above in the Lower Aral landslide case (see Fig. 21). Such debris flows, besides extremely hazardous direct effects on the population and infrastructure, result in significant flood plane aggradation.

On the other hand, intensive debris comminution typical of dams' interiors could support the internal erosion and piping, especially considering sharp contact between comminuted and coarse facies that was observed at some deeply eroded landslide bodies (Strom 2006). Free turbulent water flow through the voids in the blocky carapace could remove fines from the underlying crushed material causing deformations and settlement of the dams' crest.

Sometimes landslide dams' stability is difficult to predict. For example, the 1964 Aini dam described above, the 2002 Yigong dam (Shang et al. 2003), the Tangjiashan dam, formed during the 2008 Wenchuan earthquake (Yin et al. 2011) fail shortly after streams started passing through the spillway trenches excavated across their crests to reduce possible amount of water release. In contrast, the 2010 Attabad dam that blocked the Hunza River still exist while significant discharge passes through the spillway channel built for the same purpose (Delaney and Evans 2011).

In the region in question the most critical problem is the structure and grain-size composition of the interiors of the Usoi dam. Some researchers believe that dams' lower part is composed of a gigantic intact bedrock block(s) (Papirin 1990; Negmatullaev and Ischuk 2011). From my point of view, based on observations of numerous deeply dissected rockslides (Strom 1994, 2006; Abdrakhmatov and Strom 2006), the internal part of this natural dam is composed, most likely, of the intensively crushed and densely compacted rock debris, preventing seepage through more than 3/4 of its body. Objective solution of this issue is urgently necessary both for dam long-term stability assessment and for disaster mitigation measures elaboration.

6 Conclusions

Case studies described herein exemplify geological and geomorphic factors that predetermine formation of river-damming landslides, magnitude of the impoundment (lakes' depth and volume), its longevity and style of dams' breach. All these form the basis of the identification and quantification of hazard related to landslide dams' formation and evolution and plays an important role in selection of technical and social measures aimed to predict and/or to prevent related disasters.

If we consider not only present-day hazard provided by the existing landslide-dammed lakes that might breach, at least hypothetically, but also the long-term hazard stipulated by large-scale slope failures that could occur in future (which is quite important, in particular, for hydraulic structures with, sometimes, centuries-long life cycle), we must, first, identify areas with higher possibility/probability of such phenomena occurrence. It requires, first, regular regional mapping of landslides, those that caused river-damming in particular and creation of their complete inventory for the entire Central Asian mountainous region. Emphasis must be placed on those zones and more localized areas where recurrent large-scale landslides have occurred in the past and, especially, if there are evidence indicating future instabilities. Regardless of real nature of such clustering, they must be considered as first priority sites for detailed studies of slope stability and monitoring. Extensive dating of past landslides should be considered as an important topic of these investigations providing information, necessary for time-dependant hazard and risk assessment.

Besides, such regional mountain-system-scale studies provide relevant data for statistical analysis of various parameters of landslide dams and dammed lakes relationships in the mountainous region characterized by arid climate, which could differ somehow from those typical of the Mediterranean region or of the Longmenshan mountains with much more humid climate for which such analyses were performed at a regional scale like in the Apennines (Casagli and Ermini 1999) or for one extraordinary triggering event—the 2008 Wenchuan earthquake (Fan et al. 2012).

Site-specific landslide dams' hazard assessment and elaboration of disaster prevention/mitigation measures require data that can be revealed from the detailed analysis of the geology and geomorphology of both existing and past (breached) landslide dams. I want to point out that deeply eroded breached dams are most informative for this purpose, especially in case of extremely large features (Abdrakhmatov and Strom 2006). Same size intact landslide dams like the Usoi blockage, could be hardly studied with same details, due to extreme difficulty of either deep drilling or deep geophysical exploration of such complex and irregular bodies. Better knowledge of how past landslide dams were breached could help in elaboration of optimal disaster mitigation measures in case of similar phenomena in future.

Emptied landslide-dammed lakes also provide unique opportunity to search features at the basal units of lake sediments that can be almost simultaneous with blockage formation, thus providing additional data that can shed light on the nature of triggering event (Strom 2012b). Such studies link landslide damming hazard assessment with seismic hazard assessment which is another critically important prerequisite of disaster mitigation in Central Asia region.

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