Landslide dams in Central Asia region

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Abstract

The Central Asia region has been a scene of numerous large-scale bedrock landslides that have blocked river valleys producing landslide-dammed lakes, more than 100 of which still store water. The largest one is the **Usoi** dam 2.2 km³ in volume and more than 550 m high in Pamirs (Tajikistan) that originated in 1911 due to strong (M7.2) earthquake. It forms the 500 m deep **Sarez** Lake - the world deepest natural reservoir that poses a threat to Central Asian countries located downstream in the Pianj - Amu Daria River basin. Though many of landslide-dammed lakes should be considered as stable and safe features, catastrophic outburst floods that occurred in 20th Century, emphasize high potential hazard of such natural blockages. Several prehistoric landslide-dammed lakes in Pamirs and Tien Shan with intact dams were filled by lacustrine sediments, but most of natural dams were breached and deeply eroded providing excellent opportunity to study their internal structure and grain-size composition - parameters determining dams' short-term and long-term stability at a large extent. Additional factors, increasing or decreasing rockslide dams stability are exemplified by case studies from the Central Asia region.

Key words : landslide dam, rockslide, outburst flood, Pamirs, Tien Shan

1. Introduction

The Central Asia region extends from the Caspian Sea in the west to western part of China in the east and from Kazakh plain in the north to the northern faces of Hindu Kush and Karakorum in the south. Its large portion is occupied by the Pamirs and Tien Shan mountain systems (Fig. 1), which highest peaks rise above 7000 m.a.s.l. These mountains are the sources of most of Central Asia rivers, which, being fed by glaciers, snowmelt water and rains have incised valleys up to 2-3 km deep. Such extreme topography along with complex geological structure, active tectonics and high seismicity form background favorable for large-scale slope failures.

Numerous bedrock landslides (rockslides) have occurred in Pamirs and Tien Shan producing hazardous natural phenomena such as long runout rock avalanches and dammed lakes, more than 100 of which still store water. Much more frequent landslides in loose unconsolidated Quaternary deposits and Mesozoic and Cenozoic sediments typical of the foothill areas rarely create permanent dams, since, usually, they are smaller and their bodies, even if they block river channel, are eroded much faster.

This paper presents a brief overview of the existing and past landslide dams in Pamirs and Tien Shan. Most examples described hereafter, are from Kyrgyzstan and Tajikistan; some case studies are from Southern Kazakhstan, Afghanistan, Uzbekistan, and Xinjiang in Western China.

Though many of the existing landslide-dammed lakes should be considered as stable and safe features, catastrophic outburst floods that occurred in 20th Century, some of which are described hereafter, empha-

size high potential hazard of natural blockages. One of the potentially hazardous objects is the **Usoi** dam 2.2 km³ in volume and more than 550 m high in Pamirs (Tajikistan) that originated in 1911 due to strong (M 7.2) earthquake. The 500 m deep **Sarez** Lake that has been impounded upstream is the world deepest landslide-dammed lake (Costa & Schuster, 1991). Long-term stability assessment of this dam and lake that pose a potential threat for the communities living in the Bartang, Pianj and Amu-Daria River valleys in Tajikistan, Afghanistan, Uzbekistan and Turkmenistan with the population over 5.5 million people (Gaziev, 1984, UNISDR, 2000, Schuster, 2002), as well of some other similar dams requires better knowledge of their internal structure and composition that can be achieved, in particular, by detail study of those natural dams, which were breached and deeply eroded providing excellent opportunity to learn more about their interiors. Their characteristic features are discussed briefly hereafter.

2. Existing landslide-dammed lakes

Many fascinating mountainous lakes are known in the Central Asian region. Largest of them, like Issyk Kul in Kyrgyzstan, Kara Kul in Tajikistan or Bagrash Kul in China ('Kul' means lake in Turkic languages) fill intermountain neotectonic depressions; hundreds of small lakes at the topmost parts of ranges are glacial. There are, however, numerous lakes, both small and large, that originated due to river damming by bedrock landslides. Among them are the **Usoi** (No. 1) and the **Yashilkul** (No. 2) lakes in the Tajik and the **Shiva** Lake (No. 4) in the Afghan part of the Pamirs, the **Iskanderkul** Lake (No. 8) in the Southern Tien Shan (Tajikistan), the **Sarychelek** (No. 7), the **Karasu** (No. 5), the **Kulun** (No. 17), the **Kiolsu** (No. 26) Lakes in the Central Tien Shan (Kyrgyzstan), the **Bolshoe**

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Almaty (No. 24) and the **Kiol** (No. 27) Lakes in Southern Kazakhstan, the **Badak** Lake in Uzbekistan (No. 25), the **Tianchi** (No. 9) and the **Big Dragon** (No. 10) Lakes in the Chinese Tien Shan (numbers here and hereafter are the same as on Fig. 1). These natural reservoirs, many of which are famous tourist sites along of their beauty, store large amount of sweet water that can be used for irrigation and electricity production. Some of them, at the same time, pose a significant threat for the communities living downstream.

2.1 Rockslide-dammed lakes in Pamirs, Tajikistan

The Pamirs ("Roof of the World") is the highest mountain system of the Central Asia region. Its top-most summits-the Kongur (7719 m), the Kongurtiube (7595 m), the Mustag-Ata (7546 m) (all in the eastern, Chinese part of the Pamirs) and the Ismail Somoni (former Kommunism) peak (7495 m) in the Tajik part. Western and Eastern Pamirs are characterized by extremely rugged terrain with up to 3 km deep valleys, while its central part forms a Tibet-like plateau with wide flat valleys at 3000-4000 m.a.s.l. divided by 1-1.5 km high ranges. Case studies described hereafter are from the Western Pamirs (see Fig. 1-A).

2.1.1 Usoi Dam and Sarez Lake (No. 1)

This world largest historical non-volcanic landslide (Costa & Schuster, 1991) originated on February 18, 1911, when M7.2 earthquake caused catastrophic wedge-like failure of about 2.2 km³ (~ 6 billion tons) of quartzite, schist, shale and dolomite and formation of the 567 m high Usoi natural dam (Photo 1) named af-

ter the small village that was buried with 54 inhabitants. The 5 km long (across the valley) and 3.75 km wide dam blocks the Murgab River valley at 38° 16.5' N, 72° 36' E. Despite the remoteness and inaccessibility of the site, Russian researchers performed first studies of this unique feature soon after the event (Shpilko, 1915, Preobrajensky, 1920). Its regular studies started in 1960s (Scheko, Lekhatinov, 1970, <http://sarez.ferghana.ru/>).

The 500 m deep and 60 km long lake (Fig. 2) that has been impounded upstream contains almost 17 km³ of water. It was named after the submerged Sarez village. 3 years later, in 1914, seeping water found its way through the blockage (though source of those springs could be not the Sarez Lake itself, but either the small Shaddau Lake in the tributary valley dammed by the same landslide, or water from the glacier valleys that remain above the headscarp - see <http://sarez.ferghana.ru/>). Significant filtration through the dam started about 1925. Estimates of the present-day mean discharge passing through the dam range from 45.8 to 47 m³/s (UN International Strategy for Disaster Reduction, 2000). During the flood periods when water rises for about 5m above the mean annual level, it increases up to 85 m³/s (UN International Strategy for Disaster Reduction, 2000). The critically important fact is that seepage through the dam takes place through the uppermost ~140 m of the dam only (most permeable zones are within the uppermost 50-70 m of the blockage), while remaining 350-400 m are

Fig. 1 Location of landslide dams in the Central Asia region mentioned in this paper (numbered arrows). A and B – zoomed parts of Western Pamirs and Central Tien Shan. 1 – Usoi; 2 – Yashilkul; 3 – Shids; 4 – Shiva; 5 – Karasu; 5a – Kapkatash; 6 – Karakul; 7 – Sarychelek; 8 – Iskanderkul; 9 – Tianchi; 10 – Big Dragon; 11 – Twin – Lakes (Upper); 12 – Twin – Lakes (Lower); 13 – Issyk; 14 – Yashinkul; 15 – Aini; 16 – Beshkiol; 17 – Kulun; 18 – Kulun Mouth; 19 – Aksu; 20 – Kokomeren; 21 – Djashilkul; 22 – Arashan; 23 – Kutmankul; 24 – Bolshoe Almaty; 25 – Badak; 26 – Kiolsu; 27 – Kiol; 28 – Dead Lakes; 29 – Djuzumdybulak; 30 – Kudara; 31 – Rivakkul; 32 – Ornok

practically impermeable. Nature of such impermeability is debatable. Some researchers (Papyrin, 1990) believe that dams' lower part is composed of a gigantic, almost intact bedrock block. From my point of view, based on observations of numerous deeply dissected rockslides, the internal part of the Usoi dam is composed, most likely, of the intensively crumbled and densely compacted rock debris. This impermeable "core" is overlaid by angular boulders and large fractured blocks that form permeable carapace (Strom, 1994, 2006). Large rockslide dams featuring such internal structure will be described hereafter.

Seeping water forms powerful springs, which appear ~140 m below the lake level in the canyon that cuts the downstream slope of the blockage (see Photo 1B). Its head erodes both the dams' body and sediments left by debris flows that originate from the glacier valleys remaining above the headscarp. In 1947 a rockfall from the headscarp wall blocked the channel and diverted these debris flows towards the lake (Paramonov, 1969).

Downstream slope of the blockage is crossed by bow-shape scarps (see Photo 1B) that can be interpreted as headscarps of secondary landslide (Paramonov, 1969). Largest of them could originate when rapidly moving rockslide collided with the opposite bank of the Murgab River valley (Strom, 2010). It can be assumed that such secondary deformations have produced potential sliding surfaces, thus decreasing the overall stability of the dam.

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). Though studies performed since 60th revealed that the dam in its present state should be considered as a stable feature that could not be destroyed by water pressure or immediate overtopping, its long-term (decades and centuries) perspective is questionable. It is hypothesized, in particular, that large-scale slope failure may occur on the lakes' right bank, 4-5 km from the blockage (Photo 2),

Fig. 2 Satellite imagery of the Sarez Lake. U – the Usoi Landslide, SL – the Sarez Lake, S – the Shaddau Lake

which would cause the huge wave. The latter could gash over the dam at its lowermost section resulting in the dam's partial or complete breach (see Kazakov, <http://sarez.ferghana.ru/kazakov.html>).

Different researchers estimated volume of this "Right-bank landslide" from 0.3 to 2.0 km³. However, possibility of such a large-scale failure, its volume and rate estimates are still controversial and require more studies (UNISDR, 2000, Ischuk, 2006). Additional uncertainty of this slope stability assessment is associated with Central Pamirs high seismic activity (9 points of the MSK-64 scale, according to the official seismic zoning map of Tajikistan). 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 that long-term dam stability can not be guaranteed without special security measures.

Recently, within the frames of the World Bank Project, the early warning system has been installed aimed to record various indicators of the dams' instability (seismic strong motion, rapid increase of water level, etc.) and to allow people living downstream to escape to special shelters arranged above the endangered level.

Nevertheless, since the potential risk of the blockage breach and of the devastating outburst flood exists, special measures should be undertaken to ensure long-term safety of the Lake Sarez regardless of any dynamic effects such as strong earthquake or impact of the surge wave caused by a large-scale lake bank failure.

2.1.2 Yashilkul Dam and Lake (No. 2)

The Yashilkul landslide-dammed lake is located at 37° 47' N, 72° 44' E, 3734 m.a.s.l. Unlike the gigantic Usoi rockslide that formed rather compact and, thus, very high dam, the Yashilkul rockslide about 50×10^6 m³ in volume had converted into rock avalanche that filled the valley at a distance of about 4 km (Photo 3). The dam is characterized by dual structure with semi-rounded moraine-like bouldery material inside overlaid by carapace of angular gneiss blocks and debris. It was hypothesized that Yashilkul Lake had been first dammed by the end moraine, later on overtopped by a rockslide. I assume, however, that it is a pure rockslide dam. When about 1 km high slope collapsed, main part of rockslide composed of gneiss blocks and debris had pushed bouldery glacial deposits resting at the foot of the slope. This moraine material fell into river channel, blocked it and was overlaid by the following bedrock debris (Strom, 1994).

Rockslide had occurred before 13th Century, since Arabian inscriptions of this age were found on some angular boulders on top of the dam. The lake, fed by the Alichur River, is the source of the Gunt River. Being nearly 20 km long and with an area of 36.1 km², it

Photo 1
Helicopter views of the Usoi rockslide headscarp (A) and body (B). Notice that the downstream slope of the dam is deformed by high secondary scarps (marked by white arrows on Photo 2B). Blue water body at the right part of Photo 1B – the Shaddau Lake. Seeping water erodes the canyon visible at the lower left part of Photo 1B

Photo 2 Location of the assumed "Right-bank landslide" (marked by red arrows) that can cause a surge wave in the Sarez Lake. Concave slope just right from the Usoi headscarp – the source zone of the giant Pleistocene Murgab rockslide, according to Fedorenko (1988)

Photo 3 Overview of the Yashilkul rockslide dam. Photo courtesy N. Ischuk. (Photo was made before the spillway construction)

is rather shallow-up to 50 m only and stores about 0.5 km³ of water. The dam is stable, moreover the outflow (~ 4 m³/s as an annual mean value) passes through the coarse carapace composed of gneiss blocks. Recently it became artificially controlled by the spillway constructed across the dam's crest to increase power production of the hydraulic power plants at the lower part of the Gunt valley.

2.1.3 Shids rockslide dam (Pamirs, Tajikistan-Afghanistan border) (No. 3)

Several partially or completely eroded rockslide dams exceeding 1 km³ in volume each could be found in the Pianj River valley, along or close to the Tajik-Afghan border. One of them originated in the prehistoric times on the ~ 1.5 km high right bank of the Pianj valley composed of Proterozoic granite and gneiss ($37^{\circ}55.5' \text{ N}$, $71^{\circ}18.5' \text{ E}$). Though this 400 m high rockslide body had been almost completely incised by powerful Pianj, 20-30 m high dam still exist at Shids village and remnant lake extends about 15 km upstream Pianj valley (Fig. 3).

Further upstream lacustrine sediments could be found along the banks of Pianj and Bartang Rivers up to ~ 2000 m.a.s.l., indicating maximal extent of lake sedimentation. Since small frontal part of rockslide body that remains on the left bank of the valley rises up to ~ 2200 m.a.s.l., it can be assumed that the effective dams' height (height of the lowermost point of the dams' crest, corresponding to the maximal possible lake level) was less than its maximal thickness, and did not exceed 300 m - about one half of that of the **Usoi** dam. It is evident that powerful Pianj with mean discharge of 467 m³/s (almost 10 times more than that of the Murgab River) (State Water Inventory) should inundate the lake in several years and that the dam

Fig. 3 Shids rockslide and remnant lake in the Pianj River valley. Google Earth panoramic view. Large white arrows mark rockslide headscarp; small white arrows—frontal limit of the dam's body. Elevations of the marked points are above sea level

was breached by overtopping, which is typical of blockages at affluent rivers. However, at some specific conditions, exemplified hereafter, landslide-dammed lakes even on large rivers can exist for centuries and millennia (Korup et al., 2006, Hewitt, 2006).

2.2 Rockslide-dammed lakes in the Tien Shan

The Tien Shan Mountains, though not as high as the Pamirs, have been affected by hundreds of large-scale bedrock landslides many of which caused rivers' damming. Unlike Western (Afghan and Tajik) and Eastern (Chinese) Pamirs, where up to 3 km deep gorges dividing main mountain chains have been formed by glacial and water erosion, many of the Tien Shan ranges represent individual neotectonic anticlines divided by wide intermountain neotectonic depressions, nowadays used by river valleys (Makarov, 1977, Chedia, 1988). Most of the Tien Shan river damming sites could be found either in narrow gorges eroded through the barriers between intermountain depressions by main streams with large (thousands of square kilometers) catchments and high discharges, or in the tributary valleys that cross slopes of separate anticline ridges. The latter have much smaller catchments (dozens or few hundreds square kilometers) and runoff. Extensive study of several existing and past landslide dams in Tajikistan and Kyrgyzstan was performed in 70th - 80th (Fedorenko, 1988).

2.2.1 Rockslide-dammed lakes in the Karasu-Left River valley

The 150 m deep **Karasu Lake** (No. 5) was formed in the Karasu-Left River valley dammed by the rockslide 2.5×10^8 m³ in volume and about 250 m high, that caved from the 900 m high left bank of the valley composed of Paleozoic limestone. This dam is located at $41^{\circ}34.5' \text{ N}$, $73^{\circ}13.5' \text{ E}$ exactly over the trace of the Talas-Fergana active fault - one of the largest faults of the entire Tien Shan Mountain system. Age of this blockage is not less than 1000 years (Belousov, et al., 1994). Such a long-term existence of the lake is due to the size of the dam and small discharge of the river. Lake's volume is about 0.22 km³ - almost the same as the dams' volume. Absence of the overtopping and erosion evidence indicates its present day stability. One more much smaller landslide-dammed lake - the **Kap-katash** one (No. 5a) is located 10 km upstream, also over the trace of the Talas-Fergana fault (Fig. 4). Though its exact age is unknown it can be hypothesized that both rockslides occurred simultaneously, being triggered by one of the last strong earthquake at this segment of the Talas-Fergana fault (Mamyrov, et al., 2009).

2.2.2 The Sarychelek Dam and Lake (No. 7)

The 234-m deep landslide-dammed Sarychelek Lake is located in the upper reaches of the Karasu-Right River valley at $41^{\circ}51.5' \text{ N}$, $71^{\circ}59' \text{ E}$. It was formed by

giant prehistoric bedrock landslide about 34 km² in size that had caved from the 6.5 km long headscarp in the Devonian sedimentary rocks (Fig. 5). Dams' volume (~ 6 km³ if not more), more than one order bigger than the amount of water stored in the lake (0.48 km³), guarantees its long-term stability. Several smaller lakes are located just within the rockslide body and in the vicinity of the Sarychelek Lake; some of the latter could be dammed by landslides triggered by the M7.5 1946 Chatkal earthquake, which epicenter was close to this site.

2.2.3 The Iskandrul Dam and Lake (No. 8)

The largest existing landslide-dammed water body in the south-western, Tajik part of the Tien Shan (the Alai and Gissar Ranges) is the Iskandrul Lake located at 39°05.1' N, 68°22.9' E, 2195 m.a.s.l. The 3.4 km² and up to 72 m deep lake is the source of the Iskandrul-Daria River. Rockslide occurred on the slope composed of Paleozoic sedimentary rocks. The Iskandrul-Daria originates from the surficial outflow with 18.6 m³/s mean discharge. It erodes an up to 50-70 m deep gorge in the landslide body with a powerful waterfall at its central part (Fig. 6). It indicates that the dam undergoes intensive backward erosion, which could, in time, result in its breach.

The rockslide nearly 1 km³ in volume that dams the Iskandrul Lake is the largest one of bedrock landslide cluster located in this area. One more rockslide dam ~ 160 m high that covers 1.5 km² had blocked a

Fig. 4 The Karasu (the bigger one) and the Kapkatash rockslide dammed lakes at the Talas-Fergana fault zone. 3-D view composed from the 3" SRTM DEM. The Talas-Fergana fault passes along the Karasu-Left River valley. Distance between the dams is ~ 10 km

Fig. 5 The Sarychelek rockslide and rockslide dammed lake. Google Earth image. White arrows mark the headscarp

junction of two rivers that bring their water to the Iskandrul Lake (see Fig. 6-C). Small lakes that had been formed in both blocked valleys had been partially filled by sediments and, finally, drained.

2.2.4 Landslide-dammed lakes in the Chinese Tien Shan

Largest landslide-dammed lakes in the eastern, Chinese part of the Tien Shan are the **Tianchi** Lake (No. 9, 43°54' N, 88°07' E) and the **Big Dragon** Lake (No. 10, 43°36.3' N, 82°23.5' E). Both dams created by rockslides about 1.5-2.0 km³ in volume are nearly 400 m high. According to ¹⁰Be cosmogenic dating the **Tianchi** Lake originated during the Late Glacial epoch, about 12 ka BP (Yi, et al., 2006).

These lakes are of the same type as the **Sarychelek** one (No. 7), being formed by gigantic rockslides in the short and steep valleys dissecting neotectonic anticline limbs. Enormous size of rockslides, surpassing lakes' volume, guarantees their stability.

One more interesting case study in the Chinese Tien Shan is located at 42°41' N, 84°56.8' E. Here a rockslide that can be named as "**Twin-lake**" had caved just above junction of two river valleys and blocks both of them forming two lakes at 3025 and 2890 m.a.s.l. (No. 11 & 12) (Fig. 7). The site could be considered as a favorable one for a pumping power plant, since most expensive structures of such scheme - upper and lower reservoirs had been "constructed" by Nature. Traces of temporary surficial overflow from both lakes are visible on the Google Earth satellite imagery.

3. Outburst floods caused by landslide dams breach

Most of the above-mentioned landslide-dammed lakes have existed for a long time - from about 100 years (the Sarez Lake) up to millennia or more. However, much more landslide dams in the study region have been breached either by overtopping or due to internal erosion. Several devastating outburst floods caused by rockslide dam breach had occurred in Central Asia in the 20th Century (Pushkarenko, Nikitin, 1988).

3.1 The 1963 Issyk Lake catastrophe

On July 7, 1963 catastrophic outburst of the Issyk

Lake (No. 13) occurred east from the former capital of Kazarhstan, the Almaty city. It resulted in the devastating debris flow that passed through the Issyk valley and which traces are visible till now, almost 50 years after the disaster. The prehistoric landslide dam ($43^{\circ} 15.3' \text{ N}$, $77^{\circ} 28.9' \text{ E}$) about 0.6 km^2 in size and up to 100 m high ($\sim 25 \times 10^6 \text{ m}^3$ in volume) was composed of diorite blocks (on top) and same rock crushed at a high extent in the dams' interior (Eugen Gaspirovich, personal communication). The dam was breached by overtopping caused by debris flow that originated in the upper reaches of the catchment due to outburst of the glacial lake. Up to 6-7 million m^3 of debris was brought into the Issyk lake within 3-4 hours resulting in rapid increase of the lake level and creation of waves that hit the upper part of the blockage. They destroyed the dam's crest and water stored in the lake rushed downstream eroding the dam body as well as river banks (Gerasimov, 1965). Peak discharge recorded about 10 km downstream, close to the Issyk town, was $745 \text{ m}^3/\text{s}$, 150 times more than mean river discharge at this site - $4.96 \text{ m}^3/\text{s}$ (State Water Inventory). Only small remnant lake remained after the disaster. Later on an artificial dike was built at the eroded canyon to protect downstream valley and the Issyk town from new debris flows and to renew this

beautiful tourist site.

I want to notice that rapid erosion of the dam's body could be supported by intensive comminution of the internal part of the blockage. As soon as coarse blocky carapace was removed by surge waves produced by debris flows entering the lake, nothing could prevent further incision. This peculiarity of large rockslide dams will be described in more details in the section devoted to old breached dams internal structure.

3.2 The 1966 Yashinkul Lake catastrophe

Another well-known catastrophic outburst flood caused by the rockslide dam breach had occurred on June 18, 1966 in the Isfairamsay River basin in Southern Kyrgyzstan (No. 14). The $20\text{-}30 \times 10^6 \text{ m}^3$ rockslide composed of Paleozoic metasediments debris originated about 300 years ago, likely being triggered by an earthquake. It formed a dam about 100 m high that blocked the Tegermach River valley (right tributary of the Isfairamsay River) at $39^{\circ} 55.6' \text{ N}$, $72^{\circ} 18' \text{ E}$ and created the Yashinkul Lake (Rezvoi & Rezvoi, 1969, Rezvoi et al., 1971, Reizvikh et al, 1971). In June 1966 the dam was overtopped due to continuous raining. Outburst flood that lasted for about 7 hours with peak discharge of $5000 \text{ m}^3/\text{s}$ caused significant damage not only in Kyrgyzstan but also in Uzbekistan. Unlike the Issyk Lake that was partially reimpounded afterward,

Fig. 6

Google Earth (QuickBird) views of the Iskanderkul dammed lake. A – an overview; B – perspective view of the Iskanderkul dam; C – perspective view of the breached rockslide dam upstream from the Iskanderkul lake. Red arrows mark headscarps; thin white lines outline rockslide bodies; blue arrow on Figures A and B – waterfall in the central part of the canyon eroded through the Iskanderkul dam; green planar areas on Figure C are partially filled past dammed lakes

Fig. 7

Twin-Lakes Rockslide in Chinese Tien Shan damming two lakes, which levels differs for 135 m. Perspective Google Earth image

the Yashinkul Lake disappeared completely through the canyon up to 90 m deep, 50-60 m wide at its bottom and 280-340 m wide at the dams' crest level (Neshikhovskiy, 1988). Thus, about 10×10^6 m³ of debris (from one third to one half of the entire rockslide volume) was removed from the dams' body causing significant aggradation downstream.

3.3 The 1964 Aini Blockage - the averted disaster

Recent river-damming rockslide that could result in a terrible disaster which was, however, prevented by timely arranged measures, occurred on April 24, 1964 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) (No. 15). 20 million cubic meters of debris blocked the Zeravshan valley by a dam up to 150 m high (maximal height, the effective one was much lower, about 50-60 m only) and ~1 km along the stream. Dammed lake fed by both rivers with cumulative discharge of about 90 m³/s (in April-May, 1964; mean annual discharge at this gauge is 147 m³/s, according to State Water Inventory) started inundating. It could store up to 126×10^6 m³ of water, which release would devastate lower part of the Zeravshan River valley and ancient Samarkand City. The situation, however, was under control and 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 1200 m³/s was recorded on May 31. Lake was almost emptied at June 20, when its level dropped for 32.5 m. Three millions cubic meters of debris was eroded from the dam resulting in significant aggradation of the Zeravshan River channel. The pre-rockslide level of the stream has not been reached yet (Neshikhovskiy, 1988). This case study is one of the first examples of the successful prevention of the rockslide dam breach disaster.

4. Past rockslide dams, their evolution and internal structure

4.1 Rockslide-dammed lakes filled by sediments

River damming in mountainous regions with significant sediment yield typical of most of streams, especially during flood period, finally results either in dam breach or in lake siltation. Several landslide-dammed lakes in Central Asian region were filled by lacustrine sediments completely or partially and drained so that flat areas favorable for agriculture and housing remain upstream (see Fig. 5-C). It allows estimating the longevity of river valleys damming, which can help to predict long-term evolution of the existing rockslide-dammed lakes described above.

4.1.1 The Karakul rockslide dam and silted lake (No. 6)

The Karakul rockslide about 300×10^6 m³ in volume had blocked the Karasu-Left River mouth at 41° 38' N, 72° 39' E. Rockslide caved from the slope composed of the Devonian limestone thrust over the Permian sandstone and conglomerate. Besides the Karasu-Left River mouth it had blocked the Naryn River channel as well, but powerful Naryn had eroded its part of the dam completely, while Karasu had impounded the ~200 m deep lake and found its way through the bed-rock bench that appeared to be lower than the crest of the dam composed of the Devonian limestone debris. In time the lake was completely filled by sediments. Now this flat area is occupied by the Karakul town (Photo 4).

According to OSL (optically simulated luminiscence) dating performed by Dr. Yeong Bae Seong from Korea University, siltation should last up to 4.1-2.9 ka BP and even later (silt material was sampled from the upper part of the lake sediments, though not exactly from its top). It can be hypothesized that formation of the above-mentioned **Karasu** (No. 5) and **Kapkatash** (No. 5a) rockslide dams that blocks the same river in its upper reaches (see Fig. 4) took place after the formation of the Karakul natural dam. Otherwise river could hardly bring such a large amount of material to infill the Karakul lake. Moreover, the Karakol River that also had fallen into this water body (the Karasu-Left and Karakol Rivers present day cumulative mean discharge is 9 m³/s, according to State Water Inventory), had been blocked by a gigantic **Dead Lakes** (No. 28) rock avalanche that had occurred on the slope composed of Paleozoic metasediments (Strom, Korup, 2005). Its age is estimated as 42-47 ka (according to ¹⁰Be dating performed by Dr. Seong). This assumption provides additional, though indirect estimates of the **Karasu** rockslide age lower limit - it should be younger than ~2.9 ka.

4.1.2 The Beshkiol rockslide dam (No. 16)

The case study of an affluent river damming that resulted in almost complete siltation of the dammed lake could be found at 41° 26' N, 74° 29' E, where the Naryn River crosses the Western Akshiyriak Range (Strom, 1998, 2005, Strom and Korup, 2005, Korup et al. 2006, 2007). Gigantic (~10 km³) landslide in Neogene continental sediments (sandstone, mudstone with gypsum interbeds) mainly and in Paleozoic rocks at its proximal part had blocked the Naryn River valley at a distance of about 7 km. The dam was up to 300 m high and filled the valley slightly above the level of a tectonic bench on its right side (~1740 m.a.s.l.). Unlike most of the above-mentioned permanent rockslide dams that blocked relatively small rivers and remain for centuries and millenia, this case study represents long-term

Photo 4 Silted rockslide-dammed lake area occupied by the Karakul town (at the foreground). Hilly area at the background – the rockslide dam originated from the headscarp marked by red arrows. The source zone is composed of the Devonian limestone thrust over the Permian red conglomerate. The Karasu-Left River bypasses the dam through the triangular gorge at the left part of the panorama (blue arrow)

Photo 5 Upstream (A) and downstream (B) views on the rockslide-dam at the Kulun River mouth

damming of the powerful river with mean discharge of about $200 \text{ m}^3/\text{s}$ (State Water Inventory) that accumulates from the $31,300 \text{ km}^2$ catchment. Assuming that river's annual runoff and sediment yield at that time was of the same order as at present, the lake that had extended for about 80 km upstream (Fig. 8) should be impounded in few years. After that water had found its new way not over the dam's crest, though some evidence of piping through the Neogene debris intercalated with solution-prone gypsum beds are visible, but bypassed the dam over the above-mentioned tectonic bench composed of hard Paleozoic rocks. Before sinu-

ous, 10 km long and $\sim 250 \text{ m}$ deep bypass gorge has been eroded, lake was silted up to $\sim 1650 \text{ m.a.s.l.}$, for about $2/3$ of its assumed depth. Dividing the estimated siltation volume by the mean annual sediment yield we found that river damming had lasted for 3000-4000 years (Korup et al., 2006). Later on significant portion of lake sediments was washed out. It can be hypothesized that when the hard bedrock obstacle was cut through, further rivers' incision into soft lake sediments could be quite rapid (Korup et al., 2007). It should increase sediment yield drastically and leave some imprints in the alluvium downstream.

I want to point out that large amount of fine sediments in the Naryn River valley upstream from its crossing with the Western Akshiyriak Range was erroneously interpreted as the effect of the latter's rapid tectonic uplift (Makarov, 1977). It demonstrates the importance of the landslide damming phenomena correct interpretation for better understanding not only of the river valleys' evolution but of the regional neotectonics as well.

4.1.3 The Kulun River valley rockslide dams

The complete siltation of the rockslide-dammed lake could be observed at the Kulun River mouth. This right tributary of the Tar River had been dammed twice - in its upper reaches at $40^\circ 32' \text{ N}$, $74^\circ 17.2' \text{ E}$, where the 90 m deep **Kulun Lake** (No. 17) still exist

Fig. 8 The Beshkiol rockslide dam and former lake at its assumed level of 1740 m.a.s.l. marked by diagonal cross-hatch. Perspective view compiled from the 3" SRTM DEM

and at $40^{\circ}27.6' \text{ N}$, $74^{\circ}04.2' \text{ E}$, just upstream from its mouth. Here the **Kulun-mouth** rockslide (No. 18) that had caved from the top of the right bank composed of Paleozoic limestone, had formed a 70 m high dam and 6.5 km long lake. Later on this lake was silted completely (Photo 5).

It can be hypothesized that presence of the 250 m high blockage damming the **Kulun Lake** in the upper reaches of the same valley provides significant runoff control and decreases peak discharge, thus supporting gradual siltation of the downstream water body.

4.2 Peculiarities of the breached rockslide dams internal structure

As mentioned above, most of the Central Asian rockslide dams have been breached and deeply eroded providing excellent opportunity to study internal structure and grain-size composition of rockslide deposits (Strom, 2006). Several examples of such breached dams could be found in the Central and Northern Tien Shan (Abdrakhmatov, Strom, 2006). One of the most interesting case studies is the Kokomeren rockslide (No. 20) located in the same name river valley at $41^{\circ}55.5' \text{ N}$, $74^{\circ}13.5' \text{ E}$, downstream from the small Kyzyl-Oi intermountain depression (Strom, 1994, 2006). Its most detail description could be found in (Strom, Ab-

drakhmatov, 2009) available at <http://www.iclhq.org/>.

This Pleistocene rockslide originated most likely due to a strong earthquake (Strom, Stepanchikova, 2008). From 1.0 to 1.5 km³ of rock collapsed from the 1600 m high slope composed of alteration of various multi-colored sedimentary and igneous rocks - dark-gray shale, reddish granite, alternating red granite and dark-gray sandstone, possibly with some fault zones. Expressive variability of rock types involved in this slope failure (Photo 6) allows reconstruction of the emplacement mechanism, which model is presented on Fig. 9 (Strom, 1994, 2006, Hartvich et al., 2008).

While main part of the rockslide body rests on the ~150 m high river terrace, its frontal part had filled the Pleistocene river channel, which was about 50 m above the present-day riverbed. This part was almost completely eroded except its small portion that fills remnant of an old river channel on the modern valley right bank. Here, similar to the Beshkiol case (No. 16), the new gorge has been cut through the bedrock that should slow down the process of dams' breach significantly. The blockage with effective height of ~200 m (Hartvich, et al. 2008) had formed the lake ~1 km³ in volume that had been impounded less than in one year by powerful Kokomeren, which present-day mean annual runoff is $\sim 2.5 \times 10^9 \text{ m}^3/\text{year}$ (State Water Inventory). Presence of nearly 10^8 m^3 of well-bedded lacustrine sediments indicates that river damming could last for few centuries at least.

Two major zones can be distinguished in this natural dam. The upper one about 200-250 m thick is composed of coarse blocks and large massifs of fractured reddish granite, overlaid, in its turn, by the gray 'layer' of angular boulders of metasediments and shale (1 on Photo 6). In contrast, the lower zone, up to 150-200 m thick (2 on Photo 6), consists of heavily shattered rocks, divided into some unmixed 'layers' of granite and metasediment fragments. Besides intensive comminution, lower part of the Kokomeren rockslide dam as well as of other large-scale rockslides is characterized by dense compaction of angular or scale-like particles that makes it almost impermeable. It explains sharp heterogeneity of filtration through high natural dams as the **Usoi** blockage - water passes through their blocky carapaces only that blankets giant and almost impermeable cores.

The succession of debris 'layers' corresponds to the bedrock alternation in the headscarp (see Fig. 9). It demonstrates that this part of sliding mass, up to 150-200 m thick, moved as a single whole, without turbulence and mixing. It is assumed that intensive shattering typical of the lower part of rockslide body took place during the emplacement.

'Stratification' of rockslide bodies and intensive crushing and compaction of debris that form cores of

Fig. 9 Model of the Kokomeren rockslide emplacement mechanism (after Hartvich, et al. 2008)

Photo 6 Deeply eroded Kokomeren rockslide dam. aQ – Late Pleistocene strath terrace alluvium underlying rockslide body; 1 – coarse blocky zone; 2 – fine-grained shattered zone

Photo 7

Debris 'stratification' of the Ornok rockslide that incorporates both Paleozoic rocks (gray units) and Neogene redbeds. Bedrock Neogene strata dipping $\sim 40^\circ$ are marked out at the zoomed fragment above. The entire horizontally-bedded succession represents 'stratified' rockslide body resting over the alluvium (aQ). It should be noticed that the uppermost gray-color 'layer' originated from the Paleozoic rocks that form the topmost part of the headscarp (same as at the sketch on Figure 9)

Photo 8 The Djuzumdy Bulak recurrent rockslides. N – Neogene sediments bounded by oncoming reverse faults; pink outcrops above and aside from the Neogene are Paleozoic granite; smooth surface marked as Q_3 as well as the stony hill at the foreground – body of the Late Pleistocene rock avalanche; hummocky hill marked as Q_4 – the Holocene rockslide body; arrows mark the headscarp crown

Photo 9 Upstream view of the 400 m high Aksu rockslide dam. The original river channel had passed left from the pre-slide bedrock remnant. The green meadow at the riverbank – silted lake dammed by recent landslide that caved from the main rockslide body

such natural dams was observed at many other deeply eroded rockslide dams in Central Asia (Abdrakhmatov, Strom, 2006, Strom, 1994, 2006). Among them are the 400 Mm³ **Djashilkul** rockslide (No. 21) in the Chon-Kemin River valley ($42^\circ 46.7' \text{ N}$, $76^\circ 22' \text{ E}$), and ~ 15 Mm³ Arashan rockslide (No. 22) in the Alamedin River valley ($42^\circ 36.5' \text{ N}$, $74^\circ 40' \text{ E}$) close to Bishkek City. The most impressive 'stratification' can be observed at Ornok rockslide (No. 32) in the Kokomeren River valley ($41^\circ 43' \text{ N}$, $74^\circ 13.5' \text{ E}$) (Photo 7).

4.3 Recurrent river valley blocking

Multiple rockslide formation at some local sections of river valleys is typical both of the Pamirs and the Tien Shan. It was described, in particular, by Fedorenko (1988) and by Strom & Abdrakhmatov (2004). This phenomenon can be considered as an additional factor increasing probability of river damming at such parts of river valleys.

4.3.1 The Djuzumdybulak recurrent rockslides (No. 29)

An impressive example of recurrent river damming could be found in the Naryn River valley at $41^\circ 47' \text{ N}$,

$73^\circ 24.2' \text{ E}$, immediately upstream from the mouth of its small tributary - the Djuzumdy Creek (the Djuzumdy Bulak in Kyrgyz) (Photo 8).

The Naryn River had been blocked here at least twice - in Late Pleistocene and in Holocene. Deposits of an older rock avalanche 15-25 Mm³ in volume (marked by Q_3 on Photo 8) rest on several strath terraces from 50 to almost 100 m high over which it moved for 1.7 km climbing up as if over giant steps. Most of rock avalanche debris accumulated at the distal part of the depositional zone. Low dam formed by this event was eroded at its proximal part. Further incision led to slope undercutting that, likely along with strong ($M \sim 7.5$) earthquake that occurred almost 2000 years BP (Belousov, et al. 1994), caused next rockslide of the same order of size (about 20 Mm³). It filled the canyon and formed ~ 50 m high dam (marked by Q_4 on Photo 8). This blockage was also breached at its proximal part. Large amount of loose deposits (both rockslide debris and scree) resting in the headscarp is potentially unstable. According to unverified data short-term stream blocking at this site occurred in 1992 being triggered by the M7.3 Suusamyr earthquake.

Headscarp from which these rockslides caved, is composed of Paleozoic granite crossed by active reverse faults bounding narrow 'stripe' of Neogene sediments (see Photo 8). Earthquakes, which, most likely, triggered both rockslides, were associated with this fault zone (Belousov et al., 1994). Due to combination of active tectonics, steep slope and river erosion this site should be still considered as a rockslide-prone one.

4.3.2 Successive landslide damming of the Aksu River valley (No. 19)

Deeply incised rockslide dams form valley slopes up to several hundreds meters high composed of intensively comminuted debris overlaid by coarse blocky carapace. Being undercut by erosion they could produce large subsequent landslides, which, in turn, also block river channels. Such successive river damming can be exemplified by the case study from the Aksu River valley that dissects the northern slope of the Kyrgyz Range.

About 1.5 km³ of granite and metasediments collapsed from the 1800 m high right slope of the valley in Late Pleistocene and formed the compact Aksu blockage with effective height of about 400 m at 42° 32.5' N, 74° E (Photo 9). Considering the present-day annual runoff of 140 Mm³ (State Water Inventory) the Aksu dam should be overtopped less than in one year. Judging from the absence of lacustrine sediments upstream we hypothesize that the rate of erosion that should start at the lowermost proximal part of the dam's crest was rather high. It should, however, slow down when the stream incised the bedrock, which remnants are on the left bank of the modern stream both at the up- (see Photo 9) and downstream blockage limits. Finally the dam was dissected completely and now almost 500 m high left slope of this new valley is composed of rockslide debris.

Its distinct concave shape indicates at least two episodes of subsequent failures several millions cubic meters in volume each. One of such headscarp can be

seen on Photo 9. Another most recent and much bigger subsequent landslide not visible on this photo blocked the valley by a dam several dozens meters high. A meadow on Photo 9 foreground is a small dammed lake rapidly filled by sediments, while rapids and waterfalls represent kilometer-long section of the river downstream. Most likely this recent landslide was triggered by strong ($M \sim 7.0$) 1885 Belovodsk earthquake that occurred about 15-20 km north from the rockslide site at the Kyrgyz Range foothills. This assumption is supported by the notice made by I.V. Ignatiev, who visited the area for reconnaissance. He wrote that "...water flow in the Aksu River stopped for some time after the earthquake" (Ignatiev, 1886). No other evidence of river damming that could result in such effect are known in the valley. Landslides that originate from the slopes incised in large rockslide bodies are the 'tertiary' hazardous consequence of large-scale rockslide river damming.

5. Discussion — factors determining landslide dam evolution

Most of case studies described above and listed in Table 1 follow the regularity quantified by the 'Dimensionless Blockage Index': $DBI = \log(A_b H_d / V_d)$ where A_b is the upstream catchment area, H_d is the dam height, V_d is the landslide dam volume (Ermini, Casagli, 2003). Some of them, however, demonstrate anomalous behavior (Fig. 10), which can be explained if we consider some additional quantitative parameters characterizing landslide dams and dammed lakes.

Role of such factors can be revealed from comparative analysis of case studies that demonstrate anti-thetic deviation from the behavior that could be expected according to DBI value. One can compare the long-living **Yashilkul** rockslide dam (No. 2) in the Pamirs ($DBI = 3.71$, which correspond to the instability domain) and the gigantic **Aksu** rockslide (No. 19) in the Tien Shan, which was breached rather soon after its origin, regardless low DBI value (1.94 - within

Fig. 10 Volumes of rockslide dams scaled by height versus upstream catchment area for case studies listed in Table 1 (numbers are the same as in Table 1 and Figure 1)

Table 1 Some basic parameters of rockslide dams described above

No	Region / River	Rockslide Dam	Lake (existing, filled, breached)	Dams' parameters #		Catchment area (km ²)	DBI	DBI < 2.75 – stability domain (S) 2.75 < DBI < 3.08 uncertain domain (U) DBI > 3.08 instability domain (I) / additional comments
				volume (10 ⁶ m ³)	effective height (m)			
1	Pamirs / Murgab	1911 Usoi	Existing	2200	550	14,166	3.55	I / Should be considered as being at risk
2	Pamirs / Gunt	Yashilkul	Existing	50	50	5,166	3.71	I / Permanent lake with stable dam
3	Pamirs / Pianj	Shids	Partially breached	1200	250	57,100	4.08	I / Small remnant lake still exist
4	Pamirs / Shiva	Shiva	Existing	2000	500	232	1.76	S
5	Tien Shan / Karasu-Left	Karasu	Existing	250	350	75	2.02	S
6	Tien Shan / Karasu-Left	Karakul	Filled by sediments	300	200	1063	2.85	U / Lake had existed for a long time and was silted completely
7	Tien Shan / Karasu-Right	Sarychelek	Existing	6000	250	90	0.57	S
8	Tien Shan / Iskanderkul-Daria	Iskanderkul	Existing	700	150	752	2.21	S / Should be considered as being at risk due to surficial outflow and intensive backward erosion
9	Tien Shan	Tianchi	Existing	1500	350	153	1.55	S
10	Tien Shan	Big Dragon	Existing	2000	400	57	1.06	S
11	Tien Shan	Twin-Lakes (Damming upper Lake)	Existing	150	250	83	2.14	S
12	Tien Shan	Twin-Lakes (Damming lower Lake)	Existing	50	130	111	2.46	S
13	Tien Shan / Issyk	Issyk	Breached in 1963	25	100	189	2.87	U / Lake had existed for a long time. Dam was breached by debris flow caused by the upstream lake outburst
14	Tien Shan / Tegermach	Yashinkul	Breached in 1966	25	100	107	2.63	S / Lake had existed for a long time. Dam was breached after rainstorm
15	Tien Shan / Zeravshan	1964 Aini	Dammed lake was drained artificially	20	60	7,950	4.38	I / Lake was drained artificially
16	Tien Shan / Naryn	Beshkiol	Prehistoric lake breached after almost complete siltation	10000	300	31,300	2.97	U / Lake had existed for a long time. Bypass gorge has been eroded gradually through the bedrock close to the dams' distal boundary
17	Tien Shan / Kulun	Kulun	Existing	300	250	140	2.07	S
18	Tien Shan / Kulun	Kulun-Mouth	Filled by sediments	6	70	353	3.61	I / Lake had existed for a long time and was silted completely
19	Tien Shan / Aksu	Aksu	Breached	1500	400	329	1.94	S / Dam was breached soon, likely few years after its formation
20	Tien Shan / Kokomeren	Kokomeren	Breached	1000 (1500)	200 (250)	4,946	3.0 (2.92)	U / Lake had existed for a long time. New gorge has been eroded gradually through the bedrock
21	Tien Shan / Chong-Kemin	Djashilkul	Breached	400	200	1,093	2.74	U / Dam was breached soon, likely few years after its formation
22	Tien Shan / Alamedin	Arashan	Breached	5	40	283	3.35	I
23	Tien Shan / Mailusu	Kutmankul	Existing	200	150	46	1.54	S
24	Tien Shan / Bolshaya Almatinka	Bolshoe Almaty	Existing	500	200	90	1.56	S
25	Tien Shan / Badak	Badak	Existing	30	120	37.5	2.18	S

rough estimates based on remote sensing mapping and 3" SRTM DEM analysis

the stability domain). Both rivers have almost the same mean runoff of about 140-145 Mm³/year (State Water Inventory). I assume that such 'inverse' behavior is determined by combination of two factors - shape of the blockage and the upstream valley morphology.

The ~50 Mm³ **Yashilkul** rockslide converted into rock avalanche that formed a 4 km long dam 50 m high only. Low-gradient flow over this dam can not erode meter-size blocks resting at the dams' crest. Besides, flat topography of the area upstream led to formation

of large natural reservoir that reduces peak discharge during the flood period significantly. Both factors support dams' safety.

In contrast, the **Aksu** rockslide, almost 30 times bigger, formed a 400 m high dam that stretched along the river for 2.5 km only. Its downstream slope was so steep that overflowing water had eroded it rapidly. The dammed lake was deep but rather small due to high channel grade and could not regulate runoff significantly after initial impoundment. Thus, peak discharge passing through (over) this dam should be much bigger than in the **Yashilkul** case. In this case combination of both factors worked in favor of fast and complete breach of the blockage.

Quantitative expression of dams' compactness can be characterized by H_d/W_d ratio, where H_d is the dam's effective height, and W_d is the landslide dam width (length along the stream). Increase of this value decreases dams' ability to sustain the overflow. Capability of natural reservoir to reduce peak discharge can be quantified, as a first approximation, by the runoff during flood period (R_f) divided by lake area A_L . Higher R_f/A_L ratio means that overflow peak discharge should be bigger with higher erosive potential.

Another factor determining the landslide damming longevity is the across-valley dam profile. Two main groups of blockages can be discriminated: (A) - with proximal or central and (B) - with distal lowering. Rockslide dams with proximal/central lowering seem to be less stable than blockages with distal location of their lowermost parts. If erosion starts closer to the headscarp foot, it affects the rockslide debris through which a new channel could be incised rapidly, resulting in catastrophic outburst flood and river channel aggradation. Such phenomenon took place at the **Djashilkul** dam (No. 21, DBI=2.74), for example. Similar across-valley profile was typical of the Pleistocene **Aksu** dam (No. 19). It characterizes the **Usoi** blockage (No. 1) too, increasing risk of its breach in case of overtopping.

In contrast, if the lowermost part of rockslide dam coincides with its distal edge, it is likely that overflowing stream would erode the bedrock of the opposite bank. Such situation can be exemplified by the **Beshkiol** (No. 16, DBI=2.91), the **Kokomerren** (No. 20, DBI=2.92-3.0) and the **Karakul** (No. 6, DBI=2.85) dams, that had blocked rivers for centuries and millennia, despite of rivers' runoff. It results in significant, sometimes complete siltation of water bodies, especially if the river is not affluent and can not erode the bedrock barrier completely as it occurs in the **Karakul** case.

Presence of a blockage upstream, such as in cases of the **Karakul** (No. 6) and the **Kulun-Mouth** (No. 18) dams, should be considered as an additional factor decreasing peak discharge and favoring long-term river damming. Despite high DBI values (2.85 and 3.61 cor-

respondingly) both lakes had existed for a long time being silted almost completely. In the **Karakul** case it was conditioned both by the presence of the **Karasu Lake** (No. 5) upstream and by the across-valley dams' profile. Long-term stability of the **Kulun-Mouth** blockage could be just due to significant reduction of peak discharge provided not only by its 'own' lake, but by the upstream **Kulun Lake** (No. 17) as well. It should be mentioned, however, that outburst of an upstream lake (even if it is much smaller than the downstream one) can cause catastrophic breach of the downstream blockage, as it occurred in 1963 in the **Issyk** River basin (No. 13).

Quantitative estimates of the importance of all these factors can be done on the basis of statistical analysis, which, in turn, requires uniform inventory of the Central Asian landslide dams similar to those, available for the Alps, Apennines or New Zealand (Abele, 1974, Casagli and Ermini, 1999; Ermini, et al., 2006; Korup, 2004). Compilation of such inventory for the entire Tien Shan mountainous system that belongs for 5 countries - China, Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan is performed within the IPL (International Program on Landslides) Project.

At least two of the existing natural dams described above, i. e. the **Usoi** dam (with the **Sarez** Lake) in Pamirs (No. 1, DBI=3.55) and the **Iskanderkul** dam in the Tien Shan (No. 8, DBI=2.21) seems to be at risk. The first one, which DBI is within the instability domain, could remain for about 100 years (since 1911) due to its enormous size that provides permeable zone large enough to filter the inflow through the dams' body. Nevertheless, high long-term risk of its breach is determined by several factors: possibility of runoff increase due to climate change, potential instability of the Sarez Lake banks, backward erosion in the channel developing on the downstream slope of the blockage, distinct crest lowering at the proximal part of the blockage, internal deformations of the dam that can affect the filtration and reduce dams' stability.

Hazardous state of the Iskanderkul dam, which, according to its low DBI value, should be considered as a stable feature, could be proposed due to distinct evidence of the intensive backward erosion in the canyon incised in the dams' body. If the Iskanderkul-Daria River discharge would increase, even temporary, above its present level, the erosion rate could increase as well resulting in dam failure. High seismicity of both the Pamirs and the Tien Shan increases overall risk.

It should be noticed that origin of several large natural dams in Pamirs is still debatable. I can mention, in particular, the gigantic, about 1 km³ in volume, breached blockage in the **Kudara** River valley (No. 30) at Pasor village (38°23.5' N, 72°34.7' E) and the **Rivakkul** dam (No. 31) with small lake in the Gunt

River basin (37° 37' N, 72° 03.5' E) (No. 30 and 31 on Fig. 1). According to Nikolai and Anatoliy Ischuk opinion, based on the presence of large amount of moraine material in these blockages, they have been formed by end moraines (Anatoliy Ischuk, personal communication). From my point of view, most of such blockages have been formed by rockslides and presence of coarse rounded boulders can be explained by pushing of moraine material resting on the slopes of Pamirs river valleys by rapidly moving rockslide debris (as it was described in the **Yashilkul** rockslide case - No. 2). However, final solution of this problem requires additional field studies at each questionable site.

6. Conclusions

Central Asia region characterized by rugged terrain and excellent outcropping supported by arid climate is one of the world-best natural laboratories to study large landslides and landslide-related phenomena, river damming in particular. Being rich of both existing and breached rockslide dams it demonstrates various disturbance regime landscapes (Hewitt, 2006) resulting from different scenarios of rockslide river damming:

- Temporary (days - weeks - months - up to few years) damming, causing outburst floods and downstream aggradation soon after the initial lake impoundment that can be exemplified by the 1964 **Aini** (No. 15), and the prehistoric **Shids** (No. 3), **Aksu** (No. 19), **Djashilkul** (No. 21), and **Djuzumdybulak** (No. 29) rockslide dams.
- Permanent damming of low-discharge rivers that took place centuries or millennia ago by large-scale rockslides, which are still considered as stable and safe natural dams with large water bodies as **Yashilkul** (No. 2), **Karasu** (No. 5), **Sarychelek** (No. 7), **Kulun** (No. 17), **Tianchi** (No. 9), **Big Dragon** (No. 10), **Kutmankul** (No. 23), **Badak** (No. 25) Lakes.
- Permanent damming of a river that had lasted for a long time and, finally, resulted in almost complete lake siltation without dams' rupture like **Karakul** (No. 6) and **Kulun-Mouth** (No. 18) cases. Further evolution of such scenario can be exemplified by **Beshkiol** (No. 16) and **Kokomeren** (No. 20) past rockslide-dammed lakes that had also existed for centuries and millennia being silted at a large extent, but were emptied gradually when affluent rivers cut through the bedrock barriers.
- The most hazardous scenario is when a landslide dam that has existed for centuries, being considered as a stable feature, undergoes catastrophic failure due to extreme geological (e.g. earthquake), glacial (glacial lake outburst) or meteorological (rainstorm) phenomena as it happened in 1963 with **Issyk** dam (No. 13) and in 1966 with **Yashinkul** dam (No. 14).

Better knowledge of the regularities of the Central Asian rockslide dams evolution will allow to predict further behavior of any natural dam, the **Usoi** blockage (No. 1) in particular, and either to prevent or to minimize its potentially hazardous consequences.

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References

- Abdrakhmatov, K. E., Strom, A. L. (2006) : Dissected rockslide and rock avalanche deposits; Tien Shan Kyrgyzstan. In: Evans, S. G., Scarascia Mugnozza, G., Strom, A. L., Hermanns, R. L. (Eds.) *Landslides from Massive Rock Slope Failure*. NATO Science Series: IV : Earth and Environmental Sciences, Springer, Vol. 49, pp. 551 – 572.
- Abele, G. (1974) : *Bergsturze in den Alpen. Ihre Verbreitung, Morphologie und Folgeerscheinungen*. Wiss. Alpenvereinshefte, Vol. 25.
- Belousov, T.P., Skobelev, S.F., Strom, A. L. (1994) : On estimation of the recurrence period of Strong earthquakes in the Central Tien Shan. *Journal of Earthquake Prediction Research*, Vol. 3, pp. 226 – 236.
- Casagli, N., Ermini L. (1999) : *Geomorphic Analysis of Landslide Dams in the Northern Apennine*. Transactions, Japanese Geomorphological Union 20 – 3, pp. 219 – 249.
- Chedia, O. K. (1986) : *Morphostructures and Neotectonic of the Tien Shan*. Frunze, Ilim Publishing House, 314 pp. (in Russian).
- Costa, J. E., Schuster, R. L. (1991) : *Documented historical landslide dams from around the world*. United States Geological Survey Open-File Report 91 – 239, 486p.
- Fedorenko, V. S. (1988) : *Rockslides and rockfalls, there prediction*. Moscow State University publishers, 211 pp. (in Russian).
- Ermini, L., Casagli, N. (2003) : Prediction of the behavior of landslide dams using a geomorphological dimensionless index, *Earth Surface Processes and Landforms* Vol. 28, pp. 31 – 47.
- Ermini, L., Casagli, N., Farina, P. (2006) : *Landslide dams : analysis of case histories and new perspectives from the application of remote sensing monitoring techniques to hazard and risk assessment*. Italian Journal of Engineering Geology and Environment, Special Issue 1, pp. 45 – 52.
- Gaziev, E. (1984) : Study of the Usoi Landslide in Pamir. In *Proc. 4th Int. Symp. on Landslides*, Toronto, Vol. 1, pp. 511 – 515.
- Gerasimov, V. (1965) : The Issyk catastrophe in 1963 and its ef-

- fects on geomorphology of the Issyk River Valley. Transactions of the All-union Geographic Society. Vol. 97, issue 6, pp. 541–547 (in Russian).
- Hartvich, F., Mugnai, F., Proietti, C., Smolkova, V., Strom, A. (2008) : A reconstruction of a former rockslide-dammed lake: the case of the Kokomeran River valley (Tien Shan, Kyrgyzstan). Poster presentation at the EGU conference, Vien.
- Hewitt, K. (2006) : Disturbance regime landscapes: mountain drainage systems interrupted by large rockslides. *Progress in Physical Geography*, Vol. 30, 3, pp. 365–393.
- Ignatiev, I. V. (1886) : The earthquake in the Tokmak district in the 1885. *Proceedings of the Russian Imperial Geographic Society*, 22, Issue 2. (in Russian).
- Ischuk, A. R. (2006) : Usoi natural dam: problem of security (Lake Sarez, Pamir Mountains, Tadjikistan) *Italian Journal of Engineering Geology and Environment*, Special Issue 1, pp. 189–192.
- Kazakov, Yu. M. : Lake Sarez. The Usoi blockage and Right-bank slope. Some results of engineering-geological studies performed in 1981–1992. (in Russian) <http://sarez.ferghana.ru/kazakov.html>
- Korup, O. (2004) : Geomorphometric characteristics of New Zealand landslide dams. *Engineering Geology*, Vol. 73, pp. 13–35.
- Korup, O., Strom, A. L., Weidinger, J. T. (2006) : Fluvial response to large rock-slope failures – examples from the Himalayas, the Tien Shan, and the Southern Alps in New Zealand. *Geomorphology*, Vol. 78, pp. 3–21.
- Korup, O., Clague, J. J., Hermanns, R. L., Hewitt, K., Strom, A. L., Weidinger, J. T. (2007) : Giant landslides, topography, and erosion. *Earth and Planetary Science Letters* Vol. 261, pp. 578–589.
- Makarov V. I. (1977) : Newest tectonic structure of the Central Tien Shan. Science publishers, Moscow, 172 pp. (in Russian).
- Mamyrov, E. M., Korjenkov, A. M., Strom, A. L., et al. (2009) : Geodynamics of the Talas-Fergana fault in the Tien Shan and Natural disasters of the Central Asia. Bishkek, Arashan Publishers, 228 pp. (in Russian).
- Neshikhovskiy, R. A. (1988) : Floods on rivers and lakes. Leningrad, Hydrometeoizdat. 184 pp. (in Russian).
- Papirin, L. P. (1990) : Main regularities of water seepage through the Usoi blockage. *TajikNIINTI*, Dushanbe, pp. 6–11. (in Russian).
- Paramonov B. A. (1969) : Formation of the Usoi blockage relief. *Herald of Moscow State University*, No 5, pp. 110–112. (in Russian).
- Preobrajensky, I. A. (1920) : The Usoi Landslide. *Geol. Comm., Papers on Applied Geol.*, Vol. 14, pp. 21. (in Russian).
- Pushkarenko, V. P., Nikitin A. M. (1988) : Experience in the Regional Investigation of the State of Mountain Lake Dams in Central Asia and the Character of Breach Mudflow Formation. *Landslides and Mudflows* (in two volumes). UNESCO/UNEP. Moscow. (in Russian)
- Reizvikh, V. N., Krukovskiy, G. L., Nikitin, A. M. (1971) : Causes and conditions of the Yashinkul Lake outburst. Collection of papers of the Tashkent Hydro-Meteorological Observatory, Issue 4, pp. 49–95. (in Russian).
- Rezvoi, D. P., Rezvoi, P. D. (1969) : Lake that disappeared. *Priroda* (Nature), No 7, pp. 81–83. (in Russian).
- Rezvoi, D. P., Alexeenko, A. V., Bolgar, B. D., Ermolenko, Yu. A., Marushkin, I. A., Rezvoi, P. D., Soloshenko, I. I. (1971) : Rockfall-dammed lakes of the Alai Range – important factor of the high mountain relief formation. *Reports and News of the L'vov branch of the Ukraine Geographical Society* (1968–1969). L'vov University Publishing House, pp. 71–73. (in Russian).
- Scheko, A. I., Lekhatinov, A. M. (1970) : Current state of the Usoi Blockage and tasks of future studies. In *Materials of Scientific-technical meeting on the problems of study and forecast of the mudflows, rockfalls and landslides*, Dushanbe, pp. 219–223. (in Russian).
- Schuster, R. L. (2002) : Usoi landslide dam, southeastern Tajikistan. In *Proc. Int. Symp. on Landslide Risk Mitigation and Protection of Cultural and Natural Heritage*, Kyoto, pp. 489–505.
- Shpilko, G. A. (1915) : New data on the Usoi blockage and the Sarez Lake. In : *Proc. of the Turkestan Department of Russian Geographical Society*, 11, pp. 11–17. (in Russian).
- State Water Inventory (1986–1988) : Annual and Long-Term data on the state and resources of the on-land superficial waters. Vol. V, issue 4–Southern Kazakhstan, Vol. XI–Kyrgyzstan, Vol. XII–Tajikistan. Obninsk, VNIIGMI–World Data Center. (in Russian).
- Strom, A. L. (1994) : Mechanism of stratification and abnormal crushing of rockslide deposits, in *Proc. 7th International IAEG Congress 3*, Rotterdam, Balkema, pp. 1287–1295.
- Strom, A. L. (1996) : Some morphological types of long-runout rockslides: effect of the relief on their mechanism and on the rockslide deposits distribution. In : K. Senneset (Ed.) *Landslides. Proc. of the Seventh International Symposium on Landslides*, 1996, Trondheim, Norway, Rotterdam, Balkema, pp. 1977–1982.
- Strom, A. L. (1998) : Giant ancient rockslides and rock avalanches in the Tien Shan Mountains, Kyrgyzstan, *Landslide News*, No 11, pp. 20–23.
- Strom, A. L. (2006) : Morphology and internal structure of rockslides and rock avalanches: grounds and constraints for their modelling. In : Evans, S.G., Scarascia Mugnozza, G., Strom, A., Hermanns, R. L. (Eds.) *Landslides from Massive Rock Slope Failure*. NATO Science Series : IV : Earth and Environmental Sciences, Vol. 49, pp. 305–328.
- Strom, A. L. (2010) : Evidence of momentum transfer during large-scale rockslides' motion. In : Williams, A. L., Pinches, G. M., Chin, C. Y., McMorran, T. G., Massei, C. I. (Eds.) *Geologically Active*, Proc. of the 11th IAEG Congress, Auckland, New Zealand, 5–10 September 2010, Taylor & Francis Group, London, pp. 73–86.
- Strom, A. L., Abdrakhmatov, K. E. (2004) : Clustering of large rockslides: the phenomenon and its possible causes. In : Lacerda, W. A., Ehrlich, M., Fontoura, A. B., Sayao, A. (Eds.), *Landslides: Evaluation and Stabilization*. Taylor and Francis Group, London, pp. 317–320.
- Strom, A. L., Abdrakhmatov K. E. (2009) : Rockslides and Rock Avalanches of the Kokomeran River Basin (Central Tien Shan). *ICL Summer School on Rockslides and Related Phenomena Guidebook*. 99pp. <http://www.iclhq.org/>
- Strom, A. L., Korup, O. (2005) : Extremely large rockslides and rock avalanches in the Tien Shan Mountains, Kyrgyzstan. *Landslides*, 3, pp. 125–136.
- Strom, A. L., Stepanchikova P. (2008) : Seismic triggering of large prehistoric rockslides : Pro and Con case studies. *Proceedings of the International Conference on Management of Landslide Hazard in the Asia-Pacific Region* (Satellite symposium of the First World Landslide Forum, Tokyo), Sendai, 11th–12th November 2008, pp. 202–211.
- UN International Strategy for Disaster Reduction (2000) : Usoi Landslide Dam and Lake Sarez. An Assessment of Hazard and Risk in the Pamir Mountains, Tajikistan. *ISDR Prevention Series*, No1. UN, New York and Geneva, 115pp.
- Yi, C., Zhu, L., Seong, Y.B., Owen, L.A., Finkel, R. C. (2006) : A late glacial rock avalanche event, Tianchi Lake, Tien Shan, Xinjiang. *Quaternary International*. Vol. 154–155, pp. 26–31.

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