Possibility of landslide damming in the Vakhsh River catchment and its effect on the hydraulic schemes and population

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Abstract

Large-scale landslides in mountainous regions can create high natural dams resulting in valleys inundation and subsequent disastrous outburst floods that can devastate entire valleys and cause serious problems for the hydraulic schemes located far downstream from the unstable slope site. Thus, it is very important to identify sites where such damming could occur in the catchment areas of rivers, where artificial dams and reservoirs are constructed. Case study from the Vakhsh River catchment in Tajikistan where evidence of an extremely large slope in-stability have been identified is presented. Its safety factor was determined considering possibility of an earthquake occurrence in this tectonically active region. Height of the anticipated natural dam was estimated based on the empirical relationships, as well as volume of the dammed lake that might be created. Measures aimed to mitigate the potential risks are proposed.

1 INTRODUCTION

Large-scale landslides in mountainous regions can create high natural dams resulting in valleys inundation and, quite often, in subsequent disastrous outburst floods that can devastate entire valleys and pose a significant threat to hydraulic structures located downstream. Size of the potential slope failures that affect rock massifs millions and even billions cubic meters in volume makes their stabilization almost impossible. The only way to mitigate such hazards and associated risks it to identify the potentially hazardous site before slope failure would occur and to monitor it to be able to fix failure timely. It will allow elaboration of necessary measures prior to dammed lake infilling and breach.

Site where such hazardous chain of adverse events might occur was found in the Vakhsh River catchment, near the mouth of the Ragnow River – right tributary of the Obi-Khingou River, at 38.921º N, 70.964º E. It is located about 140 km upstream from the Rogun dam and 100 km upstream from the tail part of its reservoir (Figure 1) (Strom and Abdrakhmatov, 2018; Shakirov et al. 2018). 1.1 km high slope is dissected by numerous arcuate scarps several meters high that are well visible on the aerial and space images at an altitude up to 3100 m a.s.l. and at a distance of about 800 m from the steep slope edge (Figure 2).

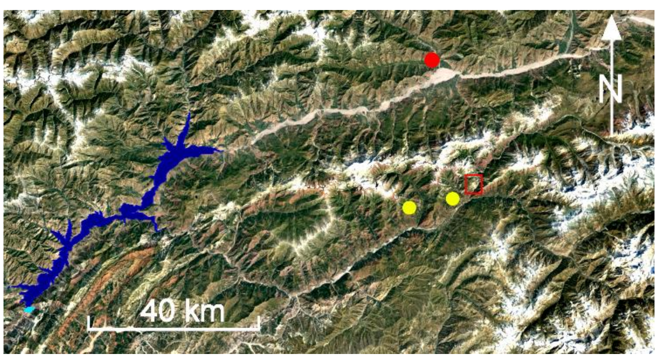

Figure 1. Location map of the anticipated Ragnow-mouth landslide marked by red quadrangle. Red dot – epicenter of the 1949 M7.4 Khait earthquake, orange dots –epicenters of the 1934 and 1935 M6.5 and M6.2 Argankul earthquakes (according to Kondorskaya and Shebalin, 1982). The Rogun dam site and reservoir are shown too.

The preliminary estimates of the potential size of this slope failure based just on expert judgement gave blockage volume of ca. 300×10^6 m^3. According to the empirical relationships between initial slope failure parameters (volume and slope height) and deposits area in the frontally confined conditions (Strom et al., 2019), the assumed dam height was estimated as ca. 250-260 m (Table 1) that could create a lake up to 410×10^6 m^3 in volume (Shakirov et al., 2018; Strom et al., 2019). These and the following estimates were made using the conservative approach – we assumed that the entire unstable rock mass could collapse in one event catastrophically, so that most of rockslide debris will fill the valley creating a landslide dam.

Table 1. Main parameters of the anticipated slope failure and landslide dam

H (km)	V (km^3)	V×H (km^4)	A (km^2)	A_{dep} (1 / 2) (km^2)	H (1 / 2) (km)
1.1	0.3	0.33	5.56	3.59 / 3.56	0.25 / 0.25
1.1	0.98	1.078	9.86	6.52 / 7.86	0.45 / 0.37
1.1	1.3	1.43	11.31	7.52 / 9.31	0.52 / 0.42

H – slope height; V – volume estimates; A - total landside affected area estimated from the relationship between A and V×H; A_{dep} (1 / 2) – landslide deposits area: 1 – estimated directly from the relationship between A_{dep} and V×H, 2 – estimated by subtraction of the assumed headscarp area of 2 km^2 from A; H (1 / 2) – dam height calculated accroding to A_{dep} 1 and 2.

However, the rough numerical simulation of this slope provided possibility of a much larger slope failure that could form higher dam. Modelling was performed considering that the study area is seismically active. Indeed, the site in question is located less than 30 km from the epicenter of the 1949 M7.4 Khait earthquake (see Fig. 1), which intensity here was estimated as 6 points of the MSK-64 scale. Moreover, earlier, on August 31, 1934 and on October 8, 1935, two Argankul earthquakes with M6.5±0.2 and M6.1±0.2 occurred near the site so that it appeared to be within their epicentral zones. Intensity of these earthquakes at the Ragnow mouth area could exceed 8 points of the MSK-64 scale (Kondorskaya and Shebalin, 1982; Schukin and Shebalin, 2016).

Figure 2. Google Earth image of the valley slope with well visible evidence of deformations.

Comparison of the available aerial images of 1956 and of the space images made in late 70's – early 80's show that the frontal face of this slope had collapsed first time within this period (Strom and Abdrakhmatov, 2018). There is also an unpublished report of the Geological Survey of Tajikistan that similar failure occurred in August 1983 (N. Ischuk, personal communication) and that river damming lasted for 3 days before the dam was breached. Most likely that just its remnants can be seen om modern space images (Figure 3).

Figure 3. Remnant of the completely eroded dam in the Ragnow River valley. 3D Google Earth image.

2 SLOPE STABILITY ASSESSMENT AND CALCULATED FAILURE VOLUME

Rockslides represent a specific group of slope processes (Zerkal, Fomenko, 2016). Their numerical modeling is complicated since compilation of the correct geomechanical model requires consideration of numerous factors such as bedding, density and orientation of fracture systems, anisotropy of rock properties, etc. We performed the numerical simulation based on the simplified geomechanical model that takes into account just general geology of the slope that can be revealed from the 1:200 000 State geological map (Figure 4), and averaged mechanical properties of the affected rock types.

The performed simulation was aimed to solve the following tasks:

- to evaluate the present-day 'static' slope stability;
- to evaluate the stability of the slope affected by seismic strong motion;
- to estimate volume of rocks that could be displaced if the entire affected rock mass will fail catastrophically.

The latter predetermine possible height of the dam that could be created and amount of water that could be stored in the dammed lake.

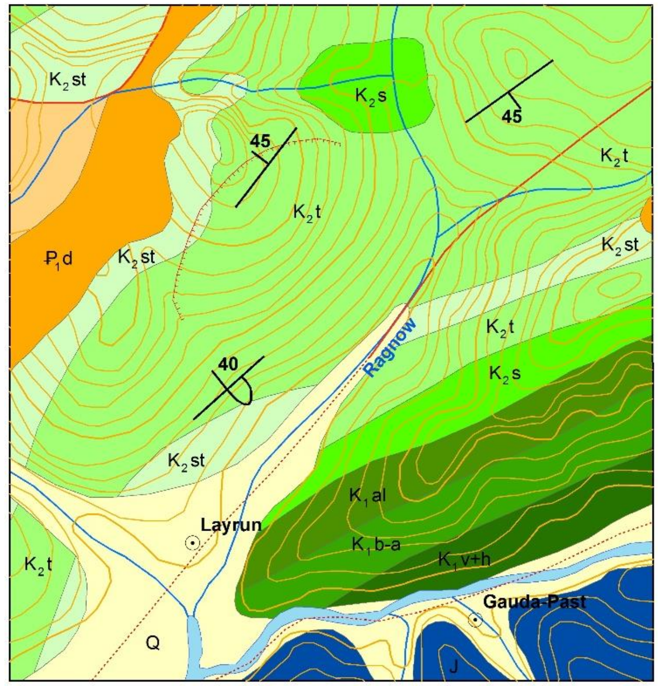

Figure 4. Geological map of the site based on the 1:200000 State geological map of the USSR, Sheet J-42-XI (1962). Ᵽ$_1$d – gypsum and clay with marl and sandstone interbeds; K_2sn – limestone, marl, clay, sandstone, gypsum; K_2t – limestone, clay, sandstone, gypsum, mudstone; K_2cm – clay, sandstone, conglomerate, limestone, gypsum; K_1v+h – K_1al – sandstone, clay, gravelly conglomerate; bold red lines – faults; dotted red lines – assumed faults; thin comb red line marks the most distant arcuate scarp (assumed headscarp crown).

3D quantitative assessment of slope stability was performed by use of the Janbu limit equilibrium method (Janbu, 1954; Fomenko, Zerkal, 2011). The Hoek-Brown failure criterion used in these calculations was determined according to rock massif classification by the Geological Strength Index (Hoek et al., 2002; Fomenko et al., 2019).

The numerical modeling was carried out in two stages. The static slope stability analysis was performed, first, to estimate factor of safety and volume of the potentially unstable massif (Figure 5). At the second stage we analyzed effect of strong motion of earthquakes with anticipated intensity of 7.0, 7.5, and 8.0 points of the MSK-64 scale (corresponding seismic accelerations 0.1g; 0.15g; 0.2 g) on the area and volume of slope failure.

Results of these modeling demonstrate rather good spatial convergence of the boundaries of the unstable rock mass revealed by simulation with arcuate scarps visible on space images and formed by earlier slope deformations (compare Figs. 2 and 5). They show that at present, even without seismic shaking, this slope is close to the limited equilibrium state – the calculated factor of safety value just slightly exceeds 1.0. In such conditions, maximal distance between sliding surface and daylight surface could reach 400 m and volume of the potentially unstable rock mass is about 980 million m^3 – 3 times more than volume revealed previously by expert's judgement (see Table 1 and Figure 6).

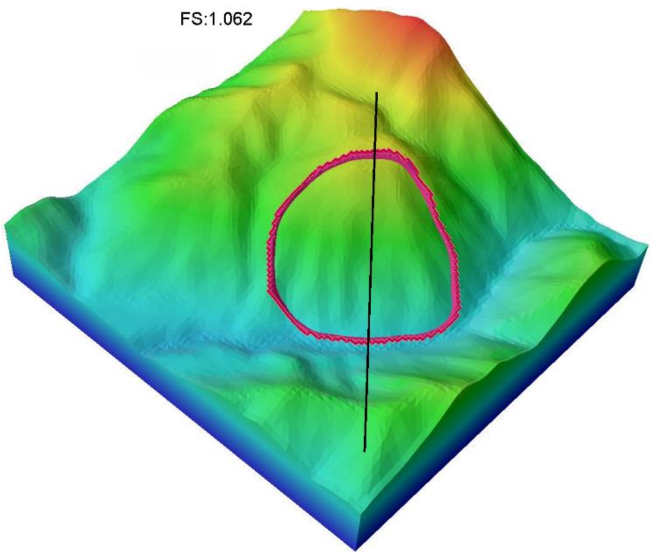

Figure 5. Boundary of the potentially unstable rock massif (red line) derived by numerical modeling in 'static' conditions (without applying seismic load). Calculated FS=1.062. Black line – profile shown in Figure 6.

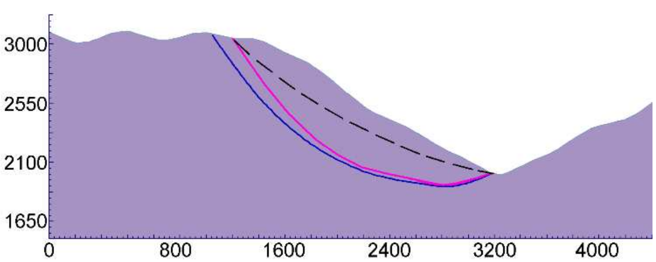

Figure 6. Cross-section of the potentially unstable slope (see Figure 5) with assumed sliding surfaces derived from numerical modeling. Red line – without seismic loading; blue line – with PGA = 0.2 g; black dashed line – previous expert judgement (Strom, et al., 2019).

The very rough, preliminary numerical modeling of the stability of the slope affected by strong earthquake shows that if its intensity will be just 7 points of the MSK-64 scale it could destabilize rock massif creating large-scale rockslide. Further increase of strong motion intensity results in gradual widening of the slope area that might be involved in failure, and with rather small increase of the sliding surface depth. It could result in increase of rockslide volume that might reach ca. 1.3 km^3 if PGA will increase up to 0.2 g (Figures 6 and 7).

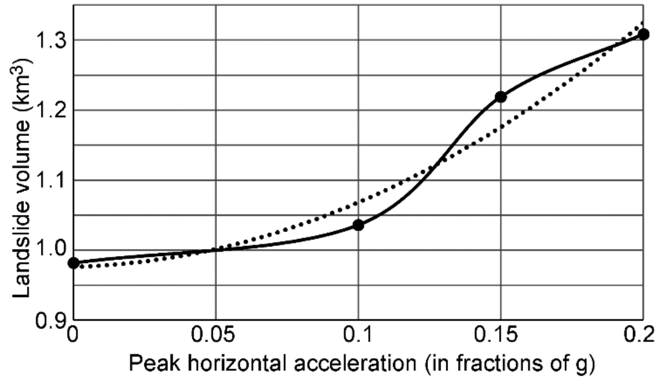

Figure 7. General dependence of the potentially unstable massif volume on horizontal PGA value. Solid line fits to calculated values (dots); dotted line – approximation.

3 HAZARD AND RISK ASSESSMENT AND MITIGATION MEASURES

If failure of about 980-1300 million m^3 of rocks will really occur, it could create a dam up to ca. 400 m high (see Table 1).

Such dams have originated in Central Asia repeatedly. Besides the famous 1911 Usoi dam with effective height about 550 m that still forms the 500 m deep Sarez Lake, there are more than 10 dams, both intact and breached, whose height exceeds 250 m (Strom, 2010; Strom and Abdrakhmatov, 2018). Thus, the anticipated phenomenon will not be anomalous for this region.

The potential Ragnow-mouth dam's height was estimated as follows. First, the total landside affected area (A) and area of the deposits (A_{dep}) were estimated according to the statistical relationships between these parameters and the product of landside volume (V) and height drop (H) (Strom and Abdrakhmatov, 2018; Strom et al., 2019) (see Table 1 and Figure 8).

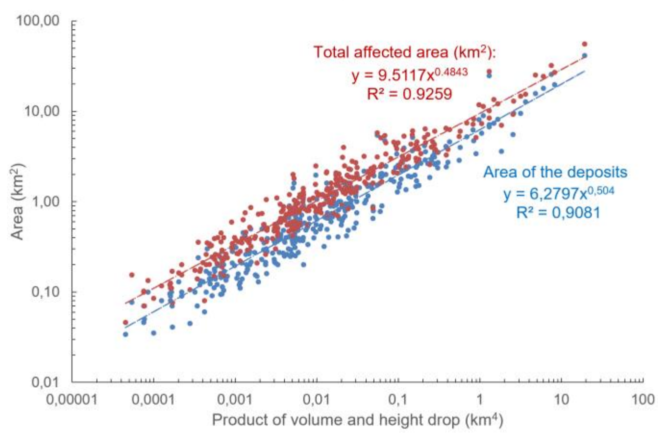

Figure 8. Relationships between total affected area (A – red dots) and area of the deposits (A_{dep} – blue dots) and the product of landslide volume and height drop for rockslides and rock avalanches with frontal confinement in the Central Asia region (331 cases)

At the second step, considering blockage, at a first approximation, as a two-pyramid body with triangular base corresponding to the valley cross-section along the dams' crest, its height was calculated (Strom et al., 2019). According to such a simplified geometrical model dam height $h=3V/A_{dep}$, where A_{dep} is the area occupied by landslide body, V – landslide volume.

We calculated total landslide affected area (A) and then subtracted 2 km^2 (the assumed headscarp area) to get A_{dep} value. Direct calculation of the landslide body area (Strom et al., 2019) gave smaller A_{dep} value for landslide volumes of 0.98-1.3 km^3 resulting in much larger dam's height – up to 520 m (see Table 1) that seems to be unrealistic in this particular case. Besides, the correlation coefficient of the relationship between A and V×H is slightly higher than between A_{dep} and V×H (see Figure 8).

Such dam could form a lake up to ca. 1.5 km^3 in volume (Figure 9) – almost 3.5 times larger than the dammed lake estimated previously (Shakirov et al., 2018).

Taking into account poor mechanical properties of the material that would form a dam (see legend in Figure 4), its catastrophic breach and almost complete emptying of the dammed lake cannot be excluded. Such outburst flood would devastate the entire Obi-Khingou River valley downstream the Ragnow River mouth and all the released water will finally reach the Rogun reservoir with an area at its full level of about 180 km^2.

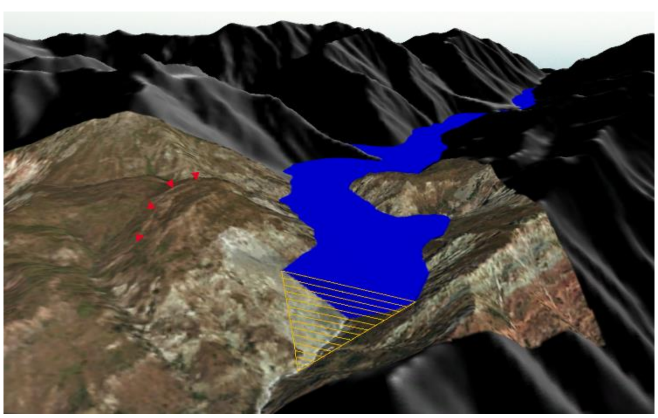

Figure 9. Impounded lake formed by assumed 400 m high landslide dam (its' quite schematic downstream slope is marked by hatched triangle). Red triangles mark the most distant arcuate scarp visible on space images. 3" SRTM DEM combined with space image and visualized by Global Mapper software.

Such a large water body could accommodate this amount so that the reservoir level will raise for ~8 m. However, since impoundment of the newly created dammed lake will take rather long period (several months even in the worst case), timely identification of the Ragnow river blocking will provide enough time to empty the reservoir to the lower water level that will guarantee accommodation of this additional inflow and safe operation of the dam and of the hydraulic power plant.

The enormous size of the anticipated landslide makes any slope stabilization measures impracticable. Thus, the only way to reduce risks associated with the potential river-damming slope failure described above is to organize the monitoring of the unstable slope. Considering remoteness and rather hard attainability of the site in question it seems that the most efficient monitoring methods could be the regular analysis of the INSAR data (Manconi et al., 2014, 2018), or periodical (4 to 6 times a year) drone stereoscopic photography and comparison of the successive DEMs (Van Persie et al., 2000; Jin et al., 2009). The alternative way to take situation under control is to have regular (weekly or monthly) contacts with local people from nearby villages who can inform regional and Rogun HPP authorities about any abnormal phenomena that might occur at this suspicious site.

4 CONCLUSIONS

The presented results are just a preliminary estimate of the size of the potential landslide that can block the Ragnow River valley creating voluminous dammed lake. Nevertheless, they demonstrate that consequences of the assumed slope failure might be even worse than it was expected by previous estimates (Shakirov et al., 2018; Strom et al., 2019) and highlight the necessity of more detailed study of the slope with evidence of ongoing instability, considering quite adverse consequences of its possible catastrophic failure.

More precise and reliable simulations require additional data on the geological structure of the right-bank unstable valley slope, on fracture systems within this rock mass, and on mechanical properties of the main types of sedimentary rocks outcropping at this site and of the entire rock massif. Specification of the geomechanical model used for the numerical simulation will increase reliability of estimates what can really occur at this site that, in turn, can be used to make more grounded selection of the optimal set of risk mitigation measures.

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