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. 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. A case study from the Vakhsh River catchment is presented where evidence of an extremely large slope instability have been identified. Its safety factor was determined considering the possibility of an earthquake occurrence in this tectonically active region. The height of the anticipated natural dam and volume of the dammed lake were estimated as well based on the empirical relationships. 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 of cubic meters in volume makes their stabilization almost impossible. The only way to mitigate such hazards and associated risks is 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 the elaboration of necessary measures prior to dammed lake infilling and breach.

A site, where such hazardous chain of 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 38.921° N, 70.964° 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, Abdraakhmatov, 2018; Shakirov et al. 2018). 1100 m high slope is dissected by numerous arcuate scarps several meters high that is well visible on aerial and space images at up to 3100 m a.s.l. at a distance of about 800 m from the steep slope edge (Figure 2).
Preliminary estimates of the potential size of this slope failure based just on expert judgement gave blockage volume of ca. $300 \times 10^6$ m$^3$. According to the empirical relationships between initial slope failure parameters (volume and slope height) and deposit area in the frontally confined conditions, the assumed dam height was estimated as ca. 250-260 m that could create a lake up to $410 \times 10^6$ m$^3$ in volume (Shakirov et al. 2018; Strom et al, 2019).

However, the numerical simulation of this slope provided the possibility of even a much larger slope failure that could form a higher dam. Modeling 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 $M6.5 \pm 0.2$ and $M6.1 \pm 0.2$ occurred near the site so that it appeared to be within its epicentral zones. The intensity of these earthquakes at the Ragnow mouth area could exceed 8 points of the MSK-64 scale (Kondorskaya, Shebalin, 1982; Schukin, Shebalin, 2016).
2. Methods

Rockslides represent a specific group of slope processes (Zerkal, Fomenko, 2016). Their numerical modeling is complicated since the compilation of the correct geomechanical model requires consideration of numerous factors such as bedding, density, and orientation of fracture systems, the anisotropy of rock properties, etc. A numerical simulation based on the simplified geomechanical model was performed. Such a model takes into account just general geology of the slope that can be revealed from the 1:200 000 State geological map (Figure 3) and averaged mechanical properties of the affected rock types.

The simulation aimed to solve the following tasks:
- assessment of the present-day 'static' slope stability;
- assessment of slope stability affected by seismic strong motion;
- assessment of the volume of rocks that could be displaced if landslide will fail catastrophically. The latter predetermines the possible height of the dam that could be created and the amount of water that could be stored in the dammed lake.

3D quantitative assessment of slope stability was performed by the 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 the factor of safety and volume of the potentially unstable massif (Figure 4). In the second stage we analyzed the effect of strong motion of earthquakes with the 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.

The 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 Figures 2 and 4). 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 the volume of the potentially unstable rock mass is about 980 million m$^3$ – 3 times more than volume revealed previously by expert's judgement (Figure 5).
Figure 3. Fragment of the 1:200000 State geological map of the USSR, Sheet J-42-XI (1962). $Cr_d(?)$ are gypsum and clay with marl and sandstone interbeds; $Cr_{dsn}$ are limestone, marl, clay, sandstone gypsum; $Cr_{st}$ are limestone, clay, sandstone, gypsum, mudstone; $Cr_{scm}$ are clay, sandstone, conglomerate, limestone, gypsum; $Cr_{v+h}$ – $Cr_{al}$ are sandstone, clay, gravelly conglomerate; red triangles mark the most distant arcuate scarp (assumed headscarp crown). To avoid any confusion ages of the stratigraphic units and their indices are the same as on the map published in 1962 when Cretaceous period was marked as "Cr".

Figure 4. The boundary of the potentially unstable rock massif (red line) derived by numerical modeling in 'static' conditions (without applying seismic load). Calculated $FS=1.062$. Blackline is profile shown in Figure 5.
Numerical modeling of the stability of the slope affected by a strong earthquake shows that if its intensity will be just 7 points 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 the failure, and with a rather small increase of the sliding surface depth. It will result in increase of rockslide volume that might reach ca. 1.3 km$^3$ if PGA will increase up to 0.2 g (Figure 5, 6).

Figure 5. Cross-section of the potentially unstable slope (see Figure 3) with assumed sliding surfaces derived from numerical modeling. Redline is without seismic loading; blue line is with seismic loading (PGA = 0.2 g); black dashed line is previous expert judgement (Strom, et al., 2019).

Figure 6. Dependence of the potentially unstable massif volume on horizontal PGA value. Blueline is calculated values (dots); red-dotted line is approximation ones.

3. Results and discussion
If failure of about 980-1300 million m$^3$ of rocks will occur, it could create a dam up to ca. 400 m high that would form a lake up to 1.5 km$^3$ in volume (Figure 7) (almost 3.5 times larger than the dammed lake estimated previously). Dam's height was estimated according to statistical relationships between landslide affected area ($A$) and product of its volume ($V$) and height drop ($H$) (Strom et al., 2019) and considering blockage, at a first approximation, as a two-pyramid body with triangular base corresponding to the valley cross-section along the dams’ crest (ibid). According to such a simplified geometrical model dam height \( h = \frac{3V}{A_{dep}} \) where $A_{dep}$ is the area occupied by landslide body, $V$ – landslide volume. We, first, calculated landslide affected area and then substracted 2 km$^2$ of the
headscarp area. Direct calculation of the landslide body area (Strom et al., 2019) gave smaller value resulting in a much larger dam's height (up to 520 m) that seems to be unrealistic in this particular case.

Taking into account poor mechanical properties of the material that would form a dam (see legend in Figure 3), 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 7. Impounded lake formed by 400 m high landslide dam (its schematic downstream slope is marked by a 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 its level will raise for ~8 m. However, since impoundment of the newly created dammed lake will take rather long time (several months even in the worst case), timely identification of the Ragnow river blocking will provide enough time to decrease the reservoir to the lower level that will guarantee the accommodation of this additional inflow and safe operation of the dam and 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 is to organize its monitoring. Considering remoteness and 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 the 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 a voluminous dammed lake. Nevertheless, they demonstrate that consequences of the assumed slope failure might be even worst than it was expected by previous estimates (Shakirov et al., 2018; Strom et al., 2019) and highlight the necessity of the more detailed study of the slope with evidence of ongoing instability and the possible consequences of its 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 mechanical properties of 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 the reliability of estimates what can occur at this site that, in turn, can be used to make a more grounded selection of the optimal set of risk mitigation measures.

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