The potential large-scale rock slope failures in the upper reaches of the Bhagirathi River valley: approach for hazard assessment and risk mitigation

Alexander Strom[1,*], Alexander Zakharov[2], Liudmila Zalkarova[2], Neelratan Singh[3], Nitin Rathi[4], Raghuveer Negi[5], Sanjeev Sharma[4], Sambrit P. Naik[6], Vinay Singh Chufal[6], Uday Bhan[6]

[1] Research Institute of Energy Structures – branch of JSC "Hydroproject Institute", Russia
[2] Kotel'nikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Russia
[3] CSIR CIMFR Roorkee Research Centre, CSIR CBRI Campus Roorkee, India
[4] CSRD, Jawaharlal Nehru University, New Delhi, India
[5] Uttarakhand Landslide Mitigation and Management Center, ULMMC, Dehradun, India
[6] Department of Petroleum Engineering and Earth Sciences, UPES, Bidholi, Dehradun, India
strom.alexandr@yandex.ru

DOI: https://doi.org/10.64944/iseg-j49/01/12

ABSTRACT

Paper presents brief description of the potentially hazardous site in the Bhagirathi River Valley (Garhwal Himalaya) where geomorphic evidence of the deep-seated gravitational slope deformations (DSGSD) was found at the left-bank watershed about 15 km upstream from the Maneri dam. The preliminary analysis of the InSAR data revealed some indications of the ongoing slope movements. Presence of several very large rock slope failures at this section of the Bhagirathi River valley, some of which had blocked it completely in the past, demonstrate reliability of the scenario of the catastrophic large-scale failures able to create natural dam that could block the river. It highlights the necessity to arrange regular monitoring of the suspicious site and to elaborate the efficient preventive/mitigation measures aimed to ensure long-term safety of the entire Bhagirathi River valley.

Keywords: *Bhagirathi River; DSGSD; Rockslide dam; InSAR; Monitoring*

1. Introduction

Numerous large-scale prehistoric rockslides were identified in the upper reaches of the Bhagirathi River valley and in the tributary valleys (Strom, Singh, 2022) upstream from the Uttarkashi town, between the Maneri HPP and the Sukki village (Figure 1). Some of such rockslides had formed natural dams, the largest of which, about 500 m high, had blocked the Bhagirathi valley at the site where nowadays the Sukki village is located, leaving an impressive remnant of the silted dammed lake upstream. About 10 km downstream from this site the Bhagirathi River had been blocked by another natural dam formed by the long runout rock avalanche that came out from its right tributary valley – the Kanodia-Ghad. Several more large-scale rockslides were identified in the tributary valleys of the Bhagirathi River, within the Central Crystalline formation, north from the Main Central Thrust (MCT).

Most of these large past rockslides had collapsed completely and do not pose any threat to population at present. However, their abundance in the study area indicates that combination of the geomorphic, geological, seismological and climatic conditions in this part of the Himalayas is favorable for large-scale rock slope failures and formation of high natural dams. Analysis performed using high-resolution space images freely available at the Google Earth and SAS Planet (http://sasgis.org/) combined with the 1 sec. SRTM DEM revealed presence of the geomorphic features indicating long-term instability of rock massif at the 2 km high left-bank slope of the Bhagirathi River valley opposite the Pala-Maradi village, about 15 km upstream from the Maneri HPP dam. Besides the geomorphic evidence, the preliminary analysis of the spaceborne SAR interferometric data provided some indications of the ongoing slope deformations. Such combination of the evidence of the long-term and of the modern ongoing deformations at this particular slope, along with numerous examples of the large-scale prehistoric rock slope failures highlights the potential hazard of the similar catastrophic events occurrence in this area.

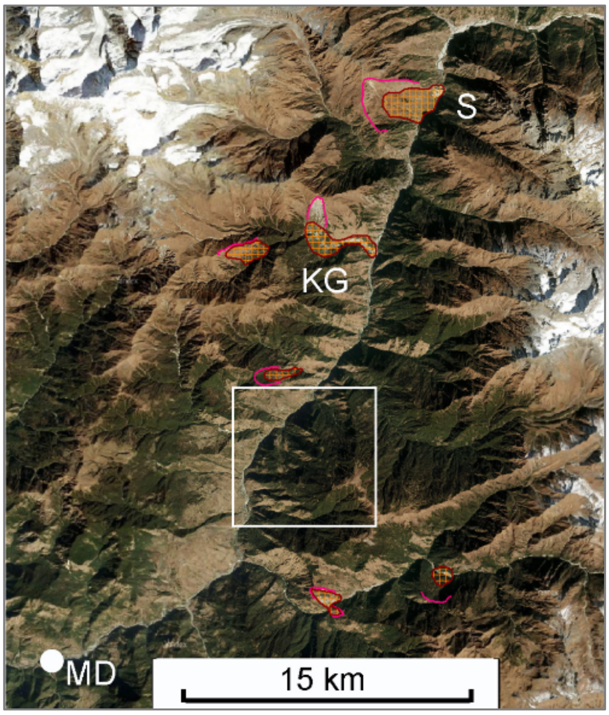

Fig 2: Left – position of the study area (marked by black rectangle) in the Uttarakhand; Right - distribution of largest past rockslides identified within the study area: red lines- headscarps, hatched areas – rockslide bodies. MD – the Maneri Dam, S – Sukki rockslide dam; KD - Kanodia Ghad rock avalanche; white square marks the suspicious site shown in Figure 3

2. Main characteristics of the study site

The area in question is located in the Garhwal Himalayas, within the hanging wall of the MCT composed of the gneiss and schist of the Central Crystalline (Geological and mineral map, 2002) (2cc in Figure 2) dipping north or north-north-east.

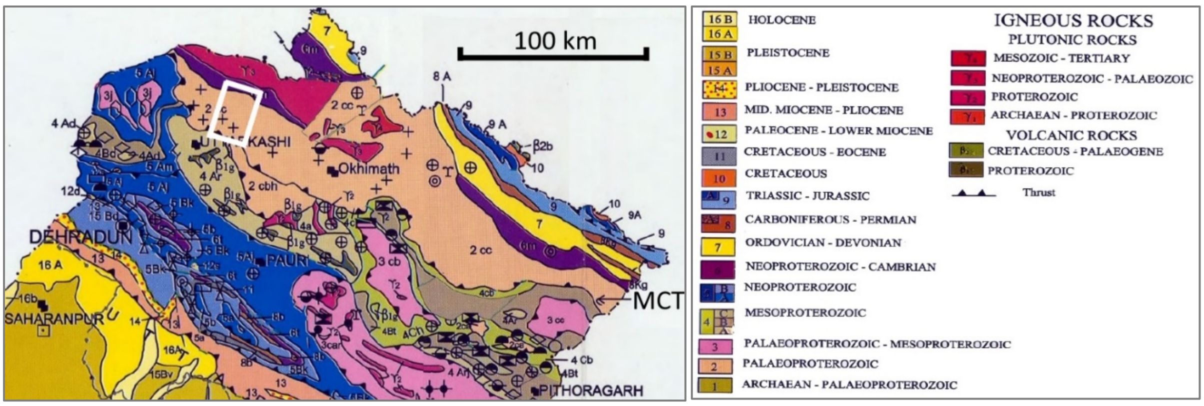

Fig 2: Position of the study area marked by white line on the of geological map with simplified legend (simplified after the Geological and mineral map of Uttar Pradesh and Uttaranchal, 2002).

This region is seismically prone, being affected by frequent moderate and by rather rare large earthquakes. According to seismic zoning of India (IS 1893, 2002) it belongs to High Damage Risk Zone (IV). Due to monsoon climate, the study area has been affected annually by intensive and prolonged rainstorms.

About 1 km long arcuate scarps indicating ongoing long-term deformations pass along at the local watershed of the left-bank slope of the Bhagirathi River valley opposite the Pala Maradi village (Figure 3). The V-shape Bhagirathi valley at this site is about 2 km deep with its bottom at ~1700 m a.s.l., while the watershed affected by the arcuate scarps is at 3500-3700 m a.s.l. Mean angle of the left-bank slope of the valley id about 25°, while its lower part more than 800 m high is much steeper – about 40° and the uppermost part of the slope more than 500 m high also dips at about 30° (Figure 4).

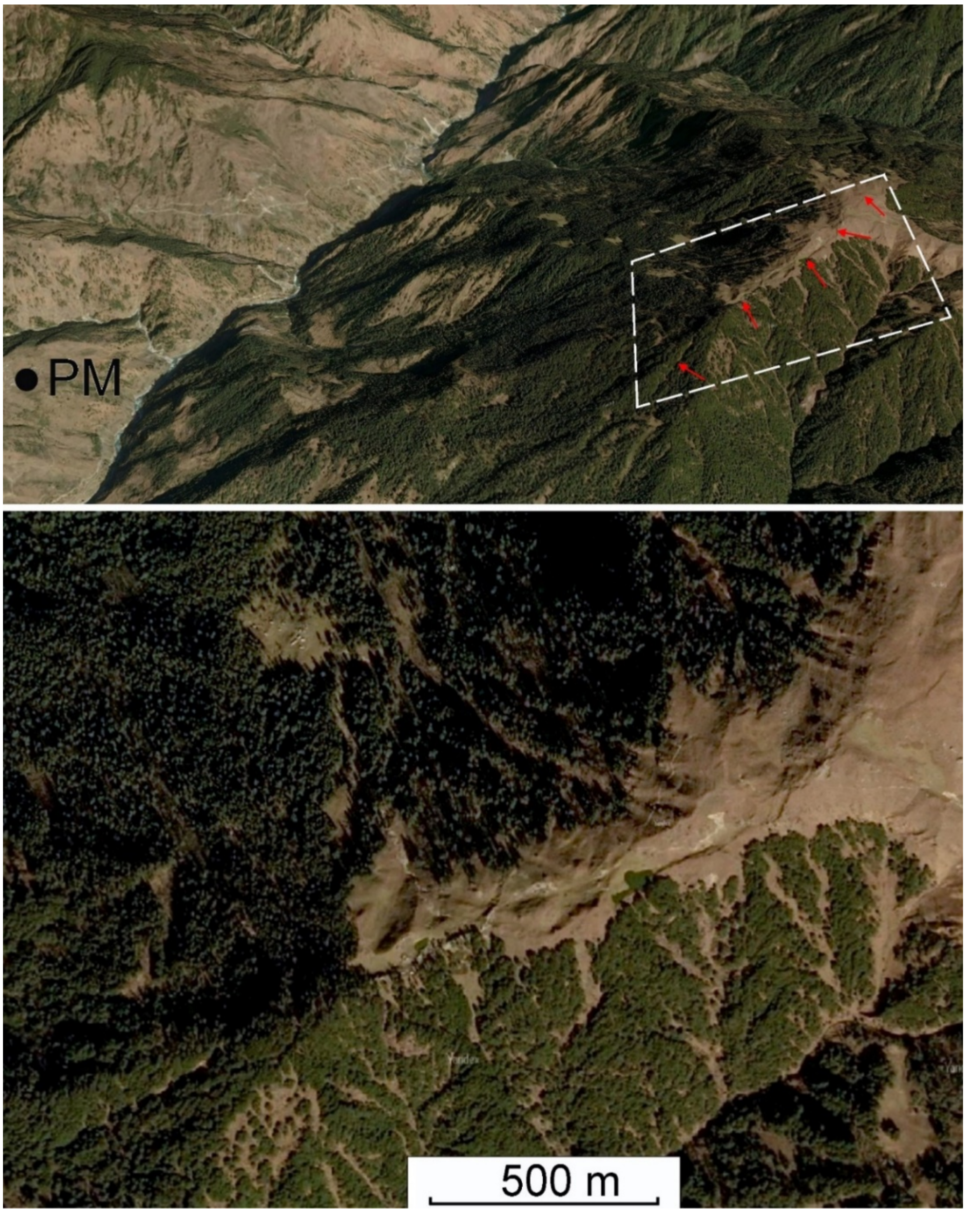

Fig 3: About 1 km long system of arcuate scarps passing along the local watershed. Above – 3D view with scarps marked by red arrows; Below – plan view of the area marked by dashed rectangle. PM – the Pala Maradi village

Now it is difficult to assume with confidence what part of the rock massif has been affected by the DSGSD – just its upper part above 2800-3000 m a.s.l., or the entire slope. In the former scenario volume of the affected rock mass could be of the order of 10-30 million cubic meters, while in the latter one it could reach 0.5-1.0 cubic kilometer.

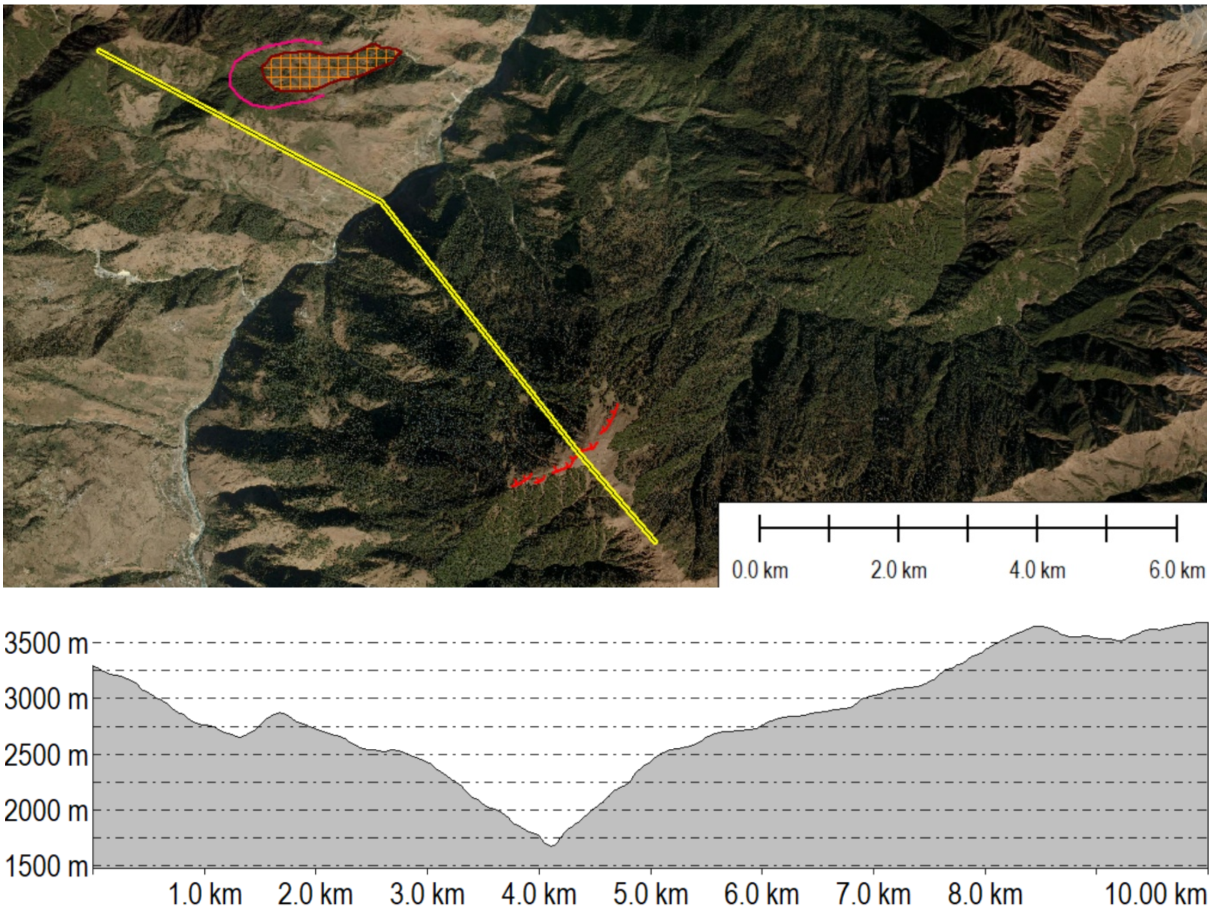

Fig 4: The hypothetical cross-section across the Bhagirathi River valley. Red arrow marks the position of the headscarps shown on the space image above. Dashed and dot-dashed lines – the hypothetical position of the assumed sliding surfaces corresponding to the first and the second scenarios described above.

The brief InSAR analysis of the ALOS PALSAR data revealed the ongoing deformations at the Bhagirathi River valley left bank (Figure 5). Most likely that an active landslide is evolving at the lower part of the left-bank slope up to ca. 900 m high and about 800 m along the river between the Dwari and Pahi villages (dark blue area). It was confirmed by the Sentinel-1 C-band InSAR data for the 12-day period from 29.10.2024 to 11.10.2024. The measured subsidence was up to 1.5 cm (mean value for the entire subsiding area was ca. 1 cm).

The most suspicious, however, are the lower part of the slope opposite the Pala Maradi village and its central part at 2500-3250 m a.s.l approximately, just below the watershed affected by the arcuate scarps shown in Figures 3 and 4. These slope sections demonstrate some uplift (red and yellow colors in Figure 5), while the uppermost part close to the watershed demonstrates the subsidence (blue colors). Such spatial variation of the deformations style, along with clear geomorphic evidence of the subsidence at the watershed shown in Figure 3, might indicate formation of the deep-seated rotational slides (see dashed and dot-dashed lines in Figure 4). Similar type of rock slope failure had taken place when the giant prehistoric Sukki rockslide had originated forming the ca. 500 m high dam that had blocked the Bhagirathi River valley (Strom, Singh, 2022). We have to notice that only few pairs of the satellite radar images were analyzed till now and that rather thick forestation of the valley slopes complicates InSAR analysis significantly.

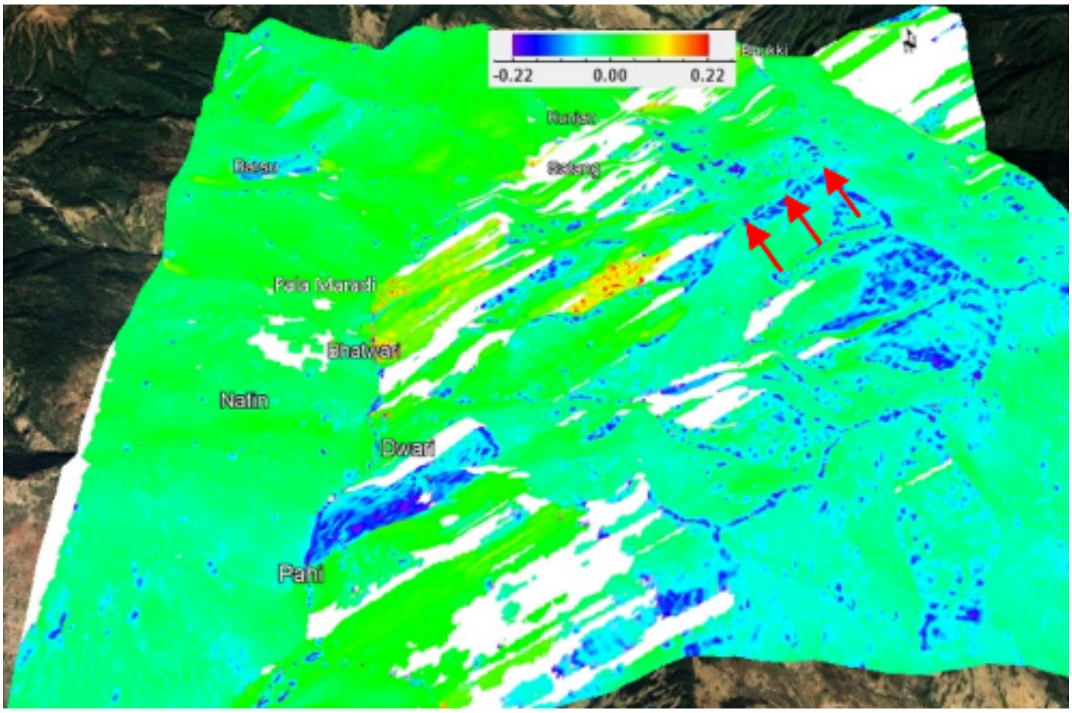

Fig 5: Downslope (blue range) and upslope (yellow –red range) deformations measured from ALOS radar data for the period from 5.08.2007 to 22.06.2008. 3D view of the interferogram overlain on the Google Earth image. Red arrows mark the position of scarps shown in Figure-3 and 4

3. Discussion and Conclusions

The InSAR-derived deformations described herein requires their justification by comprehensive analysis of the space borne radar data for the longer period. Due to significant forestation of the valley slopes, usage of the L-band radar satellites might be optimal (Bondur et al., 2019). Nevertheless, combination of geomorphic and InSAR data indicates high potential hazards of the study site. Considering rather large population of the valley, and, especially, its importance for hydropower production and pilgrimage, regular monitoring of this slope must be arranged to provide well-grounded hazard and risk assessment and to elaborate timely arranged risk mitigation measures, if necessary. If regular monitoring will reveal ongoing permanent large-scale slope deformations, it might be reasonable to envisage some engineering measures aimed to prevent the most disastrous consequences of so large rock-slope failure. It is almost impossible to stabilize so high unstable slope. But we can prevent uncontrolled inundation of the valley upstream from the natural dam and the most disastrous effect of the entire hazard chain – the catastrophic outburst flood. It can be achieved by the proactive construction of the bypass diversional tunnel at the opposite bank of the valley (Strom, 2025). If such slope failure would occur, it will freely release water downstream preventing the national-scale disaster.

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