Brief communication on the NW Himalayan towns; slipping towards potential disaster

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ABSTRACT

The NW Himalaya has been one of most affected terrains of Himalaya subjected to frequent disastrous landslides owing to active tectonics and multiple precipitation sources. This article aims at two towns (Joshimath and Bhatwari) of Uttarakhand in the NW Himalaya (India), which have been witnessing subsidence for decades. Until 9th Jan. 2023, Joshimath had witnessed widespread cracks in more than 500 houses that has created a social unrest in the region. The hillslopes accommodating both the towns comprise highly jointed gneisses with schistose interlayers rockmass, subsidence in road, broken retaining wall, holes, displacing boulders, and cracks in the houses. Recently, such slope instability phenomena have increased that is leading to social movements in the region seeking government action for possible evacuation and rehabilitation. Present study has involved continuum modeling-based slope stability simulation to determine the response of these hillslopes under various loading conditions; gravity, rainfall, building load, domestic discharge, and seismic load. Results revealed that the displacement in these hillslopes might reach up to 20-25 m that will further aggravate the situation. Occurrence of frequent extreme rainfalls in these towns and three major earthquakes i.e., 1 Sep. 1803 (M_w7.8), 20 Oct. 1991 (M_w 6.8), and 29 Mar. 1999 (M_w 6.6) having hypocentral distance less than 30 km make such study more viable for decision making.

Keywords: NW Himalaya; Landslides; Human Population; Slope Stability

The NW Himalaya has been one of most affected terrains of Himalaya subjected to frequent disastrous landslides (Martha et al., 2015; Gupta et al. 2017; Kumar et al. 2021b). Continent-continent collisional orogeny caused active tectonics and multiple precipitation sources i.e., Indian Summer Monsoon (ISM) and Western Disturbance caused extreme rainfall are main causes of such landslides (Petley, 2010; Dimri et al. 2015). The NW Himalaya has accommodated ~51 % of all the landslides in India during the years 1800-2011 (Parkash 2011). This article aims at two towns (Joshimath and Bhatwari) of Uttarakhand in the NW Himalaya, which have been witnessing subsidence for decades. Notably, Uttarakhand has been subjected to four known major flood events in last 5 decades, which are as follows; 24-26th August 1894, 20th July 1970, 16-17th June 2013, 7th Feb. 2021 (Ziegler et al. 2014; Sundriyal et al. 2015; Rana et al. 2021). Apart from floods, three major earthquakes have also caused widespread damage in the region that are as follows; 1 Sep. 1803 (M_w7.8), 20 Oct. 1991 (M_w 6.8), and 29 Mar. 1999 (M_w 6.6) (Bilham, 2019). Joshimath town (Fig. 1) had a human population of 16709 as per last census (2011) of Govt. of India and must have reached at least 18630 as per 11.5 % population growth (https://main.mohfw.gov.in/, data retrieved on 10/08/2022).

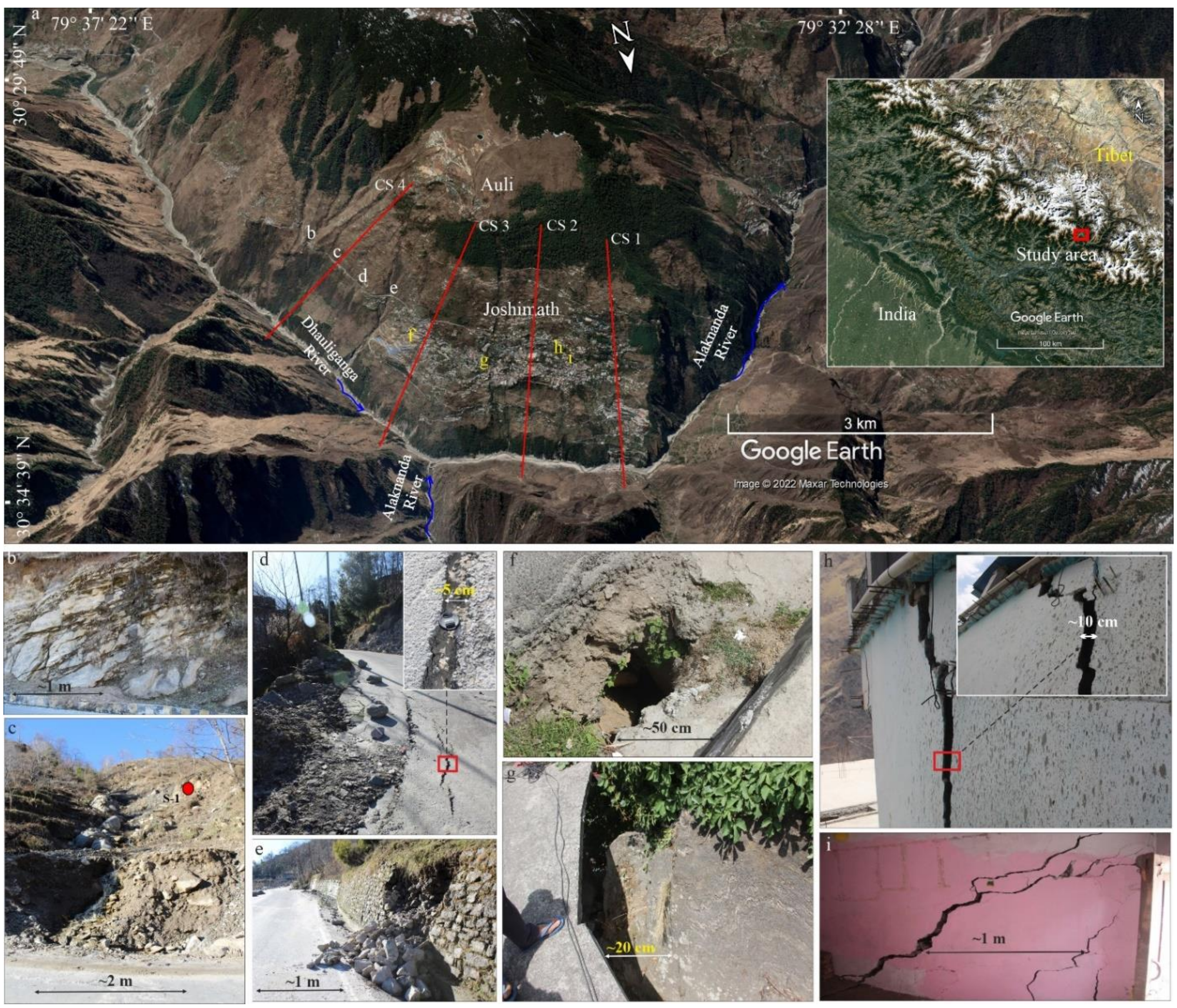

Fig. 1. Field observation of Joshimath town. (a) Location of Joshimath town with inset highlighting the position in the NW Himalaya. CS 1 to CS 4 mark the position of 2D slope sections used for the slope stability evaluation; (b) Rockmass exposure; (c) Natural drainage (Nala) through hillslope. Position of soil sampling site (S-1); (d) Cracks and displacement of road; (e) Bulging and failure of retaining wall; (f-g) Displacing hillslope material and hence pavements; (h-i) Cracks in houses. Picture (f-i) courtesy: Mr. Atul Sati.

This town has witnessed widespread cracks in more than 500 houses, even in temples until 9th Jan. 2023 that is creating a social unrest. Various media reports involving interviews of experts aim at the potential role of infrastructural projects in promoting instability in this region (https://timesofindia.indiatimes.com/city/dehradun/uttarakhand-joshimath-land-subsidence-cracks-sinking-news-live-updates-8-january 2023/liveblog/96843072.cms). The town is situated along a narrow gorge at the confluence of two major rivers; Dhauliganga and Alaknanda. The gorge owes its existence to exhumation along the Main Central Thrust (MCT) fault passing through the southern side of town (Supp. Fig. 1). This orographic barrier results in 798±116 mm/year avg. annual (years 2000-2021) rainfall in the town (Supp. Fig. 2). The uncertainty in rainfall refers to standard error of mean. In a recent study by Agarwal et al. (2022), the town belongs to a hotspot, which is experiencing changing climate and rapid anthropogenic influence. Field observation of the town revealed that hillslope of town comprises highly jointed gneisses with schistose interlayers rockmass, subsidence in road, broken retaining wall, holes, displacing boulders, and cracks in the houses (Fig. 1). Loose hillslope material comprising sandy-gravel soil (Fig. 1c), exposed in the eastern part of town points towards the possibility of paleo-landslide on which most of the town is located. The last big earthquake (29 Mar. 1999: M_w 6.6) occurred within 26 km hypocentral distance from this town.

Another town that is included in this article is Bhatwari (Fig. 2). As per census (2011) of Govt. of India, it had a population of 1268 that is 1.0 % lower than that of year 1991. Though the population migration from hilly terrain to plain area is becoming common phenomena in the NW Himalaya owing to socio-economic priorities, decreased human population of this town might be due to such slope instability problems also. Similar to Joshimath town, Bhatwari is also situated along a narrow gorge incised by Bhagirathi River valley. The hillslope of the town comprises gneissic rockmass and the MCT-I (locally termed as Vaikrita Thrust: VT) and MCT-II (locally termed as Munsiyari Thrust: MT) faults pass through the northern and southern side, respectively of this region. (Supp. Fig. 1). Two tributaries merging into Bhagirathi River bound the hillslope from northern and southern side. Bhatwari town is also situated in the orographic barrier setting and hence receives 1063±124 mm/year avg. annual (years 2000-2021) rainfall (Supp. Fig. 2). Field observation revealed exposed scarps in the upper part of town, cracks in the road, and tilting houses (Fig. 2b-g). Big (4-5 ft.) boulders and active slope failure in the loose material at the slope toe indicate the possibility of paleo-landslide on which Bhatwari town is located (Fig. 2h-i). Yadav et al. (2020) have also noted the material displacement in the range of 12-22 mm/yr. during the years 2006-2016 at this location. The last big earthquakes (1 Sep. 1803: M_w7.8, 20 Oct. 1991: M_w 6.8) occurred within 22 km hypocentral distance from this town.

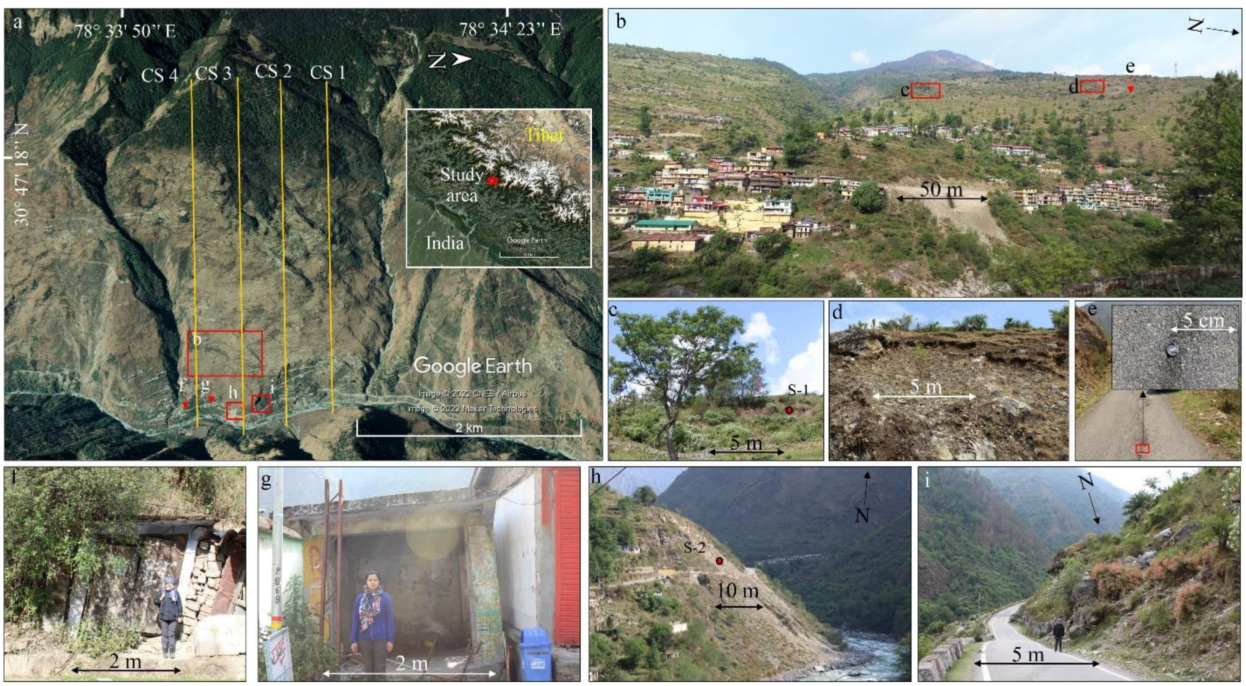

Fig. 2. Field observation of Bhatwari town. (a-b) Location of Bhatwari town with inset highlighting the position in the NW Himalaya. CS 1 to CS 4 mark the position of 2D slope sections used for the slope stability evaluation; (c-d) Exposed scarp. S-1 refers to soil sampling site; (e) Cracks and displacement of road; (f-g) Tilting houses/shops; (h) Active slope failure at slope toe; (i) Big Gneissic boulder implying paleo-landslide site.

These two towns were selected because both are subjected to similar litho-tectonic conditions and precipitation pattern (owing to orographic barrier setting). Since both of these locations comprise surficial cracks, displacing boulders, exposed scarp, possibility of the existence of paleo-landslide cannot be ignored. Though a detailed geophysical survey is being planned for future prospects to understand the subsurface regime at these locations, present study has involved continuum (Finite Element Method) based slope stability simulation.

This simulation was performed to determine the response of hillslopes that accommodate these towns, under various loading conditions; gravity, rainfall, building load, domestic discharge, and seismic load. Rainfall infiltration (RF) is based on extreme rainfall of 122 mm/day (18th Oct. 2021) and 124 mm/day (26th July 2010) at Joshimath and Bhatwari, respectively (Supp. Fig. 2. Data source: GPM IMERG Final Precipitation (Huffman et al., 2020), spatial resolution: ~ 1 km). Domestic discharge (DD) infiltration and Building load (B) are based on the Indian Standard (IS) code: 2470 (Part 1)-1985 and Indian Standard (IS) code: 875 (Part 2)-1987, respectively. Domestic discharge refers to liquid waste of a house, whereas building/house load refers to uniformly distributed load of houses. Domestic discharge load was considered because these towns lack effective sewage management plan. The values of domestic discharge (sewage & sullage) is based on the Indian Standard (IS) code: 2470 (Part 1)-1985, pp. 8. According to this code, for a family of minimum 5 members, probable peak domestic discharge may reach up to 9 litres/minute, which equals to 0.00015 m^3/s. This value was used in hillslope as point infiltration and hence m/s unit was considered. Notably, domestic discharge and building load are consistent in nature, whereas the rainfall infiltration is relatively random. Seismic loads are based on 20 Oct. 1991 (Mw 6.8) Uttarkashi earthquake and 29 Mar. 1999 (Mw 6.6) Chamoli earthquake acceleration history used for Bhatwari and Joshimath, respectively (Supp. Fig. 3. Data source: Dept of Earthquake Eng., Indian Inst. of Technology, Roorkee, India through COSMOS web portal, http://www.cosmos-eq.org/, retrieved on 03 Aug. 2022).

This continuum simulation method has been used for various hillslopes of the NW Himalaya owing to flexibility in slope geometry solution and acceptable approximation of displacement output (Kumar et al. 2021b). For estimating large strain, particularly during the dynamic analysis, discontinuum modelling could be a better option as also noted by Havenith et al. (2003); Kumar et al. (2021a). However, we also can't deny the fact that the loose overburden and complex geometry can be better simulated using a continuum approach. Discontinuum modeling having block concept also considers Finite Difference Method (one of the continuum approaches) mechanism for deformation of blocks. Further, we have used rainfall 'vertical' infiltration and domestic discharge infiltration in our study directly on the slope surface to approximate real scenario, which is limited in discontinuum concept that allows fluid transmission using joints only.

Details of slope configuration, material models, and input parameters have been summarized in Supplementary Annexure I. For both the towns, four 2D slope sections (CS 1 to CS 4) were taken to minimize the uncertainty caused by subjectivity associated to single slope section (Fig. 1, 2). A configuration model is shown in Supp. Fig. 4. Though the 3D slope stability could have been more informative, subsurface regime is yet to be explored for more comprehensive understanding.

Stability evaluation results for both the locations are discussed using the total (horizontal & vertical component) displacement in the top 5-10 m material layer along the slope surface. If horizontal and vertical displacements refer to 'x' and 'y', the total displacement is equivalent to $\sqrt{(x^2+y^2)}$. Displacement profiles for Joshimath town revealed that the slope may yield 1-4 m displacement under gravity load conditions. This gravity (or static) condition also refers to equilibrium state. The gravity caused displacement might increase up to ~6 m under combined effect of rainfall (RF) infiltration, building/house load (B), and domestic discharge (DD) (Fig. 3). In Fig. 3, JM and BT refer to Joshimath and Bhatwari, respectively. The CS 1 and CS 3 sections of Joshimath town yield relatively higher displacement under these loads, particularly near slope toe. Under seismic load condition, displacement increases rapidly in the range of 8-22 m, particularly at the knickpoints of slope surface and near slope toe. Relatively higher seismic displacement at slope toe is attributed to stress accumulation at slope toe and narrow geomorphic setting resulting in constructive seismic interference, as also noted in other case studies involving earthquake induced landslides (Meunier et al. 2008). Notably, slope crest region comprises debris layer that must have affected topographic amplification and hence relatively lower displacement, as also noted in recent study in the SE Carpathians (Kumar et al. 2021a).

Similar to Joshimath town hillslope, displacement profiles for the Bhatwari town hillslope show dominance of higher displacement (up to ~25 m) at the slope toe under seismic load conditions (Fig. 3). Notably, under combined effect of rainfall, domestic discharge, and building load, the CS 1 and CS 2 sections of Bhatwari town slope comprise pockets of higher displacement (5-20 m), particularly near slope toe. This could be attributed to thicker debris deposit and cluster of human settlement at the location of these slope sections (CS 1 and CS 2).

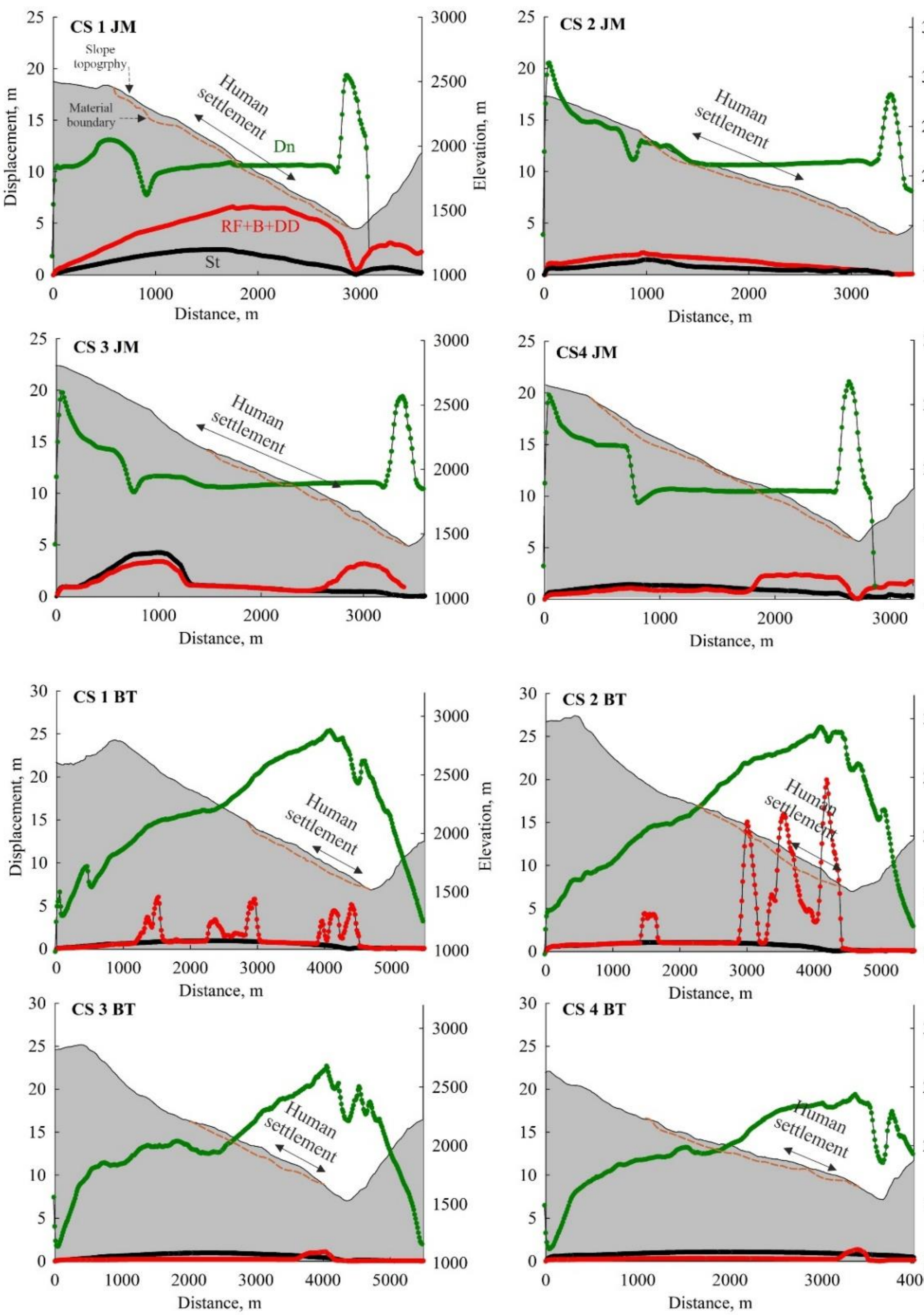

Fig. 3. Results of the Slope stability evaluation. CS 1 JM to CS 4 JM refer to Joshimath Slope sections, whereas CS 1 BT to CS 4 BT refer to slope sections of Bhatwari town hillslope. Dn, RF, B, DD, and St refer to Dynamic, Rainfall infiltration, Building load, Domestic discharge, and Static load, respectively.

Field observations of surface cracks, tilting houses, displacing hillslope material, and predictive findings of more displacement in case of local (domestic discharge, building load) and external loads (rainfall, earthquake) emphasize the critical situation of such NW Himalayan towns. Notably, recent social movements in Joshimath town seeking government action for possible evacuation, rehabilitation, and suspension of infrastructural projects (assumed as a major reason of hillslope instability) (https://timesofindia.indiatimes.com/city/dehradun/joshimath-sinking-thousands-of-fearful-residents-hit-road-in-protest/articleshow/96488198.cms) make such study more viable for decision making. A recent InSAR based study (https://discuss.terradue.com/t/results-of-advanced-insar-services-sentinel-1-indicate-that-the-town-of-joshimath-northern-india-is-sliding/1149) have also noted considerable displacement at slope toe region, as predicted in this modeling based study. In order to justify the findings of present study, we selected one slope section i.e., CS-1 and took a traverse along it during 17th -20th Jan. 2023. Field visit revealed lateral and vertical cracks in the loose overburden near the slope toe region (Supp. Fig. 5d-e). Influx of domestic discharge into slope that is estimated to increase displacement was also spotted at the poorly functioning sewage plant, which is shown in Supp. Fig. 5c. Widening cracks in the upper part of slope was also noted, as shown in Supp. Fig. 5f.

As far as the cause of slope instability in Joshimath town is concerned, a committee report (No. 142/28-5/44/76 dated 8th April 1976) submitted jointly by 17 experts headed by Late M. Mishra considered the paleo-landslide material as a major cause of slope instability. Google Earth imagery of June, 2014 (Supp. Fig. 6) also indicates growing slope toe failure, possibly leading to retrogression. However, the contribution of anthropogenic impacts involving population increase, continuing rapid construction to cater high tourist influx (Agarwal et al. 2022) and infrastructural projects can't be denied. Unlike Joshimath, Bhatwari town is witnessing population decrease and lack of tourist influx. Therefore, natural conditions i.e., loose material of paleo-landslide coupled with excessive rainfall dominate as the causative factors.

Notably, Joshimath and Bhatwari towns occupy a cornerstone to the religious and political landscape of the NW Himalaya. With the emergent threats of cracks, this paper suggests a need for a robust study to develop an integrated approach involving detailed scientific study and people's grievances against/about the development projects. Further, there is an urgent need to develop an integrative framework that combines the social composition of the region, various forms of resilience/adaptation practices and robust scientific inquiries. Often it is assumed that scientific factors that influence landscape are well understood and explained to the public. This invariably miscommunicates the potential threat causing irreversible socio-economic loss.

Code availability. Slope stability analysis simulations were performed using the RS2 (v.11.012) software (Rocscience Inc.). Figures are prepared using CorelDRAW 2021 (commercial software) and JASP v.0.15 (open source).

Data availability. Rainfall datasets are openly accessible at https://giovanni.gsfc.nasa.gov/giovanni/ (NASA, 2022). The earthquake acceleration history is available at http://www.cosmos-eq.org/).

Author contribution: YP, VK conceived the idea in view of increasing social problems at these sites. VK, NC, and SK performed the field work and collected soil samples. MKP performed the laboratory analysis. VK, NC, MP and SK interpreted the laboratory data and performed the numerical simulation. RR performed a social anthropological survey. All authors contributed to the writing of the final draft.

Competing interests: The authors declare that they have no conflict of interest.

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