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Original Article

Mountain highway stability threading on the fragile terrain of upper Ganga catchment (Uttarakhand Himalaya), India

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Abstract: Roads are the most critical means of connectivity in Himalayan villages. However, the terrain is inherently fragile with varied geological, geomorphological, ecological, and climate regimes, that result in frequent slope failure and disruption in connectivity. The risk is further to be increased by extreme events-generated hazards, which are expected to rise in frequency and magnitude with ongoing climate change. Critical scientific intervention, however, can improve the sustainability of road networks. The present study attempts to

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analyse and quantify the impacts of a major road widening project initiated in 2018 in the upper Ganga catchment, Uttarakhand Himalaya which has destabilised valley slopes along the widened segments. Also, a large quantity of excavated sediments is dumped down slopes, which is posing a threat to aquatic biodiversity. The estimates are based on Google Earth imagery of a few representative road segments recently widened in the upper Ganga catchment, which indicate a substantial increase in the landslide and unstable slope area following the road widening. The increase in unstable slope area is attributed to improper road widening approaches and poor slope management in seismically active Himalayan terrain. Further, the mean velocity plots of Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR) indicate that the segments undergoing road widening are coherent with areas of significant earth surface change. A broad correlation between the road width and sediment yield indicates that even a slight increase in road width can result in a large-scale mass removal from the toe of the hillslope, inflicting cascading impact on hillslopes. The study recommends a more flexible road construction approach based on the environmental and geological aspects of the terrain for sustainable road networks. Further, the impact of climate change is looming over the Himalayas, and the relation between climate change and its potential effects on the stability of slopes remains an open issue.

Keywords: Himalaya; Disaster resilient road; Landslide; Flash flood; Road-widening

1 Introduction

Infrastructure expansion is occurring at a dramatic rate across the globe and the Himalayas are no exception. Paved roads have increased by ~12 million km worldwide since 2000 with an additional ~25 million km projected by mid-century (Alamgir et al. 2017; Laurance 2018). Most of the roads are being built in developing nations, including many ecologically sensitive regions such as the Himalayas, which are exceptional in terms of biodiversity, ecosystem services, and rare/endangered species (Laurance et al. 2014). Himalayan road project's success lies in the early assessment of the risk posed by potential geohazards particularly, the slope instability caused due to excavation of steep slopes. It is achievable with a focused scientific investigation of the terrain before route alignment, identification of hazard-prone locations, and proactive and persistent planning of slope management following road construction (Sharma et al. 2021a). Besides road stability, an equally important artefact is the rapid penetration of roads into many of the world's ecologically sensitive and bio-diversity hot spots (national parks and wildlife centuries). From 1993 to 2009, the extent of global wilderness which houses rare and endangered species has declined by about ten per cent (Laurance et al. 2014). One of the reasons is climate change and habitat loss (Pandit 2017 and references therein).

The Himalayas along with the Tibetan Plateau have already begun to witness the impact of climate change (Sabin et al. 2020), which is likely to affect the valley slopes along with the increase in frequency and magnitude of landslides (Gariano and Guzzetti 2016; Alvioli et al. 2018). The Himalayas are witnessing significant temperature changes since the last twentieth century. The warming trend during the first (second) half of the 20th century was about 0.10°C (0.16°C) per decade, which later doubled to 0.32°C per decade from the beginning of the 21st century (Yan and Liu 2014). The incidences of forest fires in the Himalayas have increased significantly which besides weakening the soil cohesiveness (due to heat-induced dryness) is linked to the increasing incidences of cloud bursts (soot acting as cloud condensation nuclides) (Gautam et al. 2021) and further cascade into landslides and flash floods (Sharma et al. 2022). However, there are limited scientific studies assessing the comprehensive impact of global warming (changing temperature and precipitation conditions) on the stability of slopes in the Himalayan region (Hearn 2004).

In the Himalayas, slope conditions, lithology, and landforms change within short distances posing operational challenges for road engineers to ensure slope stability. Himalayan roads often cut through areas susceptible to geohazards, such as floodplains/lower valley slopes – prone to seasonal flooding, and deep-seated fractures/fissures and sheared lithology – prone to slope failures. When roads are constructed/widened to accommodate increased traffic volumes, without due attention to engineering geology/geomorphology, the slope stability is compromised (Burton and Bathurst 1998; Chung et al. 1995; Gorsevski et al. 2006; Conforti and Ietto 2019).

The inherent geology, topography, seismicity, and (sub) surface water characteristics are key factors that govern the stability of roads (Chuang and Shiu 2018). For example, vegetation cover intercepts precipitation, reducing surface erosion and improving the soil mass' cohesive strength to stabilize slopes. Thus, the slope stability of regions with dense vegetation cover is often higher than those with scarce vegetation cover (Schmidt et al. 2001). The construction of roads/highways on mountains particularly changes the toe of a slope thus, compromising the continuity of water flow (Sidle et al. 1985; Chuang and Shiu 2018). Unlike the 19th to early 20th century, road design engineers are now better equipped with valuable data on terrain, geology, and geohazards for slope-stability assessment. In the last two decades, several slope instability risk assessment systems have been developed to identify slopes at high risk of failure, and thus, long-term preventive measures can be devised (Pantelidis 2011 and references therein). The scientific studies, if capitalized, can help in the selection of road alignment, design of earthworks, and better slope management practices thus, making the Himalayan roads more sustainable (Hearn 2004).

The upper Ganga catchment in Uttarakhand Himalaya is traversed by multiple thrusts and faults, intersecting variable lithologies and increasing slope instability. The key factors for slope instability are (i) the presence of highly shattered and fractured rock mass, particularly in the vicinity of structural discontinuities (e.g., Valdiya 1980) (ii) frequent seismic activities (e.g., Gupta et al. 2021), and (iii) extreme monsoon precipitation (e.g., Vellore et al. 2016). The spatial distribution of recent and past evidence of unstable slopes suggests that as compared to the Lesser Himalayas, the Higher Himalayan rocks are subjected to high erosion (Wobus et al. 2005), primarily due to a high concentration of earthquakes (Fig. 1A), focused high-intensity rainfall, progressively high relief (Fig. 1B), and weak lithology (Rana et al. 2016; Rawat et al. 2020). Superimposed on it, the increasing anthropogenic interventions such as the excavation work for harnessing hydropower potential, further deteriorated the slope stability paving way for terrain unpredictability (Sundriyal et al. 2015; Rana et al. 2021; Shugar et al. 2021).

In recent years, socioeconomic development and strategic needs led to the launching of massive road networks, infrastructure development, and related activities in the Himalayan region. Considering the complex geological setting, steep slopes, and inherent fragility, even a small increase in the width of existing roads can significantly increase earthworks volumes (Larsen and Parks 1997). Given the fact that there is a positive correlation between road width and the magnitude of disturbance caused to natural hillslopes (Hearn and Hunt 2011), new landslide-prone zones along the Himalayan roads are likely to form, which would demand costly road maintenance. Therefore, the prime emphasis should be on maintaining road stability and sustenance to safeguard life and minimize the high maintenance cost than on increasing the road width. Over the decades, various attempts were made to stabilize the landslides that were largely triggered after the construction of a highway. The success rate is abysmal, and instead, some of the landslides became chronic due to (i) faulty road alignment through the middle/lower slopes, which were on unconsolidated alluvium and sheared lithology (ii) repeated back cutting for restoring the road width, (iii) the vibration caused by uninterrupted vehicular traffic, (iv) along with inherent seismicity coupled with episodic intensified Indian Summer Monsoon (ISM) (e.g., Prakash et al. 2015; Sarkar et al. 2015; Rana et al. 2016; Pradhan and Siddique 2020; Sabin et al. 2020; Velayudham et al. 2021). Considering that the Uttarakhand Himalaya is undergoing massive road widening (~900 km long stretch) along the existing highways since 2018, a small error in scientific reasoning may inflict irreversible damage to the slope stability and hence the terrain. In this study, we investigated some of the road segments in the upper Ganga catchment that are undergoing frequent instability, particularly after 2018. The objective of the study is to assess the factors responsible for slope instability during road widening and suggest approaches to minimise the impact on precariously balanced slopes.

2 Study Area

The roads investigated are in the upper Ganga catchment (78°E- 81°E, 29°N- 31°N), (Fig. 1A) and for clarity, are divided into three sectors. The sector-1 is in the lower Kaliganga catchment between Tanakpur-Sukhidang (NH-125); sector-2 lies in the middle Bhagirathi valley between Maneri-Bhatwari (NH-108), and; sector-3 is in the upper Ganga catchment between Tota Ghati to Lambagarh (Fig. 1A). In these

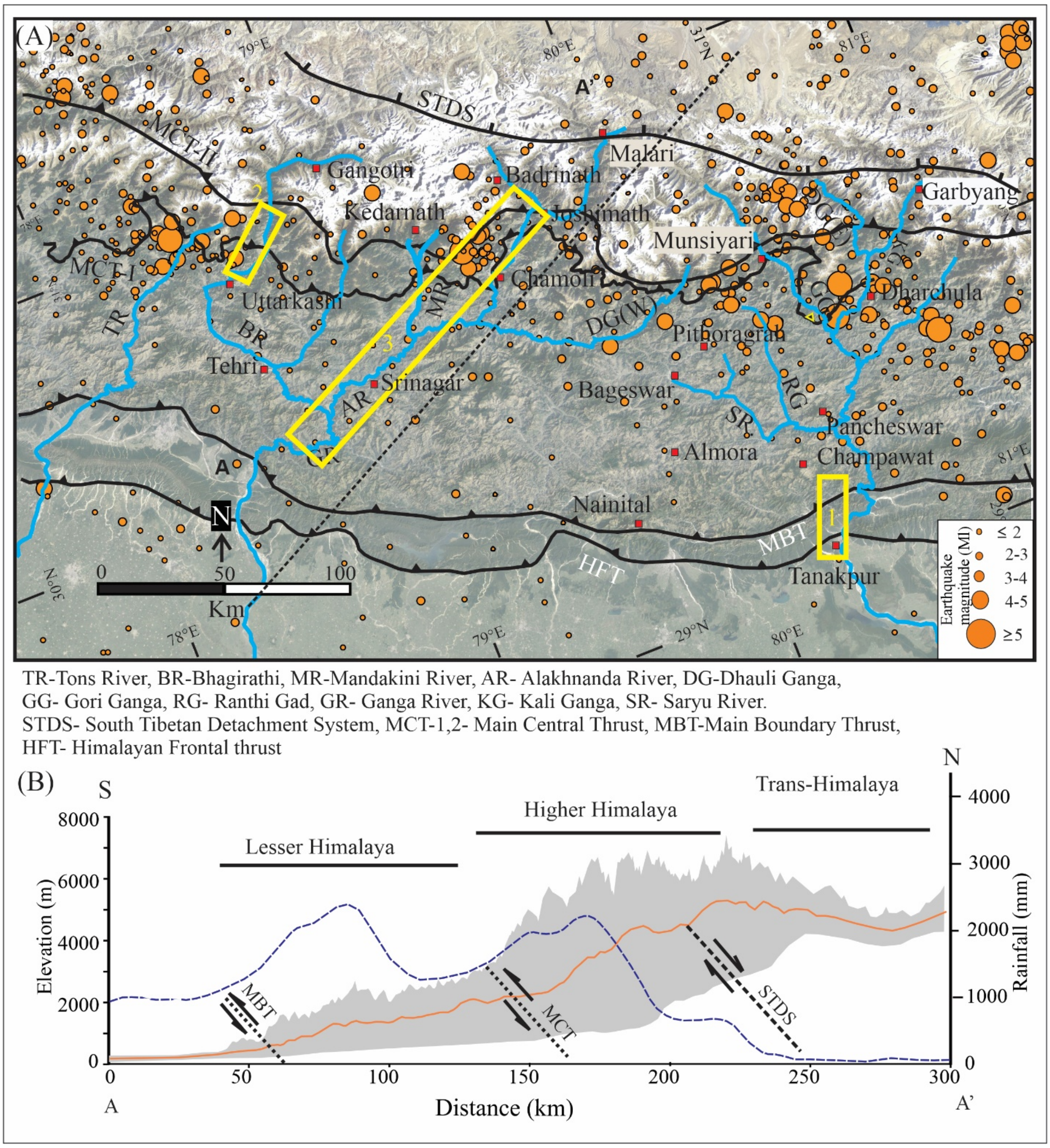

Fig. 1 (A) Digital elevation map of upper Ganga catchment (Uttarakhand Himalaya) showing major tectonic boundaries, and distribution of earthquake epicentres (orange circles). Note the high concentration of earthquake epicentres in the vicinity of the Main Central Thrust (MCT-1,2) (Modified after Sati et al. 2019). The road sectors (yellow rectangles) investigated in the present study are marked as (1) Sector-1 (Tanakpur-Sukhidang, NH-125); (2) sector-2 (Maneri-Bhatwari, Bhagirathi valley, NH-108); and (3) sector-3 (Tota Ghati to Lambagarh, Ganga and Alaknanda valley, NH-58). A-A' (dotted line) denotes the transect along which the cross-sectional is drawn in (B). (B) The precipitation profile (blue dashed line) from Ganga Plain (Haridwar) till the Tethyan Himalaya along the Alaknanda rivers overlain on the average elevation profile (orange line) with grey colour showing the minimum and maximum topographic relief. Major regional structures are also marked. The two precipitation peaks are marked in the Lesser and Higher Himalayas, where the peak along the Higher Himalayas is shown as Physiographic Transition (PT-2) which is marked by steep topography and high erosion rates.

sectors, the roads traverse through the youngest Sub-Himalayan (Siwalik group) rocks (sand/claystone), the Lesser Himalayan meta-sedimentary, and the Higher Himalayan Crystalline lithologies respectively. These lithologies are structurally differentiated by the regional structures called Main Boundary Thrust (MBT) and the Main Central Thrust (MCT) respectively. Also, there is a significant topographic variability through which the road is widened. For example, in the Sub and Lesser Himalaya, the roads dissect valley slopes with elevations ranging from ~500 to 1000 m having relatively less rugged topography. However, in the Higher Himalayas (north of MCT) the valley elevation varies from ~200 to 3000 m. The slopes are steep and overburdened with paraglacial sediments. The altitudinal variability also governs the nature and distribution of rainfall, dominantly contributed by the ISM, and varies from 100 to ~2500 mm (Fig. 1B). The physiographic transition from Lesser to Higher Himalayas (Fig. 1B) is a zone of frequent, focused, and high-intensity rainfall (cloud bursts). Consequently, the valley slopes are extremely unstable.

3 Methodology

The study pertaining to landslides in wide areas requires a complete collection, organization, and interpretation of geomorphological and geological data from scientific literature, field investigations, and remote sensing surveys (Cigna et al. 2016; Wasowski and Pisano 2020). In view of this, the present study is based on the detailed field observations supported by Google Earth imageries and Persistent Scatter Interferometric Synthetic Aperture Radar (PSInSAR) SENTINEL-1A satellite data.

The field investigation included conventional geological and geomorphological mapping of a few selected chronic landslide zones along the national highway supported by published literature. To assess the extent of slope destabilization before and after the road widening, the year 2018 is used as the marker, as a major (large-scale) road widening was initiated in the year 2018. Since there were no major road widening projects prior to 2018, slope instability/ landslides (from Google Earth imageries 2017-2010) should largely represent natural to minor anthropogenic disturbances. The pre-2018 and post-2018 slope activity were identified based on the tonal variation (appear as buff-coloured scars), loss of vegetation, and arcuate-shaped crown in the selected sectors (1 to 3; Appendix 1). About 100 locations were compared along the three sectors and analysed by visual interpretation. For sector-1, pre-2018 imagery was available from 2012-17 and the post-2018 imageries were available from 2019-22. For sector-2 and sector-3, 2010-16 imageries were used to create the pre-2018 dataset and 2019-22 imageries were used for post-2018. The area calculation of the unstable slopes for the comparison was done after exporting kml files and conversion to polygons in ArcGIS 10.8.

The volume of debris/rock mass excavated from road cut of a given width depends on two geometrical variables: the length of the road and the angle of the hill slope where the road is being excavated. For a basic estimation, the volume excavated can be calculated by assuming a uniform slope angle. Considering that in the study area there is a progressive northward increase in the slopes, we have taken slope values from a minimum of 20° to a maximum of 70°. Similarly, the road width (horizontal excavation) assumed in the calculation covers a minimum width of 2 m and a maximum width of 12 m. Geometrically, this shape can be defined as a wedge or triangular prism, and the volume thus can be calculated as:

$$\text{Volume} = l*0.5*h*b$$

where, l is the length of the road, b is the width of the road and h is the height of the hillside road cut. Considering it as a right-angled triangle cut, h can be calculated by Pythagoras theorem, if the width of the road (base) and slope angle are known.

Additionally, the quantification of sediment mobilization from the unprotected road cut slopes at fifteen locations between Saknidhar and Devprayag (~30 km) (sector-3) along NH-58 is measured after the monsoon (September 2021). The objective was to estimate the sediment contribution from the steep and unprotected road cut slopes, which is not accounted for in the road widening process (collateral damage). We observed that most of the sediment during the monsoon was transported onto the road as debris cones. Hence, we used half-cone geometry to calculate the sediment volume (V). Importantly barring the few debris cones, most of them were terminated on the road surface. The following formula was used for volume estimation:

$V=\pi r^2 l/6$, where, l is the length of a debris cone, and r is the radius (half-width) measured.

This was aided by the satellite line-of-sight (LOS) time series PSI deformation wide (IW) swath, and dual-polarization (VV+VH) PSInSAR SENTINEL-1A (C-Band) Interferometric data of SENTINEL-1A 121 images (02.02.2017 to 10.02.2021 for sector-1 and 26.10.2014 to 25.12.2020 for sector-2 and 3 respectively; Alaskan Space Facility https://search.asf.alaska.edu) with a 12-day repeat cycle (orbital path-56, 63 and 129) analysed using SARPROZ software (Lazecky et al. 2015) (Appendixes 2,3, and 4). The methodological details used in the present study are based on Kandregula et al. (2021). For sector-1, 5378 PS points were extracted from the PSI analysis. The positive values indicate that the distance between the target region and the SAR sensor in its LOS is reducing, therefore implying a surface uplift, while the negative values represent that the distance between the target and radar sensor in its LOS is increasing, hence denoting subsidence or erosion. In sector-3 ~8252 PS points were extracted between Maneri and Bhatwari, (Bhagirathi valley), 3631 PS points in Ganga and Alaknanda valley; 70 PS points for Kalyasaur landslide; and a total of 27000 PS points for the Higher Himalayan sector (Pipalkoti-Lambagarh-Joshimath-Badrinath).

4 Results

4.1 Tanakpur-Sukhidang (NH-125)

This road sector traverses through the outer and the Lesser Himalaya, where the Siwalik group of rocks comprising sandstone, claystone, and conglomerate/gravels dominates (Valdiya 1989). Structurally, the NH-125 cuts across three major thrusts. The Himalayan Frontal Thrust (HFT), which demarcates the boundary between the southern Gangetic plain and the Siwalik ranges and passes through Bastia located north of Tanakpur (Figs. 2A to 2C). The MBT passes through Sukhidang (Fig. 2C) where the topography is dominantly controlled by the structural configuration. For example, (Ladhiya) river follows the trend of the South Almora Thrust (SAT). The rocks are sheared and pulverized containing intersecting extensional joints making this sector extremely unstable (Kothyari et al. 2012). In 2011, around 31 major and minor landslides dominated by debris flow and rock falls were mapped by Agarwal and Sharma (2011). Among them, the largest Bisoriya landslide (4.25 km long; 1.6 km wide; spread over an area of 13 km^2) was initiated around 1923 CE on the southeast and northwest-facing slopes of Siwalik sandstone near Bisoriya village (Kothyari et al. 2010). Since then, this landslide is active and spreading in the southwest-northwest direction. We observed several cracks around the crown of the landslide, indicating active slope instability. The NH-125 passes east of the Bisoriya landslide (Fig. 2D).

4.2 Maneri-Bhatwari (Bhagirathi valley, NH-108)

The Bhagirathi River drains through two major lithological units- the Higher Himalayan Crystalline (north of Bhatwari village) and the Lesser Himalayan metasedimentary rocks, which continue till the confluence with the Alaknanda river (at Devprayag) (Sati et al. 2020). The valley (between Bhatwari and Gangnani) is traversed by the MCT (locally named Vaikrita Thrust) (Valdiya 1980). The valley slopes are extremely fragile and are subject to frequent landslides and land subsidence (Fig. 2E). A devastating flash flood on 6th August 1978 damaged large-scale infrastructures including the NH-108. It was triggered by a landslide dam outburst in the upper catchment of small stream (Kanodia Gad, opposite Gangnani village) (Prasad and Rawat 1978). Similarly, on 3rd August 2012, a flash flood in the tributary valley (Asi Ganga, near Uttarkashi), destroyed a hydropower project and washed away ~10 km of road (from Gangori to Dodital) (Gupta et al. 2013). While the tributary stream (Asi Ganga) was adjusting to the new channel morphology caused by sediment bulking, a second cloud burst in June 2013 transformed it into a desolate river, strewn with boulders and debris with virtually no trace of the road (Sati et al. 2020).

Being in the eco-sensitive zone (Zonal Master Plan – MoEF 2012), the road widening work above Uttarkashi to Gangotri has not been initiated. Therefore, there is overall slope stability, barring a few chronic landslide localities, along the road in the eco-sensitive zone. For instance, a small road segment (between Bhatwari and Gangnani) is persistently suffering from differential land subsidence due to a deep-seated landslide (Figs. 2E and 2F). This road segment was severely damaged during the 1991 Uttarkashi earthquake due to the intense shaking leading to the development of deep fissures (Jain et al. 1992). The recent geodetic study by Yadav et al. (2020) indicates that the slope located on the hanging wall of MCT (between Bhatwari and Raithal villages) is creeping at 12 to 22 mm/yr. Further, the study also observed subsidence of ~6 mm/yr which is geomorphologically expressed by the multiple

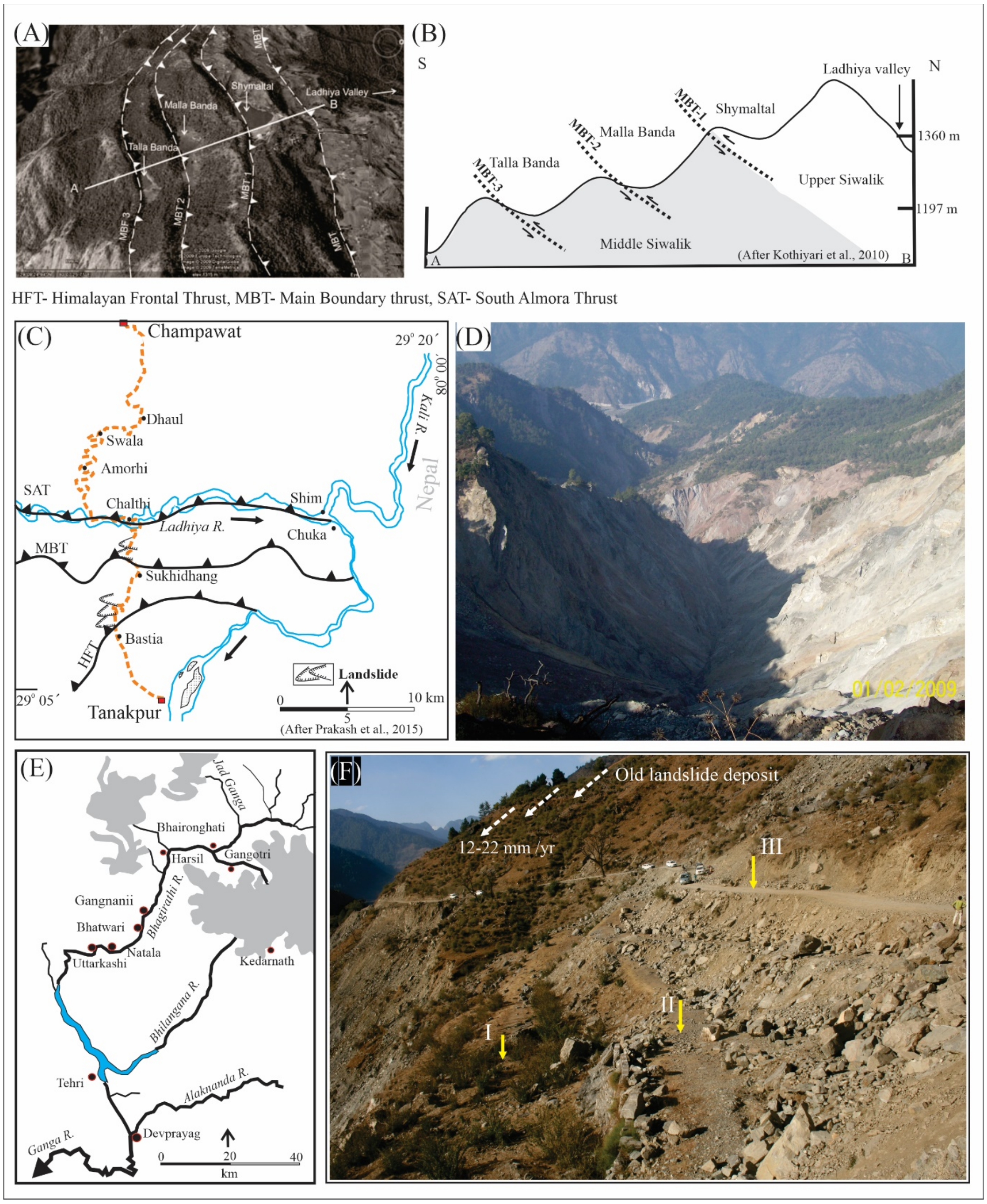

Fig. 2 (A) Google Earth imagery of Sukhidang in Sector-1 in the middle Siwalik ranges with splays of Main Boundary Thrust (MBT) overlain. The AB marks the cross-section profile drawn in (B) showing the relief and MBT splays. (C) The plan view of the map shows the road between Tankpur and Champawat (Sector-1) dissecting major structures and landslides. The multiple thrusts within short distances make the terrain vulnerable to slope failures and perturbations. (D) Photograph of Bisoriya landslide. (E) The map of Maneri-Bhatwai sector-2 in Bhagirathi valley. (F) Photograph of Bhatwari land subsidence on steep valley slopes, where I to III mark the subsequent subsidence over the years of the aligned road.

subsidence along the NH-108 (around Bhatwari in sector-2) (Fig. 2F).

4.3 Tota Ghati to Lambagarh (Ganga and Alaknanda valley, NH-58)

The Alaknanda and the Ganga Rivers drain through four major lithological units. The fossiliferous Tethyan Sedimentary Sequence to the northern flanks of Higher Himalayan Crystalline (Sinha 1989) which is dominated by schist and gneisses (Fig. 3A). Between Pipalkoti and Helong villages (Figs. 1B and 3A), highly crushed and pulverized dolomite with subordinate slate and quartzite are the major

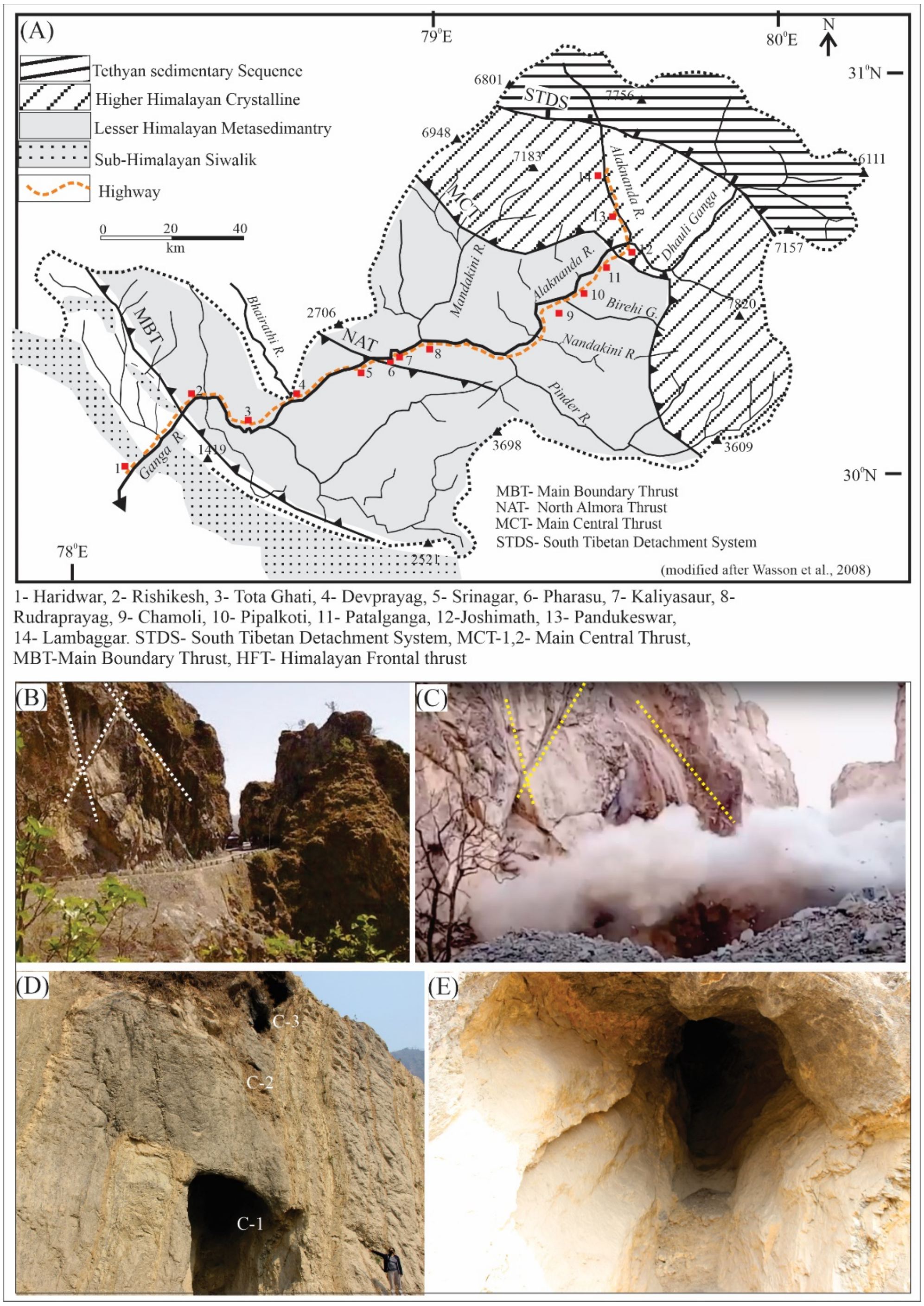

Fig. 3 (A) Simplified geological map of Alkananda catchment showing major tectonic and structural divisions. Note the location of Tota Ghati at (3). (B)-(E) Field photographs of the road segment at Tota Ghati (sector-3) showing (B) intersecting three sets of joints in dolomite, shale, and quartzite (Karol formation) before the road widening (C) dust plume due to indiscriminate dynamite blasting during road widening. (D) The linear interconnected caves (C-1 to C-3) formed due to dissolution of limestone. Note the person standing for scale in (D). (E) Close-up of C-1 cave shown in (D).

lithologies (Gaur et al. 1977). The Lesser Himalayan rocks which continue till the MBT comprises carbonaceous shale, limestone, dolomite, quartz arenite, and metavolcanic rocks, as well as argillite (Srivastava and Ahmed 1979; Valdiya 1980) (Fig. 3A). However, within the Lesser Himalaya, particularly around Tota Ghati (discussed below), the fractured, fissile, and cavernous lithology is highly susceptible to slope instability (Figs. 3B to 3E). To the south of the MBT the youngest Siwalik rocks (sandstone, mudstone, and conglomerate (Fig. 3A) are thrusted over the sediments of the modern Ganga foreland basin along the HFT (Ray and Srivastava 2010). The site-specific details from this sector are discussed below.

Fig. 4 (A) Photograph of Pharsu landslide developed on highly sheared quartzite on NH-58. The white arrows indicate the new road alignment proposed before the commissioning of the road which was not completed. The subsidence and lateral erosion of NH-58 caused due to the Reservoir Drawdown effect near the Srinagar hydropower dam (shown in the inset). (B) The chronic landslide of Kaliyasaur could not be treated despite several engineering measures over the years and had to be bypassed. (C) Google imagery of the newly aligned NH-58 built on unconsolidated fluvial terrace gravels indicates the new road's susceptibility to subsidence and toe erosion. Field investigations indicate that the road alignment above the village over solid bedrock (orange dashed line) would have been safer.

4.3.1 Tota Ghati

At this location, the road (NH-58) dissects the steeply dipping slopes (775 m a.m.s.l) after gaining elevation from 445 m near the riverbed (Kodiyala village) within a short distance of <10 km. The lithology is dominated by dolomite, shale, and quartzite rocks (Krol and Tal Formation), which are sheared having three distinct sets of intersecting joints being in the proximity of NW-SE trending (Biyasi and Saknidhar) thrusts (Pradhan and Siddique 2020) (Figs. 3B to 3E). Due to folding, the beds are variedly oriented, however, the dominant dip of the beds is towards the road/valley. According to Pantelidis (2011), failure of rock cuttings is invariably associated with the presence of lithological discontinuities, the dip orientation, and the degree of shearing and shattering across the discontinuities. Pradhan and Siddique (2020) provided insight into the vulnerability of the rocky terrain towards failure by assessing the Critical Factor of Safety (FoS) analyses around Tota Ghati slopes, which was classified into unstable to marginally stable category.

The slopes of Tota Ghati were relatively stable prior to the road widening but are marred by landslides dominated by debris avalanches. Even without rain, the vibrations caused by moving traffic at times trigger the debris avalanche. We attribute the frequent rock avalanche/landslides to the inherent weak lithology of variable competency and extensive mechanical excavation aided by blasting which led to the creation of secondary fractures (Figs. 3B and 3C). Particularly, the blasting was detrimental to the intersecting joints, which caused the widening of the pre-existing fractures/joints along with the collapsing of the interconnected caverns (Figs. 3D and 3E).

4.3.2 Pharasu

A small segment (<0.5 km) of the NH-58 is suffering from a combination of landslide and road subsidence (Fig. 4A). The landslide is in the vicinity of the North Almora Thrust (NAT) which is known to have sheared, fractured, and jointed quartzite lithology (Juyal et al. 2010). Although the exact antiquity of this landslide is not known, certainly it existed before the commissioning of the Srinagar Hydropower project. Following the filling of the Srinagar dam reservoir, the road subsidence began due to the Reservoir Drawdown Effect (RDE). A similar phenomenon is observed around the Tehri dam reservoir rim by Sati et al. (2020).

4.3.3 Sirobaggar (Kaliyasaur)

This is one of the oldest landslides in sector-3 (NH-58) which is comparable with the Bisoriya landslide in sector-1 (NH-125). The landslide is developed on highly sheared and fractured quartzite rocks of varying composition, shale, and variably weathered metavolcanic (Velayudham et al. 2021). Shearing of the rocks can be ascribed to the presence of NAT and the local Kaliyasaur fault. Archival data indicate that the landslide was initiated in 1920, whereas a major rock fall blocking the Alaknanda river occurred on 19th September 1969 (http://www.crridom.gov.in/content/documentary-kailasaur-landslide). Since then, the landslide remained intermittently active, for which besides the geological and geomorphological causes, the repeated back-cutting (essential for restoring the road width) could be a potential trigger (e.g., Jangpangi et al. 2019; Singh et al. 2017). Repeated efforts made to prevent this landslide failed which finally compelled the road building department to bypass this landslide by constructing a new road along the right bank of the Alaknanda river on fluvial terrace gravels which, unfortunately, is also prone to subsidence (Figs. 4B and 4C).

4.3.4 Pipalkoti to Patal Ganga

This is one of the highly degraded roads located in sector-3 (NH-58) and is in the south of MCT (Fig. 1B). The local lithology consists of crushed and pulverized dolomite, slate, and quartzite- collectively called the calc-zone of Chamoli (Gaur et al. 1977). The existing NH-58 is constructed after the old Badrinath road was washed away in the July 1970 Alaknanda flood (Fig. 5A). In a small stretch of ~10 km, there are two chronic landslides (viz. Tangni and Patal Ganga) which were initiated after July 1970 and are still active. Sarkar et al. (2015), observed five types of landslides in this sector - debris flow, rockfall, rockslide, debris slide, and rotational slide/subsidence. The landslide susceptibility analyses by Sarkar et al. (2015) put this sector under the category of very high to high landslide risk zone, which accords well with our field observations.

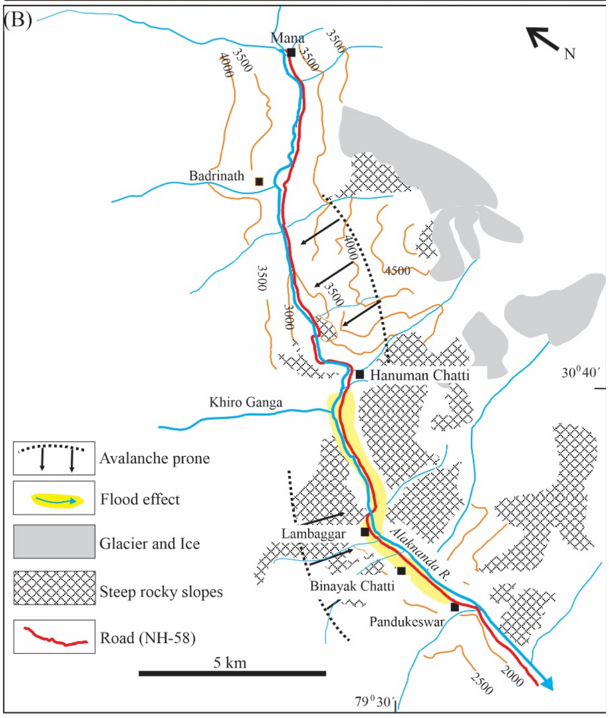

Fig. 5 (A) Photograph of highly degraded slopes between Pipalkoti and Patal Ganga in the Alaknanda valley (south of Main Central Thrust). The highly sheared and fractured rocks are dominated by dolomite, slate, and quartzite. Note the old Badrinath road that was washed away during July 1970 Alaknanda flood. (B) A simplified geomorphological map of Pandukeshwar to Badrinath (sector-2) showing NH-58 (red) prone to various disasters such as floods, debris flows, and avalanches.

4.3.5 Pandukeshwar- Lambagarh

Between Pandukeshwar and Lambagarh in sector-3 (NH-58), the road traverses through the paraglacial zone (discussed below) wherein in a stretch of <10 km, four glacial-fed streams meet the Alaknanda River from the north-western flank (Fig. 5B). The slopes are very steep and covered with highly porous old landslides and unconsolidated avalanche debris, which readily get saturated during the spring melting of snow and summer rainfall. Although debris-laden slopes make road widening relatively easy, stabilization of the vertical cut faces of unconsolidated sediment is extremely challenging. The area also experiences frequent snow and debris avalanches. For example, a glacial-fed stream near Lambagarh (between the Acoree and Pargasi villages), frequently transports debris and snow avalanches. These avalanches are generally generated from poorly defined cirques and many times have damaged the villages and NH-58, besides obstructing the Alaknanda River (Figs. 6A to 6E). One such avalanche, considered to be the largest since 1948, occurred on 14th April 1983 and was triggered from a cirque located on the north-western slope (Fig. 6E). It destroyed houses, road and temporarily obstructed the Alaknanda River at Lambagarh (Bhatt et al. 1985). In addition to this, a sudden surge in the debris-laden meltwater discharge from glacial-fed streams frequently destroys the road and culvert as happened recently during May 2021 (Fig. 6D). In view of the threat posed by the debris flow and landslide, ~200 m long buttress wall was constructed to protect the NH-58 in this area (Fig. 6E).

4.4 Sediment volume estimation

It is observed that the extension of hillslope disturbance due to road width exponentially increases with the slope angle. Also, the sediment output shows a strong dependency both on the slope angle and road width. The graphical presentation of the data shows a significant increase in the volume of rock mass for an increase of each meter width of the road. The increased curve (70°) is characterized by the power trend line ($y=1.3737x^2$) that indicates an increase in volume with a specific rate or we can say that the volume of excavated rock mass is directly proportional to the square of the width of the road. For example, in less steep slopes (between 20° and 30°) there is not much increase in sediment yield irrespective of road width (within 40 m^3/m; Fig. 7A; Appendix 5). However, as the slope increases (>30°) there is an exponential increase in the sediment yield with increasing road width, which in turn would also increase the width of disturbance. According to Megahan (1985), the total width of disturbance by a road 4 m wide increases from about 7 m on a 40° slope to 16 m on a 60° slope; on a 65° slope the width increases to 32 m and so on (Fig. 7B).

In addition to the slope-dependent road-cut sediment volume, the unprotected road-cut slopes within the 30 km stretch in sector-3 contributed 12.19×10^4 m^3 (Appendix 6), which is quite significant since post-road widening, remains unaccounted for. Most of the debris-dominated landslides are boulder detached along the cracks and joints (Fig. 7C). The phyllite-dominated segments are pulverized and the slopes from the debris slides are triggered. Assuming that similar debris flows were generated in the entire ~900 km road stretch during post-monsoon would be around 365.7×10^4 m^3. This volume remains unaccounted for in the road-cut sediment contribution.

The instability of slopes is indicated by an increase in the number and area of post-2018 active hillslopes, which have exponentially increased in comparison to pre-2018 imageries (Table 1; Appendix 7; Fig. 7D). The increase in the area is owing to the generation of fresh landslides/debris flows as well as an increase in the area/number of existing minor landslides/debris flows (Fig. 7D). Further, due to muck dumping from the excavation on the forested slopes, the initiation of debris flows on forested slopes was also observed, which remains unaccounted for in the present study.

Table 1 Comparison of the area affected by slope instability pre- and post-road widening. The estimation is based on a visual interpretation of Google Earth imagery (Appendix 1).

Sector	Unstable slope area		Change in Area	
	Pre-2018 ($\times10^3$ m^2)	Post-2018 ($\times10^3$ m^2)	($\times10^3$ m^2)	(%)
Sector 1	3.65	154.96	151.31	4147.59
Sector 2	8.68	50.93	42.25	486.91
Sector 3	38.58	144.44	105.86	274.39
Total	50.91	350.33	299.42	4908.88

4.5 Persistent Scatterer Interferometric (SENTINEL-1A)

In sector-1 (between Tanakpur and Champawat), the road cuts across the major thrusts HFT and South Almora Thrust (SAT). In this sector (Fig. 8A), the average rate of change in the surface elevation is ± 7

Fig. 6 (A) Geomorphological map of sector-3 between Binayak Chatti and Lambaggar showing many hanging glaciers. Glacial erosion generates (para)glacial sediments in the valleys which frequently damage the road. For example, (B) and (C) show the damaged NH-58 near Binayak Chatti after the summer rainfall of 2009. (D) On 21st May 2021 NH-58 was completely washed away near Lambaggar by paraglacial sediments transported by a glacial-fed stream Khiro Ganga (E) A new buttress wall near Binayak Chatti was built recently to protect the road which was frequently damaged by the mobilization of unconsolidated para glacial sediment particularly during monsoon season. Height above mean sea level and village name (black dot) and peak (black triangle) are also marked.

mm/yr with ~52% area showing positive velocity and the rest showing negative velocity. The high positive velocity segment is located between the HFT and MBT whereas, low to negative velocity is observed around Champawat and in the vicinity of the road, which seems to be the result of mass removal due to the chronic landslide (Fig. 8A). In sector-2 (between Maneri and Bhatwari, Bhagirathi valley) approximately half of the area (51.7%) shows negative velocity at a rate of 8–10.5 mm/yr. Moreover, the hanging wall of the

MCT shows a creep of 10 mm/yr (Fig. 8B), which accords well with the earlier study (Yadav et al. 2020). In Alaknanda valley (between Pharasu and Kaliyasaur), around 35.5% area is showing negative velocity of 3 to 12 mm/yr, the Kalyasaur landslide zone is showing a negative velocity of 6.5 to 11 mm/yr (Fig. 8C). The new road alignment that is proximal to the riverbed and is being excavated on Holocene fluvial terrace, shows a negative velocity range (4 to 12 mm/yr), implying that the segment is undergoing significant subsidence/erosion (Fig. 8C). Further, upstream in sector 3, the road segment traverses through Higher Himalaya, where the PSI value is ± 11 mm/yr (Fig. 8D).

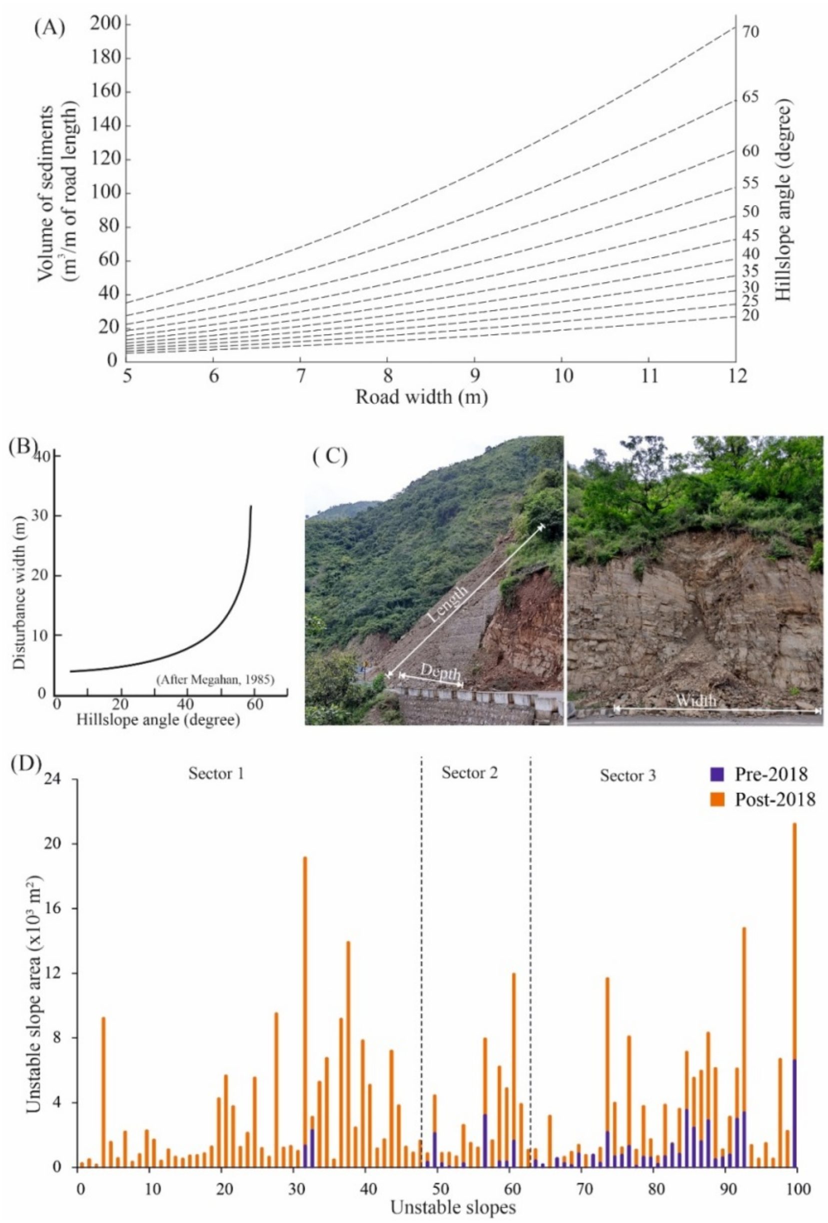

Fig. 7 (A) The graph shows an exponential increase in the volume of sediment generated on steeper and wider roads. (B) The road width disturbance (collateral damage) concerning slope increases abruptly after 30 degrees (Megahan 1985). (C) Field photographs of debris flow measured along the NH-58 in September 2021 (post-monsoon). The attributes used for volume calculation are marked. (D) A comparative plot for pre- and post-2018 major road widening project showing landslide area estimated for ~100 locations in all the three sectors. A significant increase is seen both in the number and extent of the unstable slope activity.

5 Discussion

The emergent topography of the Himalayas is an outcome of the continued north-south convergence that was initiated about 50 million years ago. Currently, the convergence is being accommodated along HFT in a stick-slip manner (Seeber and Armbruster 1981), while an inter-seismic shortening/ deformation with a higher uplift rate is focused in the south of the MCT in the Higher Himalaya (Banerjee and Burgmann 2002; Tyagi et al. 2009; Jade et al. 2014). This zone of active convergence also coincides with the zone of high rainfall and erosion (Vance et al. 2003; Rana et al. 2016) making the slopes vulnerable. In the Himalayas, the valley slopes are an outcome of a composite and complex interaction of topography, lithology, structure, drainage, soil, and vegetation cover.

As the roads in mountains often dissect the precariously balanced slopes, it increases their susceptibility to failure (Sati et al. 2012). Therefore, the entire geo-environmental setup of the slopes needs to be taken into consideration prior to road construction/widening to ensure sustainability (long-term slope stability) (e.g., Jangpangi et al. 2019), and hence safety. Particularly, in the Higher Himalayas, where slope instability can be accredited to a

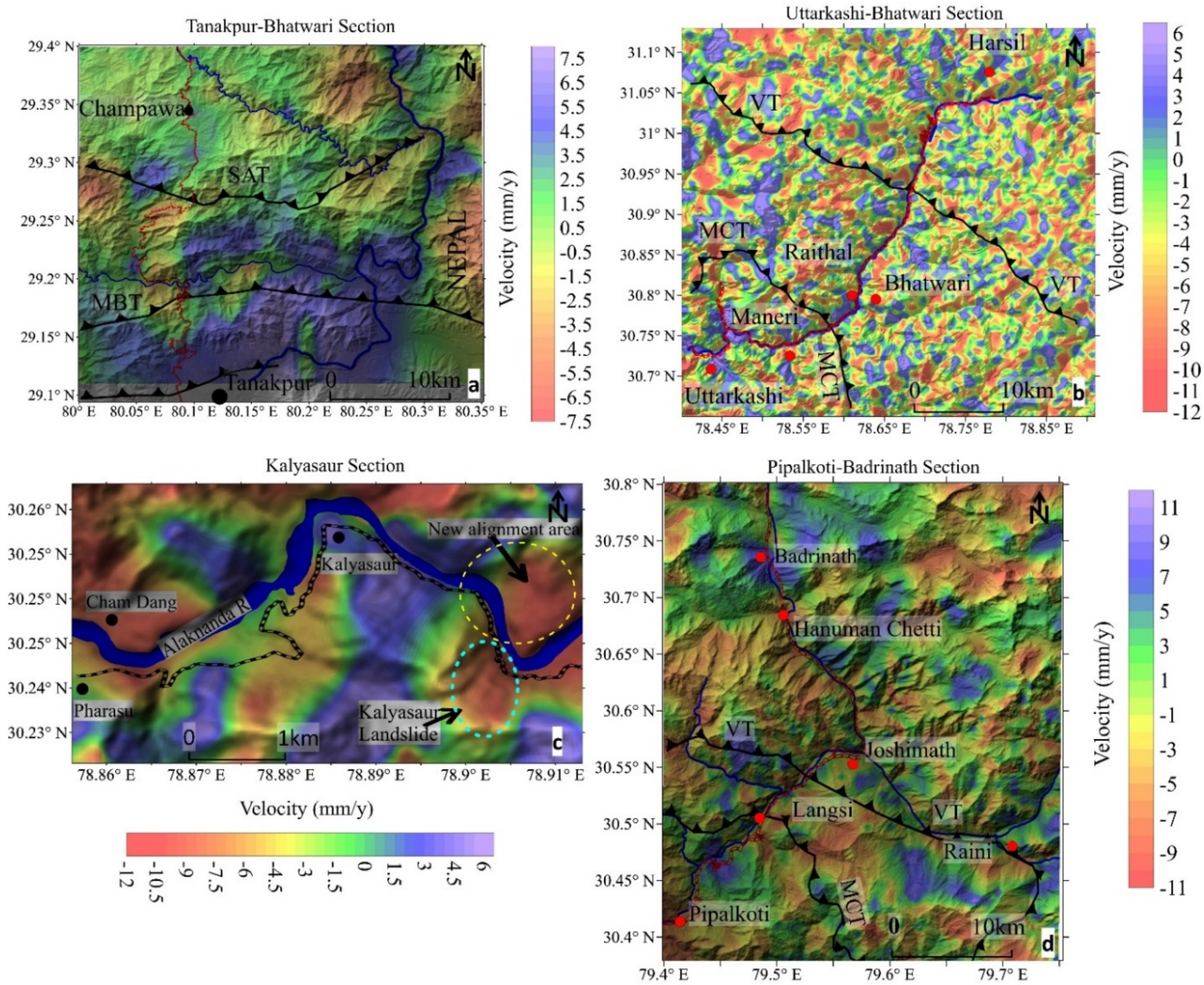

Fig. 8 The panels show PSInSAR base Line of Sight (LOS) mean surface deformation velocity in (A) sector-1 for the Tanakpur-Champawat segment, and (B) sector-2 for Uttarkashi and Harsil, Bhagirathi valley. For sector-3 (C) in Pharasu and Kalyasaur segment, Alaknanda valley, where Kalyasaur landslide shows clear subsidence (cyan ellipse) along with re-aligned road cut (yellow ellipse); (D) Pipalkoti-Joshimath-Badrinath, the values vary upto ± 11 mm/year. SAT- South Almora Thrust, MBT-Main Boundary Thrust, MCT-Main Central Thrust, VT-Vaikrita Thrust.

combined effect of the steep slopes, highly sheared lithology, focused rainfall, and seismicity, additional cautiousness is required before tempering with slopes. For example, the average valley slopes in the Lesser Himalayas and Higher Himalayas are ~30° and ~45° respectively. As demonstrated in the present study, hillslope disturbance due to road width increases exponentially with increasing slope angles (Fig. 7A). Therefore, the cut slopes in the Higher Himalayas are going to be much steeper and more unstable compared to their Lesser Himalayan counterpart. Similarly, the road width disturbance would also be significantly high, inflicting large collateral damage in terms of slope destabilization, forest loss, and biodiversity. Further, as lithology changes within short distances site-specific methodology during the excavation is required. Therefore, given the complexity of the terrain road construction policy in the Himalayas need to have tailor-made horizontal and vertical alignment standards to minimise instability and other geo-environmental damages (Megahan 1985).

The field investigations of various road segments in three different sectors (discussed above) indicate that road widening in 2018 was executed with a uniform excavation methodology where site-specific geological and altitudinally governed distinct geomorphic (earth surface) processes were not given adequate consideration. Road widening has further advanced the instability of the slopes, particularly in the proximity of chronic landslides and major structures, particularly the tectonically active HFT

(Wesnousky et al. 1999). The alternate approach taken during the road widening was to bypass existing roads traversing through the chronic landslides, as the realignment of Kaliyasaur bypass in sector-3 (NH-58). The strategy would have been successful if the re-alignment was scientifically analysed. Unfortunately, the new wider road is excavated on the Holocene fluvial-gravel terrace, proximal to the Alaknanda river (Fig. 4B) having an elevated water level due to the Hydropower reservoir. Such roads are either likely to subside/collapse as witnessed during June 2013 disaster in the Mandakini valley (Sundriyal et al. 2015). The study also stresses the need to re-align the roads much above the influence of the Reservoir Drawdown Effect (RDE), to circumvent the problem of RDE-induced subsidence. This is particularly important for Uttarakhand Himalaya with a large number of planned/commissioned hydropower projects with reasonable size reservoirs.

Sector-3 (Alaknanda valley) is one of the most challenging sectors with many chronic landslides (active for at least 50 years). The most striking and unfortunate example of ignoring geological fragility is Tota Ghati (Figs. 3B to 3E). Besides, the known history of unstable slopes, a detailed geotechnical study classified Tota Ghati as geologically unstable to a marginally stable region (e.g., Pradhan and Siddique 2020). The published study was ignored during the execution of road widening that employed heavy-duty excavators and explosives. This further widened the joints leading to collapsing of the solution cavities. Now, even during seasonal rain or vehicular vibration, the rock mass gets detached causing a severe traffic hazard. In sector-2 (Bhagirathi valley), the road widening work has yet not started (at the time of the study), and thus, the recent observations can be helpful in minimizing the vulnerability. Particularly, above Maneri and importantly between Bhatwari and Gangnani, where the field observations supported by GPS data (Yadav et al. 2021) and present InSAR data indicate that the slopes are creeping.

The study asserts on understanding of the predisposing conditions that control the type and pattern of landslides and their spatial probability of occurrence (landslide susceptibility mapping) (e.g., Carrara et al. 1999; Guzzetti et al. 1999; Soeters and Van Westen 1996; Conforti and Ietto 2021). Landslide-prone regions require frequent road maintenance which escalates the economic cost of roads as well. A recent study on the landslide susceptibility mapping in the upper Ganga catchment by Gupta et al. (2022) employed bivariate weight of evidence and information value methods and estimated that ~51% of the area is in the high-very high landslide susceptible zones, 22%–23% in the moderate, and ~26–27% in the low-very low landslide susceptible zones. Landslides in form of soil slips, slumps, debris flows, and other types of failures are frequently triggered by rainstorms generating additional sediment (besides excavation). Often to clear the right-of-way, it is dumped downslope of the highway leading increased load of debris/infill deposits on the hillslopes and thereby destabilising the same. During the road widening, hillslope over-steepening, removal of slope support, and cuts/alteration of surface runoff paths including increased depth and rates of runoff lead to instability which are likely to propagate uphill and downslope from the highways (Larsen, and Parks 1997). Identification of suitable zones/methods of muck dumping prior to excavation would help in limiting the damage.

Besides, the challenges of slope stability, especially in the Higher Himalayas, which have the largest concentration of both stabilized and active landslides (Valdiya 1985); and sequestered ~14% of unconsolidated sediments (Blöthe and Korup 2013). Most of the sediments were generated by multiple phases of glacier advances and retreat during the late Quaternary and are dominantly sequestered in regions vacated by geological advances until ~2500 m (Sharma and Owen 1996; Nainwal et al. 2007). Such zones are called the paraglacial zones, where rivers are sluggish, braid-meandering type (low stream power) (Juyal et al. 2009) and hence, are inherently incapable of evacuating the sequestered sediments. However, during extreme weather events, such as the June 2013 disaster, it was documented that even a small tributary stream (Khiro Ganga) can transport an unprecedented amount of paraglacial sediments that clogged and damaged the hydropower project. The sediment-laden water also washed away a section of the strategic NH-58 (Sundriyal et al. 2015). More recently, the April 2021 Rishi Ganga flood washed away the road and bridge and destroyed two hydropower projects (Rana et al. 2021; Shugar et al. 2021).

Additionally, in recent times increase in road construction activities has enhanced the mass wasting processes in a mountain environment (Varnes 1978).

We observed a positive correlation between the increase in valley slope and sediment yield (Fig. 7A). Similarly, the unprotected and untreated cut slopes along the road may not only lead to significant sediment contribution but also create chronic landslide zones along the highway. Another major threat to the roads is the flash floods induced by the bursting of landslide-dammed lakes, which are common in the terrain (Wasson et al. 2008; 2013; Rana et al. 2013; Sundriyal et al. 2015). Also, high-magnitude flash floods in the Higher Himalayas are often initiated from the paraglacial zones. Such floods are the major culprit for the destruction of roads, such as the July 1970 Alaknanda flood, August 2012 Asi Ganga flood, June 2013 Mandakini flood, April 2021 Rishi Ganga flood, and May 2021 Lambagarh flood. Therefore, it is important that road alignment takes into consideration the likely inundation caused during extreme weather events in the Himalayas. Besides the historical flood records (Wasson et al. 2013), the projected increase in the magnitude and frequency of Himalayan flash floods due to rising global temperature (Sabin et al. 2020) must be accounted for before any widening or re-alignment.

The IPCC Special Report (2018) indicates that human activities are likely to cause ~1°C rise in temperature (above pre-industrial levels) and reach 1.5°C between 2030 and 2052, if the trend continues. The temperature rise is likely to impact ecosystems with long-term and/or irreversible damage along with the increase in intensity and frequency of extreme weather events (Alvioli et al. 2018). According to Sabin et al. (2020), the Himalayas and the Tibetan Plateau experienced substantial warming during the 20th century. The rise in temperature and changes in precipitation patterns are a major concern not only for the health of the Himalayan snow cover/ glaciers (Sharma et al. 2021b) but also for the safety of people and infrastructures like roads. Uttarakhand government's document on an action plan for climate change (2014) indicates that there is going to be an increase in flooding which may vary between 10 and >30% of the existing magnitudes. The increase in flood magnitude and frequencies will have severe implications for the existing infrastructure such as dams, bridges, and roads and thus would require appropriate adaptation measures. Nevertheless, absolute geohazard proofing of infrastructure is unrealistic and will become even less likely if rainfall regimes are increasingly dominated by extremes (Hearn 2004). The relation between climate change and its potential effects on the stability of slopes remains an open issue. For rainfall-induced landslides, thresholds for slope failures need to be determined under the projected changes (duration and amount) in the rainfall. A study in the upland region of Central Italy (Alvioli et al. 2018) showed that while the rainfall thresholds for landslide occurrence are expected to change under the climate change scenarios; the probable distribution of landslide areas would remain unchanged. The study infers that landslide hazard is expected to change in response to the projected variations in rainfall conditions (Alvioli et al. 2018). This would probably imply that already threatened locations due to slope destabilization will aggravate if not adequately investigated and stabilized.

For disaster-resilient and hence environmentally friendly roads in the Himalayas and other regions with similar environmental settings, a detailed Environmental Impact Assessment (EIA) should be mandatory prior to the execution of projects, by independent experts with established scientific credentials and experience working in the Himalayas. As rightly pointed out by Hearn and Shakya (2017), *"Sustainable engineering for the future development of infrastructure in the Himalayas is entirely achievable as long as a carefully planned, managed, executed and inclusive approach is applied."* Since the Himalayan slopes seldom behave identical and experience frequent failures, it is important to understand their geo-environmental characteristics in terms of their vulnerability (Jangpangi et al. 2019).

6 Summary

The present study discusses some of the major factors affecting the sustainability/stability of Himalayan roads. By discussing important segments of the recently widened road, the study highlights that the Himalayan terrain is complex with enormous geological and ecological variability over short distances.

The field investigations and remote sensing based assessment of the study area reveal that site-specific geological and altitudinally governed different geomorphic processes should be given due consideration while road excavation, rather than following a uniform excavation methodology. Further, as the study demonstrates that volume of sediment generated increases exponentially with steeper slope angles therefore, optimising the road width and hence the excavation angle would help in limiting the environmental risks associated with slope stability and muck disposal.

It was observed that road widening has further increased the instability of the slopes, particularly in the proximity of chronic landslides and major structures. The realignment, as also adopted in the study area, to bypass the chronic landslides needs to be scientifically assessed to avoid segments prone to subsidence and erosion by a river or reservoir draw-down effect (e.g., terrace gravel surfaces proximal to rivers/reservoirs near Kaliyasaur in sector-3). Similarly, heavy-duty excavators and explosives must be avoided/minimised in geologically fragile sectors marked solution cavities, intersecting sets of joints, and creeping slopes (e.g., Tota Ghati, Sector-3).

The study also highlights the concerns of para-glacial sediment mobilisation from the Higher Himalayas during flash floods which have challenged the sustainability of the roads. Therefore, it would be pragmatic to incorporate estimates from the geological archives which suggest higher magnitude floods, besides the recent inundation limit of floods. This particularly becomes important given the projected rise in frequency/magnitude of extreme events due to warming temperature.

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