IOSR Journal of Applied Geology and Geophysics (IOSR-JAGG)
e-ISSN: 2321–0990, p-ISSN: 2321–0982.Volume 13, Issue 3 Ser. II (May. – June. 2025), 13-22
www.iosrjournals.org

Geo-Scientific Evaluation, Kinematics Analysis, and Mitigation Strategies for Pagal Nala landslide along Rudraprayg to Joshimath (NH-07) road corridor, Garhwal Himalaya

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Abstract
The Pagal Nala landslide located at Lat. 30° 28′ 29.00″ and Long. 79° 28′ 04.16″ on the Rishikesh–Mana highway (NH-07) at Tangni in Chamoli district of Uttarakhand is a huge threat to both the Char Dham pilgrimage route and India-China border connectivity. The geologic setting of the region is part of the Berinag Formation of the Inner Lesser Himalaya, consisting of interbedded meta-basalt, quartzite, and limestone. Differential weathering of the lithologies and proximity to the Main Central Thrust (MCT) have caused structurally fractured and jointed rock masses. Geomorphologically, the area is situated in a slope and concave spur zone with comparatively steep slopes (30°–45°) and active gully erosion that aggravates during monsoon seasons. The landslide is a high-spatial-density rainfall-driven (~1258.4 mm/year) rock-cum-debris slide involving periodic reactivation, toe cutting by a first-order stream, and unwanted road widening. Planar and toppling are indicated modes of failure by kinematic analysis. Remediation works consist of cross-drainage and contour building, breast walls with weep holes on solid bedrock, check dam gully training, and anchored wire mesh, geotextile, shotcrete, and rock bolt stabilisation to arrest further mass movement and provide long-term slope stability.

Keywords
Pagal Nala, NH-07, Char Dham, Landslide, Kinematics Analysis, Geo- Scientific Factors. Remedial Measure

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Date of Submission: 14-06-2025 Date of Acceptance: 28-06-2025

I. Introduction

Landslide refers to the instantaneous flow of soil, debris, and rock down the slope by gravity (Selamat et al., 2023). Landslides are frequent in the Himalayan region because it has high slopes, bad geology, high seismicity, high rainfall, and man-made activities such as road cutting and deforestation (Parkash et al., 2025). The young fold mountains of the region are still undergoing uplift, and hence geologically unstable. Among the susceptible areas, National Highway-07 (NH-07) running through Rishikesh to Mana is particularly vulnerable to landslides because of slope cutting, Vegetation loss, Inappropriate drainage and unplanned debris disposal (Singh et al., 2022). One of NH-07's renowned landslides is Pagal Nala landslide, whose material is essentially colluvium in nature, comprising boulders, cobbles, gravels, sand and clay. The geology of the area consists of phyllite, schist and quartzite forming a pervasive foliation plane with a dip towards the valley. The study area is situated near MCT such that a dominant shearing and deformation have been reported that result in landslides. The region has been subjected to recurring landslides mainly because of the very steep to steep slope gradient and poor vegetation cover, which weaken the slopes. These are again aggravated by heavy rainfalls and unplanned road construction activities causing disturbance to natural ground and drainage patterns. Although several workers have been working on the road corridor, no large-scale scientific investigation has been carried out by the investigators to critically analyze the phenomenon of landslide under controlled conditions. Thus, the current study is primarily centered around identification of primary geo-causative factors of the Pagal Nala Landslide. It also carries out two sets of kinematic analyses to determine slope failure mechanisms and suggests proper remedial measures to stabilize the slope.

II. Study Area

Pagal Nala landslide, also known as the Tangni landslide, is located close to Tangni village along the Rishikesh- Mana National Highway (NH-07) (**Fig. 1**). The nearest town is Pipalkoti, at a distance of approximately 10 km from the landslide site. It is fallen on Survey of India toposheet no. 53 N/7. The Geographic location of Pagal Nala landslide is Lat. 30° 28' 29.00" and Long. 79° 28' 04.16" and its average elevation is 1670 m from MSL.

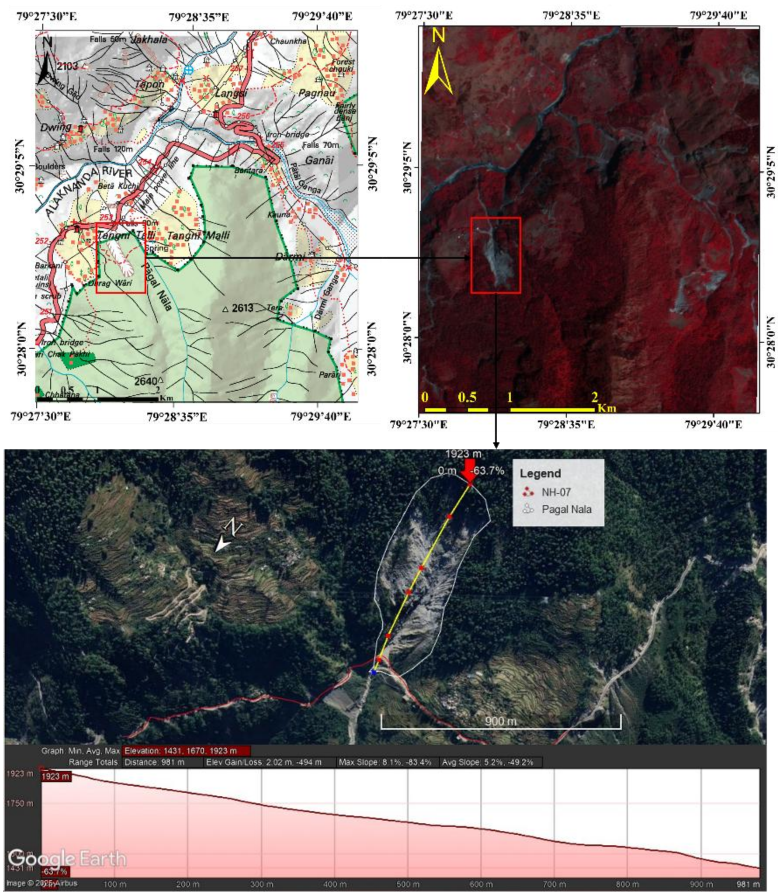


Fig. 1 Location Map

III. Geo-Scientific factors

3.1 *Geology*

The area of study is located in Tangni, which falls under Berinag Formation of Garhwal Group of the Inner Lesser Himalaya. The Berinag Formation is geologically the youngest of the Garhwal Group and falls under Mesoproterozoic age (McKenzie et al., 2011). In and around Tangni, Langsi, Gulabkoti, and Helang regions, it consists of thinly to thickly bedded quartzite interbedded with limestone and a narrow meta-basaltic band (amphibolite) (**Fig. 2**). The prevailing bedding is defined by thin laminae (thickness of a few millimeters) and layer-parallel alternating beds of different compositions such as orthoquartzite and micaceous quartzite occurring in association with limestone and meta-basalt. This sequence of metabasalt, limestone, and quartzite is in intrusive relationship with the Central Crystalline Group of granitic rocks. Difference in mechanical properties of these rocks leads to differential weathering—softer meta-basalt and limestone get weathered faster than harder quartzite—and gives rise to weak planes prone to failure. The thin laminae, alternating lithologies, and layer-parallel contacts are seepage paths of water, particularly during monsoons, that are conduits for elevated pore pressure and lowered shear strength.

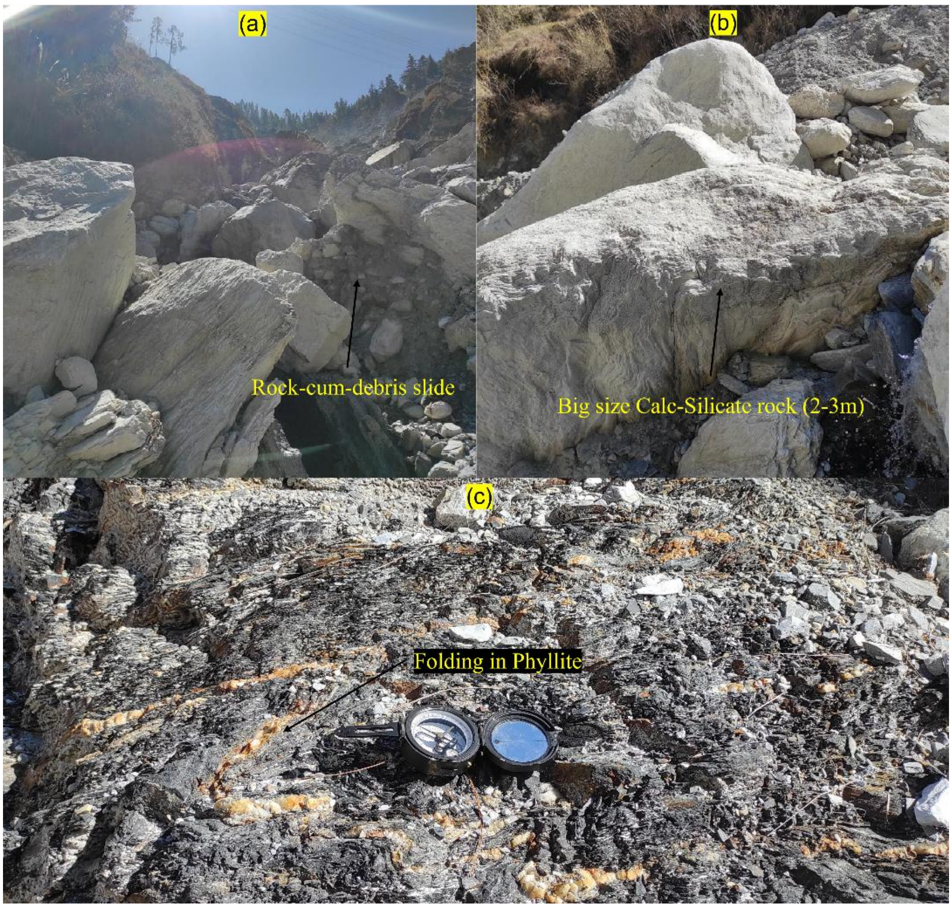


Fig. 2 Pagal Nala landslide, (a) slide view showing rock-cum-debris slide, (b) big size boulder of calc silicate rock (2-3m), (c) folding seen in phyllite

3.2 *Geomorphology*

Pagal Nala is situated in a slope and concave spur zone, a geomorphological situation highly susceptible to landslides (Zeng et al., 2024). High slope angles (30°–45°), irregular slope orientation, and active incision of the toe by a high-energy stream during the monsoon also reduce the slope base strength (Vakalas et al., 2025). Exposure of loose colluvium, weathered rock, and debris contributes to instability. The steep slope and concave topography combination permit lateral debris movement, whereas downslope-dipping bedding planes and joints are predominant failure planes in saturated conditions.

3.3 *Rainfall*

Rainfall has also been instrumental in initiating the Pagal Nala landslide, as can be seen in the 30-year CHIRPS (0.05°*0.05° resolution) record where it is receiving nearly 1258.4 mm of rainfall per year (**Fig. 3**). In an unsound geomorphological and structurally incompetent environment such as that of Pagal Nala, such rainfall serves as the main initiation factor of slope instability (Shi et al., 2025). Progressive long term and high magnitude precipitation saturates the slope material progressively, mainly the weathered meta-basalt, limestone, and meta-quartzite units of the Berinag Formation. This lowers matric suction, raises pore water pressure, and consequently lowers the shear strength of the slope-materials. Rainwater seeps into bedding planes, joints, and foliation surfaces, frequent in this tectonically deformed belt, weakening the subsurface. Hence, the combined impact of intensity and duration of surplus precipitation is responsible for triggering as well as remobilizing the landslides in the area.

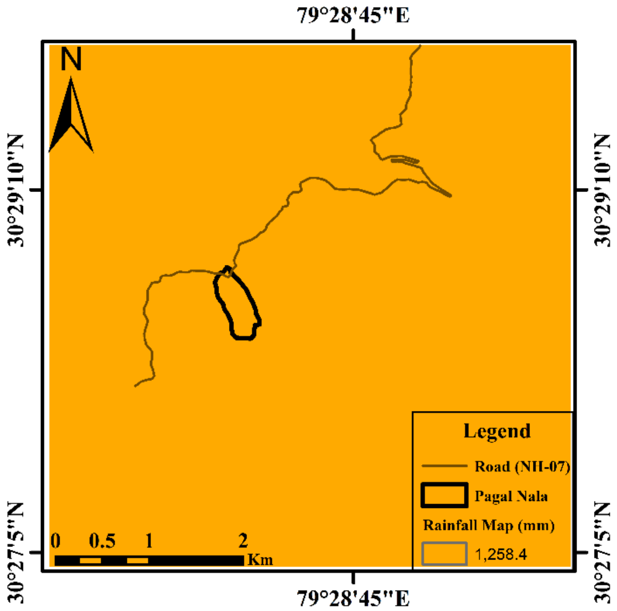


Fig. 3 Chirps Rainfall map where slide area found within 1258.4 mm rain cover (30 years average of mean annual rainfall)

3.4 *Road Proximity*

Proximity to the road has been a controlling factor in the Pagal Nala landslide by directly affecting the slope stability, specifically in the toe zone (Woldearegay, 2025). The road, as shown in the proximity map, follows or cuts the toe of the slope, where repeated excavation and widening have eroded natural support, resulting in toe undercutting (**Fig. 4**). This upsets the slope equilibrium, especially in a section consisting of weathered and interbedded lithologies. Secondly, poor drainage management and roadside litter dumping also increase surface runoff, leading to saturation and erosion. The road proximity is therefore an important human landslide cause.

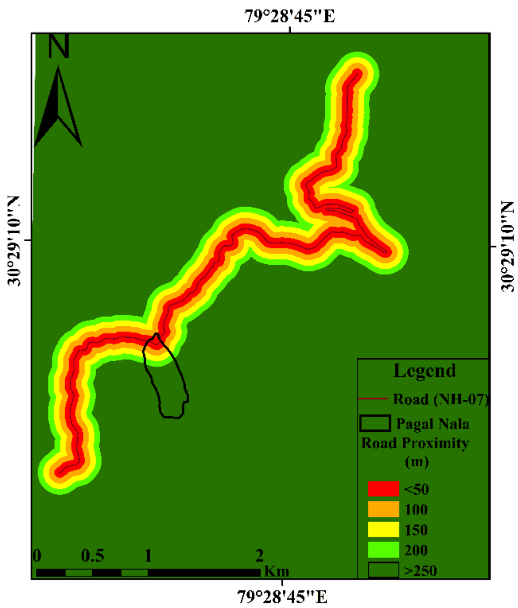


Fig. 4 shows the Road Proximity map, where road cuts the toe portion of the slide.

3.5 *Fault Proximity*

Fault proximity has had a great effect on the Pagal Nala landslide since the location of the slide is within 6000 meters of the Main Central Thrust (MCT), as shown by the fault proximity map (**Fig. 5**). This kind of tectonic proximity exposes the area to extreme deformation, fracturing, and shearing, and therefore leads to greatly jointed and weakened rock masses (Xie et al., 2025). Tectonic perturbations induce lower cohesion and shear strength of the slope-producing material, hence increasing its likelihood of failure (Coffie-Anum et al., 2024).

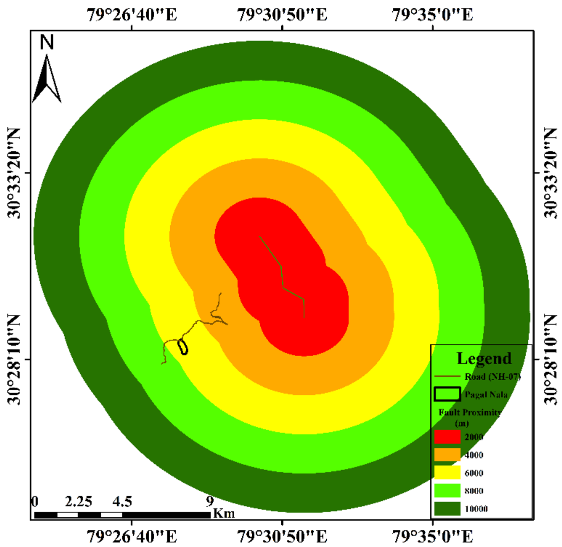


Fig. 5 illustrates the Fault proximity map where slide is found within 6000 m range of the Main Central Thrust.

3.6 *Elevation*

Elevation has been a major contributory factor in the Pagal Nala landslide, whose affected area ranges between 1400–1850 meters, as indicated by the elevation map (**Fig. 6**). The elevation is also known to overlap with the mid-slope steep areas where gravitational forces will be greater and slope inclinations will be greater (Barrie et al., 2024). These areas are prone to colluvial debris accumulation, bedrock exposure, and increased intensity of weathering, all factors contributing towards the decrease in slope stability. Furthermore, orographic processes at this height can induce localized precipitation, which brings about greater infiltration and runoff (Holden & Burt, 2002). Coupled with tectonic as well as anthropogenic pressures, elevation-driven topographic stress also plays a major role in the landslide susceptibility of this area.

IV. Kinematics Analysis

V.

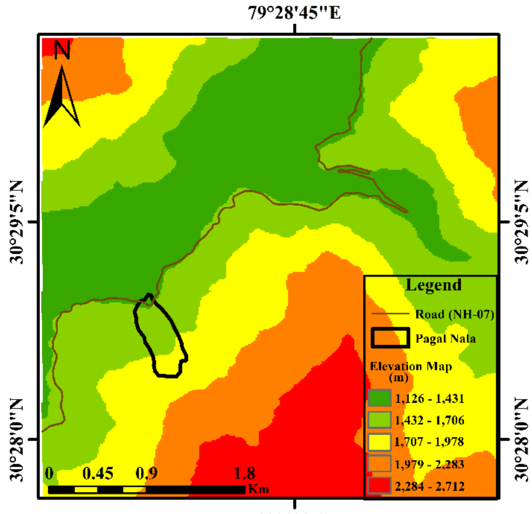


Fig. 6 depicts the Elevation map, where slide area found within the elevation ranges of 1400 to 1850 m.

Kinematic analysis is a method used to determine the probability of various failure modes in rock slopes, which is controlled by the adverse orientation of discontinuities (Olaleye & Ajibade, 2011). Testing is performed via structural measurement and follows Markland's test criteria, according to Hoek and Bray (1981), conducted with Dips software (Siddique et al., 2015). The lithology is characterized mainly by quartzite and calc-silicate rocks that, even though they are mostly competent, have degraded shear strength owing to the presence of structural discontinuities in joints, faults, and fractures **(Fig. 7)**. The orientation and persistence of such discontinuities have an important part to play in slope stability, especially under faulted ground and zones of active surface run-off or gully erosion. **Table 1** gives two sets of discontinuity orientation data that were gathered to determine precisely the structural orientation of the Pagal Nala landslide. In Set 1, no discontinuities are clearly showing planar or wedge failure tendency, although J1 is inclined towards planar failure. In Set 2, J2 and J3 intersection shows oblique toppling mode of failure with plunge angle of 82° towards N80°, and J1 continues to show planar failure susceptibility. Two sets of joints are represented in **Fig. 8.**

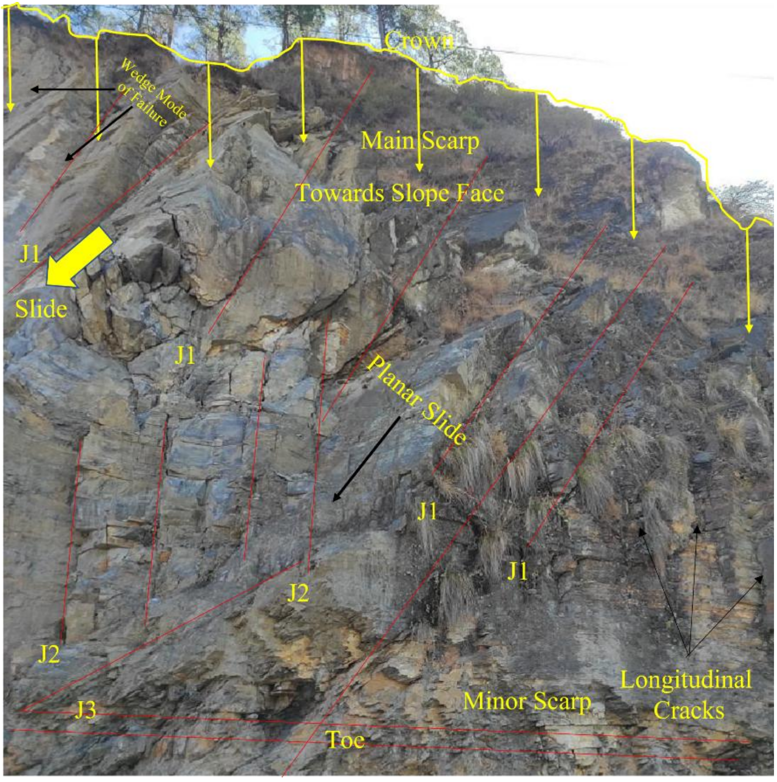
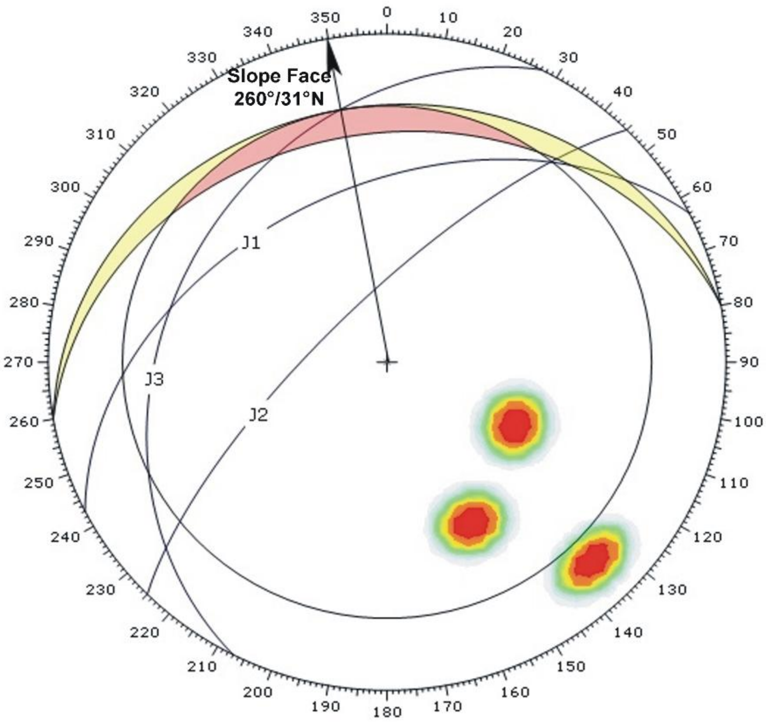


Fig. 7 Near side of Pagal Nala landslide (quartzite) where three sets of joint planes are well shown and demarcated.

Table 1 Discontinuity Orientation data

Sl. no.	Joint set no.	Joint plane	Strike	Dip amount	Dip direction
1		Slope	260°	31°	NNW
2	Set 1	J1	290°	35°	WNW
3		J2	225°	75°	NW
4		J3	243°	46°	NNW
5	Set 2	J2	179°	83°	E
6		J2	105°	87°	NNE
7		J2	105°	15°	NNE



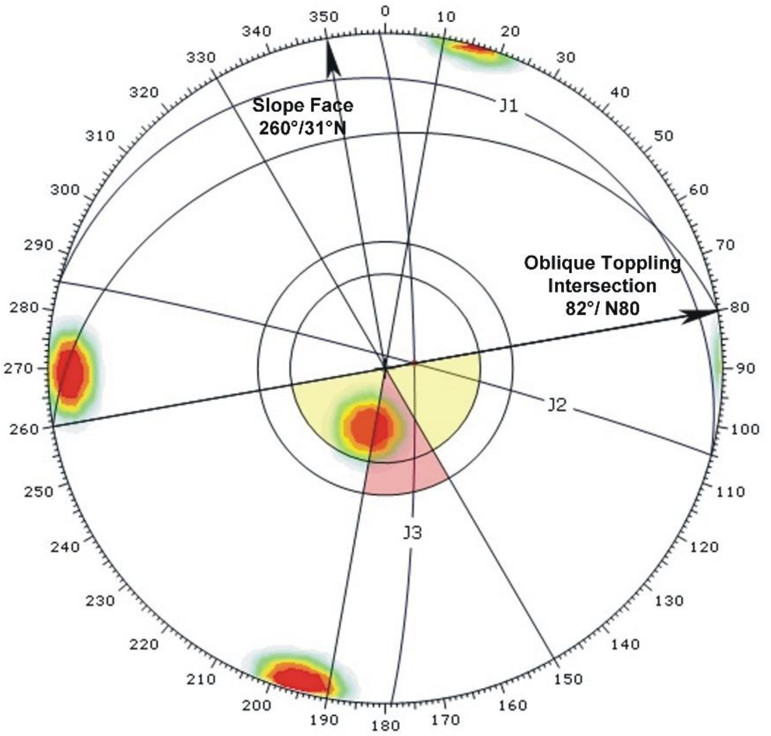


Fig. 8 Kinematics analysis at Pagal Nala landslide. Set 1, no discontinuities are clearly showing planar or wedge mode of failure. Set 2 showing oblique toppling mode of failure (J2 & J3 joint plane intersection)

VI. Landslide Description

The Pagal Nala landslide, situated along the Rishikesh–Mana highway (NH-07), is a significant and recurrent slope failure influenced by both geological and anthropogenic factors. Unengineered and unplanned road construction have destabilised the toe part of the slope, as can be seen from **Fig. 2**, in which natural support loss has created further instability. Destabilisation together with intensive monsoonal rainfall has led to frequent landslide occurrences. As most of the displaced material would be in the toe portion, every rain event introduces further reactivation due to saturation, pore water pressure rises, and reduction in the shear strength. **Fig. 9** is a clear indication of the accumulation of mixed debris and overburden material in the toe, confirming the depositional character of the landslide. Dimensionally, the landslide is approximately 891m*330m*743.3m in length*width*height, possibly having an area of 125,609.87m². The crown section exposes calc-silicate rock with interbedding phyllite and quartzite that contains three major sets of joints: J1 (290°/35° WNW), J2 (105°/87° NNE), and J3 (105/15° NNE) (**Fig. 8**). A large, unweather boulder of calc-silicate rock, measuring around 2–3 metres, is located at both the middle and toe zones, indicating significant mechanical disintegration of the slope-forming rocks (**Fig. 2(b))**. This disintegration is further supported by the site's location within a local fault zone, which enhances fracturing and the generation of loose debris. Concentration of debris at the toe is further evidence of previous high-energy displacement events that not only destabilised massive calc-silicate blocks but also crushed and pulverised more brittle phyllitic units. A perennial stream flowing through this faulted zone contributes to slope instability through pore water pressure augmentation and hydro-mechanical weakening of the slope material **(Fig. 10(a))**. **Fig. 10 (b & c)** shows a landslide profile where active gully erosion is readily apparent, with an accompanying slide cross-section showing step-like (enechelon) patterns of material displacement, characteristic of progressive failure. Geomorphologically, the site is consisting of a moderately dissected hillslope with greater than 30° slope angles, NNW slope aspect, and moderate forest canopy covered that provides moderate protection from surface erosion and hydrological stimuli.

Fig. 9 Accumulation of mixed debris and overburden material in the toe portion of the slide.

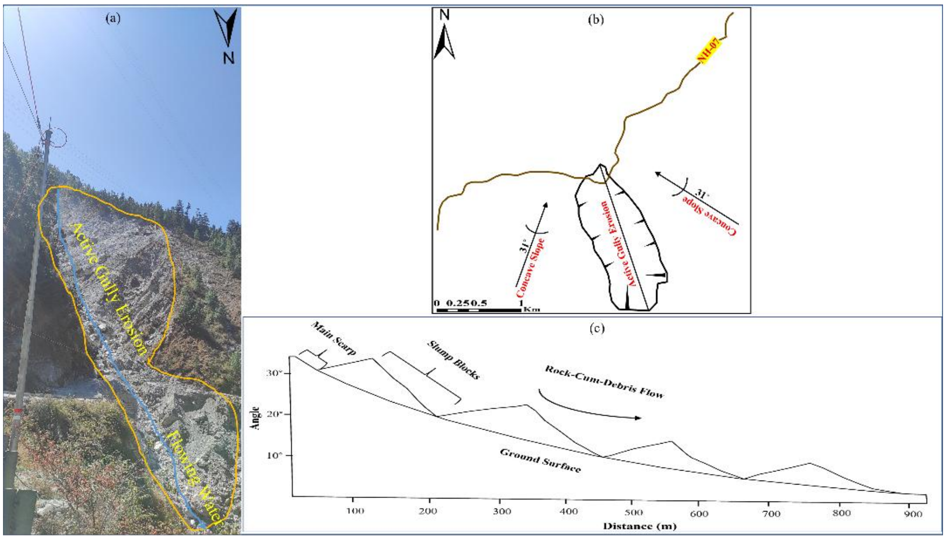


Fig. 10 (a) Pagal Nala landslide (on-site landslide view), (b &c) represent the landslide profile and cross-section.

VII. Remedial Measure

Pagal Nala landslide, caused by differential weathering, rain infiltration, active toe erosion, and uncontrolled road cutting, demands site-specific remedial measures. Contour drains and cross-drains should be installed across the surface and subsurface flow. A breast wall with weep holes, supported by competent bedrock and graded filter provision, will ensure pore pressure rise prevention and debris trapping. To mitigate stream-induced toe erosion, stepped chute drains and check dams are advocated. Wire mesh anchorage, rock bolting, and geo-textiles should anchor at distressed slope sections particularly where toppling and planar failures are kinematically possible.

VIII. Discussion

The Pagal Nala landslide must be examined because of its geological instability in the seismically active Himalayan landscape. It disrupts the Char Dham pilgrimage route road (NH-07), which halts socio-religious movement. It also disrupts the strategic India-China border connectivity, compromising national security and logistics. Integrated assessment enables sustainable road development, minimization of disaster risks, and resilient infrastructure planning. The landslide is litho-stratigraphically located within the Berinag Formation, a mechanically heterogeneous assemblage of rocks such as quartzite, meta-basalt, and limestone in which differential weathering and closely spaced discontinuities have formed planes of weakness. Geomorphologically, the location lies in a spur zone, where high slopes (30°–45°), concave profile of hills, and highly incised gully system promote lateral erosion and slope undercutting, in particular by erosional Pagal Nala stream. Hydrologically, the location receives approximately 1258.4 mm of precipitation per year that seeps into joints and bedding planes, adding pore pressure and decreasing slope materials. Closer proximity to road (NH-07) (Char Dham highway) not only compromises the safety of pilgrims but also interferes with slope stability due to regular cutting of roads, inadequate drainage, and dumping of rubble. Besides, the area is close to the Main Central Thrust, an area of high deformation, including rock mass fracturing Kinematic analysis also indicates toppling and planar failure potential. Combined, these conditions render the landslide a key hazard zone requiring immediate geotechnical attention.

IX. Conclusion

NH-07 is an important arterial road linking the Char Dham pilgrim route and running further to the Indian-China border. The landslide in Pagal Nala near Tangni along this corridor is an important threat due to its extensive spatial area, repeated monsoonal reactivation, and proximity to strategic infrastructure. The landslide is marked by a mix of geological, structural, geomorphological, and anthropogenic causative factors. The slope consists of structurally disturbed and intensely jointed interbedded Berinag Formation's limestone, meta-basalt, phyllite, and interbedded quartzite due to the tectonic proximity to the Main Central Thrust (MCT). Failure is progressive and dominantly controlled by steep spur geomorphology, active stream toe erosion, and heavy rain infiltration. Kinematic analysis indicates planar and toppling failures in unfavorably oriented sets of discontinuities. Constant toe cutting caused by road expansion, inadequate drainage, and concentration of surface runoff contribute significantly to enhanced instability. In order to counter the risk, global slope stabilization methods such as effective sub-surface and surface drainage, check dams within the gully region, rock bolting, shotcrete on exposed faces, and geo-textile installation must be implemented. Supporting the toe by retaining structures and controlling the construction work at the toe of the slope are also essential to provide long-term stability.

Acknowledgement

The authors are deeply thankful to the Department of Applied Geology, Dr. Harisingh Gour Vishwavidyalaya, Sagar, for their infrastructural, laboratory, and financial assistance precious to this research. We also acknowledge our appreciation of ALOS PALSAR for provision of DEM, Climate Hazards Group, University of California, Santa Barbara (UCSB) for CHIRPS rainfalls data, Geological Survey of India for fault data, and OpenStreetMap through Google Earth Pro for the road shapefile applied in this study.

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