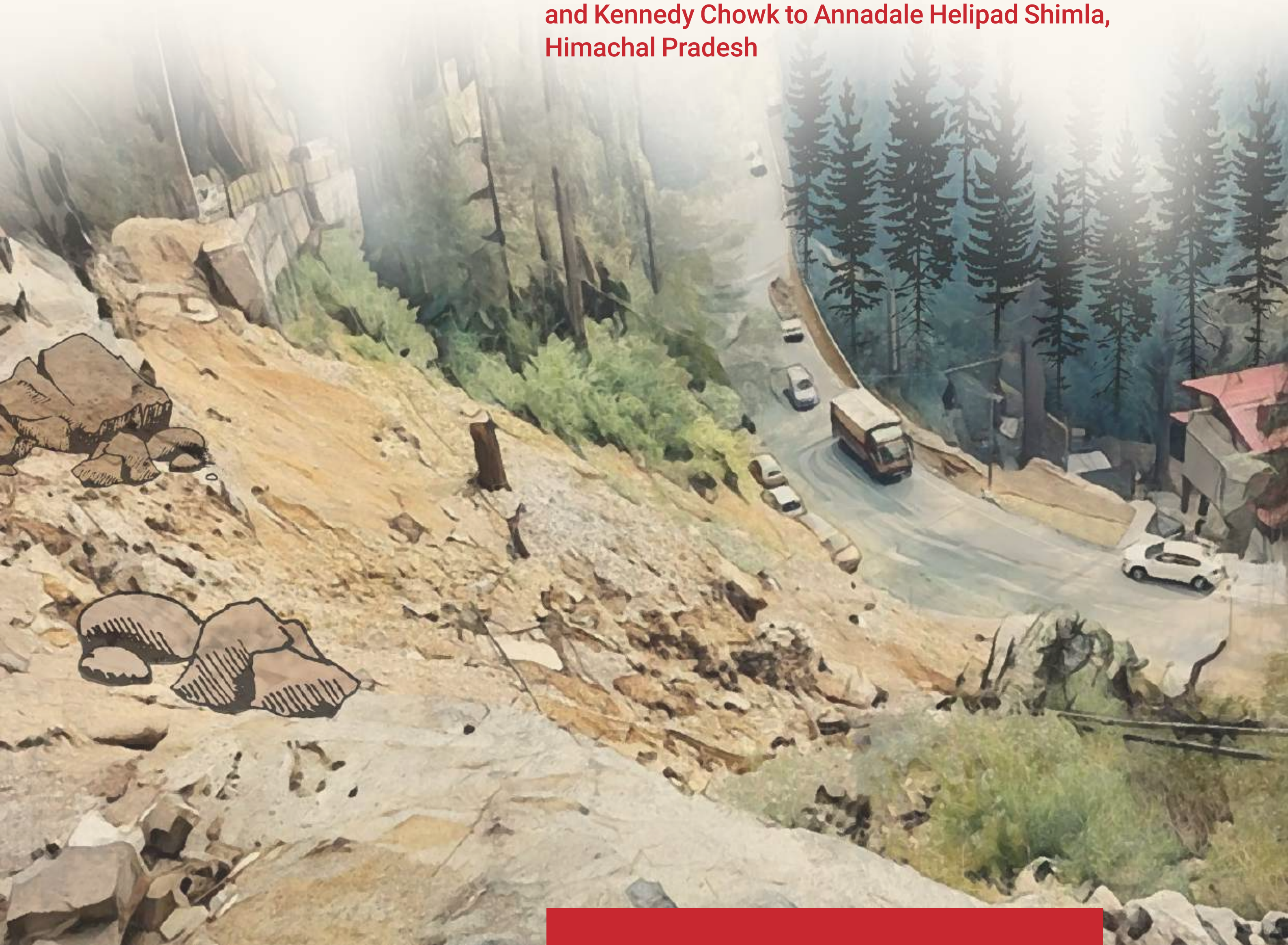
CDRI
Coalition for Disaster Resilient Infrastructure

Landslide Risk Assessment of Strategic Roads

Panthaghati to National Highway Crossing, and Kennedy Chowk to Annadale Helipad Shimla, Himachal Pradesh



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State Disaster Management Authority
Government of Himachal Pradesh

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Launched by Indian Prime Minister Narendra Modi at the 2019 UN Climate Change Summit, the Coalition for Disaster Resilient Infrastructure (CDRI) is an International Organization and a global multi-stakeholder partnership of national governments, UN agencies, programmes, multilateral development banks financing mechanisms, private sector, academic and knowledge institutions. CDRI is committed to working with various stakeholders to promote the resilience of infrastructure globally. CDRI aims to address the challenges of incorporating resilience into infrastructure systems and the development that comes with it. To date, CDRI's members and partners include 40 countries and 7 organizations, worldwide.

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Cover photo credits: District Authority, Shimla, Governemnt of Himachal Pradesh

Executive Summary

The assessment of roadside landslides for the Panthaghati-Crossing and Kennedy Chowk-Annadale Helipad Road sections in Shimla, Himachal Pradesh, highlights the significant vulnerability of these areas to landslides and emphasizes the importance of slope management. This study was conducted in response to the rising number of landslides during the rainy season, which presents considerable risks to life, property, and infrastructure in the region.

In February 2024, a technical team conducted an initial visual observational assessment, followed by a detailed assessment in June 2024. These assessments aimed to identify the types, extent, and primary causes of landslides, evaluate the stability of slopes and recommend sustainable suggestive measures to enhance the resilience of highways.

The key findings indicate that the slopes along both road sections are highly susceptible to landslides.This susceptibility is due to a combination of natural factors, such as intense rainfall and fragile geological conditions, as well as human activities, including poor drainage management and construction practices. The Panthaghati-Crossing Road, which is part of National Highway 5 (NH5), and the Kennedy Chowk-Annadale Helipad Road, both critical for strategic connectivity, have multiple sites displaying both shallow and deep-seated flow-type landslides. Intense rainstorms act as the primary trigger for these landslides byincreasing soil moisture and porewater pressure, which in turn reduces slope stability.

The study emphasizes the importance of Nature-based Solutions (NbS) for slope stabilization. Techniques such as planting vegetation, using brush layering, and constructing vegetative gabion check dams offer sustainable and cost-effective methods to enhance slope stability and prevent erosion. Additionally, the report recommends constructing and maintaining proper drainage systems to effectively manage surface runoff and prevent further destabilization of slopes.

To mitigate the risk of landslides, the report outlines several recommendations. These include improving drainage management, stabilizing vegetation, implementing structural measures such as retaining walls, and encouraging community involvement in the maintenance of these systems. Regular monitoring and additional geotechnical investigations are also advised to be conducted to ensure the long-term effectiveness of the implemented measures. A proactive approach, such as adopting a dedicated highway slope monitoring and maintenance system,is recommended to mitigate the risk of roadside landslides. By adopting these recommendations, it is anticipated that the risk of landslides can be significantly reduced, thereby protecting road infrastructure and enhancing the safety and resilience of communities in Shimla. Implementing these measures will contribute to the development of the disaster-resilient infrastructure in the region, aligning with the goals of Coalition for Disaster Resilient Infrastructures (CDRI).

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Glossary

Cloudburst: An intense and sudden rainfall event, often leading to flash floods and landslides in hilly regions.

Cracking: The formation of visible fractures in the ground or road surface, indicating potential subsidence or movement.

Cutting: The excavation of a slope to create a road or path, often leading to potential instability if not managed properly.

Erosion: The gradual removal of soil or rock by natural forces like wind or water, often leading to slope instability.

Geomorphology: The study of landforms and the processes that shape them, critical for understanding landslide risks.

Hydrology: The study related to the movement, distribution, and quality of water, influencing slope stability.

Hydrometeorology: Concerning the relationship between atmospheric and hydrological processes, important in predicting landslides.

Landslide: The movement of rock, earth, or debris down a slope, triggered by factors such as rainfall, earthquakes, or human activity.

Landslide Susceptibility: Qualitative or quantitative analysis of the classification, volume, and spatial distribution of landslide that exist or potentially can occur in an area; can also include a description of the velocity and intensity of the existing or potential landslide; a time frame is explicitly not taken into account.

Nature-Based Solution/Bioengineering: The use of vegetation and natural materials to stabilize slopes and prevent erosion.

Resilient Roads: Road infrastructure designed to withstand and adapt to extreme weather events, landslides, and climate change impacts, ensuring long-term functionality and safety.

Scouring: The removal of soil or rock from a slope or riverbed by flowing water, which can lead to slope instability.

Slope Stabilization: Techniques used to enhance the stability of a slope and prevent landslides, including both engineering and nature-based solutions.

Weathering: Breaking down rocks and soil through exposure to atmospheric conditions, influencing slope stability.

Topography: The study related to the physical features of a landscape, such as slope, elevation, and drainage patterns.

Acronyms

CDRI: Coalition for Disaster Resilient Infrastructure

DTM: Digital Terrain Model

ERT: Electrical Resistivity Tomography

IRC: Indian Road Congress

LSM: Landslide Susceptibility Model

MCA: Multi-Criteria Analysis

NbS: Nature-based Solutions

NDMA: National Disaster Management Authority

SDMA: State Disaster Management Authority

SRT: Seismic Refraction Tomography

TWI: Terrain Wetness Index

1 Introduction

1.1 Background

Historically, landslide is the most common type of natural hazard in Himachal Pradesh (HP), posing significant risks to life and property (Prakasam and Kanwar, 2021). The state is geologically fragile and ecologically sensitive, meaning that even small variations in the climatic conditions, particularly during the monsoonal rainstorms, can lead to hazards and disasters. The state government is concerned about the occurrence of landslides, avalanches, and flash floods, among other natural hazards and extreme weather events. The fragile nature of the mountainous terrain, combined with the climate extremes and intensive anthropogenic activities has made the landscape vulnerable to landslides and other climate-induced disasters.

Physio-graphically the state can be divided into three board units: (i) Lower or Outer Himalayas, (ii) Middle Himalayas, and (iii) Higher or Greater Himalayas. Each unit is susceptible to different types of hazards depending on the lithology, soil composition, climate extremes, and human activities. Due to its diverse topography and complex geological setting, the state is under the threat of one or multiple hazards, including flash floods, slope failures, avalanches, and droughts, often driven by excessive or insufficient water. While monsoonal rain is vital for the livelihoods of the people, it can also cause disasters that affect slope stability, disrupt the transport sector, and damage both public and private properties, thereby leading to significant economic losses.

Every year, the capital district of Shimla experiences landslides that cause social and economic losses. These losses include casualties, damage to houses, roads, communication lines, and agricultural lands. The mountainous landscape of the Shimla district consists of fragile geology, long and steep slopes, loose loamy soil, intense human activity, and unprecedented climate extremes(Prakasam and Kanwar, 2021; Sharma et al., 2016). These are some of the prominent factors that cause fatal landslides. Parkash (2011) compiled a list of historically socio-economically significant landslides around India, reporting a total of 371 landslide events from 1800 to 2011. The findings indicate that the western and north western regions of the Himalayas are particularly prone to landslides, accounting for about 49% of the fatalities and 51% of the landslide occurrences.

Previous studies indicate that the majority of the landslides in the district are shallow and superficial, primarily triggered by rainstorms(Kahlon et al., 2014). The most recent landslide disaster of August 2023 alone resulted in the deaths of 51 people state-wide, with 14 fatalities occurring in Shimla. During the disaster, the roads were blocked, which impacted the daily activities of the people.

Due to the increasing frequency of landslides causing significant disruptions, delays, and significant loss of life and economic resources in Himachal Pradesh, the Himachal Pradesh State Disaster Management Authority (HP SDMA) in collaboration with relevant line departments, sought technical assistance from Coalition for Disaster Resilient Infrastructure (CDRI). The aim was to develop identified road sections into a resilient infrastructure capable of withstanding climate-induced extreme weather events with a special focus on mitigating landslide risks.

As part of the CDRI's technical assistance programme, an initial on-ground assessment was conducted in February 2024.This assessment was carried out by CDRI accompanied by representatives from the stakeholders of the identified roads. The findings from this initial assessment laid the foundation for further detailed analysis. At the request of HP SDMA, a detailed mission was subsequently planned for June 2024. This mission involved experts in landslide assessment, geology, geotechnical engineering, and bioengineering. The focus was on identifying measures to be incorporated into future detailed project reports (DPRs) for the development of resilient roads.

1.2 Objectives

The primary objectives of the detailed assessment were as follows:

- Identify both structural and non-structural measures to enhance the resilience of the two identified road sections against extreme weather events.
- Identify long-term, medium-term, and short-term interventions, including both grey infrastructure and nature-based solutions (NBS).

1.3 Scope

Data Collection and Analysis: Collect comprehensive data on topography, geology, hydrology, and meteorology along the road alignment, including field surveys and historical data review.

Field Surveys: Conduct detailed on-site surveys to map the extent of existing and historical landslides, utilizing technology to accurately record landslide locations and characteristics.

Soil and Rock Sampling: Identify and visually analyse the condition of soil and rocks that are critical for understanding slope behaviour.

Geological and Geomorphological Mapping: Understand the broad geological and geomorphological features and undertake detailed mapping of individual landslides that highlight soil types, rock formations, structural features, landforms, and surface features associated with landslides.

Land Use Documentation: Record current land use practices to identify human activities contributing to slope instability, including agriculture, deforestation, construction, and other land alterations.

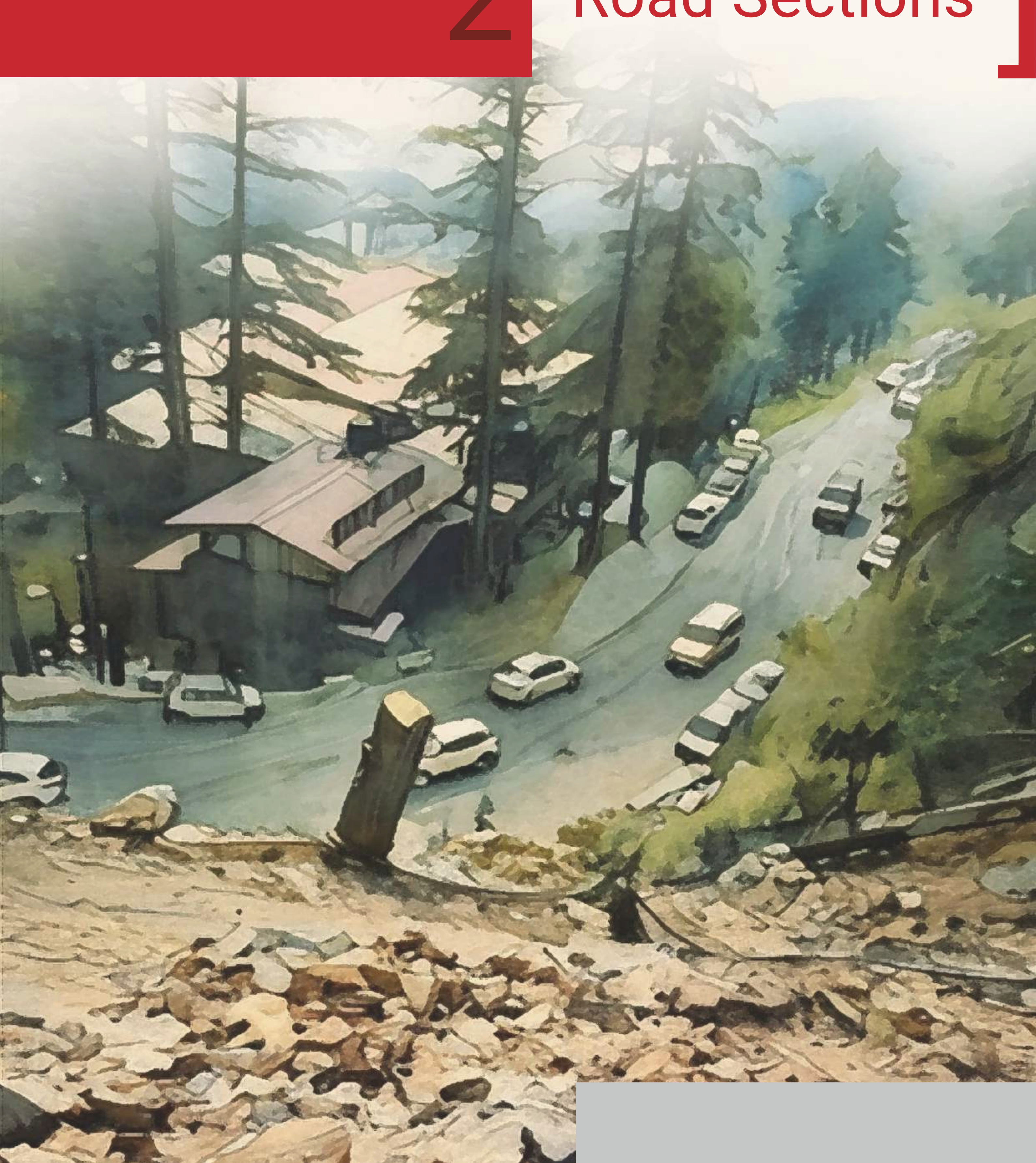
Historical Data Review: Analyse past landslide events and weather patterns to identify common triggers and trends.

Design of Mitigation Strategies: Develop conceptual schemes of engineering designs for structural measures (e.g., retaining walls, drainage systems) and non-structural measures (e.g., reforestation, slope vegetation) to enhance slope stability.

Nature-based Solutions: Explore and design NbSlike bioengineering techniques, reforestation, and the use of natural materials for slope stabilization.

Implementation and Monitoring Plans: Create detailed implementation plans for the proposed measures, including timelines, resource allocation, and responsibilities. Develop monitoring plans to track the effectiveness of the measures and ensure long-term stability.

2 Road Sections



2.1 Selection of Road Sections for Assessment

The HP SDMA identified two road sections for enhancing resilience to roadside landslides along their alignment: (i) Panthaghati- NH Crossing and (ii) Kennedy Chowk-Annadale Helipad routes (refer to Image 2.1).

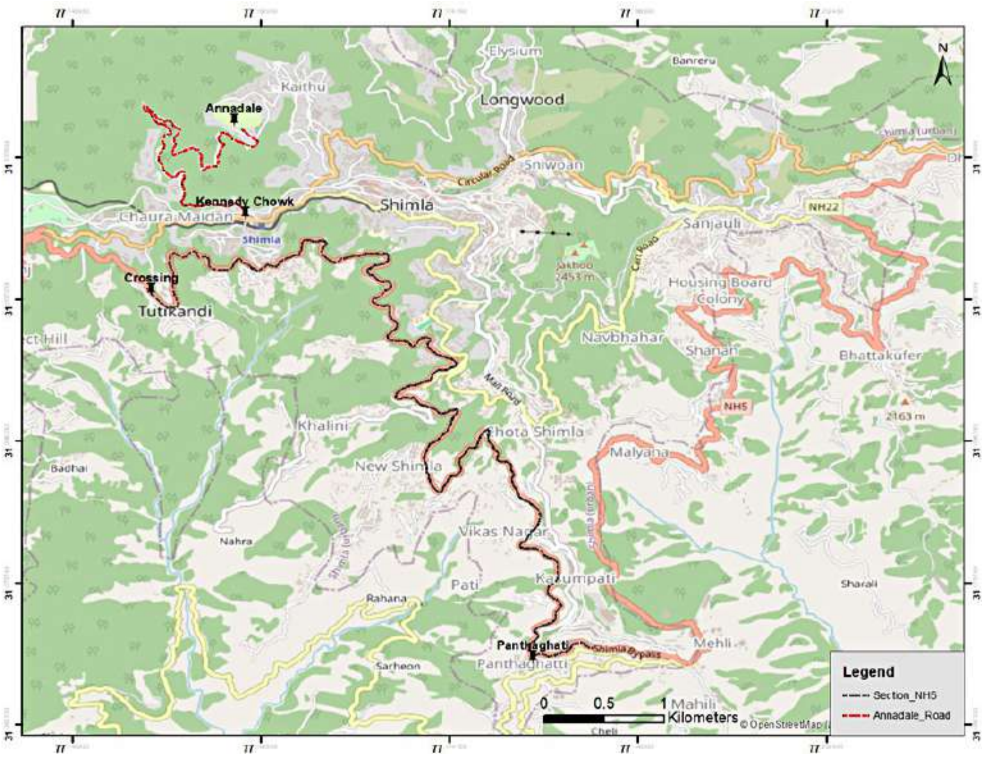


Image 2.1 - Satellite imagery of the two identified road sections in Shimla

2.1.1 Panthaghati-Crossing Road

This road was previously part of NH5, which is currently being transferred to the state as a new national highway is under construction. This road primarily serves as the main service road for Shimla City. The double-lane road has a blacktop surface, frequently crossing several second to higher-order stream channels. The road mostly runs through the middle of the hill, often surrounded by built-up hilly terrain. The road section under this study was about 10.3km in length. This section featured modified hill slopes and drainage systems.

2.1.2 Kennedy Chowk-Annadale Road

The road is considered important due to its strategic value, as it connects the Army Helipad at Annadale to various government offices in Shimla. It begins at Kennedy Chowk and stretches approximately 3.6 km to the Annadale Helipad. The road passes through the old forest filled with oak and cedar trees. The single-lane, blacktopped road is often blocked due to landslides and fallen trees. Additionally, several drainage channels intersect the road's alignment.

2.2 General Geomorphology and Geology

2.2.1 Geomorphology

The geomorphology of the Shimla area is characterized by a combination of geological features, terrain, and soil types that shape the region's physical landscape. Situated in the lower Himalayan region, Shimla is characterized by its rugged and steep terrains. The elevation ranges from about 2,104m above sea level in Shimla to higher elevations in the surrounding regions. The area features a series of parallel ridges and deep, narrow valleys formed by fluvial erosion over millions of years. The highest peak in the region is Jakhoo Hill, which stands at about 2,454m above sea level.

The region's geology is dominated by ancient crystalline rocks, such as granites and gneisses, along with carbonaceous slate, phyllite, limestone, and schist found in Jutogh. Additionally, the Shimla Group contains silt and sandstone (Bhargava and Srikantia, 2014). These rocks are often heavily folded and faulted due to the tectonic activity associated with the Himalayan orogeny. Shimla lies in a seismically active zone, with several fault lines running through the region. This tectonic activity has contributed to the region's rugged landscape and frequent landslides.

The soil in Shimla varies based on altitude and parent rock material. At higher elevations, the soils are typically thin and rocky, while lower areas tend to have deeper, more fertile soils. The dominant soil types include sandy loams and clay loams. The steep slopes and heavy monsoon rains contribute to significant soil erosion, and landslides are a common geomorphic process in the region, exacerbated by the topography and construction activities. Several perennial streams, which are tributaries of larger river systems, drain the region. These rivers have carved deep gorges and ravines into the landscape.

Cold winters and moderate to heavy monsoon rains influence the geomorphological processes of the Shimla area. During winter, freeze-thaw weathering contributes to rock fragmentation, while the monsoon rains enhance chemical weathering and erosion. The natural vegetation primarily consists of dense coniferous forests, which include species such as pine, cedar, and deodar. These forests play a crucial role in stabilizing the soil and reducing erosion. However, the trees can also contribute to landslides due to their shallow root systems and substantial weight. In areas with less steep slopes, terraced farming is practised. These terraces are carefully constructed to minimize soil erosion and manage water runoff effectively.

The landscape of Shimla often presents significant risks for landslides, especially during the monsoon season, which affects both infrastructure and settlements. Ongoing soil erosion caused by intensive construction activities remains a major environmental concern. In addition, the region's location in a seismically active zone necessitates careful planning and construction to mitigate earthquake risks. The geomorphology of Shimla is influenced by a complex interplay of geological structures, climatic influences, and human activities. Understanding these factors is crucial for sustainable development and effective disaster management in this picturesque yet geologically sensitive region.

2.2.2 General Geology

The Shimla region, a part of the Himalayan range that is geologically young and tectonically active, has fragile geology and is considered prone to natural hazards like landslides, earthquakes, and flash floods. The geological account of the Shimla region has been well-researched and illustrated in widely published academic and research journals. Below is a brief overview of the various rock formations found in the region. The terrain primarily comprises rocks from the Shimla Group, Jutogh Group, Undifferentiated Jaunsar Group, and Blaini Formation. The Jutogh Group comprises Panjerli, Manal, Bhotli, and Taradevi Formations. Specifically, the Panjerli Formation consists of carbonaceous slates, phyllite, and schist, with local interbeds of quartzite and limestone. This formation covers a small part of NH5, where landslides S6, S4, and S5 are located and a major part of Kennedy-Annadale Road.

The Manal Formation overlies the Panjerli Formation and is primarily composed of quartzite, with smaller amounts of schist and carbonaceous phyllite. This formation covers a small part of NH5 and the Kennedy-Annadale Road. Overlying the Manal Formation is the Bhotli Formation, which consists of slate, phyllite, and gametiferous schist with subordinate quartzite. This formation covers a significant part of NH5, specifically where landslides numbered S8 to S16 are located and extends to the initial section of Kennedy-Annadale Road. The subsequent Taradevi Formation comprises chiefly carbonaceous phyllite with interbeds of limestone, schist, quartzite, and gneissic bands; however, it is not encountered on any of the highways. The Jutogh Group, as described above, is thrust over the Jaunsar Group of rocks towards the south and the Blaini Formation towards the north of the area(see Image 2.2). The Jutogh Thrust, thus, separates the Jaunsar Group, Blaini Formation, and Shimla Group of rocks in the area. This thrust is an important tectonic feature of significance in the area (Bhukosh, GSI Portal). It runs in a northwest-southeast direction upstream from Krishna Nagar (Slaughter house), nearby Kaithu (Comley Bank), Ridge, and Jakhoo. Therefore, the rocks in most of the area are found to be moderately to highly fractured and, in some places, sheared.

The national highways connecting the new bus stand to the Panthaghati Bypass and the road between Kennedy Chowk and Annadale traverse along the Bhotli Formation, Panjerli Formation, and Manal Formations. These formations primarily comprise slate, phyllite, schist, and quartzite, which are the main rock types. The highly deformed metamorphic rocks such as slate, phyllite, and schist are classified as low to medium-grade. They are more susceptible to weathering and erosion than quartzite rocks, which are resistant to weathering. Additionally, the area is characterized by dense forests of pine, deodar, oak, and rhododendron.

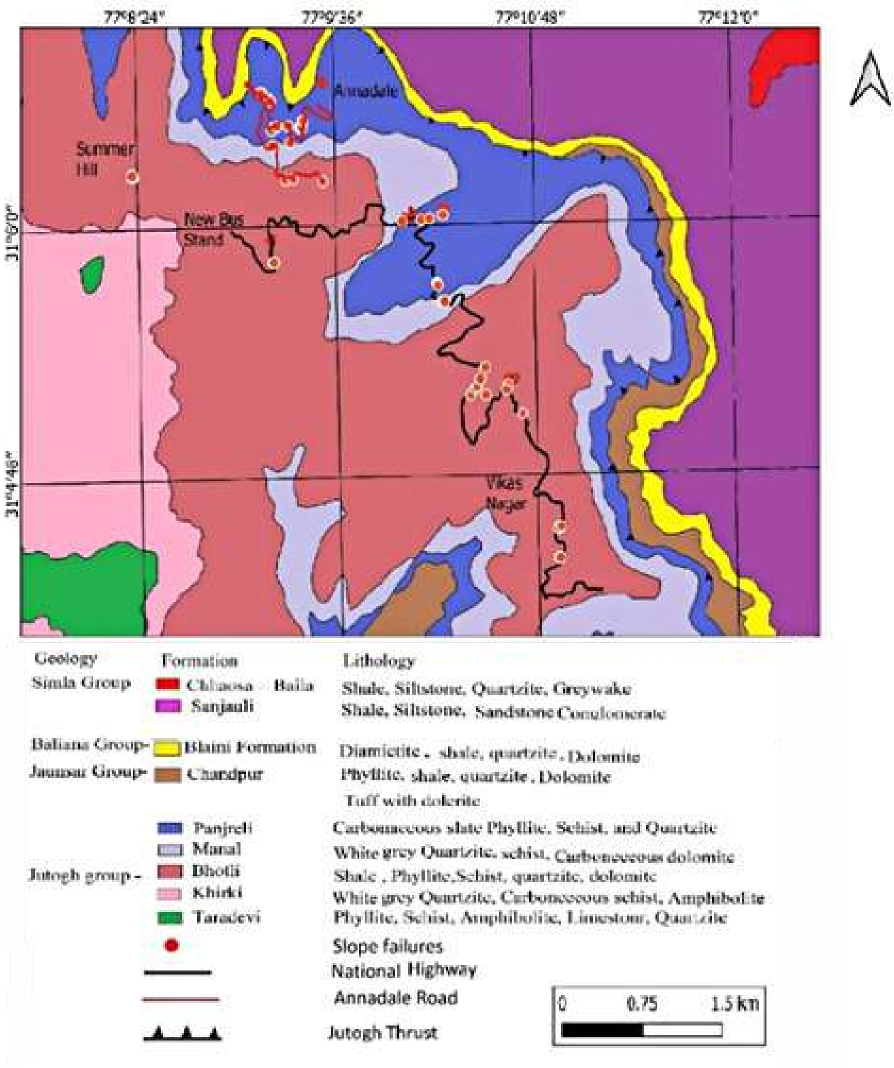


Image 2.2 - Regional geological map (after GSI) of the study area indicating the road alignments

Shimla town and its surrounding areas are situated in the Sub-Himalayan zone, which is vulnerable to earthquakes of different magnitudes. According to the Seismic Zoning Map of India, the area falls within Zone IV. As reported by the Geological Survey of India (GSI), the great Kangra earthquake (1905) of magnitude 8 had its effects reach Shimla, where the intensity ranged between isoseismal VII and VIII. Additionally, the Kinnaur earthquake (1975) also affected the town, with intensity levels measured between IV and V. However, no specific reports of any ground failure/landslides resulting from these earthquakes have been specifically recorded or were made available to the experts for reference during their investigations.

3 Approach and Methodology

3.1 Approach

The following approach was adopted by CDRI mission for the assessment during June 2024:

- Collect and review secondary data such as hydro-meteorological data, previous study reports, and scientific publications related to landslides. Additionally, study of topographical and geological maps, remote-sensing data, and guiding documents related to landslide and NbS measures for roadside slope protection.
- Review remote sensing images to prepare a landslide inventory and conduct field assessment, mapping, and verification of the landslides as part of a reconnaissance survey of the two road sections. Assess the landscape's topographic characteristics, drainage channels, soil erosion, and slope stability.

The initial phase involved collecting and reviewing secondary data, which included hydro-meteorological data, previous study reports, and scientific publications on landslides in Himachal Pradesh. This phase also included the study of topographical and geological maps, remote sensing data, and relevant guiding documents to prepare landslide susceptibility models and sustainable practices of slope protection practices, as outlined by Gray and Sotir (1996), Howell (1999), Devkota et al. (2014), (J&K-FD, 2023). Field observation facilitated the preparation of a landslide inventory, which is crucial for understanding the mechanisms behind the landslide mechanism and designing the protection measures.

3.2 Methodology

The study required a better understanding of hydrometeorology, geology, soil types, landscape topography, and land use. However, limited data were collected, particularly regarding meteorological information and hydrogeology. The assignment was limited to visual observation, consultation, and mapping conducted by experts and no laboratory tests or field investigations related to geotechnical engineering were performed.

3.2.1 Site Reconnaissance

Visual inspections were conducted on-site to identify signs of instability, including cracks, tilted trees, and water seepage. Individual landslides were mapped, and measurements such as slope angles, length, and width were collected. In addition, a preliminary geotechnical assessment was conducted, adopting expert knowledge regarding soil texture and moisture content. A vegetation survey was also conducted to understand the local plant species suitable for bioengineering measures.

3.2.2 Development of Landslide Susceptible Model

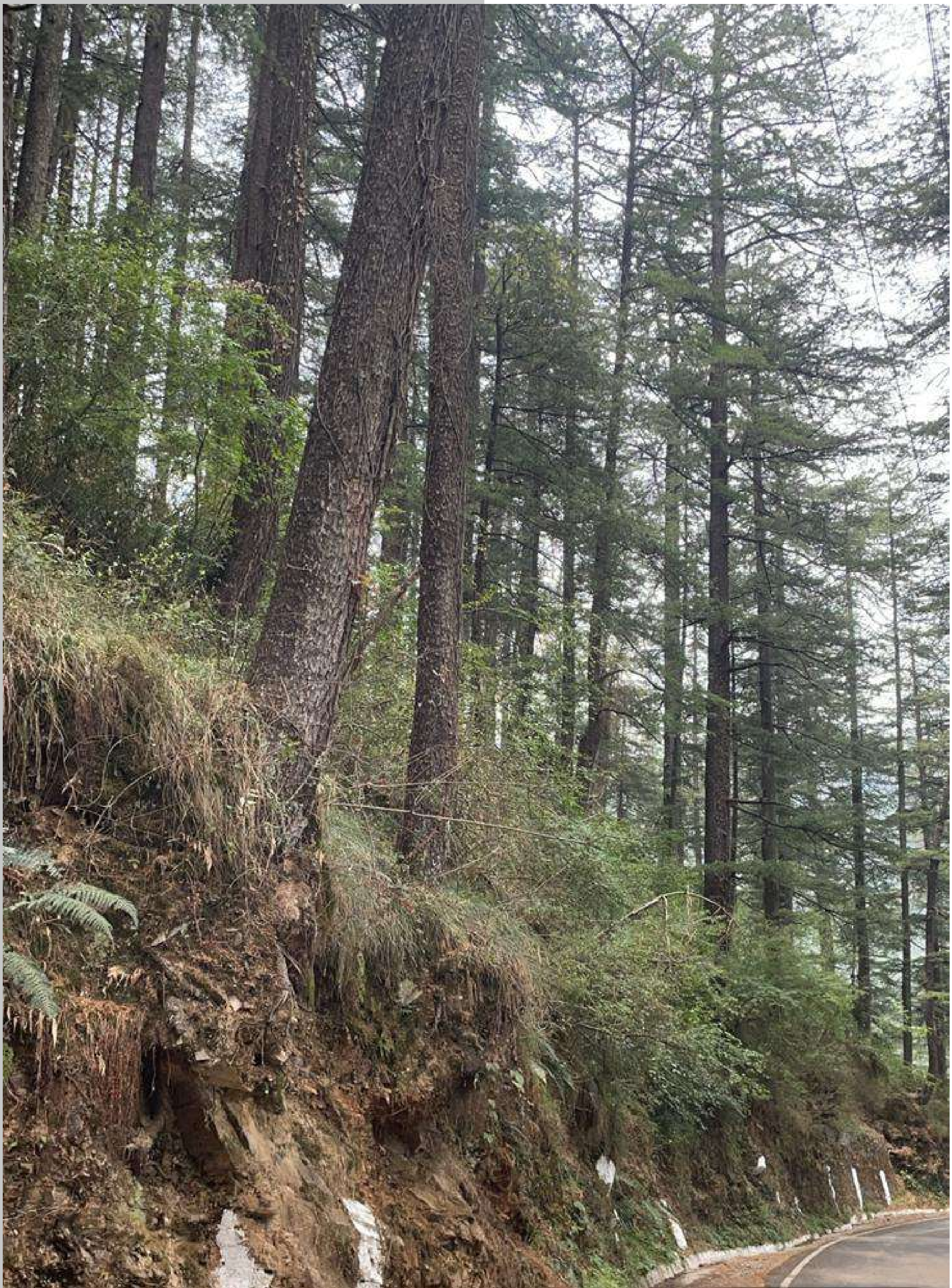
Although hourly or sub-hourly rainfall data were unavailable for this study, efforts were made to analyse historical rainfall data to identify patterns that could trigger landslides. A surface runoff model was established based on the available monthly rainfall data to identify areas prone to erosion and potential water accumulation.

Using field inventory and a 10-m resolution digital terrain model (DTM), a landslide susceptibility model (LSM) was developed for the area covering two road sectors. The model utilized factor maps such as land use, slope, curvature, aspect, terrain wetness index (TWI), distance to drainage, road distance, and soil type. The LSM was created through multi-criteria analysis (MCA) employing the frequency ratio method (FRM).

3.2.3 Slope Protection Measures

Field observations (i.e., the type and mechanism of slope failure) and consultations with key stakeholder government departments and local communities determined that NbSare the most effective alternative. NbS for roadside slope protection focuses on utilizing natural processes and materials to stabilize slopes, reduce erosion, and enhance resilience against landslides. These solutions are sustainable, cost-effective, and environmentally friendly (Devkota et al., 2019; IUCN, 2017).

Site inspection by CDRI and NH Team



4 Site-Specific Observation and Mapping

4.1 NH Crossing to Panthaghati

The road from the NH 5 crossing to Panthaghati mostly traverses through the densely built-up area, including important establishments. It features many intersections that connect to different urban and link roads, catering to a large volume of traffic to and from different parts of the city as well as to surrounding regions. It is intercepted by several large and small natural streams that often face management issues. Although the roadside cut slopes are covered with dense forest cover, they still have slope management issues, particularly in built-up areas, primarily due to unregulated human activities. As reported, the road was constructed in 1991 and was upgraded to a double lane in 1998. However, the road's right of way is often not clearly defined, and the drainage systems are poorly maintained. The topographic slopes along the road alignment from NH 5 Crossing to Panthaghati are pretty steep, ranging from about 300 to over 500 in some places on the top of the hill. The following section briefly discusses the failure mechanisms and underlying causal and triggering factors for each site, focusing on the section starting from the Crossing towards Panthaghati. During field observations, freehand sketches of each landslide were developed and a field checklist was prepared (see Annex 1). In total, 15 landslides of different types and sizes were mapped in an 11 km-long road section. Each landslide was given a specific CODE, ranging from S-1 to S-15. A GIS map was also prepared, onto which the landslide polygons were overlaid (refer to Image4-1 and Table 4.1).

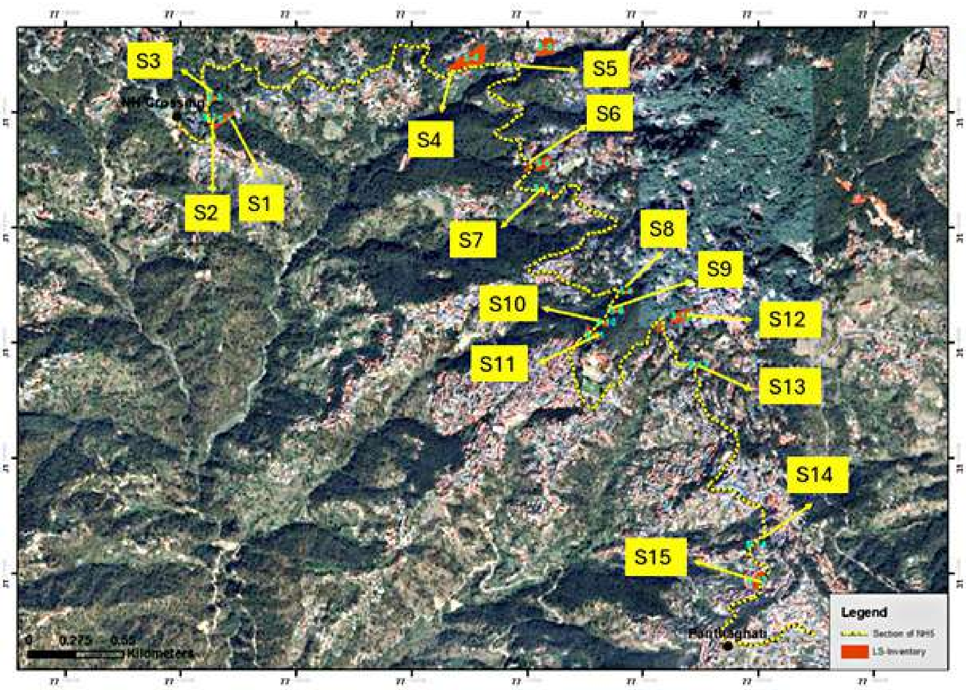


Image 4.1- Landslide inventory along the Panthaghati-Crossing Road alignment

S. No	Site No	Chainage on NH-5	Type of failure
1	S1	(CH 1+840-1+860)	Debris Flow
2	S2	(CH 1+800- 1+820)	Debris Flow
3	S8	(CH 7+620)	Debris Flow
4	S9	(CH 7+710)	Debris Flow
5	S12	(CH 9+220)	Debris Flow
6	S3	(CH 2+040 to 2+050)	Sinking
7	S7	(CH 5+625)	Debris Slide
8	S10	(CH 7+920)	Rock-cum-Debris Slide
9	S11	(CH 7+970 to 8+000)	Rock-cum-Debris Slide
10	S13	CH 10+970)	Debris Slide Translational
11	S14	CH 10+970)	Rock-cum-Debris Slide
12	S4	CH 4+120)	Major _ Compound Slide (rotational)
13	S5	Slaughterhouse	Major _ Compound Slide
14	S6	(CH 5+370)	Major _ Compound Slide
15	S12	(CH 9+220)	Major _ Compound Slide

Table 4.1 List of sites and types of failures

4.1.1 Mapping and Investigation of Landslides

Site: S1 (CH 1+840-1+860)

- The rainstorm of August 2023 caused a failure of the filled portion of the road shoulder, leading to a debris flow that moved downhill and left the roadside barrier hanging. The failure was shallow, resulting in debris being transported about 150 m downhill, where it impacted two to three houses. The depth of the slide was estimated to be about 1.5 m, with a length of about 150 m with a total area of 4,700 m2. Additionally, a damaged pipe drainage was observed at about 1.5 m below the road on the failed slope. A nearby seasonal stream runs through,indicating a similar failure along the channel in the past (refer to Annex 1-1).
- Location coordinates: Latitude 31° 5'50.06"N and Longitude 77° 9'14.04"E
- Stratigraphic Horizon: Jutogh Group- Bhotli Formation
- Lithology: Thick over burden, predominantly phyllite/shale
- Type of landslide: Manmade debris flow
- Slope angle and direction: 45-50° and N 60°
- Affected area along the slope: ~150 m long and ~30m wide at the start

Image 4.2- Rain trigger debris flow partly caused by man made reasons: (a) location, (b) debris flow path and location of the broken pipe, and (C) failure immediately to the road impacted NH5, forest, and population downhill.

Failure Mechanism/Phenomena and Contributing Factors

1) This debris flow appears to have been caused by the failure of the highway shoulder and embankment during the heavy rains of July 2023. This failure subsequently exposed and damaged the underground water supply pipe, which then unleashed a large quantity of water onto the slope, exacerbating the impact of the rainfall. This resulted in intensive erosion of the slope, leading to the generation of debris flow. Additionally, since this area is densely forested, the sudden and intense influx of water toppled/uprooted many trees.
2) The debris was transported about 150 m downhill, affecting two to three houses. The estimated depth of the slide was about 1 to 1.5 m, with a length of around 150 m, covering a total area of 4,700 m2.
3) As indicated in Image 4-2, the shoulder is still loaded with construction-demolition waste on which hawkers sit daily to make handmade traditional and domestic items. This situation may further erode the shoulder, thereby impacting the road width.
4) The probable causes of the debris flow, therefore, can be attributed to rainwater, shoulder damage, and damage to the water supply (or drainage) pipe that released a large volume of water.

Suggestive Measures

The man made debris flow created a long gully/streamlet, which may deepen further during rainfall, potentially leading to more debris flow. It is, therefore, suggested that the pavement and shoulder be rebuilt while ensuring a secure connection to the pipe. Implementing bio engineering measures, preferably stepped or benched (e.g., stepped chute or debris flow barrier)(see Image4-3), will help prevent the rain from deepening the gully or streamlet. Furthermore, it is essential to avoid piling construction debris on the shoulder and to prohibit vendors from setting up their activities by the road side. For specific protection measures, please refer to Annex 1-1 for details.

Immediate

1) Construction of a retaining wall of about 30 m long and 2 m high to support the road.
2) Construction of a vegetative stone paved surface channel of about 100 m.

Medium Term

1) Brush layering of local plants, wood cuttings, and promoting local grass species for ground cover.

Long Term

1) Roadside drainage management.

Image 4.3- Typical photo of stepped chute

Site: S2 (Chainage 1+800 to Ch 1+820)

Located adjacent to site S1 (Image 4-4), this area can be characterized as a stream-guided debris flow. Rain water accumulates along the roadside water, and water from the upstream channel passes through the culvert. However, the area downstream of the culvert, as well as the stream channel, lacks protection. This results in frequent runoff that widens the channel and creates a gully. The slope on the right side failed due to the undercutting process of the stream (refer to Annex 1-2).

- Lat/Long: 31° 5'51.77"N and 77° 9'14.01"E
- Stratigraphic horizon: Jutogh Group-Bhotli Formation
- Lithology: Thick overburden (predominantly phyllite/shale)
- Type of landslide: Debris flow
- Slope angle and direction: 40-50° and N 75°
- Affected area along the slope: ~50 m long and ~20 m wide at start

Image 4.4- (A) Location Site-S2, (B) culvert location, and (C) general view of slope failure

Failure Mechanism/Phenomena and Contributing Factors

1) This is a culvert-guided debris flow. The mouth of the culvert, which discharges a large volume of water during the rainy season, opens onto a downhill slope(refer to Image 4-4A). As discussed above, the stream from this culvert converges with the other stream at Site S1.
2) The downhill slope is unprotected, leading to the formation of a gully or streamlet due to the repeated flow of water along the entire length of the slope up to the toe, which causes repeated erosion. Additionally, it was observed that the slopes from both sides of the culvert were littered with various types of waste, including plastic. This dumping is damaging the slope and accelerating the erosion process.
3) During the rainy season, all the waste dumped on both sides of the slope flows down and obstructs the water flow from the culvert, which further damages/erodes the slope. As a result, what started as a minor issue has gradually worsened and now requires immediate attention to ensure the safety of the population living downhill.
4) Therefore, the debris flow problem is caused by uncontrolled culvert water, heavy rainfall, and waste disposed of on the slope.

Suggestive Measures

The slope failure was caused by stream undercutting during periods of excess rainfall. To address this issue, it is proposed that a gabion check dam be constructed immediately downstream of the culvert. Additionally, a vegetative stone-paved surface channel needs to be built up to the toe of the slope, followed by a local grass planting on the exposed surface. The vegetative channel will extend to the nearest natural drain (nala). It is crucial to manage waste disposal on the slope effectively. Specific protection measures can be found in Annex 1-2.

Immediate

1) A vegetative gabion check dam (~4 m long and ~1.5 m high, excluding the foundation) should be placed immediately downstream of the culvert. The spillway of the check dams must not exceed the outlet height of the culvert.

Medium Term

1) The vegetative stone-paved surface channel (~1.5-2 m wide) should extend along the foothill to the natural drainage.
2) A local grass plantation on the exposed surface should be established, covered by a jute net (~500m2).

Long Term

1) Upstream surface water management.

Site: S3 (Chainage 2+040 to 2+050)

The downhill section features a road built atop a 5 to 6m high gabion wall. The highway shoulder, part of the road (i.e. NH 5), sank due to the settling of the gabion wall (Image 4-5). The gabion wall may have settled probably because the back fill materials used had poor bearing capacity or the wall's foundation was not on stable soil. Additionally, a sewer and water pipeline passes through the slope, and the seepage of water from this pipeline might have contributed to the subsidence of the soil mass beneath NH 5 (refer to Annex 1-3). The affected area is estimated to cover 1050 m2. The length of the vulnerable area at the top measured 40 m, with an estimated height of 50 m. The soil on the slope consists of colluvium, which contains a significant amount of fine materials.

- Lat/Long: 31° 5'55.12"N and 77° 9'13.38"E
- Stratigraphic horizon: Jutogh Group- Bhotli Formation
- Lithology: Thick overburden-predominantly phyllite/shale
- Type of landslide: Sinking
- Slope angle and direction: 33-50° and N 95°
- Slope height: 50m with length of about 40m

Image 4.5 - (A) Location site -S3, (B) Repaired highway shoulder, and© and D) Landscape downhill

Failure Mechanism and Contributing Factors

1) The highway shoulder and embankment supported by gabion structures have been observed to be settling.
2) While the problem has been temporarily addressed by refilling the backfill material and relaying the pavement, the gabion downhill remains deformed. It may further subside, indicating a slope-moving type failure.
3 The benched topography downhill indicated repeated movement in the area. Additionally, there were cracks on and around the subsided gabion wall, and dampness on the slope combined with a lack of tree support in the close vicinity may further escalate to the sliding. This could ultimately result in the subsidence of the highway.
4) The gabion structure has settled, probably because of the weak foundation and poor bearing capacity of the soil. Additionally, leakage from the water pipeline running through the downhill slope may have weakened the soil, contributing to the settlement/subsidence.

Suggestive Measures

As the refilling has been completed and the pavement has been re-laid (refer to Image 4-5B), it is suggested the situation be monitored in the next monsoon season and accordingly an appropriate strategy be devises. Additionally, the pipeline should also be checked for any leakages. Proper drainage along the roadside and slopes is essential to prevent rainwater from draining onto the slope from the road or uphill side.

Immediate

1) Currently, no immediate mitigation measures are suggested, aside from monitoring the slope during the monsoon season.

Medium Term

1) Drainage management.
2) Subsurface investigation (geotechnical properties and stratification) and design of the scheme of remedial measures.

Long Term

1) Installation of retaining structures.

Site: S4 (Lalpani land slide)- (Chainage 4+120)

A large landslide reportedly occurred in July 2023 in the habitation area. However, evidence on the slope suggested that the sliding activity was present before July-August 2023 (see Image 4-6). The landslide was a combination of both shallow and deep-seated slides, featuring multiple scarps and secondary landslides throughout the affected area, which included NH5, habitation alongside NH5, and properties situated atop the sliding scarp and its surroundings. Several seasonal streams are located on the slope; however, dense vegetation made it difficult to trace their paths. The unstable area is estimated to be 12,600 m2, and the length of the unstable landscape measured along the roadside was 180 m where a concrete toe protection wall, varying in height from 1 to 1.5 m was built recently to help stabilize the area.

The extent of the landslide or its crown was not visible from the roadside (NH5). However, on traversing to the top of the slope, it was observed that the active slide boundary was almost touching the houses located at its edge (see Image 4-8C). The land around some of the nearest houses was found to be cracked and subsided. Several houses close to the edge had also developed cracks. According to eyewitness accounts, residents whose houses are situated at the edge of the head scarp take shelter every night in the nearby church due to concerns of a potential landslide. Their houses already show signs of cracking. Additionally, an unauthorized foundation was being dug at the top crown area near the closest house for the construction of a retaining wall (see Image 4-8 E). Locals indicated that this type of unauthorized construction was a normal practice that must be prevented proactively.

The left side of the slope is predominantly composed of jointed/fractured rocks covered with dense vegetation. In contrast, the slope towards the right, which experienced failure, consists of a thick overburden. On the opposite side of the highway, there are hotels, car showrooms, etc. Given that developed areas surround the landslide, it is, therefore, important to stabilize the slope for long-term safety.

- Lat/Long: 31° 6'3.98"N and 77°10'2.42"E
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Thick overburden (predominantly carbonaceous shale)
- Type of landslide: Compound debris flow and debris slide (rotational)
- Slope angle and direction: 45-55° and N 343°
- Affected area along the slope: 80+m, and length along the highway is 180 m

Failure Mechanism and Contributing Factors

1) Currently, no proper drainage system is in place to manage the domestic/rain water runoff from the top of the hill. As a result, water flows directly onto the affected slope. A small temporary diversion drain was observed to be dug to redirect some of this domestic and rainwater into the slope. Perhaps this lack of a proper drainage solution may be one of the major causes of the slope failure, as illustrated in Image 4-8 A-E.

2) The affected slope has been observed to show signs of sagging, indicating deformation in stages. The presence of secondary failure and multiple scarps within the affected slope further suggest the continued deformation following the first event of failure. Therefore, it can be inferred that the slide is active and should be taken seriously.

3) Geologically, this area also comes under the Panjreli Formation of the Jutogh Group, comprising carbonaceous shale, phyllite, slates, quartzite, and schist. However, the dominant materials at this site are moderate, highly weathered, fractured phyllite and schist, with intermittent carbonaceous shale.

4) The entire slope is used as a dumping ground for domestic waste, including plastic, contributing to its failure.

Mismanagement of the slope, combined with an inadequate drainage system on and around it, particularly at the top where domestic and rainwater should be diverted, has led to several issues. The thick overburden, along with dense vegetation and unregulated drainage flowing onto the slope, further exacerbates the problem. There are also insufficient control measures in place, and the excess surcharge from nearby buildings, along with heavy rainfall, contributes to the situation.

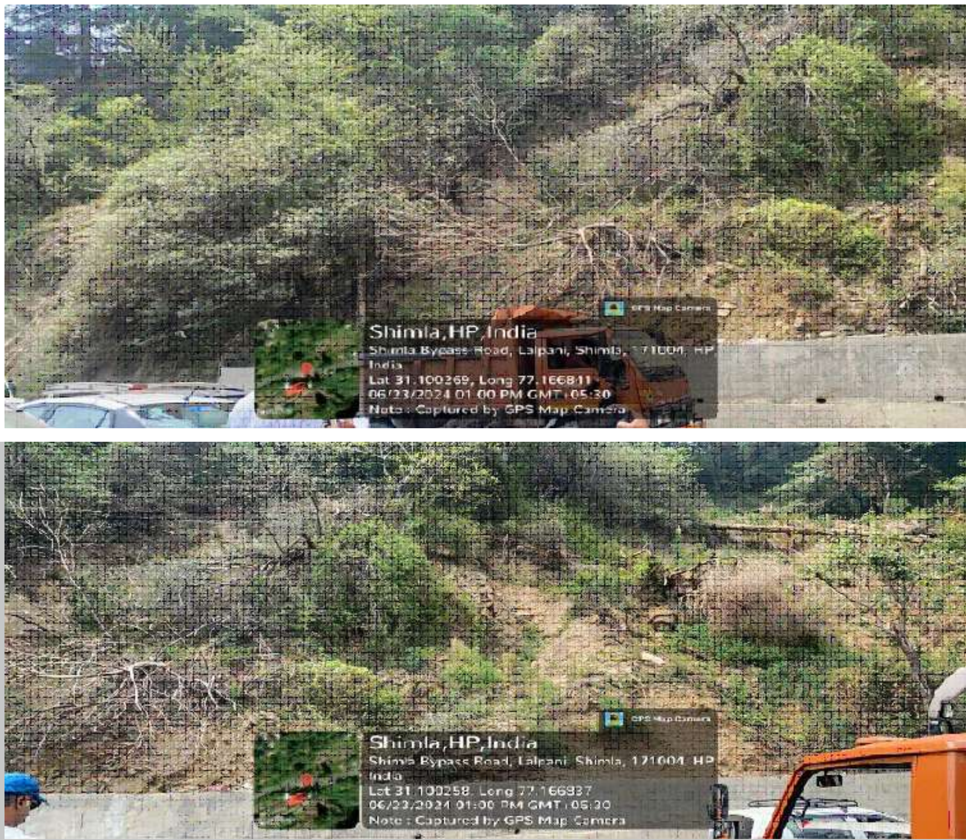


Image 4.7 - Major landslide, the part of which is visible on the highway

Image4.8- Major activities observed in the landslide area. (A-B) Mismanaged slope with domestic dumping waste, (C-D) Cracked and subsided land closer to the landslide scarp, and sandbags can be seen stacked to prevent subsidence/sliding, (E) Unauthorized foundation being dug for construction of retaining wall on the top of the slope, and (F) Temporary drain made opens directly on the slope.

Suggestive Measures

Immediate

1) Remove loose, unwanted material from the slope.
2) Seal any tension cracks.
3) Construct a vegetative stone-paved catch drain (horizontal and vertical) to divert all water from the top to the nearest main drain.
4) Plant local species and use jute netting to cover the exposed surface.
5) Stop dumping waste on the slope.

Medium Term

1) Construct a 4 m high CC cladding with fencing (see Image 4-9) at the top of the wall (IRC: SP: 106- 2015) (refer to Annex 1-2)with proper drainage measures on the right-side roadside slide slope.
2) Plant fast-growing local species with long, strong root systems using jute or coir geotextile (IRC: SP: 48-2023; IS 15872; IS 14715) (refer to Annex 1-2).
3) Construct live check dams along all three debris channels.
4) Maintain the previously constructed vegetative stone-paved catch drain.

Long Term

1) It is suggested the following should be conducted: (a) Topographical survey and investigation: Perform a large-scale survey and mapping at a 1:500 scale, with a contour interval of 0.5m or less, to capture all topographic/morphological features; (b) Geotechnical and geophysical investigation: Carry out seismic refraction tomography (SRT) and ERT (electrical resistivity tomography) (at the top of the landslide scarp. Additionally, drill one or two confirmatory boreholes to collect soil/rock samples for laboratory testing of essential engineering parameters.
2) Soil slope can be stabilized through benching techniques, combined with the installation of nails and the planting of local species that have long and strong root systems. For each benched slope, the design of benches and H:V spacing and the depth of the nails should be determined based on thorough investigation and analysis, If benching is deemed unfeasible, the entire soil slope, extending up to and slightly beyond the crown of the slide, should be reinforced with nails.
3) A 4-m high CC cladding with fencing at the top of the wall (IRC: SP: 106- 2015) and proper drainage measures on the right-side roadside slide slope should be done.
4) A vegetative stone-paved catch drain (both horizontal and vertical) is proposed for the right-side rock slope. In addition to the catch water drain at the top, and based on the investigation report, a self-driven anchors + chain link mesh (drapery mesh) +vegetation (IRC: SP: 48-2023) is recommended to prevent falling rocks from coming onto the road.

5) As some of the houses are located close to the edge of the slide, it is suggested that the residents be relocated and the houses dismantled. However, the decision should be based on the findings of the suggested investigations.

Note: As the field assessment was conducted from 23 June to 27 June 2024 before the monsoon, hence it is presumed that the morphology of the landslide areas may have changed post-monsoon/this season. Therefore, it is suggested that a detailed investigation of the specific site be conducted to prepare detailed engineering designs.

Image 4.9 - Typical photograph of slope stabilization with CC cladding and fencing

Site: S5 (Slaughter house Landslide)

During the rains of July-August 2023, a rock-cum-debris slide occurred when a large chunk of hill slope collapsed (see Image 4-10). This tragedy reportedly resulted in the deaths of at least five people and completely damaged the slaughterhouse along with other houses situated at the foot of the hill. In addition, some of the houses situated uphill were also reported to be completely damaged, while a few others nearby suffered partial damage or visible cracks, placing them at risk (refer to Image 4-11 E and F). Geologically, the area is part of the Panjreli Formation of the Jutogh Group, comprising carbonaceous shale, phyllite, slates, quartzite, and schist. However, this site is predominately composed of highly weathered carbonaceous shale (see Image 4-11 A and B). The existing vertical slope, which consists of this weathered carbonaceous shale, is highly sensitive to weathering and behaves poorly when exposed to continuous infiltration and excess surcharge, conditions that appear to have contributed to the previous landslide. It has been noted that some buildings rest on the edge of the scarp, although they have been vacated and are awaiting dismantling. However, several other houses and terraced areas adjacent to the vertical scarp also developed cracks of varying magnitude. These structures should be monitored till permanent solutions are implemented. Almost the entire slope is wet, and the drainage system above the affected area is currently inadequate. The estimated size of the landslide area is about 6,000 m2. The main concern in this location is the safety of the population living above the landslide, which necessitates urgent stabilization of the slope. In addition, this site requires further investigation.

Image 4.10 - Location of landslide that damaged slaughterhouse

- Lat/Long: 31° 6'6.44"N and 77°10'15.69"E
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Thick overburden (predominantly carbonaceous shale)
- Type of landslide: Plain failure
- Slope angle and direction: 35-65° and N 105-114°
- Crest/scarp of the slide: 40+m(H) and affected slope length along the toe-over 60+m

Failure Mechanism and Contributing Factors

The leading causes of the slide, based on field observations and discussions with concerned officials and residents, include poor management of the slope, an inadequate drainage system, unauthorized construction of houses, unregulated domestic water runoff onto the slope, the presence of weathered carbonaceous shale that is inherently weak and sensitive to weathering when wet, toe cutting by the nearby nala, and ineffective support system.

Suggestive Measures

Immediate

The slope needs long-term measures as soon as possible; however, the following preliminary/preparatory measures must be taken immediately:

1) Improve drainage on the top of the slide and the settlement in the upslope. No water from uphill should be allowed onto the slope.
2) Dismantle the abandoned houses.
3) Earmark the building at risk, dismantle the vulnerable houses, and rehabilitate people; restrict people from entering the slide area.
4) Seal the cracks near the buildings and install a drainage system to avoid expansion of slope failure towards the upslope.

Medium Term

1) Large-scale topographic survey and mapping 1:500 scale with a contour interval of 0.5m or less capturing all topographic/morphological features.
2) Geotechnical and geophysical investigation: SRT and ERT with at least two confirmatory boreholes with an option of possible in situ tests and collection of soil/rock samples for laboratory testing (required parameters IRC: SP 48-2023).
3) Analyse the slope stability and design protection measures (e.g. concrete cribs, anchor bolts, and NbS).

Image 4.11 - (A-B) Landslide view, (C) Vulnerable houses and settlements, (D) Lower portion of the landslide exposed to infiltration, and (E-F) Buildings closer to the landslide scarp

Long Term

One of the two following alternate schemes should be implemented post-suggested investigations, analysis, and design.

1. Option 1: Construct concrete cribs with a beam on top of a well-designed rigid foundation, ensuring both vertical and horizontal beams are correctly designed. Implement an effective surface drainage system, including both horizontal and vertical drainage. Install anchor bolts at each crossing of the cribs beams and plan for plantation in the open area between the cribs(IRC: SP 48-2023)(refer to Annex 1-5).
2. Option 2: The entire vertical slope should be equipped with SD nails (as per FHWA-NHI-14-007 GEC 007; CIRIA C637). The vertical and horizontal spacing and the nails' depth must be designed based on the soil and rock parameters and the geometry of the slope selected for stability analysis and design. Additionally, a concrete breast wall should be constructed in a stepped manner, featuring designed reinforcement extending to a specified height throughout the toe of the vertical slope. Proper drainage measures must also be implemented, including horizontal drains placed on the slope and behind the wall. The foundation of the wall should be laid on a rock or a competent mass.
3. Houses near the existing scarp that show signs of cracks, either on the structures themselves or the surrounding land, should be demolished. Additionally, a comprehensive surface water drainage system, including a catch water drain along the entire slope, needs to be constructed.

Note: As the field assessment was conducted from 23 June to 27 June 2024 before the monsoon, it is presumed that the morphology of the landslide areas may have changed post-monsoon/this season. Therefore, it is suggested that a detailed investigation of the specific site be conducted to prepare detailed engineering designs.

Site: S6 (Chainage 5+370: Opposite to Rajvir Motors)

The slide complex reportedly started as a debris slide, damaging the Rajeev Motors building at the foot of the affected slope on the opposite side of NH5. After the initial event, the slope experienced multiple failures and remains vulnerable to further incidents. Geologically, the area falls under the Panjreli Formation of the Jutogh Group, comprising carbonaceous shale, phyllite, slates, quartzite, and schist. The rocks in the slide area are predominately moderate to highly fractured and weathered phyllites. The slope features a thick, overburdened soil composed of silty sandy and clayey loam and moderately to highly weathered rocks.

The area is characterized by an old landslide deposit, where the deformation of the soil mass indicates the presence of groundwater. Further, the construction of a retaining wall and local access road uphill has obstructed both sub-surface and surface drainage. Cracks and deformation in the soil mass can also be observed in the upper part of the slope. Furthermore, the concrete retaining wall built to support the local road in the middle of the slope has collapsed, and some trees have tilted due to ground movement.

- Lat/Long: 31° 6'6.44"N and 77°10'15.69"E
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Thick overburden, silty sandy, clayey loam with less to highly weathered and fractured phyllite/slate/schist/quartzite
- Type of landslide: Compound debris flow and debris slide (rotational)
- Slope angle and direction: 45-65° and N 105-114°
- Slope height: 40+m and length over 40 m

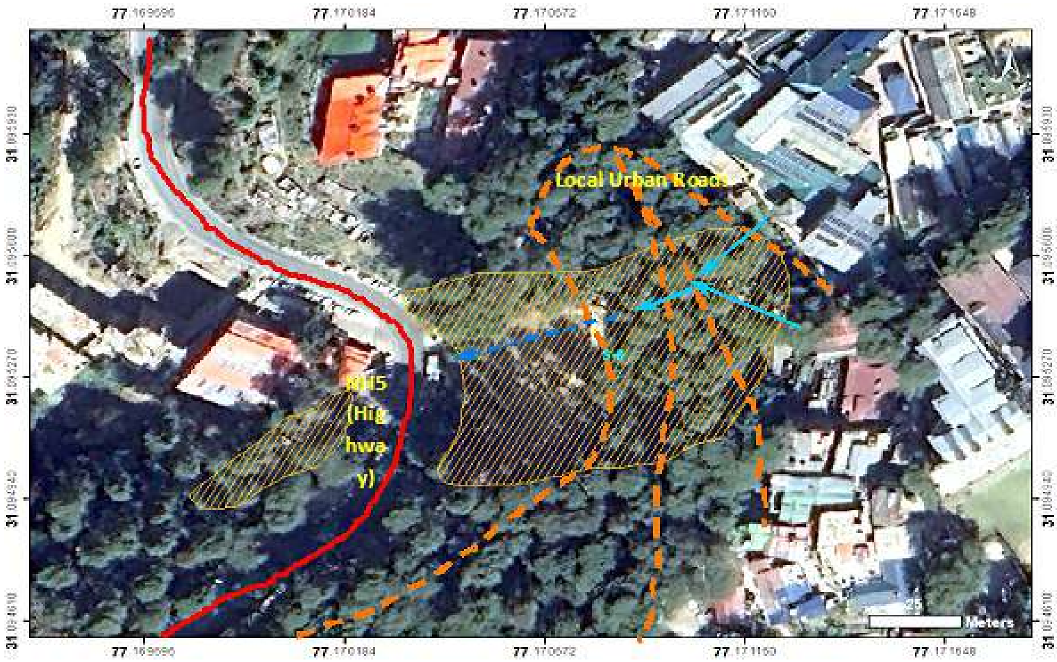


Image 4.12- Aerial view of the extent of the affected area

Failure Mechanism and Contributing Factors

1. For ease of understanding, the slope (Images 4-14 and 4-15) can be divided into four parts (Images 4-16, 4-17, and 4-18).

   (a) The central part between NH5 and the first middle local road (Images 4-16) leads to habitation.

   (b) The second part is between the first local road and the second footpath (Image 4-17).

   (c) The slope between the second unpaved footpath and the upper paved road, including habitation (Image 4-18).

   (d) Lower left (while facing towards the slide) part.

2. The central area between NH5 and the first, middle local road features a stream path and thick overburden debris significantly damaged due to the forceful and excess flow of rainwater over the slope. The drainage system designed to handle water from uphill could not withstand the overflow pressure and became completely damaged, contributing additional debris to the flowing water. The roadside culvert that was constructed was reportedly blocked and damaged. As a result, the debris flow caused damage to both the highway and the buildings located downhill. Additionally, the middle road, which includes a concrete retaining wall 15m long and the culvert, was completely damaged. The extent of the impact of the debris flow can be seen in Image 4-14.

3. The extensive damage was caused by a large quantity of debris generated due to heavy runoff over both the upper paved and unpaved roads, and the slope uphill due to the heavy rain.

4. The unpaved road that connects the first local road (now damaged) to the uppermost paved road may have also contributed to the situation, as it is intersected by two nalas that manage water discharge from the uphill area, including domestic wastewater (see Images 4-17 and 4-18).

Image 4.13 - Panoramic view of the landslide

5. Some subsidence and cracks were observed on the upper paved road at the base of the habited area and the slope below it. Although the drainage from the habitation above is lined further down, it was found to be unlined in this section, which appears to be a significant cause of the damage (see Image 4-16).
6. A large slope failure has also occurred on the left side of the central part, facing the slide. Fortunately, this failure was contained by a ridge of dense forest cover alongside the middle road. However, if not properly addressed, this poses a potential risk for future landslides. As shown in Image 4-15, this section of the slope consists of thick overburden, which is important for the stability of both the road and the nearby habitation on its left as well as NH5.
7. The landslide was primarily triggered by rainwater and exacerbated by the mismanagement of the slope, including inadequate drainage system for both roads and residences. In addition, the roadside slope protection was insufficient in view of the landscape soil mass and habitation at the top of the hill.

Image 4.14 - The central part between NH5 and the first, middle local road prominently damaged due to the excessive flow of rainwater over the slope.

Image 4-15. A top view with three roads: barren slope, unlined drainage, and collapsed slope


Image 4.16 - Middle road leading to habitation severely damaged, roadside slope, reattaining wall, and slope failure

Image 4.17 - Dumping of slope drainage and unlined temporary drainage opening directly on the slope

Image 4.18 - Unlined drainage from higher slope opening persistently onto it

Suggestive Measures

Short Term

1) Cleaning and removing loose debris and tree trunks from the slope and preparing a uniform, compact slope.
2) Cleaning, strengthening, and managing the open sewerage channels available on the upper part of the slope. These channels must be safely connected to the main drainage channel at NH5.
3) Roadside drains on all the roads must relate to the longitudinal channels.
4) Use geotextile to cover the vulnerable slope and areas where cracks are formed.

Medium Term

1) Large-scale survey and mapping at 1:500 scale with a contour interval of 0.5m or less, capturing all topographic/morphological features.
2) Geotechnical and geophysical investigation: SRT and ERT with at least two confirmatory boreholes with an option of possible in situ tests and collection of soil/rock samples for laboratory testing (as per IRC: SP:48 - 2023).
3) Implement stability analysis and design hybrid-type (grey-green) mitigation measures from top to bottom (i.e. from the middle slope to the highway).
4) Maintenance of drainage and surface catch drainage built earlier.
5) Implement bioengineering measures (e.g. brush layering and live check dams).
6) Remove tilted trees located on the slope.

Long Term

1) Construction of cross drainage structure in all roads connecting the settlement's upslope.
2) Lined roadside drains on all the roads connected to the chute/culverts.
3) Implement structural measures if stability analysis suggests, such as:

    • Retaining wall below the middle road all along the affected slope with provision of drainage.

    • Concrete toe/retaining wall all along the uphill side slope on this road. All roads must be paved, and the slope in between the roads may be nailed as perthe design post-investigation.

    • The left lower landslide must be stabilized by raising the height of the breast wall by at least 1 m and application of SD nails and bioengineering shall serve the purpose. The nailing intervals and depth are calculated based on the stability analysis.

Note: As the field assessment was conducted from 23 June to 27 June 2024 before the monsoon, it is presumed that the morphology of the landslide areas may have changed post-monsoon/this season. Therefore, it is suggested that a detailed investigation of the specific site be conducted to prepare detailed engineering designs.

Site: S7 (Chainage 5+625)

This debris slide consists of a thick layer of silty, clayey, sandy soil overlying highly weathered and fractured phyllite, schist, and slate rocks underneath. The morphology of the slope indicates deeper movement of the debris. However, the angle of the vegetation downhill indicates a shallow movement, likely occurring after the initial sliding event.

Streams bound the affected area, but their impact on the present slide appears to be negligible. The affected slope length from the roadside seems only up to 25-30m. However, there is a significantly larger area above this slope that extends to a concrete urban road about 75 m from NH5. This area is not visible from the highway because of the dense forest cover. The slope uphill has been observed fractured/cracked throughout the section that connects to NH5 and both streams.

- Lat/Long: 31.093900 N and 77.170653 E
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Silty, sandy, clayey loam with weathered phyllite/slate
- Type of landslide: Debris slide (rotational)
- Slope angle and direction: 35-65° and N 50°
- The crest of the slide: variable 15-40+m and affected length on the highway over 25m

Image 4.19 - Aerial view of the landslide location showing the impact area

Image4.20 - Roadside landslides in thick colluvium deposits are mainly attributed to inadequate drainage and protection measures

Failure Mechanism and Contributing Factors

1) The debris slide comprised thick, overburdened soil on weathered bedrock.
2) An unlined irrigation channel was observed running all through the affected slope, facilitating infiltration, which depicted seepage marks.
3) Domestic mixed waste, including plastic, was found dumped on the slope uphill on the stream, which should be prohibited.
4) The area above the roadside slide has dense forest cover, which increases the surcharge on the weaker slope.
5) Though the upper urban concrete road had a good roadside drain, the rainwater still crosses over the road surface onto the slope, impacting it.
6) Excess surface runoff during the rainstorms triggered the shallow debris slide.

Suggestive Measures

Immediate

1) Construct seepage-free drainage to catch surface runoff that comes from the upslope road and settlement and divert the flow to the nearby natural drainage channel.
2) Remove loose debris deposits on the slope and prepare a uniform/levelled slope.
3) Construct a vegetative stone paved surface channel on the slope.
4) Cover the slope with jute Geotextile (IS 14715)with vegetation turfing to avoid further erosion and formations of rills.

Medium Term

1) Bench the slope up to a possible height with soil nailing
2) Increase the toe wall height by 1 m more.
3) Install brush-layering/bally benching using local woody cuttings.

Site: S8 (Chainage 7+620)

This is another instance of debris flow, which was initiated from the base of an urban local road located at its crest (see Image 4-21). As can be inferred from the field inspection, a large volume of water overflowed the urban road during the July 2023 rains and was discharged onto the slope. The slope material involved in debris flow seemed to be already saturated due to the cumulative rainfall impact over the previous days, prior to the heavy rain and heavy discharge from uphill. This might have added to the already charged slope, resulting in the debris flow.

The slope consists of a mixture of silty clay loam and moderately to highly weathered rocks. The flow of material has been directed by the rock bed slope, which is characterized by highly fractured and weathered slates/phyllites. Although the topsoil is only a thin layer, the surrounding slope is covered by dense forest. There is no culvert at this location, indicating no established seasonal stream.

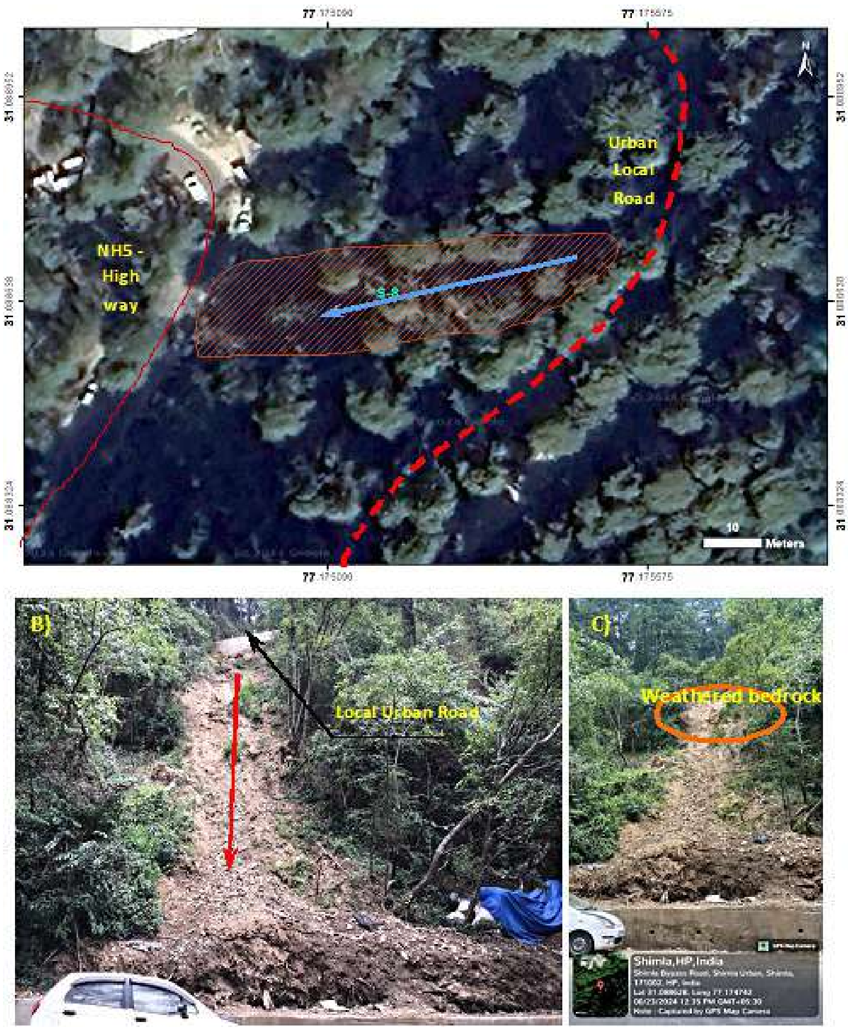


Image 4.21 - (A) Aerial view of the landslide location and (B and C) View of the debris path. Note: There was thick deposit and uprooted tree

The landslide at the toe is 15 m wide, and the slope length is about 60 m. The estimated slope gradient is between 45° and 50°, with highly weathered bedrock exposed in the middle of the debris channel.

- Lat/Long: 31° 5'15.02"N latitude and 77°10'28.96"E longitude
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Silty clayey loam with weathered phyllite/slate
- Type of landslide: Stream-guided debris slow
- Slope angle and direction: 45-55° N126°
- Slope height: 15m and length: 60m

Failure Mechanism and Contributing Factors

1) This landslide was a shallow debris slide, which was turned to debris flow as the water increased.
2) Steep slope, shallow soil overlaid on weathered bedrock and large-size trees added a surcharge load on the slope.
3) A road runs through the crown part of the landslide (see Image 4-21B). Like other areas in the town, there was no proper drainage channel built to safely discharge accumulated runoff.
4) The cumulative rainfall saturated the soil on the steep slope, leading to a debris slide initially, followed by a debris flow.

Suggestive Measures

Immediate

1) Clearing loose debris deposits, managing drainage along the local urban road (catch drain), and diverting water to the nearby natural drainage channel.
2) Constructing a vegetative surface channel ~1.5 m wide in the middle of the debris channel.
3) Installing live check dams using woody cuttings alternatively to brush layering (refer to Annex 4).

Medium Term

1) As this area does not have an established stream-guided debris flow, it is important to prevent a large quantity of water from flowing onto it from the uphill side. To address this, the height of the breast (toe wall) should be increased by at least 0.5m.

Site: S9 (Chainage 7+710)

This is a stream-guided debris flow that occurred on its path during the intense rains in July 2023 (see Image 4-22). The culvert located on the roadside at the foot of the slide indicates the presence of a seasonal stream on the slope. However, such a large debris flow reportedly occurred for the first time. The slope is covered with thick soil of silty clayey loam mixed with highly weathered and disintegrated rock mass. The soil is cohesive, appears to have a good moisture content, and supports dense vegetation, including a thick forest cover.

The highway is built over a drain, the path of which downhill was found to be littered with domestic plastic and other waste products (see Image 4-23B). This accumulation of debris harms both the drainage path and the slope. If this issue is not addressed, it could lead to problems for the highway, as scouring has begun at the toe of the retaining wall. Additionally, the culvert was discovered to be blocked (see Image 4-23A).

Image 4.22 - Stream-guided slope failure/debris flow: (A) Aerial view of the location and (B and C) Debris flow channel

- Lat/Long: 31° 5'12.72"N and 77°10'26.95"E
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Silty clayey loam with highly disintegrated phyllite/slate
- Type of landslide: Stream-guided debris slow
- Slope angle and direction: 40-50°
- Slope height: 15m and Length: ~55 m

Failure Mechanism and Contributing Factors

1) The debris flow began about 50m upslope, likely triggered by several days of cumulative rainfall followed by a heavy downpour. The slope may have become saturated during the steady rain, increasing the pore water pressure (PWP). The subsequent heavy rain then transformed this saturation into a violent debris flow slide.

Image 4.23 - Activities observed along NH5 and downslope. (A) Choked culvert, (B) Dumping of wastes, and (C) Uprooted trees

2) The force of the debris flow could be understood by observing the large, uprooted trees (see Image 4-23C). The primary cause of the debris flow could belong-duration rainfall as well as intense, short-duration rainfall.

3) The initial trigger occurred at the top of an existing stream, which was situated over a thick, overburdened soil and highly weathered, disintegrated rock mass. When fully charged from the cumulative impact of the rain, the stream surged down its path, damaging the stream bed and the side slopes and uprooting large trees along the way. Furthermore, the stream lacked proper guidance through a lined chute, likely because such an incident had not been anticipated before.

Suggestive Measures

Immediate

1. Check the upslope roadside drainage and construct a runoff diversion drainage channel to the nearby natural drainage.
2. Clear the loose debris and tilted trees from the slope, ensuring the slope is uniform and properly compacted.
3. Use waterproof geotextile to cover the slope.
4. Clean the culvert inlet.

Medium Term

1. Construction of stone-paved (stepped chute) throughout the main drainage channel and intermediate check dams.
2. Brush layering using local woody cuttings or perform hydroseeding alongside jute/coir geotextile (IRC SP 48: 2023 Clause No. 4.3.2 F4, Page No 83; IRC SP 106: 2016 Clause No. 8.3.8.1 and Table 8.7, Page No. 84 and 85).
3. Construction of vegetative gabion check dam on the downstream slope of the road (i.e. outlet of the culvert) to reduce erosion.
4. Alternatively, the slope can be protected by installing steel wire mesh and nailing them on the slope, and hydroseeding local grass species.

Site: S10 (Chainage 7+920)

The shallow debris landslide was triggered by the rain in July 2023. It originated from the cut slope created for the footpath/local road at the upper end of the affected slope (see Image 4-24). The affected slope was reportedly covered with thin topsoil, which supported good vegetation, similar to the surrounding areas. However, the landslide exposed the underlying overburden and revealed the phyllite/slate rocks dipping outside the slope towards the highway.

The interface between the overburden and the slate/phyllite rock layers acted as a sliding surface. The vertical cut slope, along with the footpath/local road, may have contributed to the drainage of large amounts of surface runoff onto the slope during the rains of July 2023. As a result, the slope became saturated, charging the interface and reducing friction, which ultimately led to sliding under the force of gravity.

Image 4.24 - (A) Aerial view of rainfall triggered debris slide, (B and C) View of failure slope
Note: There was exposed bedrock

- Lat/Long: 31° 5'10.38"N and 77°10'24.69"E
- Stratigraphic horizon: Jutogh Group-Panjreli Formation
- Lithology: Highly weathered phyllite/slate
- Type of landslide: Rock-cum-debris side
- Slope angle and direction: 45-65° and N 126°
- Slope height: 25m and Length: 35-40 m

Failure Mechanism and Contributing Factors

The footpath/local road constructed in the middle of the slope was left unpaved and lacked an adequate drainage system. Additionally, the cut slope was left unprotected, resulting in significant erosion. During rainfall and periods of saturation, water infiltrated the slope. This led to complete saturation of the slope under the dense forest cover, causing it to slide along the interface between the saturated soil and the underlying rocks.

The slope does not have a very thick overburden and the rock was not involved in sliding, which indicates that it was a shallow planar slide. However, the retrogressive expansion of the landslide boundary may further complicate the situation further if timely counter measures are not taken.

Additionally, the presence of large size trees on the slope, combined with the shallow soil overlaying the bedrock, will also contribute to destabilizing the slope in the event of rainstorms.

Suggestive Measures

Immediate

1. Removal of the loose debris mass (soil mass) resting on the rock surface.
2. Construction of a seepage-free catch drain on the upper part of the landslide crown and safer discharge near the natural drainage channel.
3. Cover the slope using waterproof geotextile.

Medium Term

1. Increase the height of the breast wall by at least 1 m and iron fencing at the top 1.5m
2. If the restoration of the footpath is necessary, it should involve constructing a retaining wall on the rock foundation with proper reinforcement and drainage measures, while cutting the slope (hillside) and protecting with it a side wall.
3. Plantation of local grass species (not trees as the soil is too shallow).

Site: S11 (Chainage 7+970 to 8+000)

The landslide is classified as a debris overburden slide, as indicated in Image 4-25. It is controlled by the phyllite bedrock, which dips towards the valley side. The interface between the thick overburden and the bedrock acted as a sliding surface. As per reports, the landslide was initiated during the July 2023 rains. Once the overlying debris mass became saturated, the slide took place along the interface. The landslide scarp extends 25m in height along the slope, marking its boundary with an upper urban road. It appears that the slide was likely triggered by excess runoff overflowing the slope. The landslide covered a length of about 35m along the highway. During a field inspection, a seasonal stream was observed in the middle of the slide, which likely caused the initial failure. Additionally, some of the trees were found uprooted.

During the inspection, it was found that the slope was stable. However, the slide mass and the loose, overburdened soil that is exposed and unprotected above the rocks and breast wall, is at risk of further sliding if saturated during rainfall. Although the slide mass has very little vegetation, it is surrounded by a dense forest that covers a thin layer of topsoil.

- Lat/Long: 31° 5'10.38"N and 77°10'24.69"E
- Stratigraphic horizon: Jutogh Group-Bhotli Formation

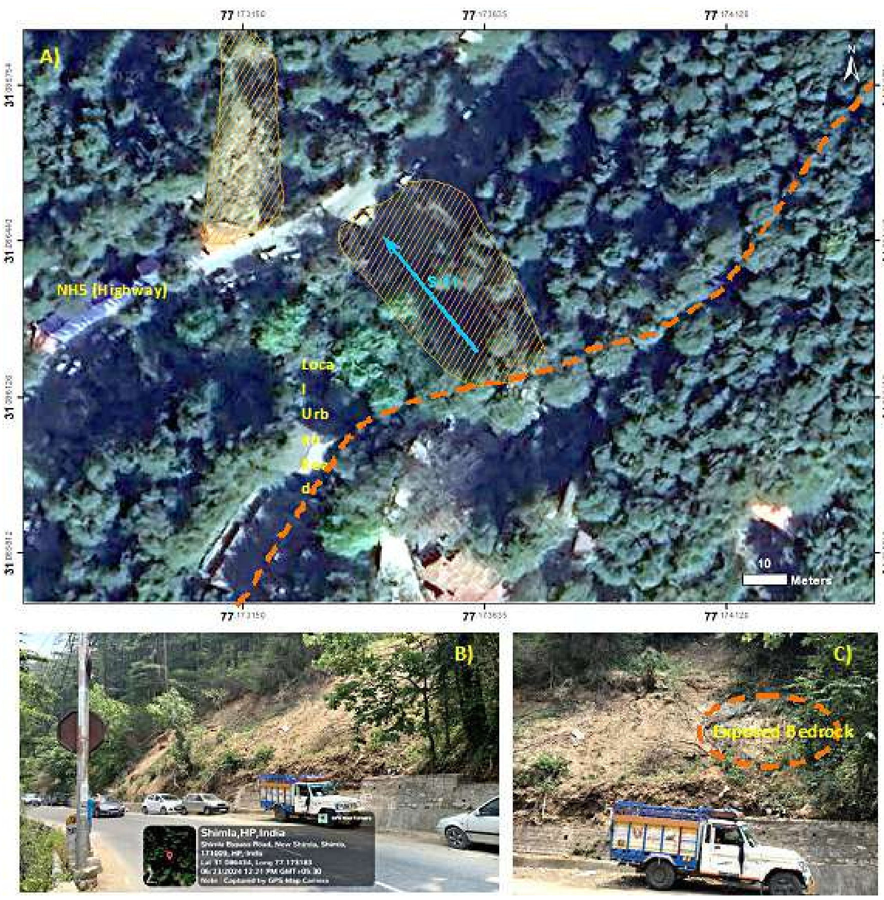


Image 4.25 - (A) Aerial view of the landslide location, (B and C) View of landslide.
Note: There is exposed bedrock and toe wall

- Lithology: Highly weathered phyllite/slate
- Type of landslide: Rock-cum-debris side
- Slope angle and direction: 55-60° and N 141°
- Landslide scarp: 25m(H) andslope length: 40m
- Affected slope length along the highway is 35-40 m

Failure Mechanism and Contributing Factors

1) The highway stands over a drain, and the downhill path was found to be clogged with domestic plastic and other waste materials. This accumulation not only obstructs the drainage path but also affects the slope negatively. If left unaddressed, this issue could soon pose problems for both the downhill and the uphill areas, as well as the highway, as scouring was also observed at the toe of the retaining wall.
2) Just above the vertical scarp mentioned earlier, there is an urban local road alongside residential buildings. A large volume of water from domestic usage is directed through roadside drains. However, during heavy rains, these drains overflow, causing water to flow down the lower slope.
3) As the slope is left uncovered, the surface continues to erode. The slope was also found in damp conditions indicating some water on the surface.
4) Heavy rain, overflow of water from the upper urban road, thin soil cover holding large trees, thick overburden interface with rocks dipping outside the slope, inadequate drainage.

Suggestive Measures

Immediate

1. Removal of unwanted material (debris deposits) including loose mass from the slope.
2. Construction of a vegetative stone-paved surface channel along the main debris channel.
3. Covering the slope with waterproof geotextile.

Medium Term

1. Increase the height of the toe wall by 1 m more.
2. Install a wire or geosynthetic mesh net on top of a jute or coir net above the exposed bedrock area, and secure the net using soil nails(a special design is required for this).
3. Hydro-seedling over the net surface.
4. Brush layering on the right flank of the slide using local woodcuttings.

Site: S12 (Vikash Nagar Chota-Shimla: Chainage 9+220)

Geologically, this area is part of the Bhatoli Formation of the Jutogh Group comprising shale, phyllite, schist, quartzite, and dolomite. However, the site predominately has moderate to highly weathered and fractured phyllite schist and intermittent shale. This is a stream-guided debris flow; however, extensive slope deformation was also observed on the side slopes on the right-side slopes of the nala (see Image 4-26). The deformation extends up to the boundary of a Pine resort situated about 250m above NH5, on the side of the nala. Traverses taken along the uphill side slope, following a footpath to Chhota Shimla, indicate differential deformation characterized by subsidence, cracks, and sliding (see Image 4-27). As the team ascended, the nala side slope exhibited extensive cracking and areas of subsidence. Further up the slope, the sliding was observed, extending up to the boundary of the pine resort.

At certain places, partially damaged and subsided gabion walls were observed (see Image 4-28). The presence of such structures on the slope indicates a history of movement in the area. While the damage to the slope and the debris flow on the nala can be attributed to rainfall, it is important to note that the side slopes are inherently weak and have also experienced sliding in the past. Additionally, some of the debris that had collected and flowed over the nala may have originated from the side slopes.

The stream and its surrounding slopes were found littered with domestic and other debris, including plastic, which hinders the stream flow. At places, the streams are so narrow that they can become blocked by the waste along their course (see Image 4-28). The slope has experienced extensive erosion, and many trees were found uprooted. There is no culvert immediately downstream of the streams across the road; instead, the water flow is diverted along the inner side of the road through drainage channels. The drainage near the stream is larger but it decreases significantly in size as it continues downstream. A Hume pipe was installed across the road to manage the stream discharge. However, the outlet of the Humepipe was not properly treated, leading to excessive erosion on the downstream side of the road. Additionally, it was reported that a landslide had occurred on a private property, impacting the area up to the road.

- Lat/Long: 31° 5'14.23"N and 77°10'39.69"E
- Stratigraphic horizon: Jutogh Group-Bhotli Formation
- Lithology: Thick overburden (predominantly carbonaceous shale)
- Type of landslide: Stream-guided debris flow
- Slope angle and direction: Variable 15-65°
- Slope length along the slope: Variable up to about 250+m
- Length along the highway: 40m

Image 4.26 - Aerial view of the landslide-prone area

Failure Mechanism and Contributing Factors

1) The stream had not been properly cleaned, which led to an excess volume of water that caused it to overflow. This overflow resulted in the erosion of the toe of the side slopes, particularly on the right bank of the stream. This process perhaps was just an initial push followed by sliding, subsidence, and cracking of the side slope, as was observed during the field inspection.
2) The side slope, as observed, has a history of deformation/sliding, and the heavy rain in July 2023 worsened the situation, causing severe erosion and uprooting some large trees.
3) The loose and sensitive soil on the right slope (up to the Pine Resort area), along with a large Deodar tree and undercutting of the stream (known as toe cutting) were some of the causal factors to the landslide. Intense rain storms acted as the triggering factor for this event.

Image 4.27 - Streamside slope failure, subsidence, intensive erosion, and slope failure

Suggestive Measures

Short Term

1) Remove the tilted trees.
2) Clear the stream course to accommodate the monsoonal flow.
3) Install live check dams along the stream channel; however, if water flow velocity is high, the CC check dams instead of live check dams should be installed with intermitted debris barriers.
4) Seal the cracks in the landslide zone (in the Pine Resort area) and use waterproof geotextile.

Medium Term

1) As the slope had already cracked, subsided, and slid, the area should be mapped with a large scale of 1:500 to capture all the micromorphological features.
2) Sub-surface investigations, including geotechnical and geophysical investigations, are necessary to design a scheme of remedial measures.
3) Continue cleaning the stream course.

Image 4.28 - Activities across the landslide area

Long Term

1) Redesign the roadside drainage where the section is reduced and rebuild and check the size of the Hume pipe based on the runoff. If needed, replace it with a box culvert.
2) Implement the recommended remedial measures as per design. For an uphill slope that is cracked/subsided and has slid, the application of SD Nails (CIRIA C637; FHWA-NHI-14-007 GEC 007) along with bioengineering measures could be a better solution without cutting down the tree cover.
3) On the uphill side, a 3 m-high RCC retailing wall with fencing at the top should be constructed at the edge of the right-of-way.
4) Regular monitoring and maintenance of the measures implemented.

Note: As the field assessment was conducted from 23 June to 27 June 2024 before the monsoon, it is presumed that the morphology of the landslide areas may have changed post-monsoon/this season. Therefore, it is suggested that a detailed investigation of the specific site be conducted to prepare detailed engineering designs.

Site: S13 (Vikash Nagar near Petrol Pump: Chainage 10+970)

Located just upstream of the unstable slope are settlements and roads that have impervious surfaces, which causes increased surface runoff during rainstorms. During the inspection, no visible signs of subsurface water activity, such as seepage or wet areas, were observed at the landslide site. The more active part lay on the northern side of the slope and largely comprised colluvium debris of well-graded fine gravel with some fines, along with some boulder-sized particles sparsely distributed throughout the slide area. Two natural gullies had formed on both the northern and southern flanks of the slide area. In the southern part of the unstable area, there is a narrow area that is relatively inactive, extending from the top to the bottom of the slide. This feature indicates differential activity within the landslide area. In addition, another landslide scar was found within the main body of the landslide, indicating that movement is still occurring and that reactivation can happen if timely mitigation measures are not implemented.

It was observed that a canal had been constructed at the upper section of this slope with a road passing above it that connected the settlements located at the top. The top part of the slope is gentle, and presently, no visible signs of instability were observed in this part.

- 31° 5'38.41"N and 77°10'14.76"E
- The width of the main slide along the highway is about 20 m
- Length along the slope of about 30 m
- Slope angle varies between 45-55°
- Type of failure: shallow translational

Image 4.29 - (A) Aerial view of landslide area and (B) View of landslide
Note:Consider the slope angle, soil,and uprooted tree

Failure Mechanism and Contributing Factors

1) The debris slide was composed of thick, overburdened soil on weathered bedrock.
2) An irrigation channel was observed on the uphill running all through the affected slope, facilitating infiltration.
3) Domestic mixed waste, including plastic, was found dumped on the slope uphill.
4) The area above the roadside slide has dense forest cover, which increases the surcharge on the weaker slope.
5) The upper urban concrete road has a proper roadside drain; however, rainwater still crosses over the road surface onto the slope impacting it.
6) The excess surface runoff during rainstorms caused the landslide on the soil slope.

Suggestive Measures

Immediate

- Remove the loose debris from the slope and make the slope uniform.
- Check the drainage in the upper reach of the slope and avoid any runoff into the slope.
- Construct catch water drain and vegetative stone paved surface channel within the landslide area.
- Cover the landslide area with waterproof geotextile.

Medium Term

- Modify the slope by providing at least two berms/benches if the possibility exists.
- Construct a catchwater drain above the slide and at every bench (if benches are constructed).
- Install Brush layering/bally benching using local wood cuttings on the contline.
- Raise the height of the toe wall by 1 m.

Site: S14 (Shiva Mandir Area: Chainage 10+970)

This is a common debris slide triggered by the modified slopes. The soil consists of colluvium or transported soil, where rock exposure was noticed to be highly weathered and fractured phyllites. The slope, as observed during the field inspection, was stable but at a critical point of stability. It could become destabilized during rainfall, as the slope remains unprotected and composed of loose to semi-compact material.

The main scarp of the landslide extends 50 m (of which 30 m is actively unstable) along the highway and 30m along the slope (from crest to toe) (see Image 4-30). The failure was reportedly triggered by a heavy downpour on 13 July 2023. The slope is divided into two sections by a small ridge that remained unaffected by the slide. It consists of a thin top soil layer, only a few centimetres deep, which overlays thick colluvium and highly weathered phyllites/slate rocks. The soil contains some clay and has a greater depth in comparison to other areas along the road alignment. Although the affected slope lacked vegetation, the surrounding area is densely vegetated, including a cover of pine trees.

Just above the vertical scarp of the slide, there are residential buildings, at least two of which have been impacted and reportedly declared unsafe. There are also nearby structures that, while not visibly damaged, fall under the concerned category. On and above the scarp of the slide, several cracks have developed, creating a visibly sagged topography with rocks displaying wide fractures and joints, indicating loose mass that poses a risk to the buildings. The exposed slide slope is unprotected and prone to severe erosion, which could lead to larger landslide/slope failure in the future.

- Lat/Long: 31° 4'30.78"N and 77°10'55.06"E
- Longitude stratigraphic horizon: Jutogh Group-Bhotli Formation
- Lithology: Highly weathered phyllite/slate
- Type of landslide: Rock-cum-debris shallow failure
- Slope angle and direction: 48° and N 325°
- Affected slope height: 30m and slope length: 30 m (+20m unaffected)

Failure Mechanism and Contributing Factors

1) Debris slide composed of thick overburdened soil on weathered bedrock.
2) A house is located a few meters above the landslide crown, and the toilet is situated on the fractured slope. The seepage water from the toilet, combined with rainwater, may have destabilized the slope and caused the landslide.
3) No adequate drainage measures were observed to channel domestic and natural water away from the slope.
4) A shallow debris slide occurred as a result of rainstorms.

Suggested Measures

Immediate

1. Remove loose debris and rock blocks and prepare the slope uniform.
2. Seal the cracks on the top.
3. Manage upstream drainage to divert surface runoff away from the landslide and remove the toilet.
4. Prepare stone rip-rap vegetative surface channel.
5. Cover the slope with waterproof geotextile.

Image 4.30 - (A) Aerial view of the landslide location; (B-C) View of landslide triggered due to rainstorms coupled with manmade activities and inherent weak bedrock Note: The ridge separates the actively unstable zone.

Long Term

1. Constructa breast wall of 1.5-2 m high with proper drainage provision.
2. Install wire mesh and fix them with SD nails/anchors at regular intervals. Cover the entire slope with a green geogrid carpet underneath the wire mesh, and perform hydro seeding/planting.
3. Since the safety of residential houses at the crown is crucial, the slope can be stabilized with CC cladding and anchors. The spacing and length of the anchors must be determined based on the design.

Site: S15 (Panthaghati: Chainage 11+260)

The road passes through a densely populated area where a section of the roadway collapsed, impacting several houses situated on the downslope. The slope has an angle of approximately 45° to 55°. The slide material comprises colluvial soil, which could be likely composed of material that was dumped during road excavation. The debris includes well-graded gravel with some finer particles. A natural gully has formed in the middle of the failure area. The settlements affected by this slide are highly vulnerable and their vulnerability could increase in the future because of the potential expansion of the slide, which cannot be discounted.

The slope protection and mitigation work began in June 2024, as observed by some authorities. An RCC structure is currently under construction to protect the toe of the slope and prevent the slide materials from reaching to the houses located downslope. Given the ongoing construction, conducting a detailed study of this slide site is not practical. However, diverting the rainwater from the top of the slope in the road area is equally important to prevent it from flowing through the affected slide part.

Additionally, the area's morphology indicated that the slope can be divided into two parts. Part 1 is the actively unstable area, while Part 2 is marginally stable (see Image 4-31). The construction of a retaining wall does not address the dormant side of the slope.

Image 4.31 - (A) Aerial view of the landslide area (note the active and dormant area), (B and C) View of landslide, settlements, and construction of retaining wall

4.2 Kennedy Chowk to Annadale Road Alignment

The road linking Shimla from Kennedy Chowk to Annadale Army helipad (see Image 4-32) and cantonment serves multiple purposes. It facilitates movement for both the Army and VIPs and is a critical network for evacuations during emergencies or disasters. The road primarily passes through dense forests of cedar, oak, and pine and is intersected by a few big nalas and several small streams.

The road has not experienced major landslides; however, visual observations made during the traverses from Kennedy Chowk to the Army Heritage Museum (Annadale) revealed several significant issues related to slope maintenance and management. These issues include road subsidence, shallow slope failure and subsidence, erosion, cracking, tree bending, and uprooting. A major issue is the dumping of waste on the slopes and in the streams.

Geologically, the area also comes under the Jutogh Group, representing three formations: Bhotli, Manal, and Panjreli. These formations consist of carbonaceous shale, slate, phyllite, schist, quartzite, and dolomite. The hills are comparatively gentler, dissected, structurally controlled, and covered with a thin cover of topsoil. Beneath the topsoil lies variably thick colluvium and highly weathered rocks, making the terrain susceptible to slope failure.

The following is a brief account of some important issues that must be addressed for disaster-resilient and sustainable roads. The areas requiring attention have been mapped and marked in Image 4-33(refer to Annex II) and are assigned codes: S for slope protection, D for drainage management, and T for tree protection.

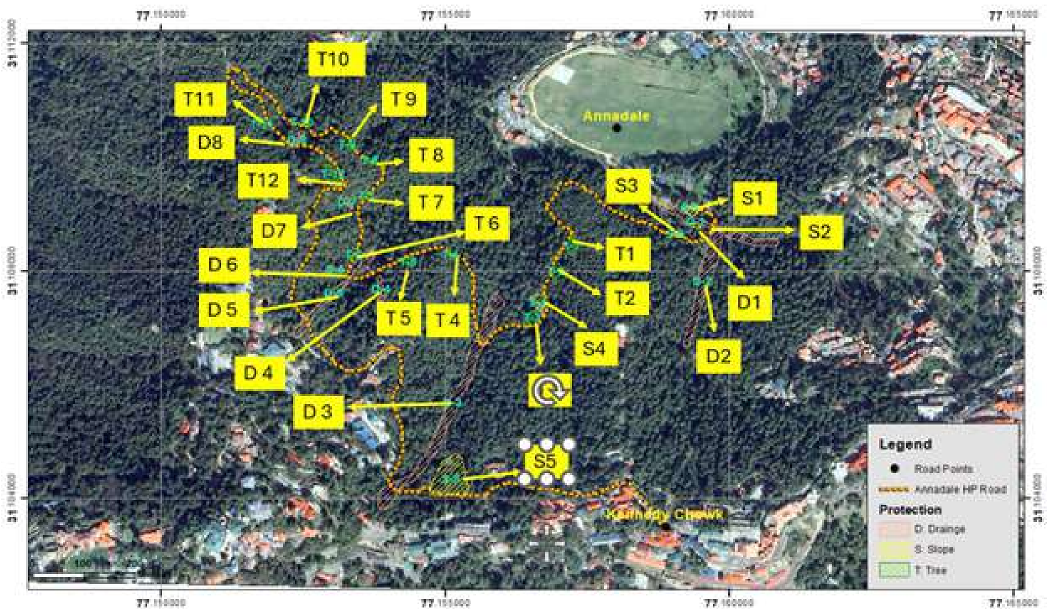


Image 4.32 - A view of the road alignment connecting Kennedy Chowk to Annadale Helipad
Note: There is a dense forest cover

4.2.1 Mapping and Assessment

Site: S1, S2, and S3 (Near Army Heritage Museum Entrance)

A major stream flows close to the Army Heritage Museum and merges with another stream a few meters downstream (see Image 4-35). These two streams are divided by a small park/resting area developed downhill of the road in front of the museum. Both streams have cut their beds and banks repeatedly, resulting in ongoing toe-cutting and scouring (see Image 4-35).

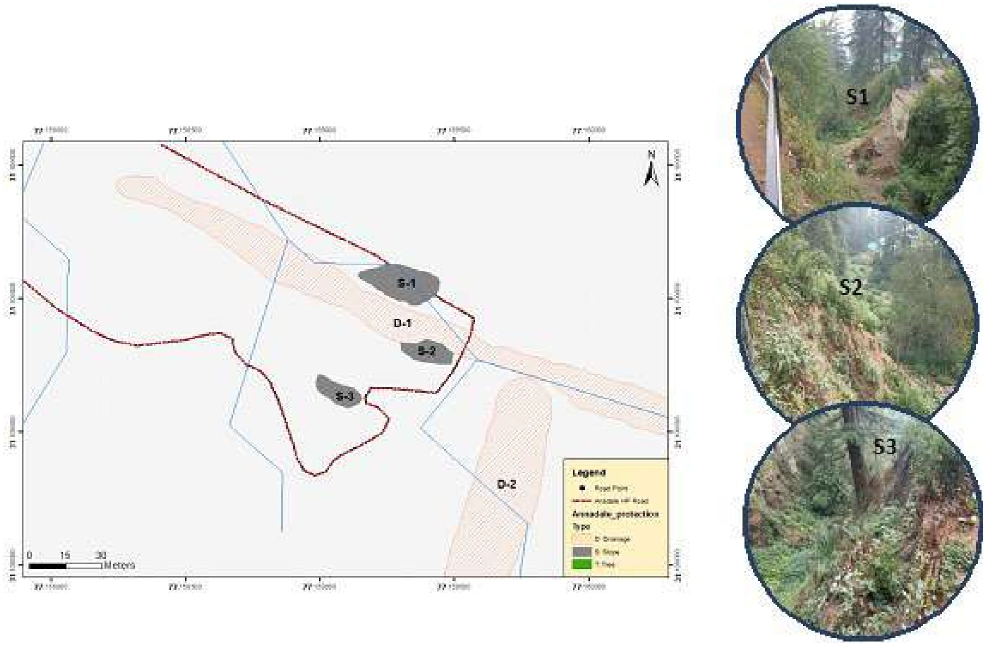


Image 4.33 - Locationand view of slope failure (S1-S3 and D1 and D2) due to stream undercutting
Note: The S stands for slope protection, and the D stands for drainage protection

Concrete retaining walls, constructed at limited lengths to protect the road from erosion, may still be impacted if the stream course is not managed correctly. The park, which was designed for rest/children's play, was found damaged on all sides due to significant bank erosion and toe erosion. There are several tension cracks, instances of subsidence, and sliding within the park (see Image 4-34). The unsupported toe and the slopes of the park are at risk of further erosion and sliding, particularly during rainy weather. Water can seep through the tension cracks/subsidence, further accelerating the sliding problem.

Some houses are situated on the slide near the stream's meeting point. This precarious situation needs to be addressed and accordingly prioritized for corrective measures. Both the banks of the museum/road and the adjacent park must be protected from cutting, scouring, and erosion.

Image 4.34 - The park which divides the streams is severely eroded, subsided, and cracked

Image 4.35 - The right-side stream close to the museum with extensive erosion on both its banks

Image 4.36 - The park which divides the streams is severely eroded, subsided, and cracked

The course of both the streams was found to be obstructed by dumped waste, including plastic, which hinders the smooth flow of water. This waste also creates additional environmental issues.

It is, therefore, recommended that both streams (D1 and D2) be equipped with lined chutes, along with the intermittent application of debris flow barriers (e.g. check dams) to collect the debris. The number of such barriers required for each stream should be determined based on a detailed investigation of the stream gradient. This study estimated that the drainage lengths necessary for protection are approximately 250m for Stream D1 and 200m for Stream D2.

Suggested Measures

Immediate Measures

1) Clear the stream channel that obstructs the flow.
2) Construct a series of Gabion Check dams across the stream to reduce bed erosion and bank undercutting (refer to Annex for Check Dam design). This requires further measurement of the stream gradient to design the check dams.
3) Install Brush layering using the local woody cuttings to stabilize the stream banks alongside the live fence at the toe side of the banks.
4) Assess the individual large Himalayan Deodar (Cedrus deodara) trees; if needed, pruning can also be done, but this will require expert consultation.

Medium Term

1) Continuous monitoring of Live Fence and Brush Layering. If dead species are found, replace them.
2) Structural measures are essential, such as constructing reinforcement/bracing walls around the individual or a group of trees and using tree bracing for additional support.
3) Excess surface runoff should be avoided and the tree trunk area should be kept dry as far as possible.

Long Term

1) Regular monitoring and observation.
2) In case of any failure of the roadside slope, the retaining wall should be continued up to the road level.
3) Promotion of small, fast-growing local shrub species along the roadside.

Site: S4 (Lat/Long: 31.107472 N and 77.15650 E)

Initially, a tree was uprooted on the downhill side of the road. To protect the road, a retaining wall was built and the leftover soil was left on the slope. Over time, this area became a dumping ground for construction debris and waste. As a result, the debris eventually made its way into a small stream flowing downhill, obstructing its flow. The terrain slope varies between 40° and 50° and the estimated area of the exposed surface is about 500m2. The trees on the slope are situated on shallow overburden, resting on weathered bedrock underneath (see Image 4-37). The location is susceptible to slope failure, and further uprooting of trees is likely. Therefore, the location needs proper treatment.

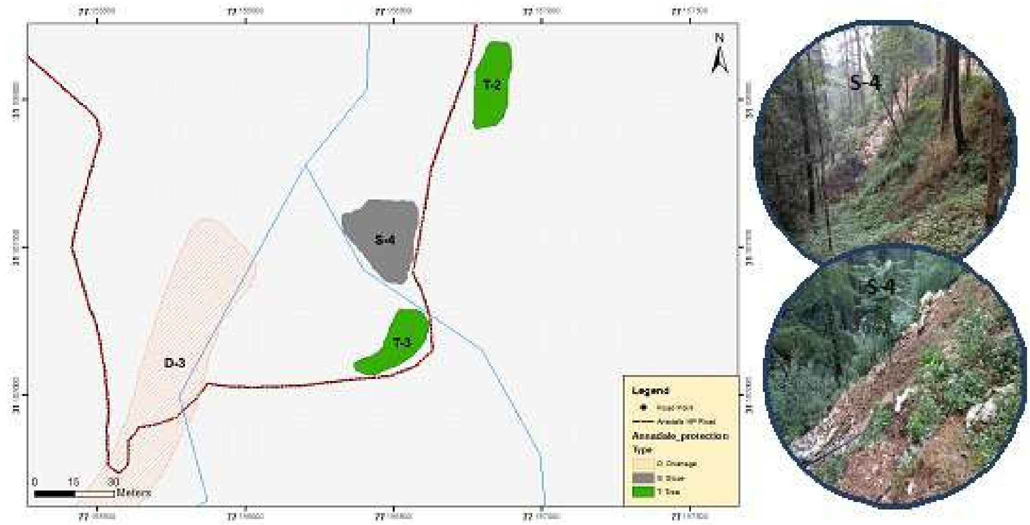


Image 4.37 - Location of S-4, slope failure, and terrain morphology

Suggested Measures

Immediate

1) Remove the undegradable waste/garbage from the slope and restrict the location from any dumping.
2) Make the slope uniform with some degree of compaction and build a vegetative stone paved surface channel. Make sure that the surface slopes toward the channel.
3) Install a jute net (or coir net) avoiding the stone-paved channel, cover the slope, and anchor the net properly.
4) Plant local shrubs in a contour line at 1-1.5-m intervals to form a live fence to retain the soil and local grass plantation between the two rows of the plantation that cover the bare surface faster.
5) To reinforce the slope, install a live fence (start from the bottom) using Himalayan Bamboo or other similar species.

Long Term

1) Monitoring the plantation area and maintenance such as replacing dead species and maintaining any erosion until the plant is established.

Site: S5 (Lat. /Long: 31.104232 N, 77.155038 E)

Similar to Site S4, trees were uprooted during last year's monsoon, which damaged the downhill side of the road. The road was restored, and a concrete retaining wall was built (see Image 4-38). However, the slope was left bare without any treatment. The loose construction spoil and debris made the slope vulnerable. During the monsoon, surface runoff can cause this loose debris to move downhill, potentially destabilizing the trees and leading to further uprooting. Further, as the debris moves, it may reach the road further downhill, causing damage. If the trees on the slope are uprooted, the damage will be more significant. Therefore, this slope needs protection.

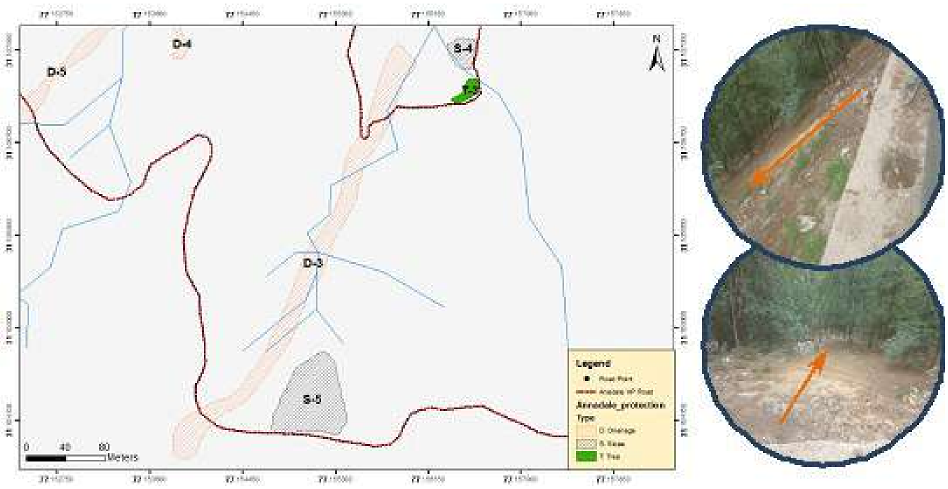


Image 4.38 - Location of S-5 and view of the bare slope filled with debris materials

Suggested Measures

Immediate

1) Make the slope uniform with some degree of compaction and build a vegetative stone paved surface channel. Make sure that the surface slopes toward the channel and can catch the runoff from the slope.
2) To reinforce the slope, install a live fence using Himalayan Bamboo or other similar species at the toe side of the slope.
3) Install Brush Layering using the woody cuttings of local plant species (use shrubs only) at about 1.5-2m intervals in contour line and grass plantation between the space of brush layering.

Long Term

1) Monitoring the plantation area and maintenance such as replacement of dead species and maintaining any erosion until the plant is established.
2) Regular observation and maintenance of the surface catch drain.

Site: T7 and T10

It was observed that the road, mainly towards the outer shoulder (valley side), had subsided and/or cracked(see Image 4-39). This issue may be linked to the large tree on the downhill slope, which indicates destabilization of the slope. However, other likely factors are inadequate roadside drainage, improper camber, and unsupported embankments. During heavy rain, the roadside drains overflow, leading to erosion of the road surface, the downhill side shoulder, and the embankment.

In some cases, the embankment on the downhill side may lack proper support, resulting in subsidence during rainy periods. Additionally, some sections may require a redesign of the camber. To address these issues, it is recommended that the road surface geometry be assessed and necessary modifications be made to the camber, shoulders, roadside drains, and embankment as per the respective IRC codes.

Image 4.39 - Subsidence and cracks on the road surface
Note: Circular cracks were noticed towards the tree

Suggested Measures

Immediate

1) Seal the crack and avoid any seepage.
2) Maintain the roadside drainage.

Long Term

1) Monitor if any crack has developed.
2) Prune treesafter consulting species experts to help reduce some surcharge load on the slope.
3) Build a support wall around the tree trunk, avoid any surface runoff around the tree as possible, and use cable bracing to support the tree.

Site: T1-T6, T8, T9, T11, and T12

This road passes through a dense reserved forest cover, making it challenging to prevent all trees from being exposed along the side slopes. However, it is essential to protect trees that are close to the road to prevent further deterioration/erosion/instability. In this study, an effort was made to map the trees along the road and ten such locations were identified that needed to be protected (see Table 4.2 and Image 4-40).

S. No	Type of Protection (proposed)	Code	Area (m2)	Longitude, E	Latitude, N
1	Breast Wall and Tree Trunk Support Wall	T-11	182	77.1518	31.1106
2	Breast Wall and Tree Trunk Support Wall	T-1	348	77.157	31.1085
3	Breast Wall and Tree Trunk Support Wall	T-2	309	77.1568	31.108
4	Breast Wall and Tree Trunk Support Wall	T-3	285	77.1565	31.1072
5	Breast Wall and Tree Trunk Support Wall	T-4	134	77.1551	31.1083
6	Breast Wall and Tree Trunk Support Wall	T-9	258	77.1533	31.1102
7	Breast Wall and Tree Trunk Support Wall	T-12	308	77.153	31.1097
8	Breast Wall and Tree Trunk Support Wall	T-5	179	77.1543	31.1082
9	Breast Wall and Tree Trunk Support Wall	T-6	90	77.1534	31.1082
10	Breast Wall and Tree Trunk Support Wall	T-8	93	77.1537	31.1099

Table 4.2 - List of Locations for roadside slope and tree protection along the road alignment

On the other hand, if some trees cannot be restored, in view of the impending risk, it is better to remove them. It was also observed that some of the trees were exposed to the edge of the cut slope as indicated in Image 4-41. This may impact the stability of the slope in the long run. It is suggested to conduct a detailed mapping of the area and prepare an inventory of such trees both along the roadside and nearby, within the close vicinity of the highway. This inventory will help in making informed decisions regarding the protection or removal of these trees, based on the risks they pose and the feasibility of such actions.

While the inventory is being prepared, it is suggested that the trees that are on the edge of the cut slope be protected by providing the appropriate support system so that further erosion, etc., may be prevented.

Image 4.40 - Location of road slope and roadside tree protection

Several slope failure, erosion, and subsidence cases were observed along the road alignment. Three notable cases are as follows:

1) Tree root exposure due to continuous erosion and their load on the edges of vertical cut slopes, as explained above.
2) Some occurred on the side slopes of the streams/drainage channel, which have been eroded and failed/subsided on the roadside.
3) Some observed on the unprotected cut slope (see Image 4-42).

In many cases, the primary causes of slope instability can be traced back to unprotected roadside cut slopes, particularly in areas with fractured rocks and exposed trees. Other contributing factors include inadequate drainage measures and erosion. However, some slopes are impacted by large-scale failures that need to be investigated in detail.

It is, therefore, suggested that an inventory be compiled for all the cut slopes, including those with significant failures. This inventory should capture all relevant geological, topographic, geomorphological, hydrological, etc. characteristics. Such data will help to analyse the stability of the slopes and accordingly design suitable remedial measures, with a preference for green solutions.

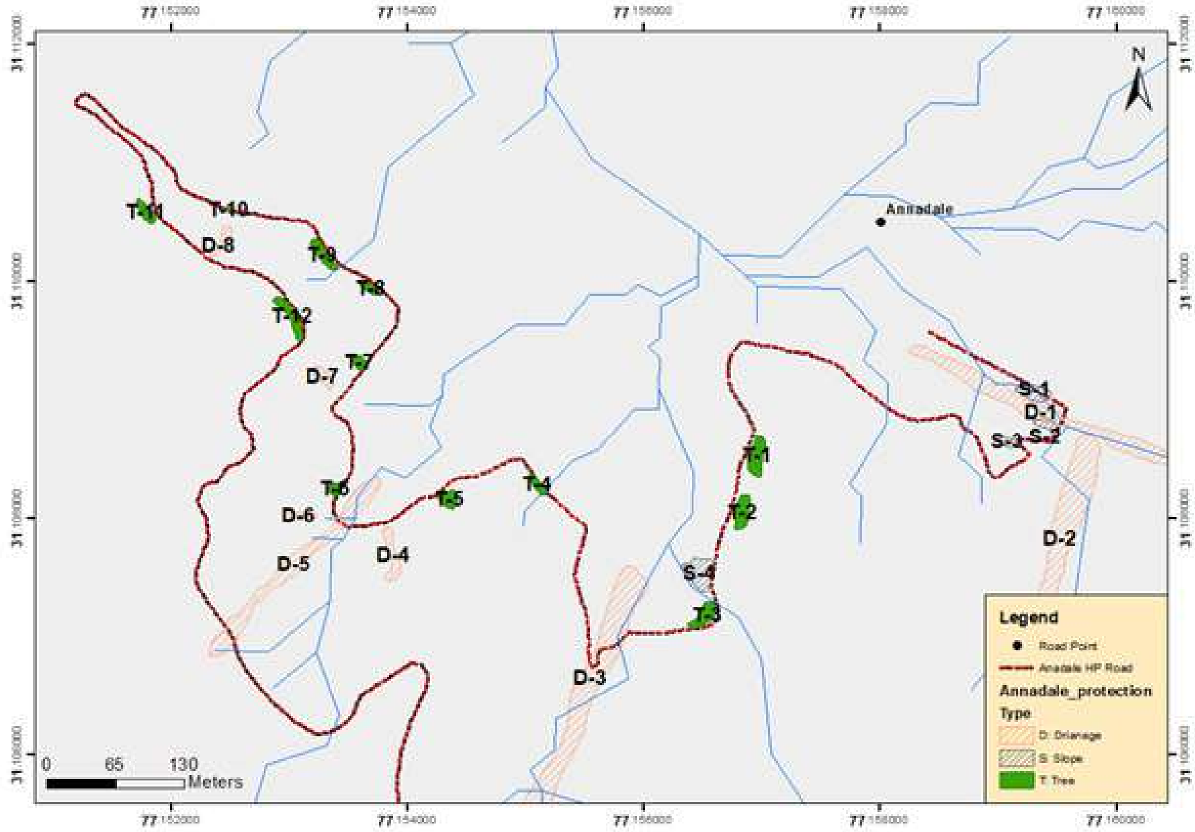


Image 4.41 - Trees exposed on the side of the road need to be protected

Suggested Measures

In most of the above-identified issues, it would be relatively straightforward to implement solutions at this stage. However, if these issues remain unaddressed, they could pose greater risks to both the road and the commuters, potentially requiring more effort, budget, and time to resolve later. The general approach to treatment will include the following:

1) Concrete breast wall with additional reinforcement (if required) at places where trees are exposed and stand at or near the edge of the cut slopes.
2) Masonry breast walls with good drainage options may work in other vulnerable cut slope locations.
3) Stone paved vegetative channel for erosion control for the season drainage channel.
4) Plantation of deep-rooted locally available species of grasses and bushes.

Erosion control along the stream has to be a coupled solution, which may include the lining/chute of the stream as well as Live check dams for the steam banks to be reinforced.

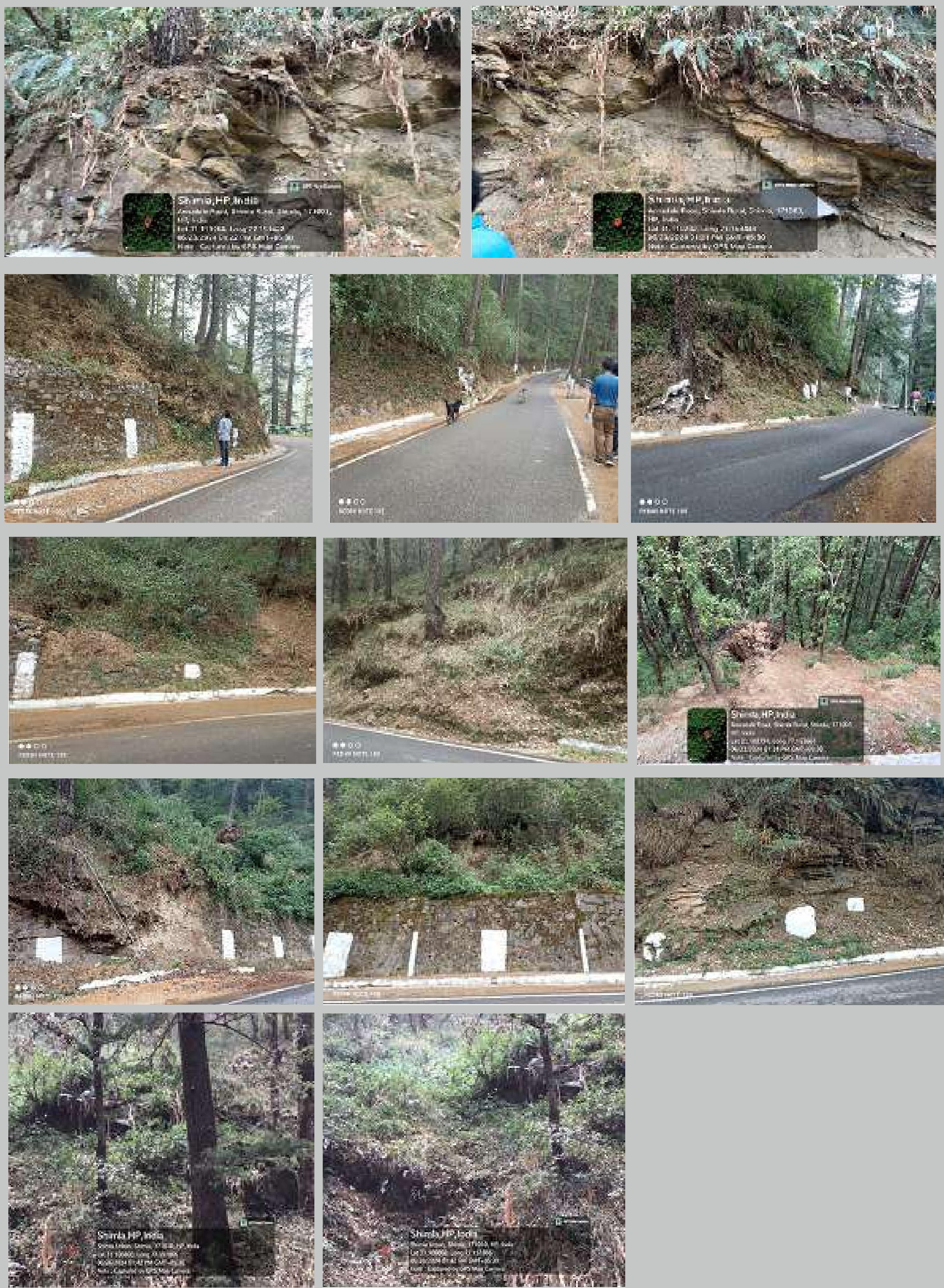


Image 4-41. Various situations of roadside slope failure, erosion, and subsidence.
In most cases, the role of the exposed trees and drainage is predominant. The inherent weathered rock and overlying shallow soil cover do not support trees well when the surcharge increases.

Site: D1 to D8 (Drainage/Stream Management)

Apart from the major streams, there are several other seasonal channels on the slopes that connect to the road, leading to extensive erosion/subsidence and even slope failure. As indicated in Image 4-44, these streams not only cut into the slopes but also contribute to their collapse and failure. It is recommended that further detailed mapping of these areas be conducted to clearly define the extent of the streams and assess their impact.

Image 4.42 - Incision of slope by streams followed by slope failure

In some slopes where the stream is suspected to carry a large debris load, installing debris flow barriers may be a beneficial option. Additionally, it is important to use a culvert of appropriate size and type and line the stream path up to a certain distance. For the rest of the stream, management should include removing any obstructions before and after the rainy season and implementing bioengineering solutions.

This study has identified some major streams and drainage channels that significantly impact slope stability and the uprooting of trees. Following Image 4-43 presents the major streams and drainage channels suggested for the treatment.

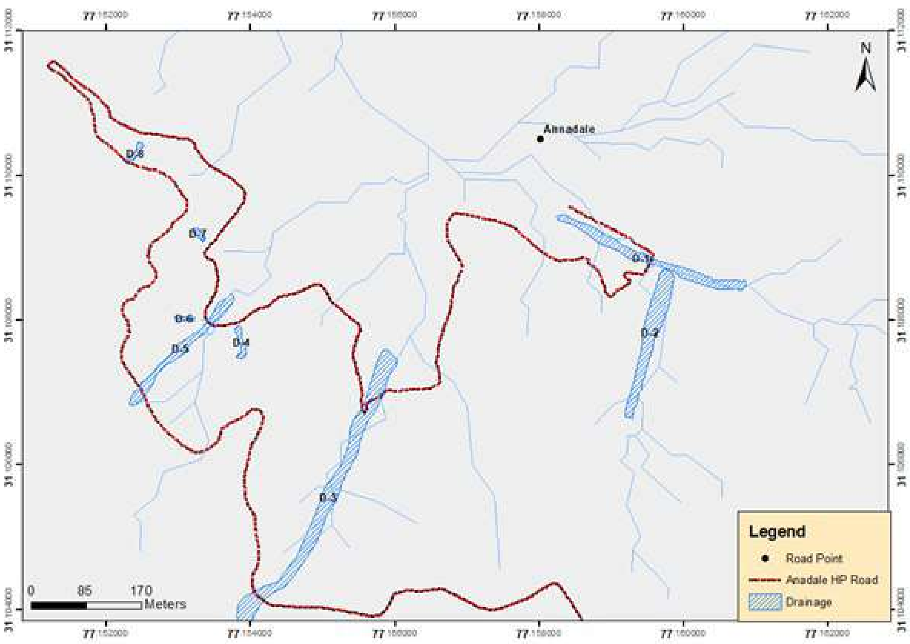


Image 4.43 - Stream and drainage channel to be protected

S. No	Code	Type of Protection (proposed)	Length (m)	Area (m2)
1	D-1	Gabion Check Dams and Intermittent Live Check Dams, Brush Layering for bank protection	250	3299
2	D-2	Gabion Check Dams and Intermittent Live Check Dams, Brush Layering for bank protection	225	3869
3	D-3	Channel improvement, Stone pavement, Check Dams, Brushwood on either side (Palisade)	400	8047
4	D-4	Channel Improvement, stone Pavement and Check Dams, Plantation of woody cutting on either side of the channel	60	353
5	D-5	Channel Improvement, stone Pavement and Check Dams and Plantation of Woody cuttings on either side	215	2263
6	D-6	Channel Improvement, stone pavement and live check dams	40	126
7	D-7	Channel Improvement, stone pavement and live check dams	40	158
8	D-8	Channel Improvement, stone pavement and live check dams	50	216

Table 4.3 - List of drainage channels and treatment techniques

Dumping on the Roadside Slopes and Streams

Dumping is a significant issue that needs to be addressed, particularly along the downhill slopes of the roads and in the course of the streams. As indicated in Image 4-44 and Image 4-45, several cases of C&D and domestic waste dumping have been observed in these areas. It seems there are no established provisions for the safe disposal of such waste. Many natural streams are found blocked and threatened due to this dumping, and none of the dumping sites have been found to have adequate stabilization or protective measures in place. This unauthorized dumping in forests and natural streams poses a threat to the ecology and habitats downhill. It is suggested that these occurrences be documented and appropriate management measures be implemented while also enforcing a ban on further dumping at unplanned sites.

Almost all the major streams in the area along Annadale Road were found to be polluted with a variety of wastes. However, as the Images below indicate, plastic waste can remain intact for years. This not only pollutes the water but also obstructs the stream's flow, contributing to their degradation.

Image 4.44 - Streams found dumped with waste material, culverts choked, and drains half full

Image 4.45 - Several cases of dumping on the slope resulting in permanent damage of topsoil cover and weathering of underlying soil and rocks

5 Slope Stability Analysis

5.1 Factors Triggering Landslides

The major cause of the landslides in the Annadale road section seems to be structurally controlled due to the shearing effect of the thrust, as evidenced by the highly deformed and shattered rock exposures found in areas directly above the existing road (see Images 5-1). However, the increased instability in the road section was likely triggered by prolonged or intense precipitation that affected the thin debris layers. These layers consist of poorly consolidated materials (Rahardjo et al., 2007) from previous landslides and unconsolidated materials that were dumped during the road construction process using the 'Cut and Fill' method. The heavy trees growing in these poorly consolidated materials struggle to sustain their weight in the unstable, thin soil, leading to a loss of stability during periods of intense precipitation (Zhang and Ding, 2019).

Image 5.1 - Deformed, shattered, jointed, and weathered rock mass exposed upslope along the Kennedy Chock to Annadale area

The drainage management in the area is poor, leading to the formation of many new gullies following intense rainfall in recent years. The existing drainage system also faces challenges due to anthropogenic activities such as dumping garbage into the channels, which causes subsequent blockages. Additionally, poor drainage management may have worsened the side cutting, further intensifying slope instability.

Further, the permeability difference between the thin soil debris and the rock interface likely created extra water pressure (Leroueil et al., 2009).This increased the driving force acting on the slope while simultaneously decreasing the shear strength of the materials, resulting in instability (van Beek et al., 2008).

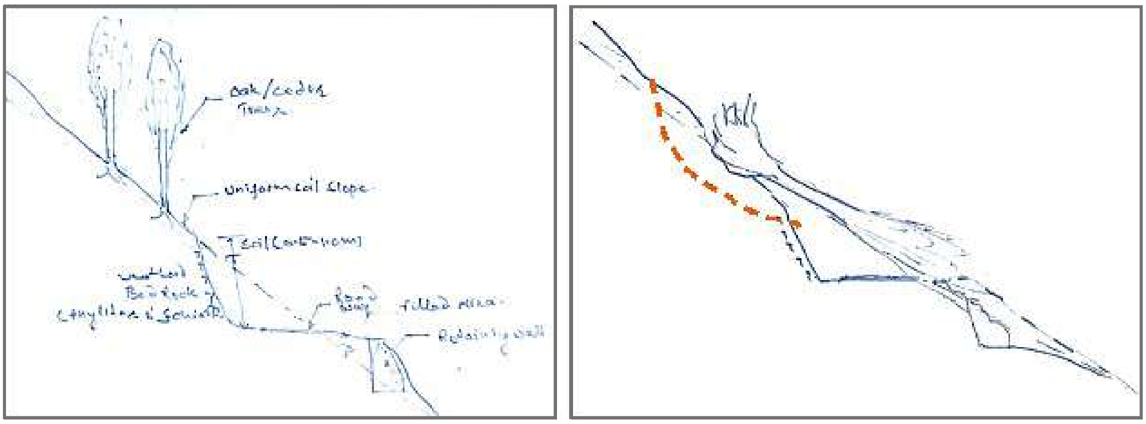


Image 5.2 - (Left) Typical X-section view and (right) tree uprooting and damage to the road

Similarly, the presence of angular debris soil, rocks, high levels of human activities, and the bedrock beneath the sliding mass indicates that the instabilities occur above the bedrock. Importantly, instability is not observed whenever bedrock is exposed.

The nature of the shallow failures along the Panthaghati-Crossing Road section indicates that these instabilities could be reduced through prolonged or intense rainfall. At the same time, both can trigger landslides, and they operate through different mechanisms.

5.2 Rainfall Affects the Slope Stability

Rainfall-induced landslides are common in mountainous and hilly regions, where the combination of steep slopes and loose or weak soil conditions makes the terrain particularly susceptible. The rainfall processes are highly variable to space and time and thus there is variability in slope instability. The mechanism of slope failure can be further discussed according to the rainfall duration and intensity.

5.2.1 Long Duration Light Rainfall

Long-duration but light rainfall can destabilize a slope through gradual infiltration and accumulation of water in the soil, leading to a delayed yet potentially significant reduction in slope stability.

Mechanism

- Soil Saturation: Long periods of light rain can lead to the gradual saturation of the soil. When the soil becomes fully saturated, its ability to absorb more water is reduced, leading to increased pore water pressure.

- Reduced Cohesion: Saturated soils have reduced cohesion and internal friction, making them more susceptible to sliding.
- Seepage Forces: Prolonged rainfall can cause seepage forces to build up within the slope, pushing soil particles apart and reducing the overall stability of the slope.
- Increased Weight: The added water content increases the weight of the soil, adding additional stress to the slope.

Effects

- Slow Onset: Landslides caused by long-duration light rain tend to develop more slowly and may be preceded by signs such as soil creep or cracks.
- Widespread: These landslides can affect larger areas because the saturation effect can spread over a broad region.

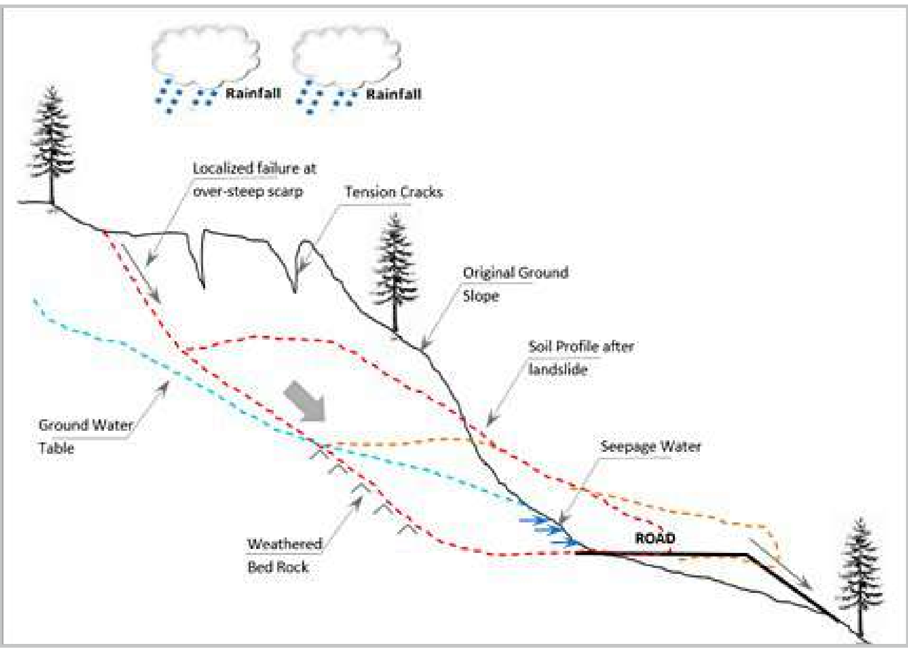


Image 5.3 - Slope failure mechanism due to rainfall and the effect of topography and human activities

5.2.2 Short-Duration Intense Rain

Short duration but intense rainfall can significantly and immediately impact slope stability, often leading to rapid and potentially catastrophic landslides such as debris flows.

Mechanism

- Rapid Infiltration: Intense rain in a short period can cause rapid infiltration of water into the soil, leading to a quick increase in pore water pressure.
- Surface Erosion: Heavy rainfall can cause significant surface erosion, removing the top layer of soil and destabilizing the slope.
- Overland Flow: When the rainfall rate exceeds the infiltration capacity of the soil, it results in overland flow, which can erode the soil and create channels that destabilize the slope.
- Hydraulic Pressure: Rapid water accumulation can lead to localized increases in hydraulic pressure, which can cause the soil to fail.

Effects

- Rapid Onset: Landslides triggered by intense rainfall can occur suddenly and with little warning, making them particularly dangerous.
- Localized: These landslides are often more localized but can be highly destructive, especially in steep terrain.

At the same time, flow in the local drainage channel increases toe-cutting and surface erosion on the unprotected roadside slope,finally triggering the landslides.

5.3 Landslide Characteristics

Abbreviated Classification of Slope Movements				
Type of movement		TYPE OF MATERIAL		
		Bed Rock	Engineering Soils	
			Predominantly Course	Predominantly Fine
Fall		Rock Fall	Debris Fall	Earth Fall
Topple		Rock Topple	Debris Topple	Earth Topple
Slide	Rotational (Slump)		Rotational Debris Slide	Rotational Earth Slide
	Translational	Translational Rock Slide	Translational Debris Slide	TranslationalEarth Slide
Lateral Spread		Rock Spread	Debris Spread	Earth Spread
Flow		Rock Flow (Deep creep)	Debris Flow (Soil Creep)	Earth Flow (Soil Creep)
Complex	Combination of two or more principal types of movement			

Image 5.4 - Classification of slope movement

Types of Movement

Falls: Falls are rapid movements of rocks and boulders detached from steep slopes or cliffs along fractures, joints, and bedding planes.

Topple: It is the forward rotation of a mass of debris or rock out of a slope. Slope failure generally occurs at a point near the base of the block of rock.

Slides: A slide is a downslope movement of material that occurs along a slip surface.

- Rotational Slide: In this slide, the movement is roughly rotational about an axis that is parallel to the ground surface and transverses across the slide.
- Translational Slide: In this slide, the landslide mass moves along a planar surface with rotation or backward tilting.

Types of Materials

- **Rock:** Hard or firm mass.
- **Debris:** 20% to 80% of the particles are larger than 2mm and the remainder is less than 2mm.
- **Earth:** Material in which 80% or more of the particles are smaller than 2mm.
- **Soil:** An aggregate of solid particles, generally of minerals and rocks.
- **Mud:** Material in which 80% or more of the particles are smaller than 0.06mm.

Types of Flows

- **Debris Flow:** A rapid mass movement involving a combination of loose soil, rock, organic matter, and slurry that flows downslope. These flows are commonly triggered by intense precipitation or rapid snowmelt.
- **Earth Flow:** A downslope viscous flow of fine-grained material saturated with water.
- **Mudflow:** A wet or viscous fluid mass of fine and coarse-grained material that flows rapidly along drainage channels.
- **Creep:** The slow, steady, downward movement of material under gravity, occurring over a large area.

The common characteristics of landslides and slope failures in both the road sections involve soil or debris deposits, and these slides are uncommon in rock slopes. The other similarity is that the failures occur in the form of shallow slides either upslope or downslope of the road. Key factors contributing to these landslides include intensive human activities such as slope and drainage modification, unmanaged roadside drainage, unplanned scattered settlements, steep cuts of roadside slopes, and climate action. Along the Kennedy-Chowk to Annadale road alignment, bedrocks were fairly exposed in the road cut sections, which were highly shattered, weathered, and jointed. Recent failures in this section were shallow, likely due to the heavy weight of large trees that had grown naturally in the thin soil or because of new excavations made below the existing road. It is important to note that recent episodes of intense rainfall should be considered a significant triggering factor for these failures.

Along the NH 5 alignment, several areas have been experiencing instabilities. In some locations, the outer edge of the road shoulder had subsided or developed tension cracks (e.g. Image4-8), indicating a potential risk of failure in the near future, even without external triggers like earthquakes or heavy rainfall. These issues result from soil loosening in the downslope area of the road, which was exacerbated by heavy precipitation, the presence of large trees, and the recent excavation of roads on the downhill slope.

Most of the instabilities were found in thin layers of debris soil above the bedrock, although in a few locations, the instabilities occurred solely in thick debris deposits (Image 4-13). Importantly, these instabilities are very close to settlements, roads, and houses, putting the area at high risk. For instance, the failure near the slaughterhouse was likely caused by the construction of houses built on loose debris deposits, which should have been washed away during periods of intense precipitation in the area. The slide area contains several gullies, likely formed by unmanaged water flow of during intense rainfall. Additionally, poor drainage systems have contributed to debris slides (e.g. Image 4-14 and Image 4-22). Most landslides originate from the upper slope of the road, while a few are moving from the downslope of the road, leading to undercutting the road and causing subsidence along the outer shoulder.

5.4 Landslide Stability Modelling

Highways constructed without considering potential vulnerabilities often face frequent issues related to slope stability, making it difficult for them to be disaster resilient. The primary challenge before the highway engineers is to anticipate hazard scenarios along highway routes and ensure that these roads remain safe and resilient to multiple hazards. To maintain highways sustainably post-construction, it is necessary to classify highway slopes based on their degree of propensity to sliding. This classification process is complex and involves identifying various factors that contribute to landslides or slope failure. An effort, however, was made to model slope stability utilizing the available coarse-resolution datasets depicted in the following models. These models were observed to be representative, indicating that both road alignments fall within a high to very high susceptibility range for slope failure. To stabilize the slopes, NbS measures are proposed as cost-effective and sustainable alternatives. However, it is important to note that not all types of landslides can be prevented through NbS. In such cases, hybrid solutions may be more effective.

5.5 Hydrology vs Landslides

Broadly, the Kufri-Dhalli-Sanjauli-Ridge-Tutu spinal region serves as a drainage divide for Shimla city. The tributaries to the south flow into the Yamuna River, while those to the north feed into the Sutlej River. Shimla has 13 major nullahs and several minor ones, which act as natural drains for both rainwater and, increasingly, wastewater (GoHP, 2022). Shimla, being a hill town, its natural drains carry the water to valleys and khads, which are used as water supply sources for the city. However, it has been reported and is evident on the ground that many natural streams have been encroached upon, with household garbage and debris dumped nearby. This practice adversely impacts the course of the natural streams. The continuous disposal of various types of waste, including plastic and wastewater, not only alters the stream morphology but also creates instabilities on the watercourse and its side slopes. Moreover, increased urbanization, climate change impact, extreme weather events, developmental activities, and a rise in the frequency of landslides and slope failures are also altering the hydrogeology of Shimla.

The unusually high precipitation of 268 mm in Shimla on July 7-11, 2023, against its normal of 35mm in five days with a deviation of over 600% and 430.8mm, on July 14-24, 2023, 254% higher from the normal (121.6mm) of this duration, has created widespread destruction including landslides resulting in severe breakdown of surface mobility, hardship, and risk to the people. The damage and disruption that occurred due to landslides/slope failure during July-August 2023 was mostly observed on/along the roads, particularly with the involvement of natural streams, which have not been properly maintained and interrupted through a number of anthropogenic activities. Such disasters may recur during similar events of rainfall if appropriate measures are not taken.

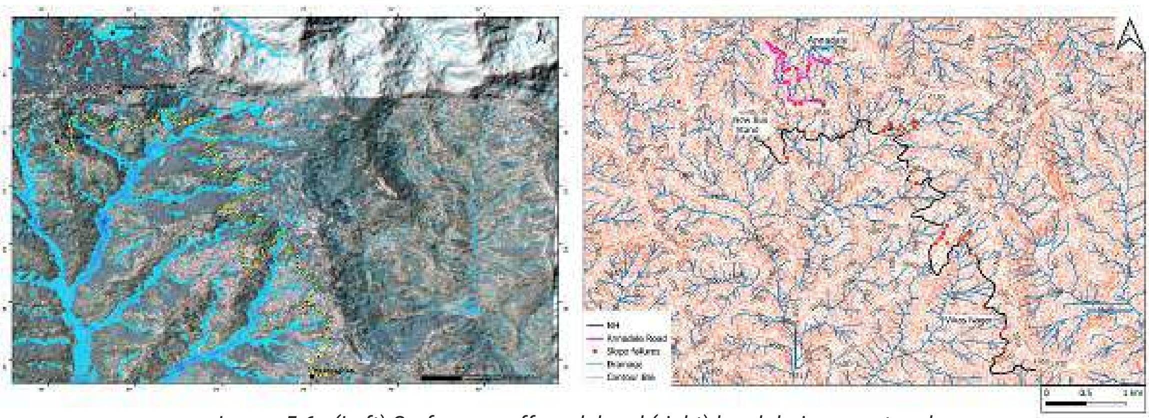


Image 5-6. (Left) Surface runoff model and (right) local drainage network
Note:The roadside landslide/debris flow on the stream path

In the case of NH5 from NH crossing to the Panthaghati, the highway is cut across by several streams, and most of the identified large landslides/debris flows that occurred during the rains of 2023 are located on or near these streams. For example, S5 (slaughterhouse landslide), S8, and S13 are on the stream path that was found to be mostly mismanaged. The rest of the landslides, e.g. S4, S6-S12, S14-S16, have been developed in or near the immediate vicinity of the settlements where, in most cases, the natural drainage system had been altered or mismanaged. The Kennedy House to Annadale road section also suffers from poor drainage management including the dumping of garbage in the channel and subsequent blockage, leading to a variety of slope failures. This demands appropriate and priority action for proper management and safety of existing infrastructures, including the drainage network, from such unprecedented rainfall.

Although the sub-hourly rainfall data was unavailable for this study, an effort was made to analyse historical rainfall data to identify patterns that could trigger landslides. A surface runoff model was established based on the available monthly rainfall data to identify erosion-prone areas and potential water accumulation. The study revealed that the slope failure along the two road alignments was triggered by the intense rainstorms, while there are several causal factors, among which human activities are the main ones. Unmanaged surface runoff and drainage systems are often unmanaged and lack maintenance. To visualize the effect of surface runoff, rainfall-runoff modelling was carried out (see Image 5-6). The model helps to locate the requirements for drainage and design of the facilities.

Image 5-5. Landslide susceptibility model of the study area

Top-to-bottom view assessed for landslide hazards during site visit

6 Slope Protection Measures

6.1 Nature-based Solutions (NbS)

Nature-based Solutions (NbS) for roadside slope protection utilize natural processes and vegetation to stabilize slopes, prevent erosion, and enhance ecological health. Vegetation, particularly deep-rooted and fast-growing plant, plays a crucial role in stabilizing the slopes. The roots bind soil particles together, enhancing the soil's shear strength, providing surface cover, and reducing the likelihood of landslides and soil erosion. This root reinforcement creates a natural network that stabilizes the soil mass. In addition, vegetation helps regulate the microclimate around the slope by reducing temperature fluctuations, which can cause soil expansion and contraction, ultimately leading to slope instability. A stable microclimate contributes to maintaining the integrity of the landscape. NbS often includes creating vegetated channels to catch excess surface runoff and other systems that manage water runoff effectively. Proper water management reduces soil saturation, a common trigger for landslides. By controlling water flow and infiltration, NbS prevents excessive water accumulation that could weaken the soil structure.

6.1.1 NbS Techniques

NbS for roadside slope protection involves using natural processes, materials, and ecosystems to stabilize and protect slopes along roadways. These solutions offer sustainable, cost-effective, and environmentally friendly alternatives to traditional engineering methods. Here are some NbS techniques that can be applied for roadside slope protection.

Vegetative Cover

- **Grassing and Turfing:** Planting grass and ground cover plants on slopes protects soil from erosion by reducing the impact of raindrops and slowing down surface runoff. Grassroots bind the soil, which improves slope stability.
- **Shrubs:** Deep-rooted shrubs provide additional reinforcement to slopes by anchoring the soil with their roots, creating a network that stabilizes the soil and prevents it from sliding.

Bioengineering Techniques

- **Live Staking:** This involves driving live cuttings of woody plants into the ground. These stakes take root and grow, providing immediate soil stabilization. This technique is often used on slopes prone to erosion.
- **Brush Layering:** This is a method where live branches are laid in trenches along the slope, covered with soil, and allowed to sprout. The branches help stabilize the slope and reduce erosion by reinforcing the soil with roots.

- **Fascines:** This involves placing bundles of live branches in shallow trenches along the contour of the slope. These bundles root and grow, forming a living barrier that stabilizes the slope and reduces erosion.
- **Palisade:** A palisade (often referred to as a palisade wall) is a type of fence or wall typically made from vertical stakes or wooden timbers, sometimes reinforced with other materials. Palisades have historically been used as defensive structures, particularly in fortifications, due to their ability to deter and protect against intruders.

Riparian Buffers

- **Vegetated Buffers:** Planting vegetation, such as trees, shrubs, and grasses, along waterways near slopes can help stabilize the soil, filter runoff, and reduce erosion. Riparian buffers are particularly effective in protecting slopes adjacent to rivers or streams.

Green Terracing

- **Terraces with Vegetation:** Constructing terraces on steep slopes and planting them with vegetation reduces the slope gradient, which in turn reduces the velocity of surface runoff. This helps in minimizing erosion and landslide risks.
- **Contour Planting:** Planting vegetation along the contour lines of a slope helps to slow down water flow and reduce soil erosion, stabilizing the slope.

Bio-retention Systems

- **Bio-retention Cells:** These are shallow, vegetated depressions that capture and treat stormwater runoff. They help to reduce the amount of surface water on slopes, lowering the risk of soil saturation and subsequent slope failure.
- **Rain Gardens:** Similar to bio-retention cells, rain gardens are planted areas designed to absorb and filter stormwater runoff. They can be used on roadside slopes to manage water and stabilize the soil.

Jute or Coir Rolls and Mats

- **Coir Rolls:** These are natural fibre rolls placed along the contour of the slope to prevent soil erosion. They can be planted with vegetation, which takes root and further stabilizes the slope.
- **Coir Mats:** Biodegradable mats made from coconut fibre can be laid over exposed soil on slopes. They protect the soil from erosion and support the establishment of vegetation.

Slope Drainage Systems

- **Vegetated Swales:** Swales are shallow, vegetated channels (e.g. Stone Paved Vegetative Channels) that capture and slow down runoff, allowing it to infiltrate the soil. They reduce the amount of water that flows down the slope, which helps in stabilizing it.

- **Permeable Ditches:** Ditches lined with permeable materials and planted with vegetation can help in managing water runoff from slopes, reducing the risk of erosion and slope failure.

Mulching

- **Organic Mulching:** Applying organic mulch (such as wood chips or straw) to the slope surface helps to retain soil moisture, reduce erosion, and encourage the growth of vegetation. Over time, the mulch decomposes and adds nutrients to the soil, improving its structure and stability.

Natural Rock Barriers

- **Rock Mulching:** Placing rocks on the surface of the slope can help to protect the soil from erosion while allowing water to infiltrate. This method is often combined with vegetation for added stability.
- **Check Dams:** Small, vegetated check dams (e.g. live check dams, vegetative gabion check dams, and dry stone check dams) can be built on steep slopes to slow down water flow and encourage sediment deposition, stabilizing the slope.

Wetland and Riparian Restoration

- **Wetland Buffers:** Restoring wetlands near roadways can provide a buffer zone that absorbs runoff, filters pollutants, and reduces the impact of water flow on slopes. Wetlands also contribute to overall ecosystem health and biodiversity.
- **Riparian Zone Restoration:** Restoring riparian zones with native vegetation along rivers and streams helps to protect slopes from erosion and provides a natural barrier against water flow.

Monitoring and Adaptive Management

- **Regular Monitoring:** Implementing a monitoring plan to assess the effectiveness of NbS on slopes, allowing for timely interventions if any issues arise.
- **Adaptive Management:** Adjusting NbS strategies based on monitoring results and changing environmental conditions to ensure long-term slope stability.

6.2 Proposed Hybrid and NbS Techniques

Drainage Management

- **Check Dams:** Check dams are small barriers across drainage paths that slow down water flow, reduce erosion, and trap sediment. They are used in channels and ravines to manage runoff and prevent soil degradation during heavy rains (IRC:SP:42-2014&IRC:SP:50-2013).
- **Gabion Check Dams:** Gabion check dams use mesh cages filled with stones to slow water velocity and filter debris while stabilizing the channel. These flexible structures are ideal for steep streams and gullies, providing long-term erosion control.
- **Intermittent Live Check Dams:** Intermittent live check dams use natural materials like branches or brushwood to reduce runoff and promote vegetation growth. These semi-permanent barriers are suitable for restoring small streams and controlling short-term erosion.
- **Vegetative Gabion Check Dams:** Vegetative gabion check dams integrate plant material within gabion structures, providing erosion control while encouraging vegetation growth. This dual-purpose solution stabilizes banks and improves the ecological health of streams.



Structural Measures

- **Toe Wall (Tree Protection):** A wall built at the end of the slope of the earthen embankment to prevent slipping of earth or pitching on the embankment (IRC:40-2002).
- **Breast Wall:** Breast walls are normally stone masonry walls provided to protect the slopes of cutting in the natural ground from the action of weather (IS 14458 (Part 2): 1997).
- **Soil Nailing:** Soil nailing essentially involves reinforcing and strengthening existing grounds by installing closely spaced steel bars, called nails, into hill slopes. A soil-nailed system can override local weaknesses in the ground through stress redistribution and is less vulnerable than unsupported cuts to undetected adverse ground and groundwater conditions that have not been accounted for in the slope stability analysis (IRC:SP: 106-2015).
- **Subsurface Investigation:** Conducting geological surveys and soil testing to assess slope stability and determine appropriate stabilization measures. This is crucial for landslide-prone areas (IRC: SP:19-2020).

Channel and Bank Stabilization

- **Channel Improvement:** Channel improvement involves reshaping or realigning drainage channels to control water flow, prevent erosion, and manage flood risks. It is often combined with benching or drapery mesh to protect unstable slopes and improve water management.
- **Concrete Cladding:** It involves applying a concrete layer over steep slopes to prevent erosion and provide additional support. It is often combined with soil nailing or anchors for better results (IRC: SP:48-2023, IRC:SP:59-2019).
- **Stone Pavement:** Stone pavement involves placing stones along channels or slopes to protect surfaces from erosion. In areas with steep runoff, palisade or brush layering is often used alongside stone pavement to further stabilize slopes.
- **Dry Stone Rip-Rap:** Dry stone rip-rap consists of loose stones placed on slopes to control erosion and dissipate water energy. The technique is often applied along riverbanks or roadsides and can be supplemented with jute geotextiles or vegetative cover for added stability.
- **SD Anchors + Chain Link Mesh (Drapery Mesh):** This system uses high-tensile anchors and chain-link mesh to cover slopes, preventing rockfalls and erosion. It is effective on steep terrains and often combined with hydroseeding to establish vegetation and protect slopes long-term (IRC: SP 48 – 2023).

6.2.1 Panthaghati - NH5 Crossing

S. No	Measures	ID
1	Retaining wall, drainage vegetative stone paved surface channel and palisade	S-1
2	Clearing of the loose debris deposits, upstream drainage management (catch drain), vegetative surface channel, brush layering using woody cuttings, steel/synthetic mesh, and nailing	S-9
3	Retaining wall to support the uphill road, catch drain construction, stone rip-rap surface channel construction, and grass plantation (local species)	S-10
4	Clearing of the loos debris deposits, upstream drainage management (catch drain), vegetative surface channel, brush layering using woody cuttings, breast wall, wire/geosynthetic mesh net, soil nailing, hydroseeding	S-11
5	Check dam and plantation	
6	Reconstruction of retaining wall, drainage management and plantation (local grass species), culvert, drainage chute, debris flow barrier, RCC retaining wall, fencing on top of the RCC wall, soil nailing. This site, however, requires further investigation and topographic survey	S-12
7	Drainage management (catch drain), removing tilted trees and shrubs or grass plantation, vertical and horizontal surface channel construction, geotextile, breast wall, wire mesh, concrete cladding, soil nailing, hydroseeding	S-13
8	Vegetative gabion check dams	
9	Drainage management, reconstruction of retaining wall and plantation, check dams	S-14
10	Remove loose debris and rock blocks, upstream drainage management, remove the toilet, stone rip-rap vegetative surface channel and brush layering	S-15
11	Drainage management, and plantation of local grass species	S-16
12	Retaining wall, vegetative stone paved surface channel and palisade/brush layering; roadside drainage	S-2
13	Drainage management, catch drain, and Himalayan bamboo plantation	S-3
14	Vegetative stone paved catch drain (horizontal and vertical), plantation of local species with a long and strong root system, brush layering, and grass plantation, concrete cladding with fencing, benching of the slope, nailing, this site, however, requires further investigation and topographic survey;SD anchors + chain link mesh (drapery mesh, dismantling the identified houses)	S-4
15	Drainage management (cascade drainage, cross drainage), brush layering, concrete crib beam and plantation; nailing, concrete breast wall in stepped manner, dismantling the identified houses close to the sliding boundary; this site however requires further investigation and topographic survey	S-5
16	Drainage management (cascade drainage from the ridge to the roadside), removing loose debris materials, vegetative gabion wall and brush layering, soil nailing, this site however requires further investigation and topographic survey	S-6
17	Drainage management (applicable to all the sites)	All
18	Plantation of local plant species (applicable to all the sites)	All
19	Drainage management-construction catch drainage and plantation of local species with long and strong root systems, benching, soil nailing, toe/breast wall, jute geotextile	S-7

Table 6.1 - Proposed hybrid (NbS + civil engineering) techniques: Panthaghati - NH5 Crossing Road Alignment

S. No	Measures	ID
1	Brush Layering	S-1
2	Brush Layering	S-2
3	Drainage Management-Check Dams	D-1
4	Toe Wall (Tree Protection)	T-1
5	Toe Wall (Tree Protection)	T-2
6	Dry Stone Rip-Rap	DS-1
7	Brush Layering	S-3
8	Drainage Management - Check Dams	D-2
9	Toe Wall (Tree Protection)	T-3
10	Toe Wall (Tree Protection)	T-4
11	Drainage Management -Check Dams	D-3
12	Toe Wall (Tree Protection)	T-5
13	Drainage Management - Check Dams	D-4
14	Drainage Management -Check Dams	D-5
15	Toe Wall (Tree Protection)	T-6
16	Toe Wall (Tree Protection)	T-7
17	Toe Wall (Tree Protection)	T-8
18	Toe Wall (Tree Protection)	T-9
19	Drainage Management - Check Dams	D-6
20	Toe Wall (Tree Protection)	T-10
21	Brush Layering	S-4
22	Bracing of Trees	

S-Slope Protection, D-Drainage Management, T-Tree Protection, DS-Dry Stone Rip

7 Suggestive Implementation Plan

7.1 Objectives and Scope

7.1.1 Objective

The objective of this implementation plan is to stabilize the slopes along the Panthaghati-Crossing and Kennedy Chowk-Annadale Helipad Road sections in Shimla. This will reduce the risk of landslides and ensure the safety of road users, nearby settlements, and infrastructure.

7.1.2 Scope of Work

The implementation will involve the following key activities:

- Site preparation and debris removal
- Drainage improvement and management
- Slope stabilization including Nature-based Solutions (NbS)
- Structural reinforcement
- Monitoring and maintenance

7.2 Phased Implementation Plan

A Phase Implementation Plan refers to a structured approach to carrying out a project or set of activities in stages, rather than attempting to complete everything at once. Each phase is designed to accomplish specific objectives within a defined timeframe, with the outcomes of one phase often influencing the start or direction of the next.

- Phase 1 (Immediate): 0-6 months
- Phase 2 (MediumTerm): 6-18 months
- Phase 3 (LongTerm): 18 months - 3 years

7.2.1 Phase 1:Immediate Actions

Site Preparation

- Remove loose debris and unwanted material from the slopes.
- Stabilize the ground temporarily with geotextile covers (just before monsoon).
- Clear drainage channels of any blockages.

Drainage Improvement

- Repair and install proper drainage systems to prevent water accumulation on slopes.
- Construct vegetative stone-paved surface channels to guide surface runoff safely away from the slopes.

Slope Stabilization

- Begin the plantation of local grass species and use geotextile to cover exposed surfaces.
- Implement brush layering using local plant cuttings for immediate slope protection.

Monitoring

- Set up regular inspections to monitor the stability of the slopes and the effectiveness of immediate measures.
- Install sensors for real-time monitoring of slope movement in critical areas.

7.2.2 Phase 2: Medium-Term Actions

Structural Reinforcement

- Construct retaining walls and gabion check dams at critical locations to provide structural support to the slopes.
- Install soil nailing and other geotechnical measures where necessary to reinforce the slopes.

Enhanced Drainage Management

- Implement stepped trench/chute drainage systems along the slopes to manage surface runoff more effectively.
- Extend and connect drainage systems to the nearest natural drainage channels.

Advanced Vegetative Stabilization

- Continue planting local tree species with long and strong root systems.
- Install vegetative gabion check dams to further stabilize the slopes.

Community Involvement

- Engage local communities in maintaining slope stabilization measures, particularly vegetative solutions.

7.2.3 Phase 3: Long-Term Actions

Comprehensive Slope Stabilization

- Complete the construction of long-term structural measures, including concrete cribs and anchor bolts/nailing/cladding, etc. where necessary.
- Finalize the planting of trees and shrubs, ensuring a dense vegetative cover that stabilizes the soil.

Highway Slope Monitoring System

- Implement a Highway Slope Monitoring and Maintenance System, incorporating modern geotechnical monitoring tools.
- Ensure regular geotechnical inspections and maintenance of the installed slope protection measures.

Risk Mitigation and Preparedness

- Develop emergency response plans in case of landslide events.
- Train local authorities and communities on slope monitoring and emergency response.

7.3 Resource Allocation

In the context of a project,resources refer to the various inputs required to complete the project successfully. These inputs include materials, labour, equipment, time, and financial capital. Resource allocation is the process of assigning and managing these resources effectively to achieve the project goals within the given constraints.

Human Resources

- Engage geotechnical engineers, environmental scientists, and local contractors for implementation.
- Form a task force for regular monitoring and maintenance.

Materials

- Source local plant species for vegetative stabilization.
- Procure necessary materials for drainage systems, retaining walls, and other structural supports.

Budget

- Allocate budget in phases, ensuring funds for immediate actions are available promptly.
- Plan for contingencies and long-term maintenance.

7.4 Monitoring and Evaluation

The monitoring and evaluation (M&E) plan for the roadside slope protection measures, as discussed above, is a crucial component of ensuring the long-term success and sustainability of the project. The suggested M&E plan is divided into the following four categories.

7.4.1 Comprehensive Monitoring Strategy

- **Regular Inspections:** The plan includes both routine and event-triggered inspections, ensuring that potential issues are identified and addressed promptly, particularly during critical periods like the monsoon season.
- **Use of Technology:** Incorporating modern tools such as inclinometers, piezometers, and drones adds a layer of precision and early warning capability to the monitoring efforts, which is essential in a region prone to landslides.
- **Community Involvement:** Engaging the local community in reporting and monitoring activities enhances the plan by leveraging local knowledge and ensuring a rapid response to emerging issues.

7.4.2 Structured Maintenance Approach

- **Vegetative and Structural Maintenance:** The plan addresses both vegetative and structural components, ensuring that all aspects of slope stabilization are maintained over time. This dual focus helps in managing both immediate and long-term slope stability.
- **Erosion Control:** Proactive measures like reapplying geotextiles (IRC SP 59) and maintaining drainage systems are included, which are essential for preventing further erosion and maintaining the integrity of the slope.

7.4.3 Clear Documentation and Reporting

- **Maintenance Logs and Annual Reviews:** Keeping detailed records of all maintenance activities and conducting annual reviews allows for continuous improvement and adjustment of strategies based on real-world performance.

7.4.4 Flexibility and Adaptability

- **Emergency Preparedness:** The plan accounts for emergency scenarios, ensuring that the project can respond quickly to unforeseen events, such as landslides or heavy rainfall, minimizing damage and disruption.

- **Phased Resource Allocation:** The phased approach to resource allocation ensures that critical resources are available when needed, reducing the risk of delays or resource shortages.
- This plan aims to ensure that the slopes along the identified road sections are stabilized in a sustainable and resilient manner, reducing the risk of landslides and protecting both the infrastructure and the surrounding communities.

8 Concluding Remarks

8.1 Conclusions

- The field observation study of identified landslides and slope failures revealed several important issues related to their causes along the NH Crossing to Panthaghati and Kennedy Chowk to Annadale, as well as management strategies hereafter.
- The 15 trouble sites investigated on NH5, from the NH crossing to Panthaghati, were classified into three categories: (1) Debris flow slides, (2) Landslides, which also include slump slides, and (3) Compound slope failures involving more than one type.
- The road from Kennedy Chowk to Annadale has not experienced major landslides; however, visual observations revealed a number of slope maintenance and management issues. These included road subsidence, shallow slope failure and subsidence, erosion, cracking, and tree bending.
- Several natural streams that cross the highways were found encroached upon, with household garbage/C&D and other waste dumped on or near the streams. The continuous dumping of a variety of waste, including plastic, not only altered the morphology of the stream but also created instabilities on the course as well as on the side slopes.
- Though there was no hourly rainfall data available, the precipitation in Shimla on July 7-11, 2023, was unusually high at 268 mm against its normal 35mm for that five-day period. This represented a deviation of over 600%. Additionally, from July 14-24, 2023, the area received 430.8 mm of rain, which was 254% higher than the normal (121.6 mm) for that duration. This extreme rainfall caused widespread destruction, including landslides, resulting in severe breakdown of surface mobility and increased hardship and risk for the people.
- The damage and disruption caused by landslides/slope failure during July-August 2023 were mostly observed on/along the roads, particularly where natural streams are poorly maintained and affected by several anthropogenic activities. If appropriate measures are not taken, similar disasters may recur during future rainfall events.
- To stabilize slopes, NbS offer a cost-effective and sustainable alternative. However, it is important to note that not all types of landslides can be prevented solely through NbS. In such cases, hybrid solutions can be effective. Therefore, a hybrid that incorporates both NbS and engineering solutions is recommended.
- A surface runoff model was established using the available monthly rainfall data to identify erosion-prone areas and potential water accumulation. The model revealed that the slope failure along two road alignments was triggered by intense rainstorms. Among several causal factors, human activities were identified as the primary cause.

8.2 Suggestive Actions

1. The suggestive/preventive measures suggested in the report are mainly based on field observations and available historical data/maps/discussion and not on detailed integrated geological, geotechnical, and geomorphological investigations. It is, therefore, suggested that the long-term measures recommended in the report be designed based on these suggested investigations during the DPR preparation.
2. The scheme of measures suggested for each landslide must be implemented as a whole scheme, divided into phases: short-term, medium-term, and long-term. Implementing only part of the scheme while neglecting others may not achieve the desired outcomes and may prove to be counter productive.
3. Given the recent disasters and the inherently fragile terrain that experiences high-intensity rains along with the possibility of unpredicted heavy storms, it is important to prepare the inventory of the existing highway slopes, including landslides. This inventory will help identify both active and dormant landslides/unstable slopes by examining historical background in relation to current ground realities, x-raying the conditions, and causes of their recurrences and correlating with ground conditions, estimating human and economic losses, etc. thereby helping to prioritize the slopes for appropriate action.
4. Highways that are constructed without anticipating vulnerabilities and risk assessment tend to develop frequent problems for slope stability and, therefore, cannot be disaster resilient. Similarly, to maintain the highways in a sustainable manner post-construction, it is necessary to classify the highway slopes (including already identified landslides) based on their degree of propensity (susceptibility) to sliding/failure and risk from them. Moreover, resources for earthworks protection and repairs are frequently insufficient, requiring prioritization of needs. This underscores the importance of conducting a thorough risk assessment.
5. Generally, there is an accepted method for the maintenance of highways but there is no such practice (or guidelines) to proactively maintain the highway slopes, except otherwise when a landslide/slope failure happens. It is therefore recommended that a Highway Slope Monitoring and Maintenance System (HSMM) be developed, which starts with uncovering susceptible/hazardous slopes. The system will ensure that the hazardous slopes are effectively maintained, and the concerned agencies and the common people are kept informed about impending risks, allowing for appropriate and timely action to prevent loss of life. Additionally, the HSMM would help improve the design and methods of maintenance of highway and highway slopes, ensuring safe and uninterrupted operation of these roads. The proposed HSMM, if developed, will go a long way in the safety and sustainability of the highway and highway slopes, post-construction. On the contrary, the consequences of delay in dealing with the highway slope vulnerabilities may not only add

to the number and expanse of existing active and dormant landslides and further endanger highway safety but also rob us of the opportunity to effectively manage problems that have already become complex and challenging.

6. It is crucial to identify specific sites for debris disposal, as debris is highly susceptible to further sliding in the valley. When selecting debris disposal sites, it is advisable to follow the IRC Guidelines for the Use of Construction and Demolition Waste in the Road Sector (IRC 121-2017) for detailed technical guidance.

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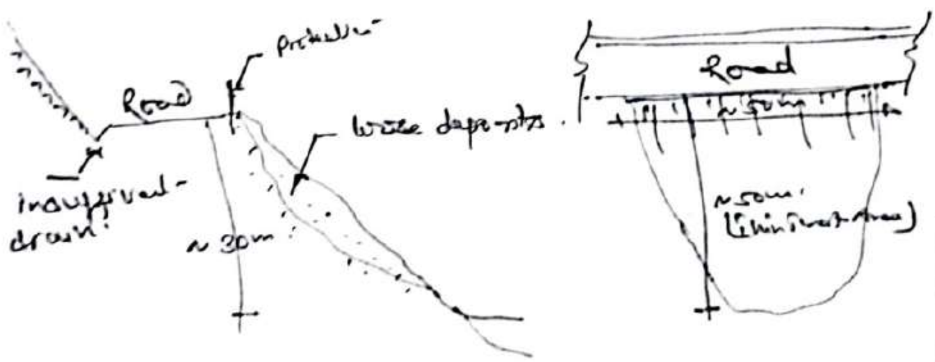
Annexure 1
Field Check List

Field Check List for Landslide Mapping (3)

Shimla Town

Name of Location	CROSSING AREA	Date of Survey:	24th July 2024
Lat./Long.	31.098774; 77.153516	Date of Landslide	old
Type of Road	NH 5		
Name of Surveyor:	S. Dawkita & Team		
Name of Local Person:		Contact No.	
Type of Landslide	subsidence (Shallow)	Bed rock exposure:	—
Landslide Activity:	Dormant	Type of Bedrock:	—
Landslide Size:	30 x 100 m.	Discontunity	—
Soil Type:	Silty. Clay	Soil Depth:	Road side spoils deposits.
Slope Degree	~ 40°	Slope Aspect:	S
Landuse Type:	Shrubs/forest.		
Presence of Seepage Water:	NO		
Stream Nearby:	No	Drainage Condition:	—

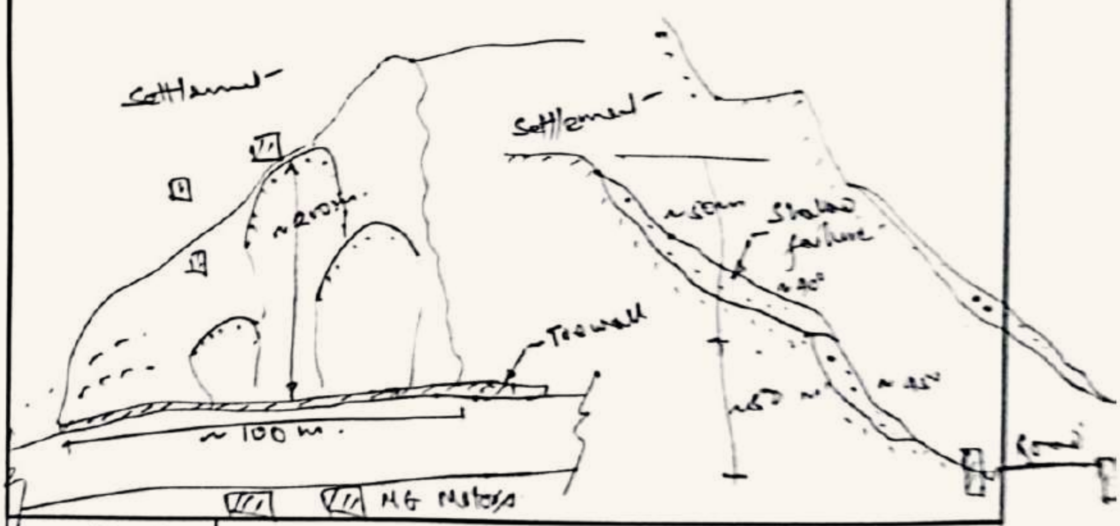


Damaged Caused	
No. of Lives:	—
No. House(s):	— Vulnerable HH: —
Agricultural Land:	—
Road:	Yes
Others Damage:	-
Causal Factor:	Slope/Soil Type/Ground Water/Road/Human activity/Landuse/Others/ Surface Runoff.
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

Shimla Town

Name of Location	Lalpani (MG Mistora)	**Date of Survey:**	24 Jun 2024
Lat./Long.	31.150282, 77.186376	Date of Landslide	
Type of Road	NH5		
Name of Surveyor:	S Dhakal & Team.		
Name of Local Person:		**Contact No.**	
Type of Landslide	Active shallow failure	Bed rock exposure:	Yes, occasional
Landslide Activity:	Active	Type of Bedrock:	Phyllites
Landslide Size:	~(80 × 250) m.	Discontunity	–
Soil Type:	Colluvium, silty-clay	Soil Depth:	1-3 m. (deeper in toe area)
Slope Degree	35°-45°	Slope Aspect:	S
Landuse Type:	Barren with partial presence of trees.		
Presence of Seepage Water:	No but open drainage & run off from the settlement uphill.		
Stream Nearby:	No.	Drainage Condition:	—

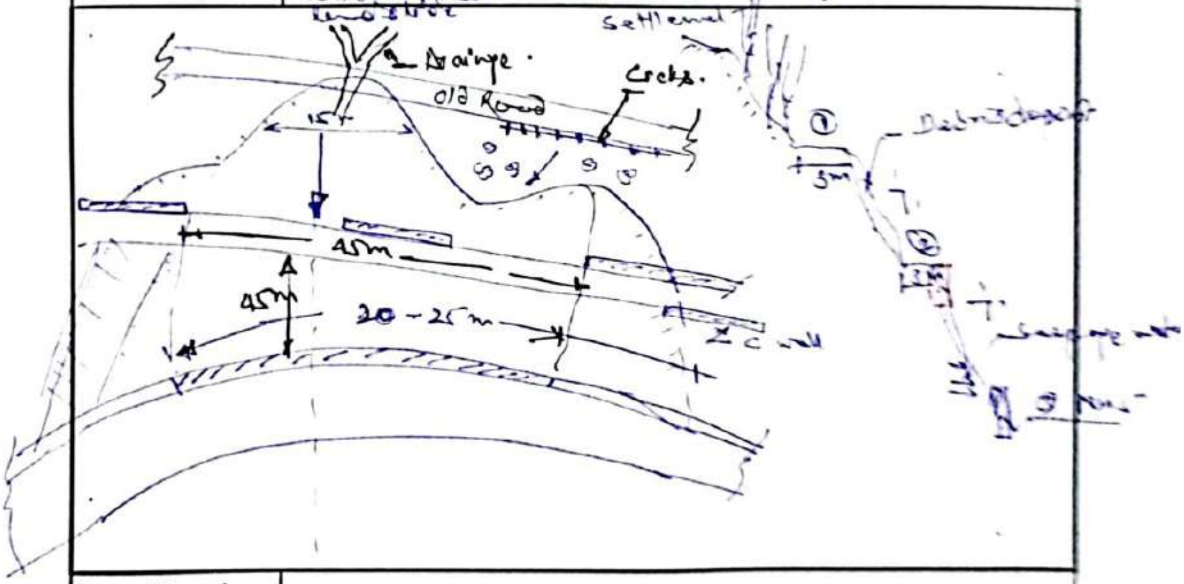


Damaged Caused	
No. of Lives:	—
No. House(s):	— Vulnerable HH: 3-4
Agricultural Land:	-
Road:	Yes
Others Damage:	—
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others / open drainage
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

Shimla Town

Name of Location	Rajvir Motors.	**Date of Survey:**	24 June 2024
Lat./Long.	31.095846, 77.17064	**Date of Landslide**	Aug 2023
Type of Road	NH 05		
Name of Surveyor:	SDSU Kelta & Team		
Name of Local Person:		**Contact No.**	
Type of Landslide	Deep seated/ complex	**Bed rock exposure:**	upper part of landslide
Landslide Activity:	Active	**Type of Bedrock:**	phyllites
Landslide Size:	(50 x 80) m	**Discontunity**	—
Soil Type:	Colluvium deposit (silty loamy)	**Soil Depth:**	2 - 3 m
Slope Degree	40 - 45	**Slope Aspect:**	S
Landuse Type:	Barren, Road, Forest-		
Presence of Seepage Water:	Yes. in the Toe side of landslide		
Stream Nearby:	[illegible] through middle of the landslide	**Drainage Condition:**	Dry.

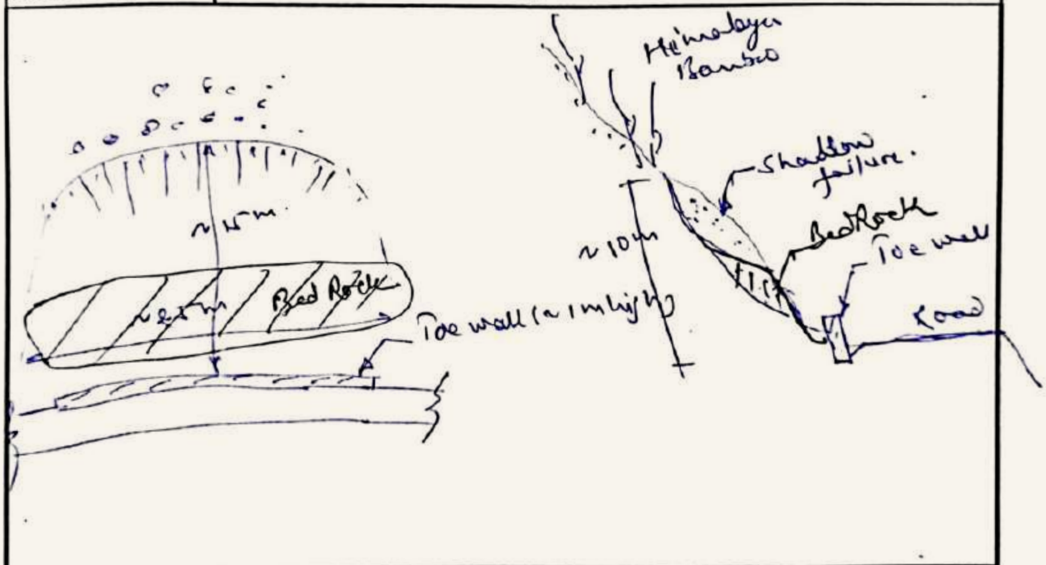


Damaged Caused	
No. of Lives:	—
No. House(s):	— **Vulnerable HH:** 3 HH.
Agricultural Land:	—
Road:	Yes.
Others Damage:	—
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

Shimla Town

Name of Location		**Date of Survey:**	24 June 2024
Lat./Long.	31.094016, 77.170611	**Date of Landslide**	Aug 2023
Type of Road	NH5		
Name of Surveyor:	Chandrakala & Team.		
Name of Local Person:	-	**Contact No.**	
Type of Landslide	Shallow	Bed rock exposure:	–
Landslide Activity:	Active	Type of Bedrock:	–
Landslide Size: ~	(25 × 15)m	Discontunity	–
Soil Type:	Silty loam.	Soil Depth:	
Slope Degree	~(40 - 45)°	Slope Aspect:	S
Landuse Type:	Forest-		
Presence of Seepage Water:	NO		
Stream Nearby:	–	Drainage Condition:	–

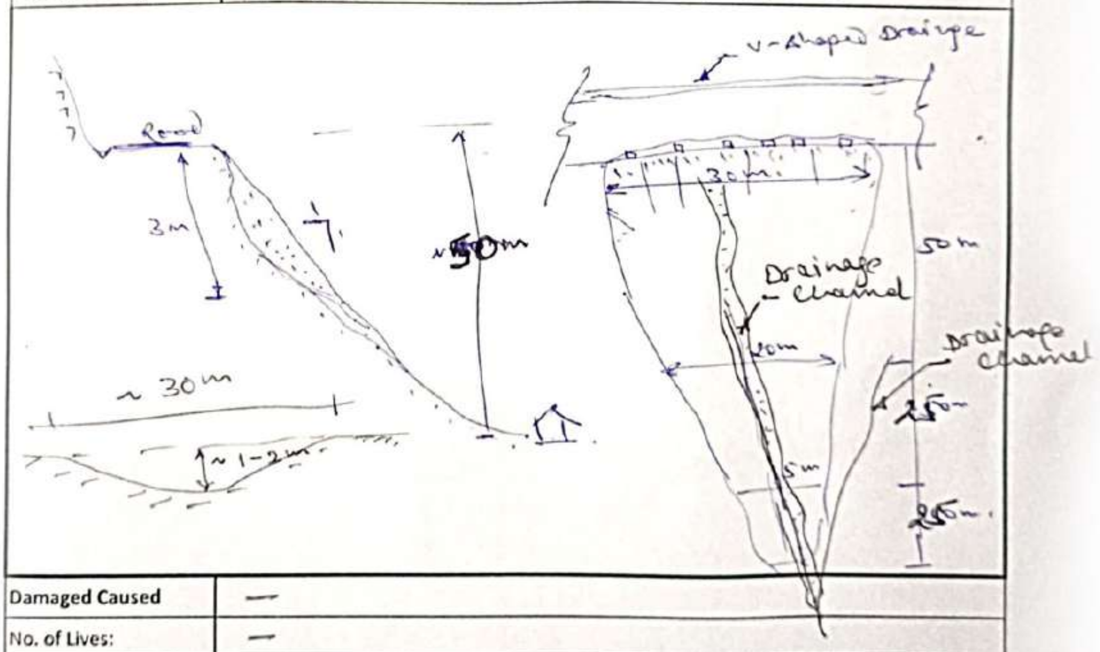


Damaged Caused			
No. of Lives:	–		
No. House(s):	–	Vulnerable HH:	–
Agricultural Land:	–		
Road:	Tree, Road Blocked		
Others Damage:	–		
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

Field Check List for Landslide Mapping

Shimla Town

Name of Location	CROSSING AREA	Date of Survey:	24 June 2024
Lat./Long.	31.09718, 77.15328	Date of Landslide	Aug. 2023
Type of Road	NH5		
Name of Surveyor:	S. Dutta & Team		
Name of Local Person:		Contact No.	
Type of Landslide	Shallow debris	Bed rock exposure:	NA
Landslide Activity:	Active	Type of Bedrock:	
Landslide Size:	(30 x 100) m	Discontunity	
Soil Type:	Silty-clay	Soil Depth:	Roadside filled materials
Slope Degree	≈ 40 – 45°	Slope Aspect:	S-E
Landuse Type:	Forest		
Presence of Seepage Water:	No, But presence of drainage pipe		
Stream Nearby:	Yes ≈ 20 m	Drainage Condition:	Seasonal

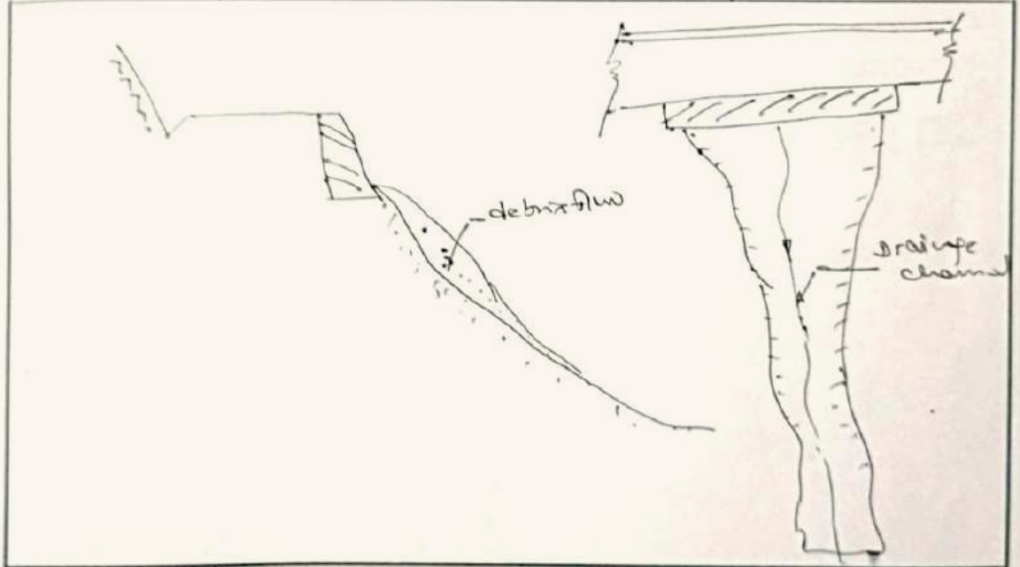


Damaged Caused	—		
No. of Lives:	—		
No. House(s):	—	Vulnerable HH:	3-4 HH down hill.
Agricultural Land:	—		
Road:	Yes road side slope failure		
Others Damage:	forest trees.		
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

Field Check List for Landslide Mapping

Shimla Town

Name of Location	CROSSING AREA	Date of Survey:	24 July 2024
Lat./Long.	31.03[illegible], 77.153683	Date of Landslide	Aug. 2023 (Before)
Type of Road	NH 05		
Name of Surveyor:	[illegible] & Team.		
Name of Local Person:		Contact No.	
Type of Landslide	Old debris flow	Bed rock exposure:	NO
Landslide Activity	dormant	Type of Bedrock:	NA
Landslide Size	20 x 200 m	Discontunity	NA
Soil Type	Silty - loam	Soil Depth:	Roadside filled materials.
Slope Degree	40-45°	Slope Aspect:	S-E
Landuse Type:	Forest		
Presence of Seepage Water	NO		
Stream Nearby:	Yes, drainage line	Drainage Condition:	Dry, seasonal.

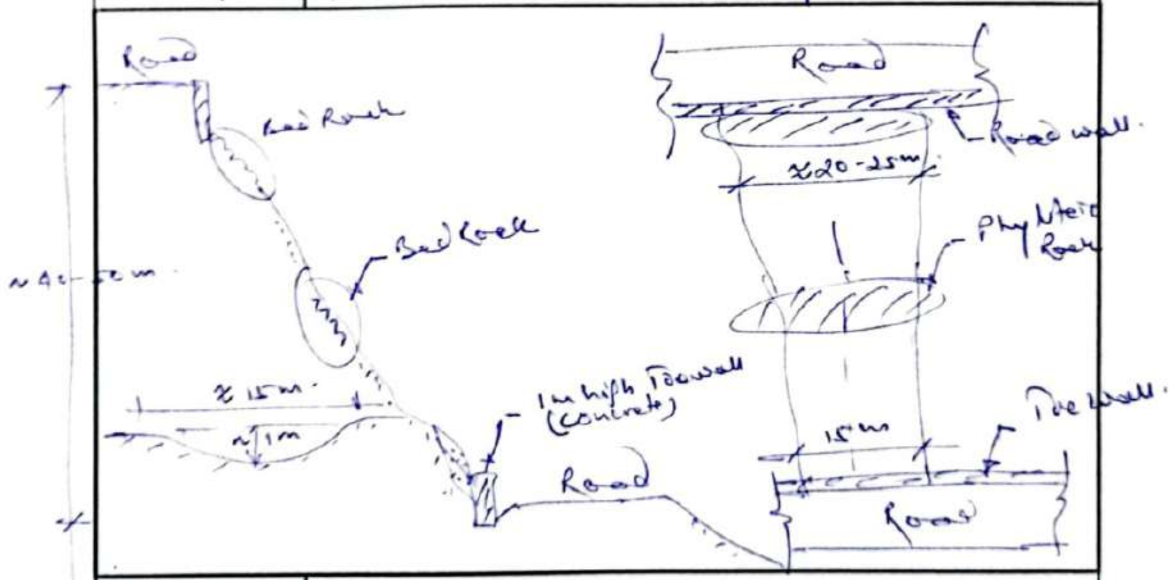


Damaged Caused			
No. of Lives:	—		
No. House(s):	—	Vulnerable HH:	3-4 HH.
Agricultural Land:	—		
Road:	Yes.		
Others Damage:	–		
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others / Stream.		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

Field Check List for Landslide Mapping

Shimla Town

Name of Location	–	**Date of Survey:**	25 Jun 2024
Lat./Long.	31.087732; 77.174348	**Date of Landslide**	
Type of Road	NH-5		
Name of Surveyor:	S Dwivedi & Team		
Name of Local Person:	–	**Contact No.**	
Type of Landslide	Shallow	**Bed rock exposure:**	– Upper part weathered phyllites
Landslide Activity:	Active	**Type of Bedrock:**	
Landslide Size:	(15 × 45) m	**Discontunity**	–
Soil Type:	colluvium, silty loam	**Soil Depth:**	Shallow (0.5 – 1m)
Slope Degree	(45 - 50)	**Slope Aspect:**	S-W
Landuse Type:	Forest		
Presence of Seepage Water:	NO		
Stream Nearby:	Yes	**Drainage Condition:**	dry

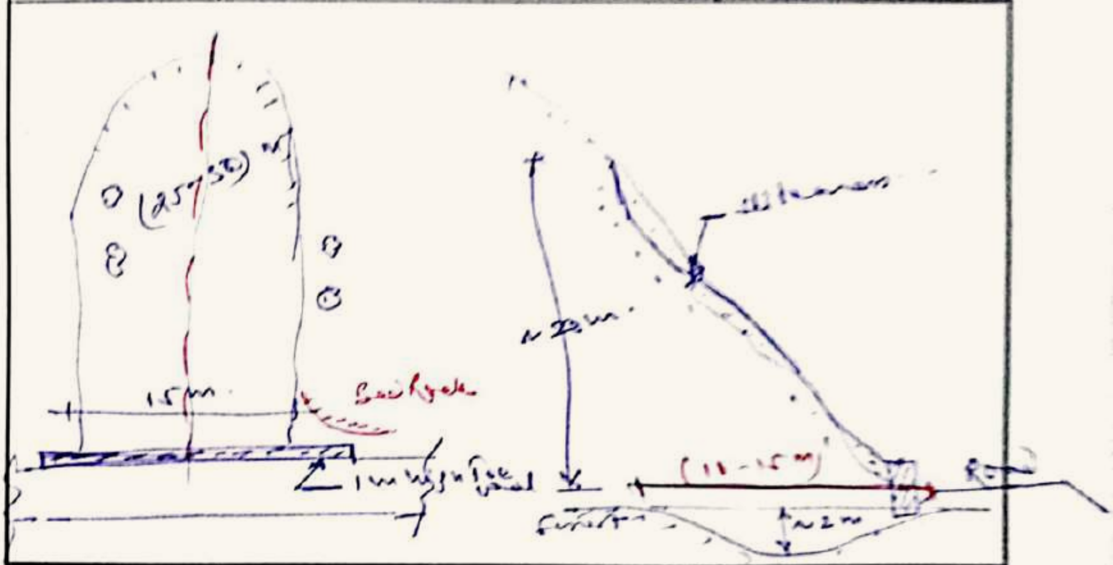


Damaged Caused			
No. of Lives:	–		
No. House(s):	–	**Vulnerable HH:**	–
Agricultural Land:	–		
Road:	Road Blocked		
Others Damage:	–		
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

Field Check List for Landslide Mapping

Mirik Team

Name of Location		Date of Survey:	[illegible]
Lat./Long.	[illegible]	Date of Landslide:	[illegible]
Type of Road	[illegible]		
Name of Surveyor:	[illegible]		
Name of Local Person:		Contact No.	
Type of Landslide	[illegible]	Bed/Jack/Japanese:	[illegible]
Landslide Activity:	Active	Type of Bedrock:	–
Landslide Size:	[illegible]	Discontinuity:	–
Soil Type:	[illegible]	Soil Depth:	[illegible]
Slope Degree:	[illegible]	Slope Aspect:	[illegible]
Landuse Type:	[illegible]		
Presence of Seepage Water:	[illegible]		
Stream Nearby:	–	Drainage Condition:	[illegible]

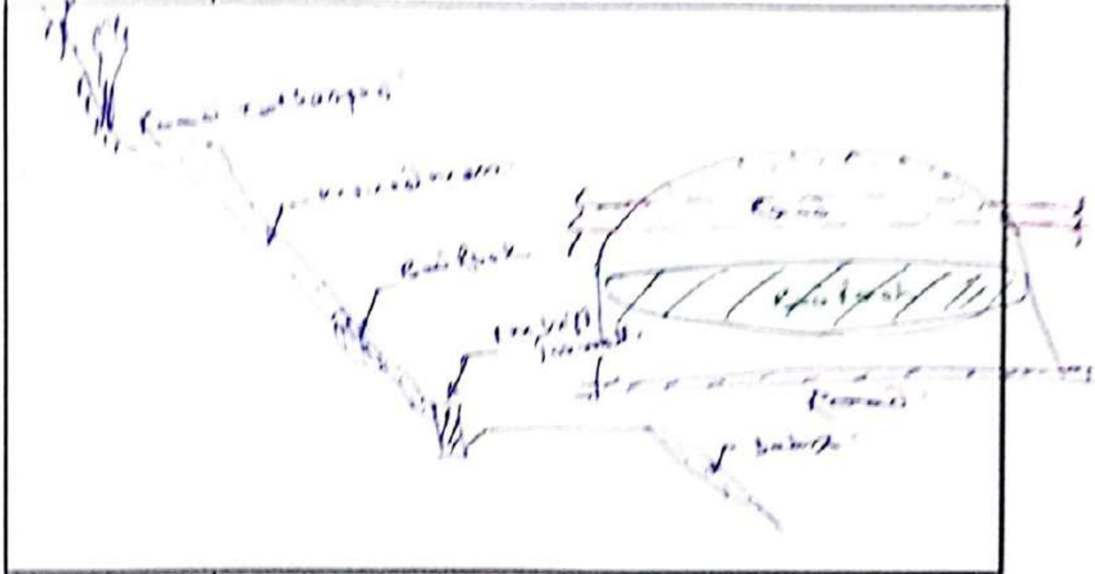


Damaged Caused	
No. of Lives:	—
No. House(s):	— Vulnerable HH: —
Agricultural Land:	—
Road:	Road blocked
Others Damage:	—
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

Mandi Town

Name of Location		Date of Survey:	[illegible]
Lat /Long	[illegible]	Date of Landslide	[illegible]
Type of Road	[illegible]		
Name of Surveyor:	[illegible]		
Name of Local Person:		Contact No.	
Type of Landslide	[illegible]	Bed rock exposure	
Landslide Activity	[illegible]	Type of Bedrock:	
Landslide Size	[illegible]	Discontinuity	
Soil Type	[illegible]	Soil Depth:	[illegible]
Slope Degree	[illegible]	Slope Aspect:	[illegible]
Landuse Type	[illegible]		
Presence of Seepage Water:	—		
Stream Nearby	—	Drainage Condition:	—

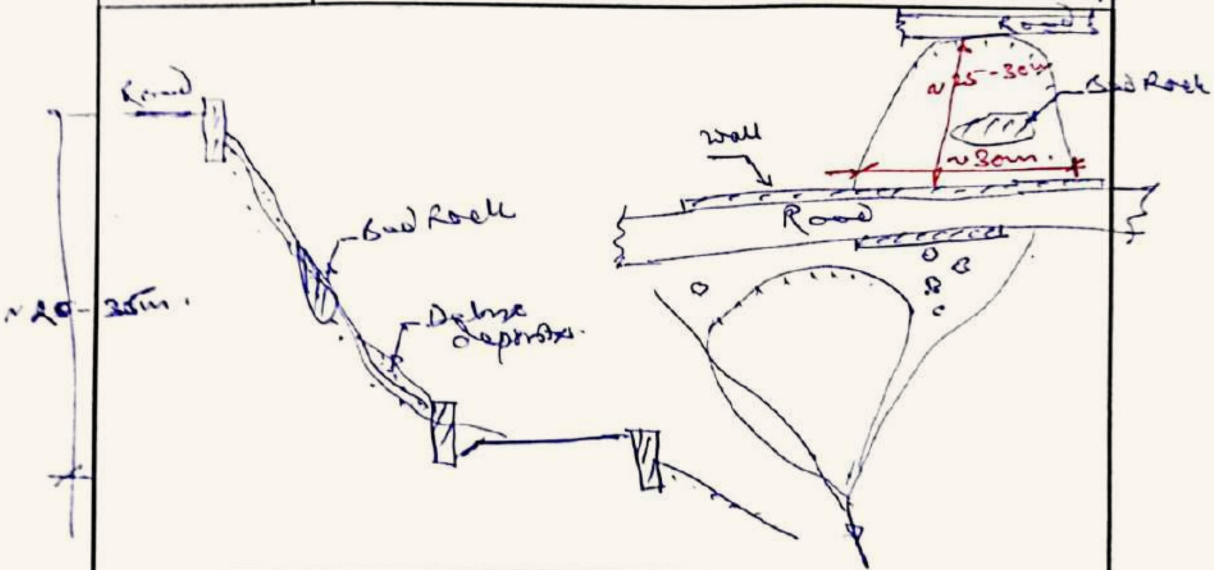


Damaged Caused			
No. of Lives:	—		
No. House(s):	—	Vulnerable HH:	—
Agricultural Land:	—		
Road:	[illegible]		
Others Damage:	—		
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

Field Check List for Landslide Mapping

Shimla Town

Name of Location		Date of Survey:	25 June 2024
Lat./Long.	[illegible], 77.173266	Date of Landslide	Aug. 2023
Type of Road	NH 5		
Name of Surveyor:	[illegible] & Team.		
Name of Local Person:		Contact No.	
Type of Landslide	[illegible]	Bed rock exposure:	Yes
Landslide Activity:	Dormant	Type of Bedrock:	weathered Phyllites
Landslide Size:	(50 x 45) m.	Discontunity	—
Soil Type	Colluvium.	Soil Depth:	(1–2) m
Slope Degree	45–50°	Slope Aspect:	E-W
Landuse Type:	forest		
Presence of Seepage Water:	—		
Stream Nearby:	Yes	Drainage Condition:	Unmaintained. Dry.

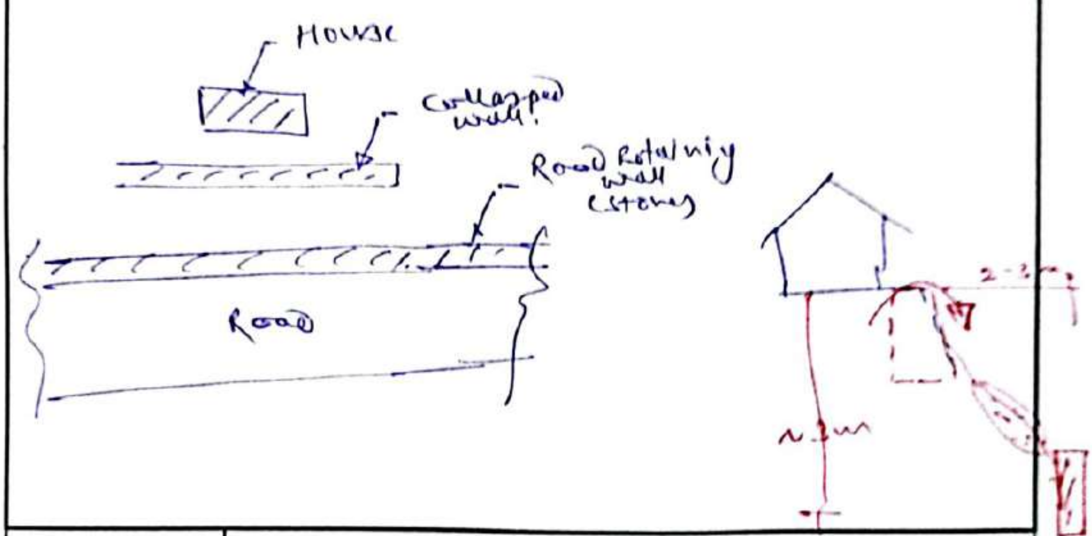


Damaged Caused	
No. of Lives:	—
No. House(s):	— Vulnerable HH:
Agricultural Land:	—
Road:	Road blocked
Others Damage:	—
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

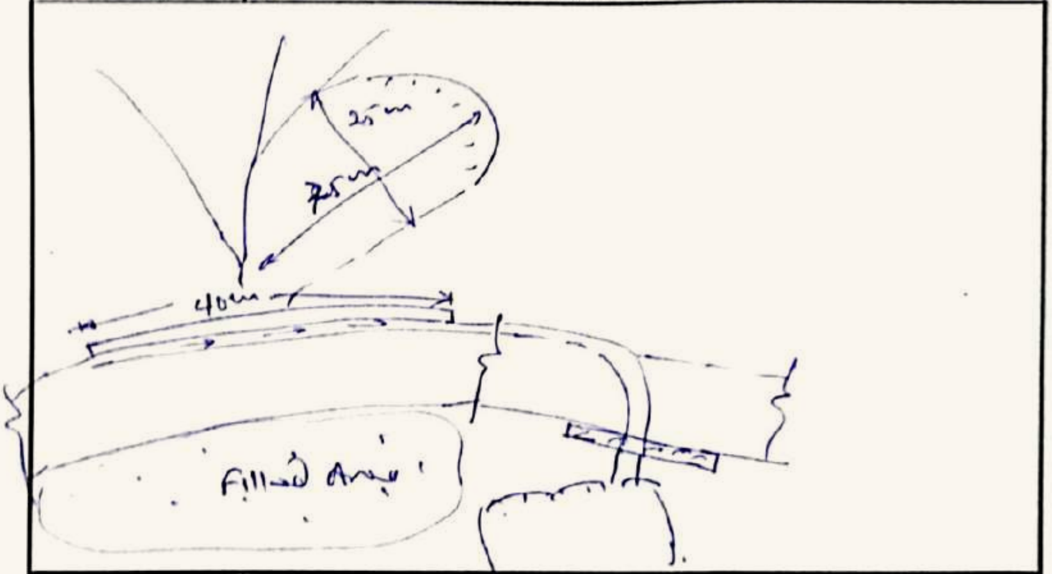
Shimla Town

Name of Location	[illegible]	Date of Survey:	[illegible]
Lat./Long.		Date of Landslide	Aug [illegible]
Type of Road	NH-5		
Name of Surveyor:			
Name of Local Person:		Contact No.	
Type of Landslide	Shallow	Bed rock exposure:	
Landslide Activity:	Dormant	Type of Bedrock:	weathered Rock
Landslide Size:	[illegible]	Discontunity	–
Soil Type:	Colluvium comprising silty [illegible]	Soil Depth:	filled slope
Slope Degree	~ 45 - 50	Slope Aspect:	
Landuse Type:	Bare surface		
Presence of Seepage Water:	–		
Stream Nearby:	–	Drainage Condition:	–



Damaged Caused	
No. of Lives:	–
No. House(s):	– Vulnerable HH: 1
Agricultural Land:	–
Road:	–
Others Damage:	–
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping Shimla Town			
Name of Location	[illegible] Nagar / [illegible] Shimla	Date of Survey:	25 June 2024
Lat./Long.	31.0[illegible], 77.17[illegible]	Date of Landslide	Aug. 2023
Type of Road	NH-5		
Name of Surveyor:	[illegible]		
Name of Local Person:	–	Contact No.	
Type of Landslide	Slumping (active)	Bed rock exposure:	–
Landslide Activity:	Active	Type of Bedrock:	–
Landslide Size:	(70 x 25) m	Discontunity	–
Soil Type:	[illegible] (Silty Loamy)	Soil Depth:	2-3 m
Slope Degree	35-40	Slope Aspect:	~~[illegible]~~ W
Landuse Type:	forest / Barren (private)		
Presence of Seepage Water:	In monsoon / Seasonal		
Stream Nearby:	Yes	Drainage Condition:	Modified across the road

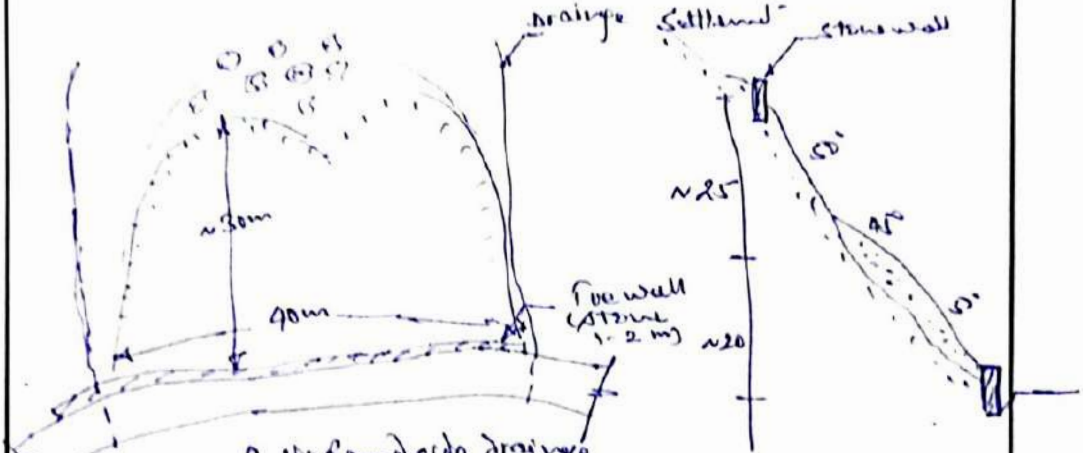


Damaged Caused	
No. of Lives:	–
No. House(s):	– Vulnerable HH:
Agricultural Land:	–
Road:	Yes, Road blocked
Others Damage:	–
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others Trees
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

Shimla Town

Name of Location	Vikash Nagar	**Date of Survey:**	25 June 2024
Lat./Long.	31.084896, 77.179505	**Date of Landslide**	
Type of Road	NH-5		
Name of Surveyor:	SDMA & Team		
Name of Local Person:	Ashok Sharma	**Contact No.**	
Type of Landslide	Shallow	**Bed rock exposure:**	weathered Phyllites
Landslide Activity:	Active	**Type of Bedrock:**	Phyllites
Landslide Size:	(40×30)	**Discontunity**	fractured Rock
Soil Type:	Colluvial gravelly soil	**Soil Depth:**	(1-2) m
Slope Degree	40°-45°	**Slope Aspect:**	S-W
Landuse Type:	Forest		
Presence of Seepage Water:	Yes		
Stream Nearby:	Adjacent	**Drainage Condition:**	Roadside Drainage



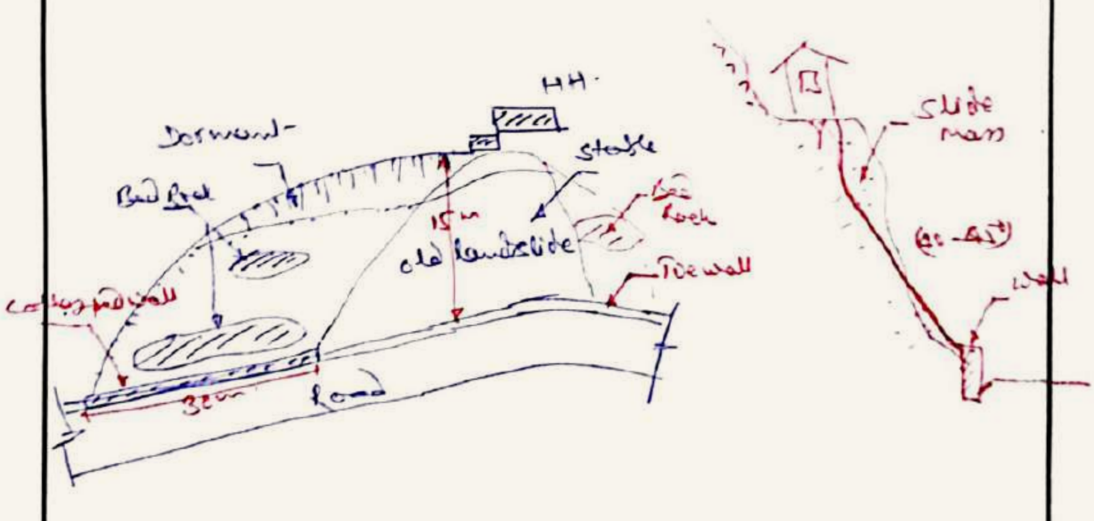
1) No Roadside drainage
2) ground water (seepage water)
3) Steep slope & loose soil

Damaged Caused			
No. of Lives:	—		
No. House(s):	—	**Vulnerable HH:**	4-5
Agricultural Land:	—		
Road:	Road Blocked		
Others Damage:	—		
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

Field Check List for Landslide Mapping

Shimla Town

Name of Location	[illegible] / Shiva Mandir	Date of Survey:	25 July 2024
Lat./Long.	31.0[illegible], 77.12192	Date of Landslide	Aug 23
Type of Road	NH-5		
Name of Surveyor:	[illegible]		
Name of Local Person:		Contact No.	
Type of Landslide	Shallow	Bed rock exposure:	[illegible] Block / [illegible] Block
Landslide Activity:	Active	Type of Bedrock:	weathered
Landslide Size:	(15 x 20) m	Discontunity	—
Soil Type:	Colluvium	Soil Depth:	2 - 3 m [illegible]
Slope Degree	(40 - 45)	Slope Aspect:	S - W
Landuse Type:	Barren land / Forest on left side		
Presence of Seepage Water:	No		
Stream Nearby:	—	Drainage Condition:	—

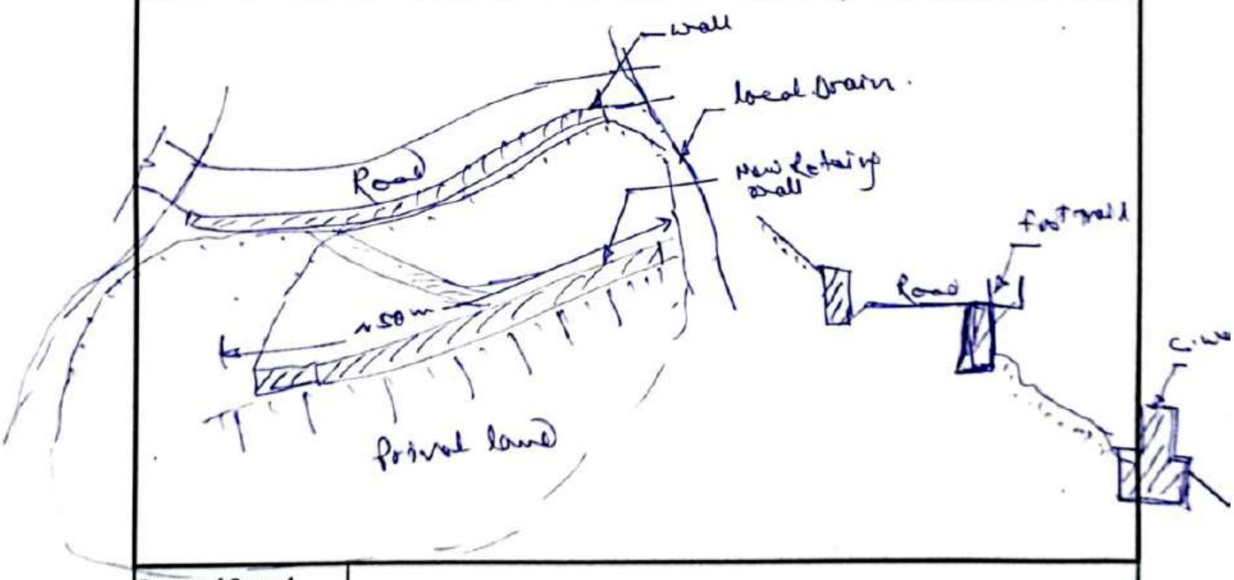


Damaged Caused	
No. of Lives:	—
No. House(s):	— Vulnerable HH: 2 - 3
Agricultural Land:	—
Road:	Road Blocked
Others Damage:	—
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others

Field Check List for Landslide Mapping

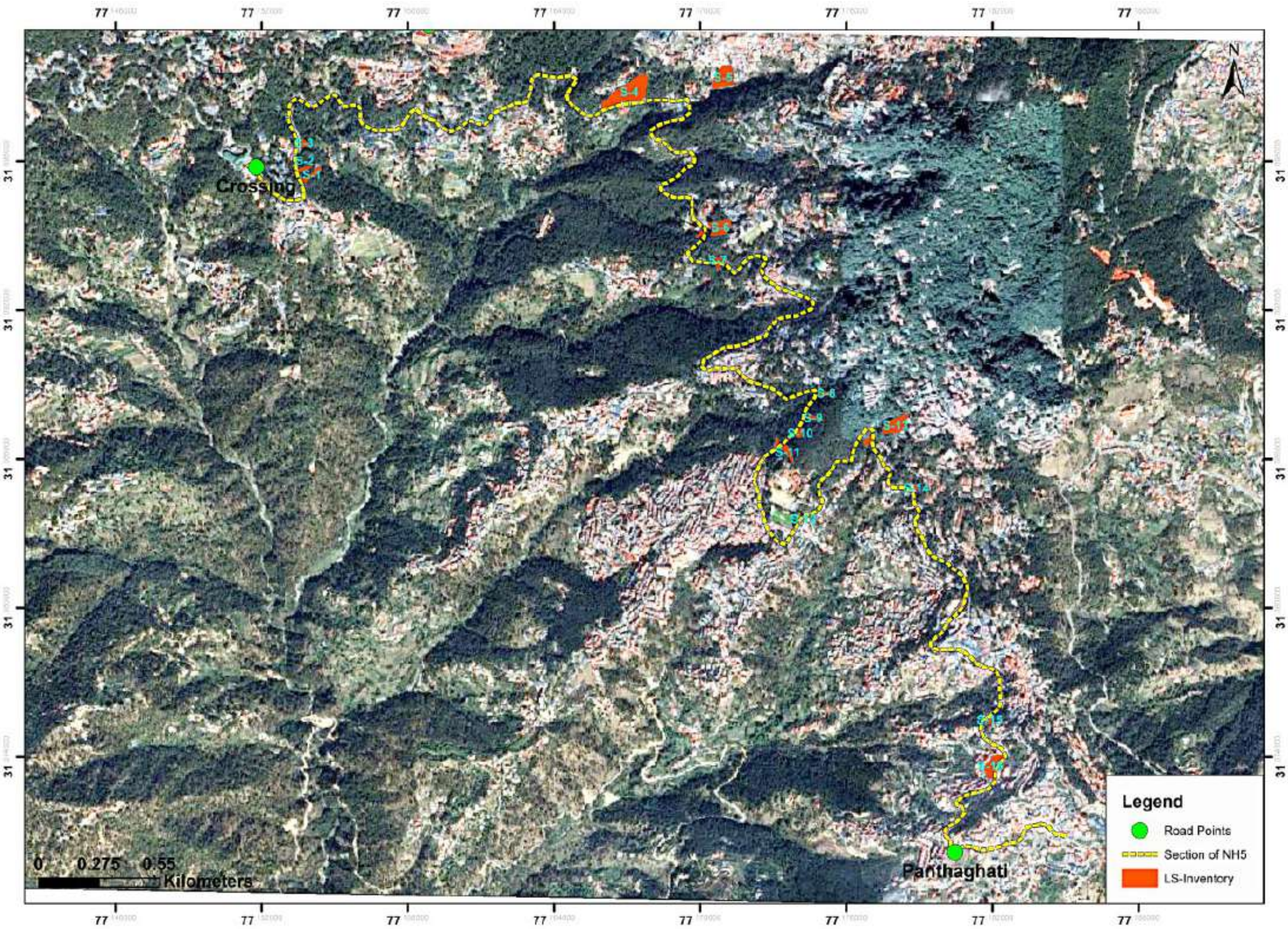
Shimla Town

Name of Location	Pantha Ghati	**Date of Survey:**	25 July 2024
Lat./Long.	31.078595 ; 77.182095	**Date of Landslide**	Aug. 23
Type of Road	NH-5		
Name of Surveyor:	SDavkota & Team		
Name of Local Person:	Deep	**Contact No.**	
Type of Landslide	~~Dormant~~, Shallow	**Bed rock exposure:**	Not detected
Landslide Activity:	Dormant	**Type of Bedrock:**	—
Landslide Size:	(50 × 15) m	**Discontunity**	
Soil Type:	colluvium uniformly	**Soil Depth:**	filled material (~3-4)
Slope Degree	> 50	**Slope Aspect:**	W
Landuse Type:	Bare land		
Presence of Seepage Water:	—		
Stream Nearby:	either side	**Drainage Condition:**	Dry, unmaintained.

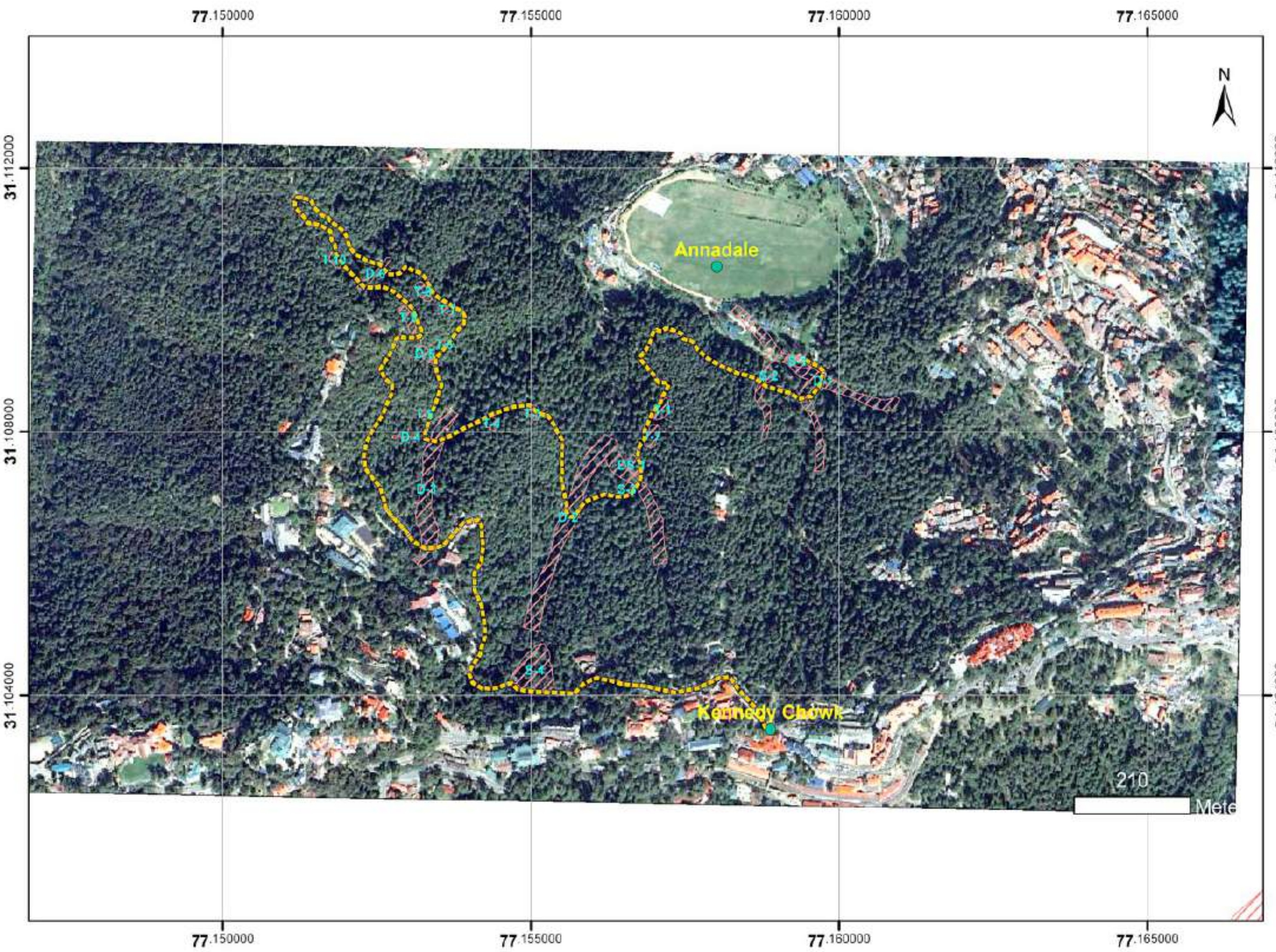


Damaged Caused			
No. of Lives:	—		
No. House(s):	—	**Vulnerable HH:**	Several
Agricultural Land:	—		
Road:			
Others Damage:			
Causal Factor:	Slope/Soil type/Ground Water/Road/Human activity/Landuse/Others		
Triggering Factor:	Rainstorm/Earthquake/change in ground water/Others		

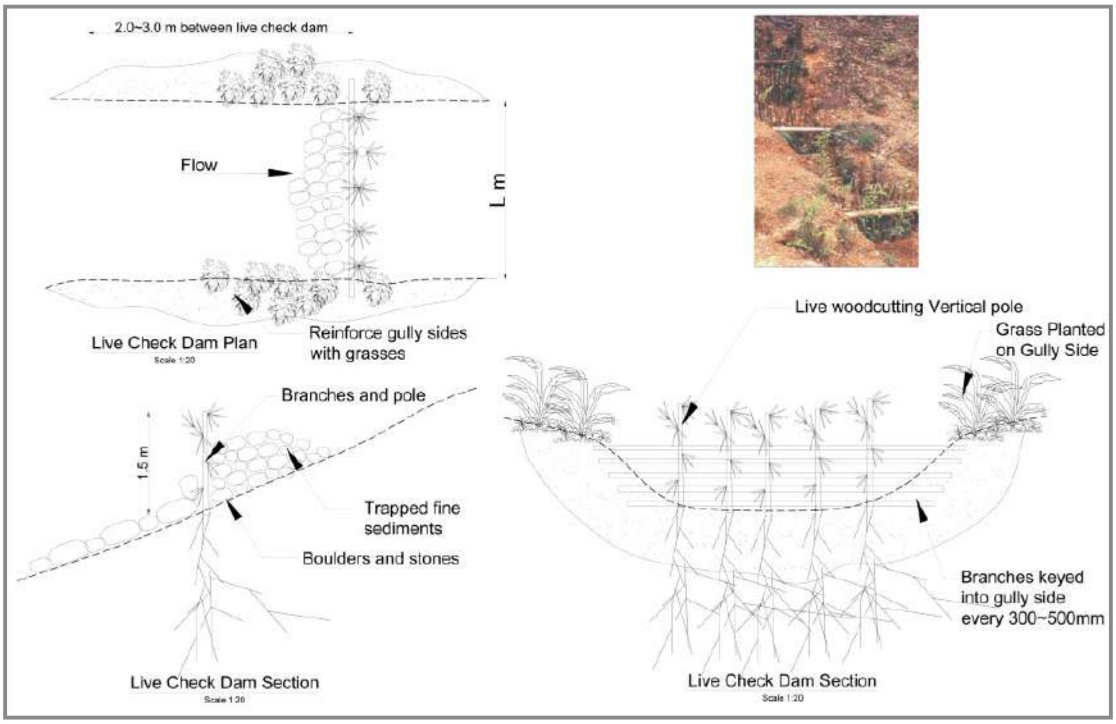
Annexure 2.1
NH5 Section alignment

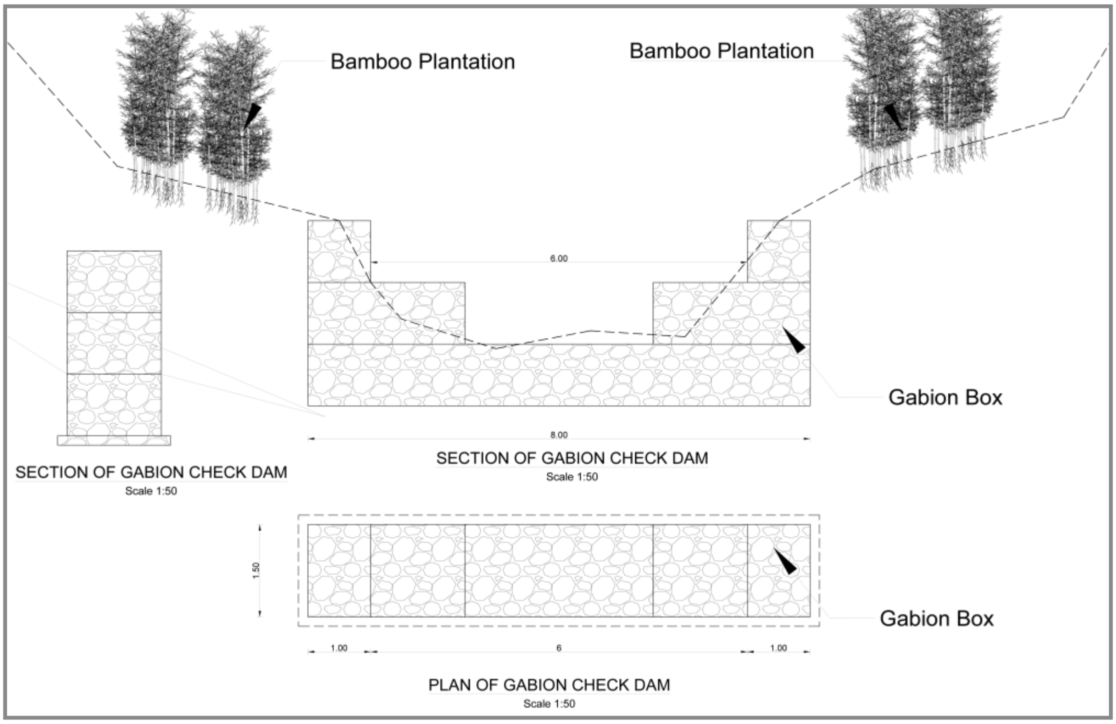


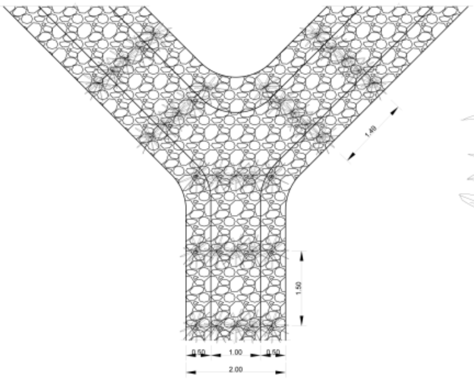
Annexure 2.2
KH-Annadale Road Alignment



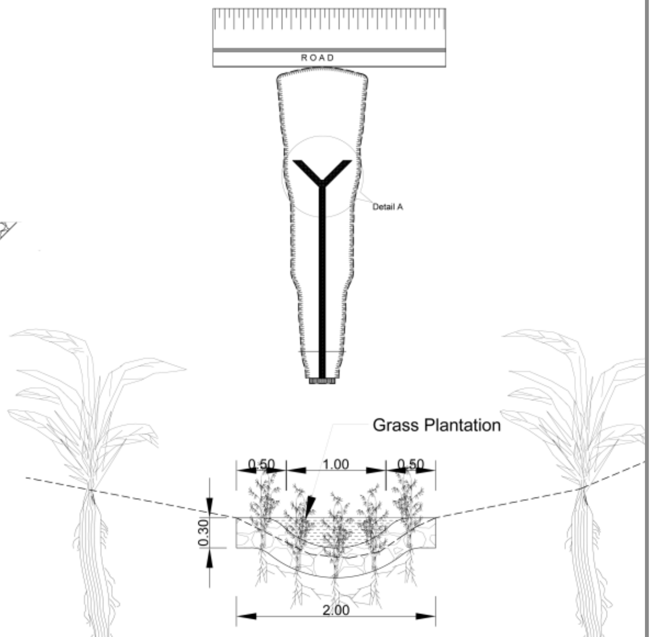
Annexure 3
Type Design



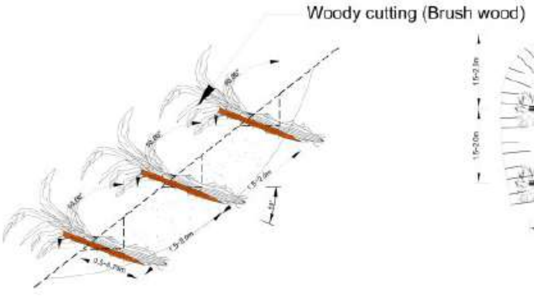




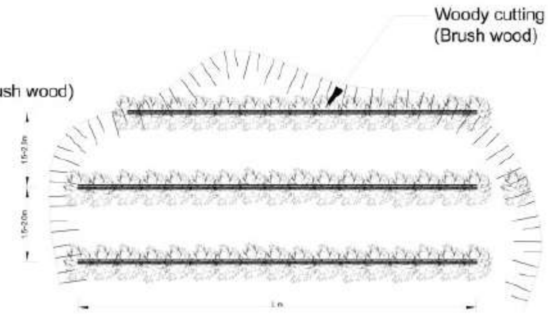
PLAN OF STONE PAVED VEGETATIVE SURFACE CHANNEL
Scale 1:100



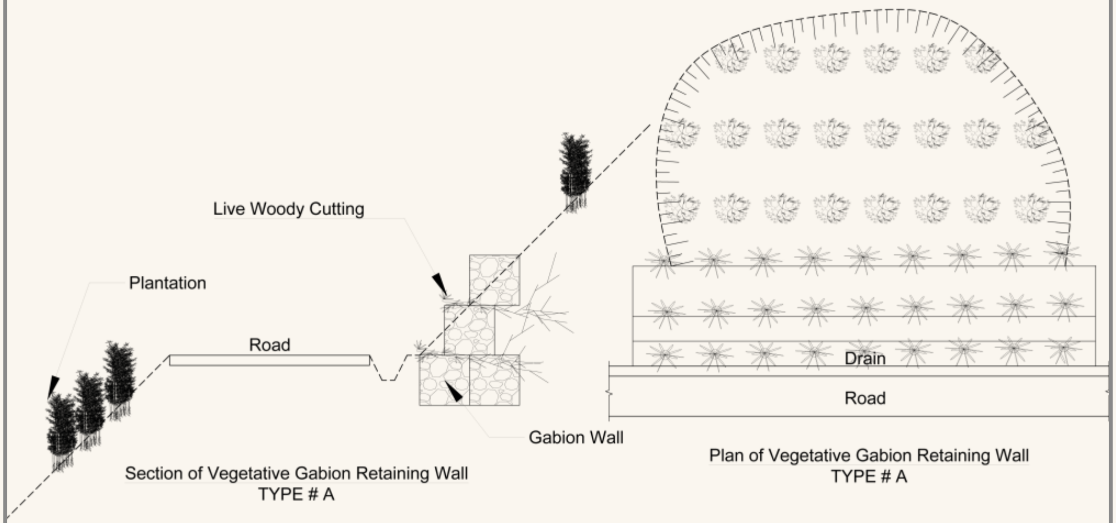
SECTION OF STONE PAVED VEGETATIVE SURFACE CHANNEL
Scale 1:100



TYPICAL SECTION OF BRUSH LAYERING

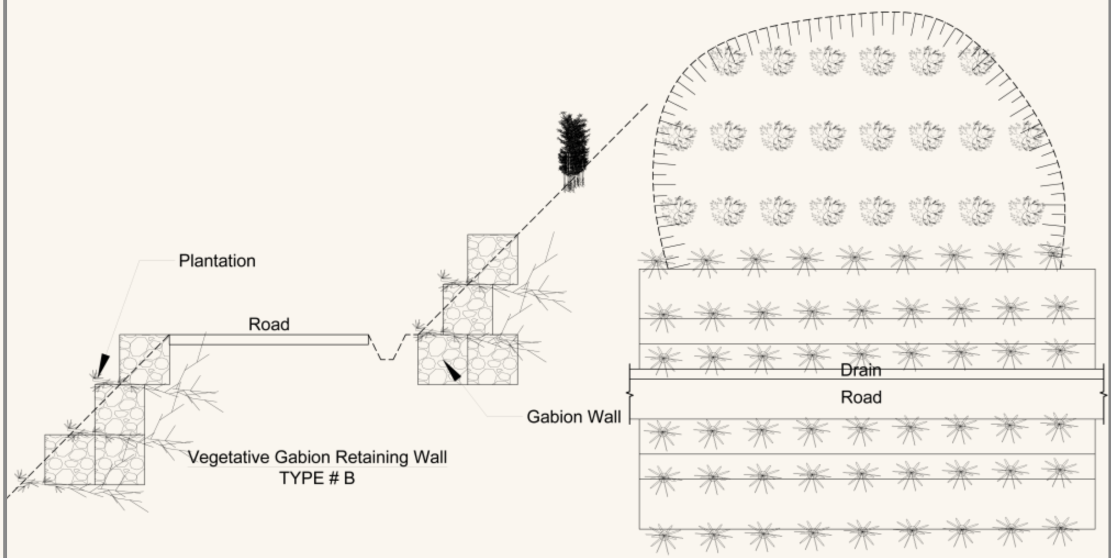


TYPICAL PLAN OF BRUSH LAYERING



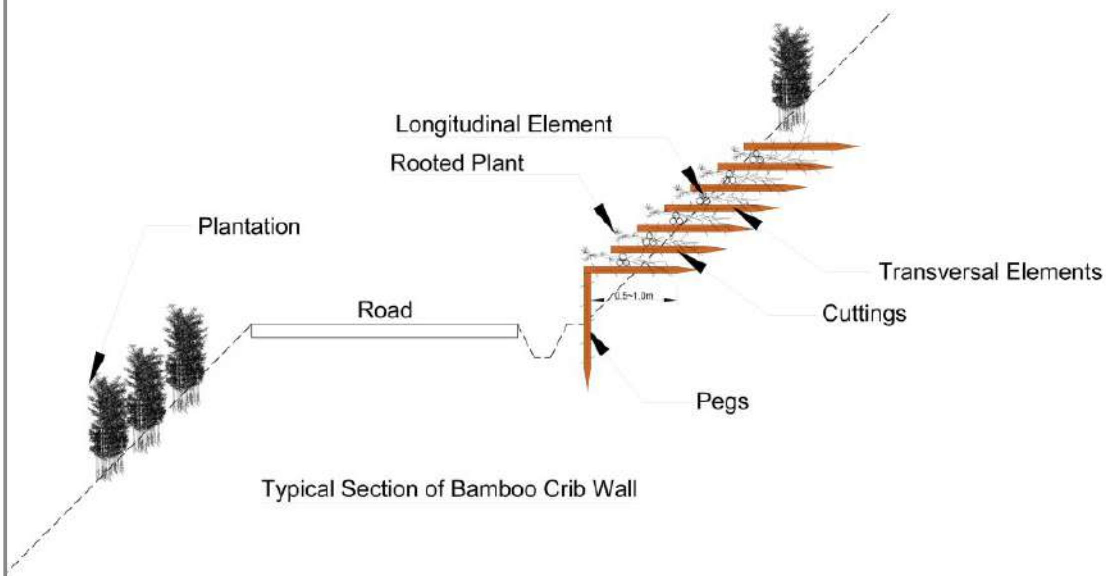
Section of Vegetative Gabion Retaining Wall
TYPE # A

Plan of Vegetative Gabion Retaining Wall
TYPE # A

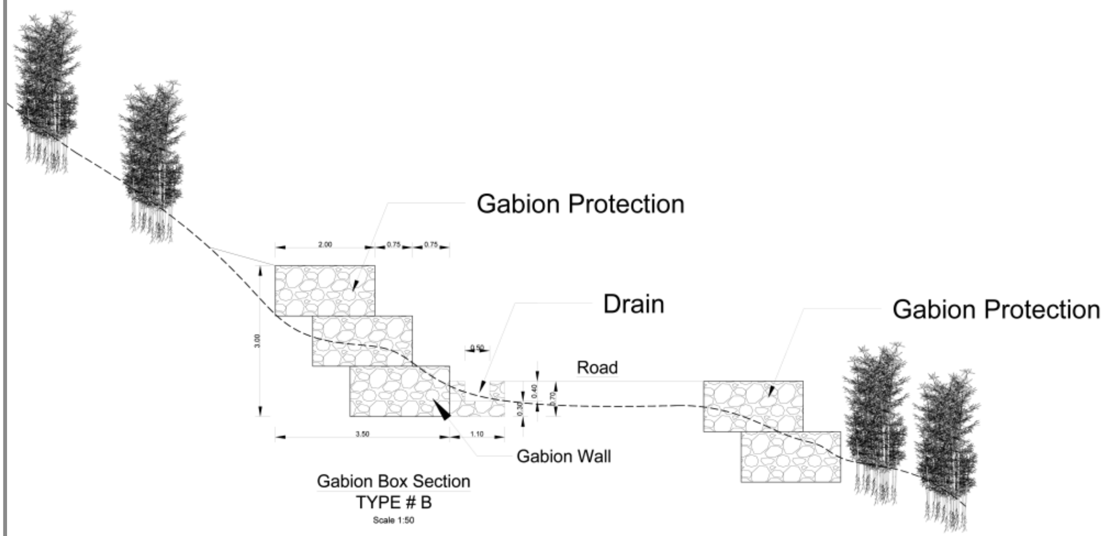


Vegetative Gabion Retaining Wall
TYPE # B

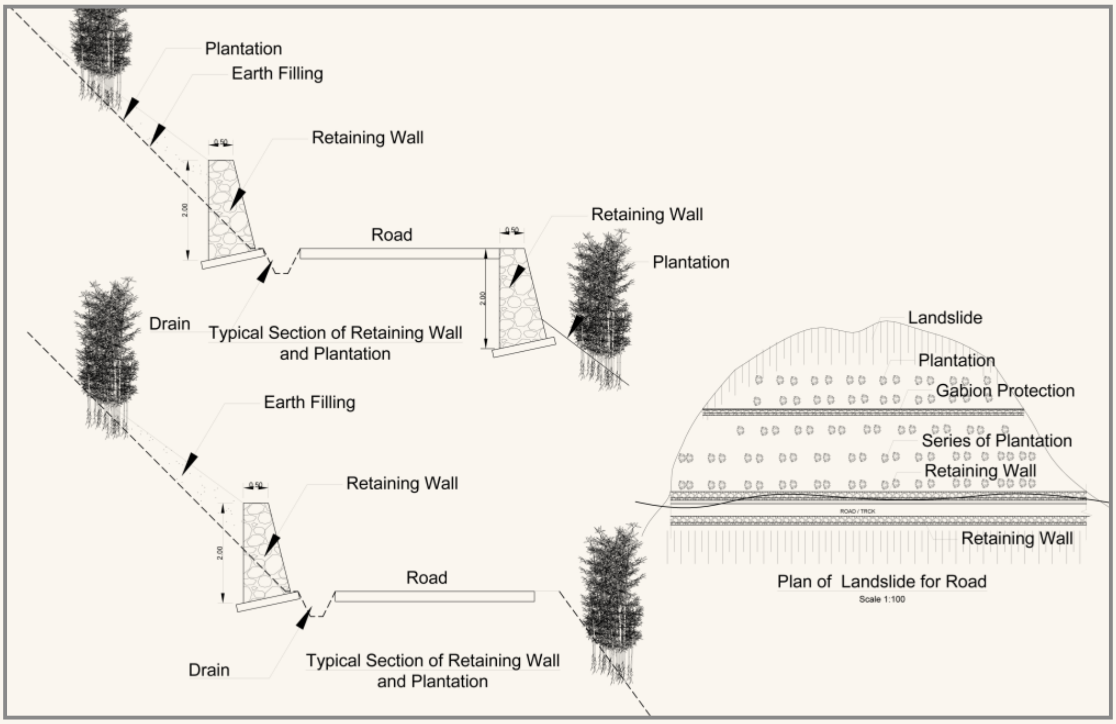
Plan of Vegetative Gabion Retaining Wall
TYPE # B

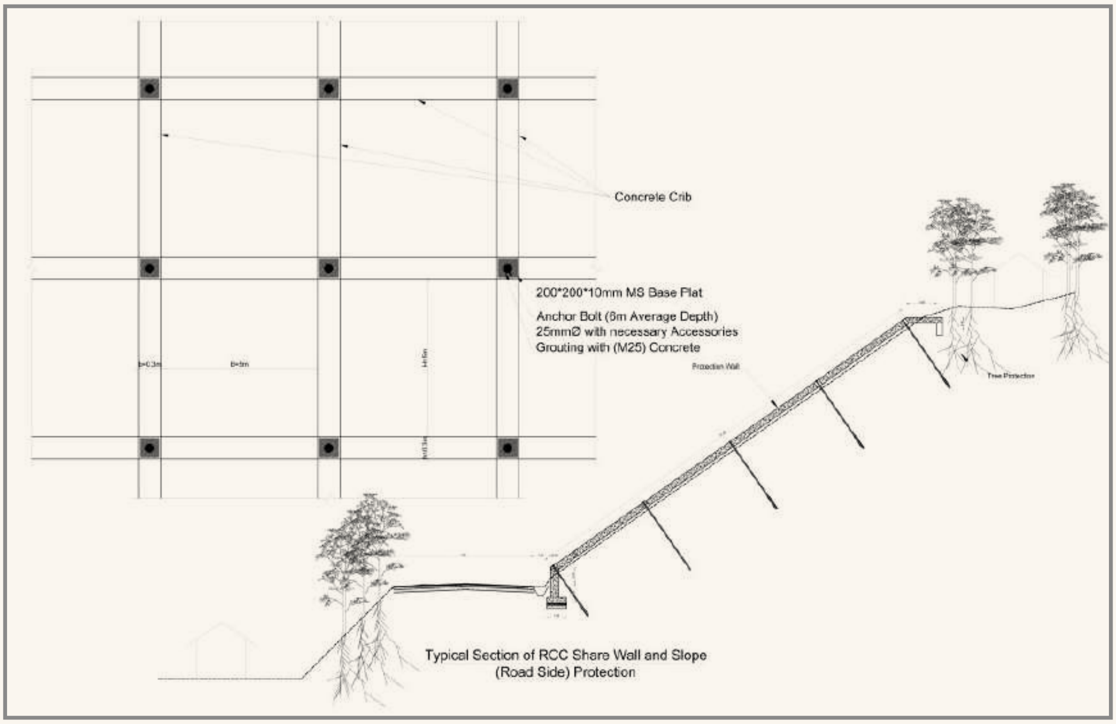


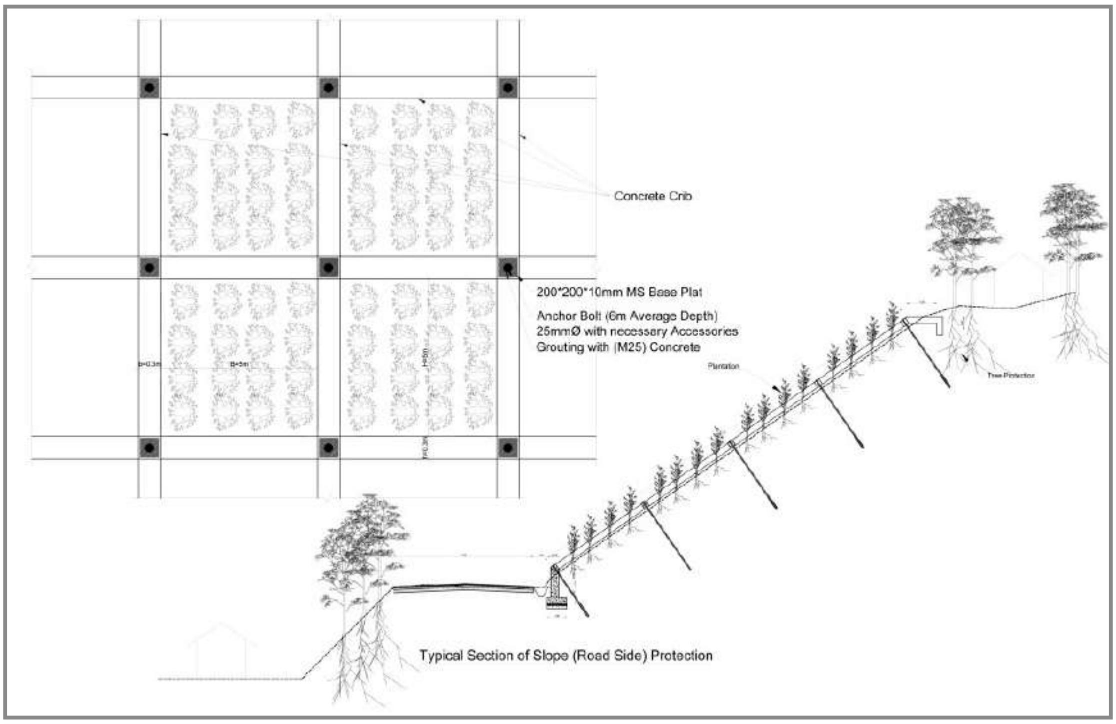
Typical Section of Bamboo Crib Wall



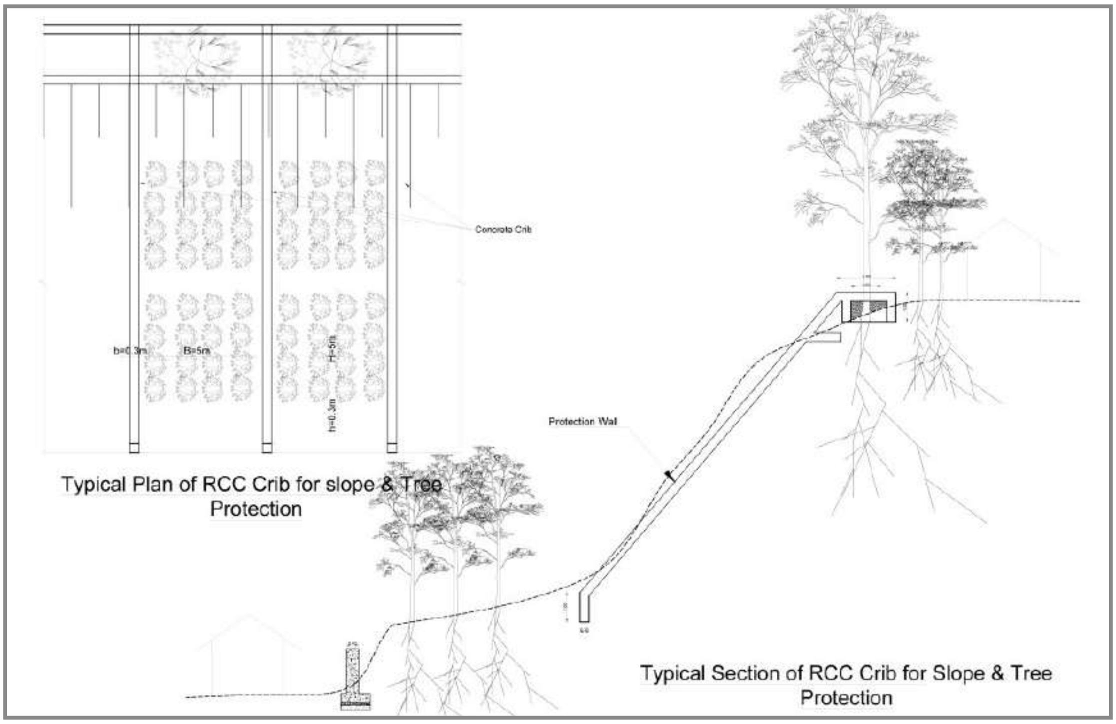
Gabion Box Section
TYPE # B
Scale 1:50


Plantation
Earth Filling
Retaining Wall
Road
Retaining Wall
Plantation
Drain
Typical Section of Retaining Wall and Plantation
Earth Filling
Retaining Wall
Road
Drain
Typical Section of Retaining Wall and Plantation
Landslide
Plantation
Gabion Protection
Series of Plantation
Retaining Wall
Retaining Wall
Plan of Landslide for Road
Scale 1:100


Concrete Crib
200*200*10mm MS Base Plat
Anchor Bolt (6m Average Depth)
25mmØ with necessary Accessories
Grouting with (M25) Concrete
Typical Section of RCC Share Wall and Slope
(Road Side) Protection



Typical Section of Slope (Road Side) Protection



Typical Plan of RCC Crib for slope & Tree Protection

Typical Section of RCC Crib for Slope & Tree Protection

Annexure 4A
Retaining wall based on construction materials

Dry stone masonry: Dry stone masonry walls are usually the cheapest wall structures and are suitable for heights up to 3–4 m. A skilled mason, suitable stones, and bonding of stones with keystones are required to make a good quality wall. In general, the width-to-height ratio varies from 1:1–0.6:1 for walls with heights of 1–4 m.

Gabion wall: A gabion is a heavy duty basket-like structure made in the shape of a box from welded or twisted galvanized iron wire mesh, divided by wire diaphragms into cells, and filled with heavy material (typically rocks or broken concrete) that cannot escape through the mesh openings. Gabions are generally used as construction blocks, and are tied together with galvanized iron binding wire to form larger structures. Gabion walls are constructed using gabion boxes of various sizes stacked next to and on top of each other before tying. Good quality stone should be used to fill the boxes, with dimensions preferably not less than 10 cm, or at least greater than the mesh size. Stones should be packed as tight as possible to increase the density of the gabion wall. The gabion structures are flexible and provide good drainage due to the dry stone packing.

Cement masonry wall: Cement masonry walls are constructed using good quality stones with cement sand mortar. These walls are rigid and designed as gravity structures with a base width varying from 0.5–0.75 times the wall height. The foundation must be on firm, risk-free ground. Weep holes of at least 75 mm diameter should be included every 2 x 2 m2 in a staggered pattern for drainage. As these walls are rigid and impermeable, they are not appropriate for construction to hold wet colluvial slopes or where ground movement is expected.

Composite masonry wall: Composite masonry walls are similar to cement masonry walls except that they have panels of dry stone masonry of about 0.6–1 m square forming a grid on the face and separated by 0.5 m strips of cement masonry. They are stronger than dry masonry walls but retain the advantage of having relatively good water drainage.

Cement concrete wall: Cantilever, counter fort, and buttressed retaining walls are constructed with reinforced cement concrete. The reinforced steel in the wall takes up the tensile stress that the wall is exposed to. The amount of steel required is calculated by analyzing the load on the wall.

Crib wall: A crib wall is a box-type structure built from interlocking struts of timber, precast reinforced concrete, steel, or other material, and is usually infilled with soil or stone. The whole unit acts as a gravity wall. Due to its construction without fixed joints, and the segmented nature of the elements, crib walls are flexible and thus to some extent resist differential settlement and deformation.

Safety of a retaining wall:

Retaining structures can fail for a variety of reasons. The major types of failure are 1) sliding, 2) over turning, 3) bearing capacity failure, 4) tension failure and 5) deep sheeted failure. The measures used to protect a wall against these different types of failure are summarized in the following sections.

Safety against sliding: Retaining walls should be able to resist the sliding force exerted by the lateral pressure (P) which tends to cause slide along the plane below the bottom slab, which is resisted by the shear force developed between the bottom slab and the ground (frictional resistance). If μ is the coefficient of friction between the base of the wall and the soil, the maximum frictional resistance is equal to μW. Thus for stability against sliding, P must never exceed μW. The factor of safety (F) is given by

$F = \mu W/P$.

A minimum factor of safety of 1.5 is generally recommended.

Safety against overturning: Retaining walls should be able to resist the overturning moment exerted by the horizontal component of the lateral earth pressure. The resisting moment is composed of the vertical component of the lateral earth pressure and the self-weight.

The section is in equilibrium under the action of four forces:

- the horizontal pressure of the earth (P) acting at H/3 from the base of the wall;
- the weight of the wall (W) acting at a distance X from the wall face BC;
- the vertical component (RV) equal to W and acting at E; and
- the horizontal component (RH) equal to P and resulting from the frictional resistance between the wall body and the ground.

The section can overturn about the point A. As long as the resultant R touches the base, the section cannot overturn. If R touches the base at A, the section is on the point of overturning, and if it falls outside the base, the section will overturn. Hence, the limiting value is when F coincides with A, i.e., EF = EA, when the balancing moment will have a value equal to W x EA.

Factor of safety = (W x EA)/(PxH/3)

The recommended factor of safety against overturning is usually 1.5–2.0.

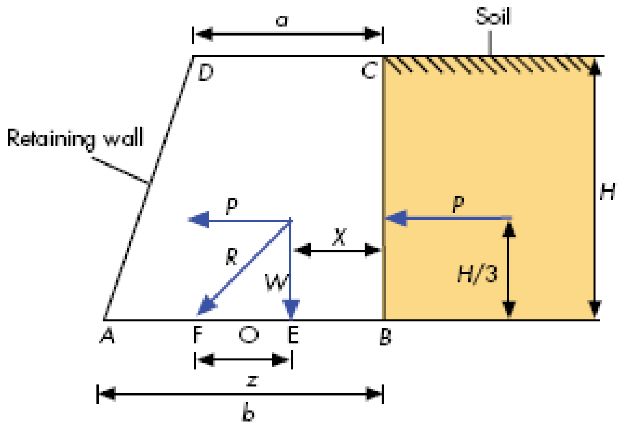


Figure A-1 Gravity retaining wall showing the dimensions (ICMOD, 2008)

Safety against bearing capacity failure: The supporting strength of soil or rock is referred to as its bearing capacity. The maximum pressure which soil can carry safely without risk of shear failure is the safe bearing capacity. In order to avoid bearing capacity failure of the soil at the base, the maximum comprehensive stress acting normal to the base must be less than the allowable bearing capacity of the soil. The maximum comprehensive stress normal to the base must also be less than the maximum comprehensive stress for the masonry to avoid crushing the masonry at the base.

Factor of safety = permissible comprehensive stress /Maximum comprehensive stress at the base of wall.

Factor of Safety of 3 is recommended for safety against bearing capacity failure.

Safety against tension failure: There should be no tension at the base of the wall. To avoid tension within the structure, the eccentricity (e) should be not more than b/6 on either side of middle of the base, i.e., at the point O. Under such conditions, the resultant, R must be within the middle third of the base width. In Figure A-1Gravity retaining wall showing the dimensions (ICMOD, 2008) designing a gravity type retaining wall, a trial section is chosen and checked for all the stability conditions mentioned above. If the stability checks yield unsatisfactory results, the section is changed and rechecked. Table A-1 shows the design dimensions for a typical retaining wall structure.

Type	Dry stone masonry	Composite masonry	Cement masonry	Gabion	
				Low	High
Top width	0.6-1.0 m	0.6-1.0 m	0.5-1.0 m	1.0 m	1-2 m
Base width	0.5-0.7 H	0.6-0.65 H	0.5-0.65 H	0.6-0.75 H	0.55-0.65 H
Front batter	vertical	varies	10:01	6:01	6:01
Back batter	varies	vertical	varies	varies	varies
Inward dip of foundation	1:03	1:03	horizontal or 1:6	1:06	1:06
Foundation depth below drain	0.5 m	0.5-1 m m	0.5 -1m	0.5 m	1 m
Height range (H)	1-6 m	6-8 m	1-10 m	1-6 m	6-10 m
Hill slope	<35^{0}	20^{0}	35-60^{0}	35-60^{0}	35-60^{0}
Toe protection in case of soft rock/soil	Boulder pitching				
General	Set stones along the foundation bed. Use long bond stones.	Cement 50 cm thick, masonry bands at 3 m centre to centre	Make weep holes of 75 mm diameter at 1-2 m c/c. Provide 50 cm rubble backing for drainage.	Hand pack stones. Select block shapes in preference to flat. Specify maximum/ minimum stone size. Do not use weathered stone. Compact granular backfill in a layer (<15 com).	
	Foundation to be stepped up if rock encountered. All walls require durable rock filling of small to medium size. Drainage of wall bases not shown.				
Application	Least durable		Most durable	Can adjust to settlement and slope movement	
	Non-ductile structures, susceptible to earthquake damage			Very flexible structures	

Annexure 4B
Design of Check Dams

The discharge rate through the channel must be calculated first. The hydraulic element of the design, especially the spillway section, is also very important as any fault in the hydraulic design can reduce the life of the structure.

Spacing

The spacing between dams is an important factor in the design. The space between consecutive check dams is selected to obtain the desired gradient between the bottom of the upper dam and the top of the lower dam – known as the compensation gradient. The spacing depends on the slope of the original waterway, the compensation gradient, and the effective height of the dams (DWSCWM, 2004) as shown in below equation:

$d = h \times 10 / S0\text{-}Se$

where,
d = spacing between two successive check dams (horizontal distance),
h = height of the check dams up to the notch,
S0 = existing slope of bed in per cent, and
Se = stabilizing slope of bed in per cent (usually 3–5%).

The number of check dams (N) is calculated as follows (DWSCWM, 2004):
$N = a\text{-}b/H$
where,
a = total vertical distance between the first and the last check dam in that portion of the gully or torrent,
b = total vertical distance calculated according to the compensation gradient for that portion of the gully, and
H = average height of the dams

Runoff estimation

Various methods are used to estimate the runoff rate. The rational formula is the simplest method for determining peak discharge from drainage basin runoff, but the calculation is only possible if the rainfall intensity, area of watershed, and runoff coefficient are known (DWSCWM, 2004).
$Q = c \times Itc \times A / 360$
where,
Q = rate of runoff in m3/s,
Itc = rainfall intensity in mm/hr for a designed frequency and a duration equal to the time of concentration (tc),
A = area of watershed in ha, and
C = dimensionless runoff coefficient.

The time of concentration (gathering time) is calculated from

$Tc = L^{1.15}/(15xH^{0.38})$
where,
tc = time of concentration (gathering time) in hours,
L = length of the watershed along the main stream from the outlet to the most distant ridge in km, and
H = difference in elevation between the watershed outlet and the most distant ridge in km.

Note: The rational formula can only be used when rainfall intensity (Itc) map of the given area is available with frequencies of 5, 10, 25, 50, and 100 years. If no is map available, the following discharge formulae must be used instead (Kresnik's run-off equation and Manning's velocity or runoff rate formula).

The Kresnik run-off equation is:
$Qmax = C x A^{1/2}$
where,
Q max = maximum permissible discharge in m3/s,
A = catchment area of the gully above the proposed check dam in km2, and
C = coefficient ranging from 0.6–2.0 (depending on land use type).

Note: the Kresnik equation gives the best results for gullies with catchment areas of less than 20 ha. It can also be used in torrent control for catchments up to 300 ha.

The Manning formula estimates the runoff rate from the riverbed characteristics:
$V = 1/n x R^{1/2} xS^{1/2}$
where,
V = velocity of flowing water (m/s),
n = roughness coefficient of the channel (for gully channels, n can be set at 0.025),
S = gradient of the gulley channel (%),
R = hydraulic radius (wetted area divided by wetted perimeter) (m) or R = A/P,
A = cross-sectional area of the river (m2), and
P = wet surface of the river (m).

Note, however, this formula is not accurate for rivers with a high bed load or with mudflow, because this changes the specific weight of the water.

The notch of the check dam, i.e., the spillway section, is designed to allow the spillway to accommodate peak runoff. The dimensions are calculated from

$Q = C \times L \times D^{2/3}$
where,
Q = maximum discharge of the gully catchment at the proposed check dam point (m3/s),
C = coefficient, 3.0 for loose rock, boulder, log, and brushwood dams; 1.8 for gabion and cement masonry dams,
L = length of spillway (m), and
D = depth of spillway (m).

Foundation depth

The check dams are built on a foundation which anchors them into the ground to increase stability and ensure that they do not collapse or overturn when the peak flow or runoff occurs or the dams are silted up. The following should be taken into account in the design and construction of the foundation:

- The bottom of the foundation should lie below the scour level.
- In erodible strata, if D is the anticipated maximum depth of scour below the designed highest flood level, including possible concentration of flow, the minimum depth of foundation below the highest flood level should be 1.33D.
- The scour depth should be taken from the expected bed level after siltation of the lower check dam and establishment of the new bed gradient, due to the reduced bed load after the erosion control.
- As a rule of thumb, take the foundation to be 1 m.

Scour depth

The safety of the check dams is mostly endangered by scouring. Scour occurs when the bed velocity of the stream reaches the velocity that can move the particles of the bed material. The scouring action of the current is not uniform; it is deeper at the obstruction and at bends.

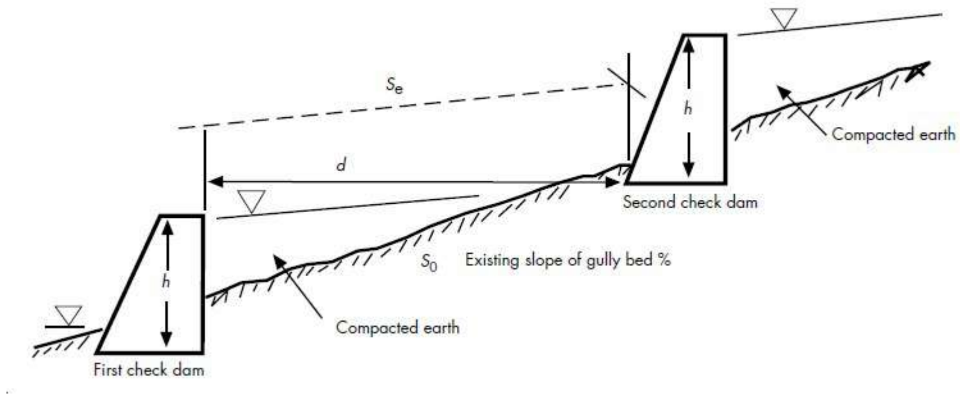


Figure 4-B: Spacing of check dams

The scour depth is calculated from Schocklitch's formula (DWSCWM, 2004):

Scour depth (Ds) = $(4.75 \times h^{0.2} \times q^{0.57})/dm^{0.35}$

where,

Ds = scour depth in m below water level,

dm = grain diameter in mm, determined on the basis that 90% of the bed material is smaller than dm,

h = water level difference in m above and below the check dam, and

q = runoff in m3/m width of spillway.

The breadth of the scour hole is calculated as 1.5 × length of the notch.

The length of the scour hole or apron is calculated as $4 \times (0.467 \times q^{2/3})1.5 \times h^{0.5}$.

General design considerations:

Check dams are designed for safety against overturning, safety against sliding, and safety against the bearing pressure on the foundation soil. Table 4B-1 summarizes the suggested general design specifications for different types of check dam.

Dam type	Maximum effective height	Minimum foundation depth	Thickness of dam at spillway level	Slope of the downstream face of the dam	Slope of the upstream face of the dam	Thickness of the base of the dam
Brushwood	1 m from ground level	0.75-1 m				
Loose stone	1.0 m	0.5 m	0.5-0.7 m	20% (1:1/5)	vertical	calculated accordingly
Boulder	2.0 m	half of effective height	preferably 1.0	30% (1:3)	vertical	calculated accordingly
Gabion	may vary (recommended not more than 5.0 m)	half of effective height	>1 m	20% sloped, stepped, or vertical	stepped or vertical	calculated accordingly

Note: Use of these dimensions means no stability test is needed against overturning, collapsing, or sliding. However, the size of the spillway needs to be calculated according to the maximum discharge of gully watershed area.

Basic considerations for check dam construction

The function of check dams is to reduce the gradient and minimize the hydraulic energy of the flowing water. The flow velocity, and thus the erosion capacity, is controlled by the size of the dams and spillways. The following should be considered when constructing check dams.

- Construction should normally start at the downstream end of the active section of a gully.
- The top of the check dam should be below the level of the adjacent land to prevent pillover of flood to either side of the gully.
- The height of the outflow should be no more than 1 m. The lower the check dam, the smaller the risk of collapse and overflow to the side and of the need for repair. The ideal height of the spillway is often 0.5–0.6 m. It is better to build two low dams in a cascade than one high dam.
- The check dam should be made lower at the centre to form a spillway. The spillway will draw the stream to the middle, thus hindering erosion of the gully sides.
- The check dam should extend into the gully floor and the sides of the gully. This 'keying in' will help prevent erosion scouring and tunnelling under or around the check dam. The depth of the keying in depends on the local soil conditions, but should usually be between 0.3 and 1.0 m, more when the sides of the gully are unstable.
- An apron should be constructed in the gully area immediately downstream of the check dam to protect it from the erosive forces of the falling water. Without an apron, the check dam will be undercut and will eventually collapse. Apron should be 1.5–2 times longer than the height of the check dam depending on the slope of the gully. The greater the slope, the greater should be the length of the apron. Both the floor and the sides, from the top of the spillway to the downstream end of the apron, should be protected by piling stones.

Annexure 4C
Popular bioengineering methods in Nepal and their effectiveness in different environments (modified from DWMSC, 2013)

S.No.	Systems	Location	Main functions	Other functions
1	Grass plantation (vertical)	Loose soil, embankment and fill slopes	Drain, Armour	Armour
2	Grass plantation (Diagonal)	Loose soil, embankment and fill slopes	Catch	Armour
3	Grass plantation (Horizontal)	Loose soil, embankment and fill slopes	Armour	Catch, Drain
4	Random plantation	very steep (30-40 degree)	Armour, anchoring	Catch, Drain
5	Grass seed sowing	New Loose soil, steep and relatively dry	Armour, reinforcement	Catch
6	Turfing	New deposited soil, embankment	Armour	
7	Brush layering	Loose soil, shallow slope protection	Carch, armour, reinforement	
8	Palisade	Loose soil, slope protection, gully protection	Carch, armour, reinforcement	
9	Fascine	Gully protection, shallow slope protection	Support	Catch, reinforce
10	Tree, shrub plantation		Reinforcement	Anchoring, support
11	Tree and Shrub seed plantation	Very steep, rock, instable Slope	Reinforcement	Anchoring
12	Bamboo plantation	River bank and slope protection	Catch, reinforcement	
13	Live Checkdam	Gully and shallow slope protection	Catch, Armour, reinforcement	

Annexure 4D
Comparison of Different Vegetation and Engineering Functions (after Howell, 1999)

Engineering Function	Woody Vegetations			Non Woody Vegetation		
	Trees	Shrubs	Bamboos	Clumping Grasses	Matting Grasses	Other Herbs
Catch	♣	♣♣♣	♣♣♣	♣♣	♣	Λ
Armour	♣	♣	♣	♣♣♣	♣♣♣	♣
Reinforce	♣	♣♣♣	♣	♣♣	♣	Λ
Anchor	♣♣♣	♣♣	Λ	Λ	Λ	Λ
Support	♣♣♣	♣♣	♣♣♣	Λ	Λ	Λ
Drain	Λ	Λ	Λ	♣♣♣	♣	Λ

Symbols:- ♣♣♣ *Excellent* ♣♣ *Good* ♣ *Moderately useful* Λ *Not useful at all*

Annexure 4D
Recommended Bio-engineering Techniques and Timing of Implementation (Modified from Howell, 1999)

Site type	Materials and drainage	Aspect (orientation)	Recommended technique *	Timing of site works
Cut slopes in undisturbed ground (Usually >35°)	Poorly drained materials liable to saturated slumping	North and east	Grass lines (diagonal)	Winter above 1800 m Monsoon below 1800 m
		South and west	Grass lines (diagonal)	Monsoon
	Other materials	North and east	Grass lines (diagonal)	Winter above 1800 m Monsoon below 1800 m
		South and west	Grass lines (contour)	Monsoon
Cut sloops in loose colluvial debris (Usually <35°)	All materials	North and east	Brush layering	Winter above 1800 m Monsoon below 1800 m
		South and west	Grass lines (contour)	Monsoon
· Fill slopes in mixed debris · Unconsolidated landslide debris · Tipped debris masses (Always <35°)	Fine-textured matrix with impeded drainage	All	Fascine or vegetated stone-pitched slope drain with diagonal brush layering, plus grass lines (diagonal) within 5 m of road	Winter above 1800 m Monsoon below 1800 m
	Coarse angular debris	All	Brush layering (contour), plus grass lines (diagonal) within 5 m of road	Monsoon
	Very rocky debris with no fines	All	Palisades	Monsoon
Backfill above and around foundations of structures (Always <35°)	Fine-textured matrix with impeded drainage	North and east	Grass lines (diagonal)	Winter above 1800 m Monsoon below 1800 m
		South and west	Grass lines (contour)	Monsoon
	Coarse angular debris	North and east	Grass lines (contour)	Winter above 1800 m Monsoon below 1800 m
		South and west	Grass lines (contour)	Monsoon
Landslide head scars (Usually >45°)	Slopes less than 50° in materials that can be excavated by hand	All	Grass lines (contour)	Monsoon
	All other sites	All	Shrub seeding	Any time
Gully beds (Usually 15-35°)	Damp, shady sites	All	Live check dams Bamboo planting	Winter above 1800 m Monsoon below 1800 m
	All other sites	All	Live check dams Bamboo planting	Monsoon
Lower side engineered road shoulders	Any	All	Grass lines (contour)	Monsoon
Bare, unvegetated slopes above cuts and below fill slopes	Any	All	Tree and shrub planting	Monsoon [Winter, for north- and east-facing sites above 1800 m]

** Requires verification through individual site assessment.*

Special Situations	Supplementary Technique
	Bamboo crib walling
Long slopes in angular, well-drained and unconsolidated debris where the slope angle does not exceed 35° and there is seepage or monsoon flow, but no concentrated torrent of water. Choose technique to suit the availability of local, cheap materials.	Vegetated dry stone walling
Narrow channels in landslides and gullies where there is periodic concentrated water flow.	Live check dams
Channels and drains below springs and in gullies where significant water flow is common.	Vegetated stone pitching
Steep (>45°) cut slopes in fine-textured, consolidated materials such as residual soils, but not on north-facing slopes or near seepage lines.	Jute or coir netting with random grass planting

Annexure 5

Relevant IRC Codes & Morth Publications for reference of engineers to include them in practice and engineering design (DPRs). The following are indicative lists and suggested to refer to the revised and updated publications.

S. No	Publication	Title of the Publication
1	IRC:7-2017	Recommended Practice for Numbering Culverts, Bridges and Tunnels
2	IRC:52-2019	Guidelines for the Alignment Survey and Geometric Design of Hill Roads
3	IRC:56-2011	Recommended Practices for Treatment of Embankment and Roadside Slopes for Erosion Control First Revision
4	IRC:89-2019	Guidelines for Design and Construction of River Training & Control Works for Road Bridges (Second Revision)
5	IRC:138-2023	Guidelines for Highway Engineers on Disaster Resilient Green Highways in Multi-Hazard Ecosystem
6	IRC: SP:48-2023	Hill Road Manual
7	IRC:113-2013	Guidelines for the Design and Construction of Geosynthetic Reinforced Embankments on Soft Subsoils
8	IRC: SP:19-2020	Manual for Survey, Investigation and Preparation of Road Projects
9	IRC: SP:42-2014	Guidelines on Road Drainage
10	IRC: SP:59-2019	Guidelines for Use of Geosynthetics in Road Pavements and Associated Works (First Revision)
11	IRC: SP:102-2014	Guidelines for Design and Construction of Reinforced Soil Walls
12	IRC: SP-106-2015	Engineering Guidelines on Landslide Mitigation Measures for Indian Roads
13	IRC: SP:116-2018	Guidelines for Design and Installation of Gabion Structures
14	IRC: SP:129-2022	Guidelines for the Design and Construction of Roads using Coir Geotextiles
15	MORTH	Capacity Development Project on Highways in Mountainous Regions - Guidelines for Slope Protection & Embankment with Advanced Technology

Annexure 6

List of Landslide sites identified for detailed assessment

S. No	Code	Chainage	Latitude	Longitude
1	S1	1+840-1+860	31° 5'50.06"N	77° 9'14.04"E
2	S2	1+800 to 1+820	31° 5'51.77"N	77° 9'14.01"E
3	S3	2+040 to 2+050	31° 5'55.12"N	77° 9'13.38"E
4	S4	4+120	31° 6'3.98"N	77°10'2.42"E
5	S5		31° 6'6.44"N	77°10'15.69"E
6	S6	5+370	31° 6'6.44"N	77°10'15.69"E
7	S7	5+625	31.093900 N	77.170653 E
8	S8	7+620	31° 5'15.02"N	77°10'28.96"E
9	S9	7+710	31° 5'12.72"N	77°10'26.95"E
10	S10	7+920	31° 5'10.38"N	77°10'24.69"E
11	S11	7+970 to 8+000	31° 5'10.38"N	77°10'24.69"E
12	S12	9+220	31° 5'14.23"N	77°10'39.69"E
13	S13	10+970	31° 5'38.41"N	77°10'14.76"E
14	S14	10+970	31° 4'30.78"N	77°10'55.06"E
15	S15	11+260	31.073522 N	77.182053 E

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