A Geotechnical Asset Management Framework for the Department of Roads in Bhutan

by

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Abstract

Countries around the world strive to improve the well-being of their people; one of the means to achieve that is to ensure a safe, resilient, and efficient transportation network. Bhutan, a developing country, in southeast Asia, share the common goal of poverty reduction and economic growth through provision of reliable and resilient road infrastructure. Roads are a predominant mode of transport, and given its complex geological settings, road infrastructures are not only costly to build but expensive to maintain. With the limited resources available, the key challenge has been to effectively manage the existing assets. The road network in Bhutan is continuously affected by geohazards and particularly landslides. The Department of Roads (DoR) of Bhutan has recorded over 300 roadblocks caused by landslides alone in 2020; likewise, a portion of department's fund is spent on clearing those roadblocks every year. Though the department has a Road Asset Management System in place, a comprehensive Geotechnical Asset Management System, focusing solely on the management of the geotechnical assets can help in balancing hazard and risk when prioritizing slopes for funding.

The review of the existing asset management literature emphasizes the importance of geotechnical assets in a transportation network, assists in developing the taxonomy of geotechnical assets and reinforces the criterions established for the risk assessment of the geotechnical assets. This research takes the state of practice for geotechnical asset management, landslide risk assessment frameworks, and current landslide monitoring practices; to develop a geotechnical asset management framework oriented at optimizing the use of limited available resources for risk mitigation. This framework is

developed for Bhutan and includes steps to proactively and strategically prioritize geotechnical assets supported by risk assessment, to identify relevant and cost-effective treatment options to prolong life of assets and hence eventually shift from reacting to failures to proactively managing them. The framework ensures that it is implementable right away, without having to incur huge initial investments. The applicability of the framework is supported by test implementation to a number of assets in a regional office of Bhutan and three slope assets in Western Canada. Importantly, the framework can be used as a basis for other regions with similar hazard profiles and limited resources for risk mitigation.

A Geotechnical Asset Management (GAM) is the process of maintaining, inspecting, and planning for the repair or replacement of geotechnical assets such as slopes, embankments, subgrades, and retaining walls. It involves assessing the current condition of the assets, identifying potential risks or hazards, and developing plans to address those risks in order to ensure the continued safety and functionality of the asset over time. A major portion of this research discusses one of the important components of the GAMS, which is to track and monitor the performance of geotechnical assets. Geotechnical asset monitoring using conventional methods as well as remote sensing technology, can help identify changes in the condition of the asset, such as surface displacement or settlement or even provide an early warning system for potential problems. The review of the existing literature on application of remote sensing to geohazards emphasizes the methodology, applicability and pros and cons of some of the emerging remote sensing technologies used in Canada and around the world. This discussion has been reinforced with case examples of three slope assets in Western Canada.

Preface

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
AH	Asian Highway
ALS	Airborne Laser Scanning
AT	Alberta Transportation
BSR	Bhutan Schedule of Rates
CEP	Conceptual Engineering Assessment
CDOT	Colorado Department of Transportation
C2C	Cloud to Cloud
DEM	Digital Elevation Model
DoR	Department of Roads
DOT	Department of Transportation
DSD	Decision Sight Distance
DSI	Distributed Scatterers Interferometry
FHWA	Federal Highway Administration
GAM	Geotechnical Asset Management
GAMP	Geotechnical Asset Management Program
GAMS	Geotechnical Asset Management System
GCP	Ground Control Point
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRMP	Geohazard Risk Management Program
IIMM	International Infrastructure Management Manual
ICG	International Centre for Geohazards
ICP	Iterative Closest Point
InSAR	Interferometry Synthetic Aperture
ISO	International Organization for Standardization
KCB	Klohn Crippen Berger

LCCA	Life Cycle Cost Analysis
LiDAR	Light Detection and Aperture Radar
LoS	Line of Sight
MoWHS	Ministry of Works and Human Settlement
MSE	Mechanically Stabilized Earth
M3C2	Multi-spectral Model to Model Cloud Comparison
NCHRP	National Cooperative Highway Research Program
NPV	Net Present Value
PNH	Primary National Highway
PSI	Persistent Scatterers Interferometry
RAMS	Road Asset Management System
RGoB	Royal Government of Bhutan
RO	Regional Office
ROW	Right of Way
SNH	Secondary National Highway
TAM	Transportation Asset Management
TLS	Terrestrial Land Scanning
UAV	Unmanned Aerial Vehicle

1. Introduction

Bhutan, a small kingdom in south-east Asia, is landlocked between China to the north and Indian states of Arunachal Pradesh to the east, Sikkim to the west and West Bengal and Assam to the south. South Asia is home to the Hindu Kush Himalayas, one of the most challenging terrains in the world. The country lies between latitudes 26’45’ N and 280”10’ N and longitudes 88’45’ E and 92’10’ E. It has a total land coverage of 38,394 square kilometres. Figure 1 shows where Bhutan lies in the Asian continent. Bhutan currently houses a population of over 780,000. It is known to the world for its concept of developmental philosophy of Gross National Happiness, whereby the developmental activities are measured against the wellbeing and happiness of the people.

Figure 1: Location of Bhutan (Google Map)

The physiographical region of Bhutan is broadly segregated into three regions from north to south: the Greater Himalayas, the Inner Himalayas, and the Southern Foothills. Due to the absence of railways and limited air connectivity, roads are the primary mode of transportation in the country. Bhutan has over 18,000 kilometres of roads at present, of which over 2400 kilometres are double-laned highway network (Road Classification and Network Information of Bhutan, 2020). The Department of Roads (DoR) under the Ministry of Works and Human Settlement (MoWHS) is the sole agency in the Royal Government of Bhutan (RGoB) mandated to design, construct and maintain road infrastructure in the country. The DoR has 9 Regional Offices (ROs) located in various parts of the country and each RO has multiple road networks in its jurisdiction. DoR has built a substantial length of road in the country; however, in the past the emphasis has been on the connectivity rather than the standard and quality of road. It is slowly transitioning to building roads at par with the standards of the developed countries using state-of-the-art technology.

Being located in the fragile terrains of Himalayas, infrastructures in Bhutan remain highly vulnerable to numerous geo-hazards and earthquakes. Geo-hazards such as landslides, debris flows, rockfalls, etc. triggered by rainfall coupled with developmental activities have been continuously affecting the livelihood of the people and the overall economy of the country. The occurrence of geo-hazards differ in various physiographic regions of the country as different physiographic regions are located at different altitudes and have differing climatic conditions.

There are significant gaps between the developed and developing countries in terms of building as well as managing the key infrastructures such as roads, bridges, airports, energy and so on. Developed countries have much more advanced and well-maintained infrastructure system. Some of the factors which contribute to this gap are:

- Scarce financial resources in developing countries.
- Limited capacity for institutions and regulatory frameworks to support infrastructure planning and management in developing countries.
- Limited technical expertise, especially in engineering, architecture, and construction.

While the benefits of a simple GAMS may be similar between developing and developed countries, the specific context and factors may influence their importance and impact. A system like that can be a valuable tool but it may need to be adapted to suit the specific needs and resources of each context.

Like many other developing countries around the world, resources are limited in Bhutan. Emphasis has been on the connectivity of regions and hence construction of roads has been prioritized over maintenance for many years. Road maintenance did not gain much attention and had neither attracted the funding nor the expertise to evaluate the need for maintenance work. However, it was soon realized that deferring needed maintenance could become costly and disruptive, not only for the government having to spend more resources, but also for commuters who could be exposed to increasing safety risks, and at a minimum would suffer discomfort, slower speeds, and higher vehicle wear and tear on underperforming roads. Therefore, as a part of placing emphasis on the maintenance of roads, the need for a Road Asset Management System (RAMS) was realized and established by the DoR. Like any other

Transportation Asset Management (TAM) System around the world, RAMS was put in place by the DoR to minimize the total cost of acquiring, operating, maintaining, and upgrading/ replacing the assets to consistently deliver desired commuter satisfaction and regulators' requirements. It was primarily established to effectively manage the road assets using the limited resources available. Road assets include pavements, bridges, cross drainage structures, and geotechnical assets, such as soil and rock slopes, earth embankments, retaining walls, and subgrade soils. However, the primary focus of RAMS has been on the road pavements, bridges, and cross drainage structures. Hence, this brings the need for a comprehensive Geotechnical Asset Management System (GAMS), focusing solely on the geotechnical assets, which would go a long way towards increasing the profile of geotechnical assets and be useful for balancing hazard and risk when prioritizing geotechnical assets for funding. Such system has proven to have resulted in life-cycle cost savings, reductions in performance and operational disruptions, and fewer stabilization projects (National Cooperative Highway Research Program (NCHRP) Research Report 903: Geotechnical Asset Management, Volume 2: Implementation Manual 2019). For a developing country like Bhutan, keeping in view the limited availability of resources, a GAMS can be started simply, without having to incur huge expenditure and with an incomplete inventory that advances with time, as suggested by NCHRP GAM Report 903: Volume 1 and 2 (2019). A system that is cost-effective, implementable, flexible, and adaptable has the maximum probability of being adopted especially by developing countries.

1.1 Objectives of this thesis

- To identify, classify and quantify the common geo-hazards occurring in Bhutan and the relationship of its occurrence with the physiographic regions of the country.
- To develop a Geotechnical Asset Management framework for the Department of Roads with the aim to balance hazard and risk when prioritizing geotechnical assets for funding that reflects the characteristics of the geohazards in the region and availability of resources. Illustrate the use of the framework with case examples from Bhutan and Western Canada.
- To evaluate the practicability of some of the best practices and novel technologies implemented in Western Canada for geotechnical asset monitoring to the characteristics of geo-hazards and resources available in Bhutan.

1.2 Methodology

In order to know the severity of impacts caused by geo-hazards, it is crucial to obtain information on the common geo-hazards that affect the road network and various other infrastructures in Bhutan. Oftentimes, geo-hazards are not obvious until they are pointed out and quantified. Most of the geo-hazards could be considered dormant until they are triggered. Having detailed information on geo-hazard occurrence and its type can facilitate the development of an informed risk-based asset management system. By identifying which geo-hazards may affect the road network in the country and taking steps to lessen the risk, one can significantly increase the safety of the commuters and reduce the impact on the national economy. Hence, the roadblock data from the DoR has been analyzed and segregated into roadblocks that occurred once and the ones that have occurred multiple times caused by various geo-hazards. A complete set of data from the year 2020 has been computed and analyzed for this purpose. The roadblock data collected by all nine ROs using KoboCollect application has been segregated into the following groups based on the potential causes:

- Roadblocks caused by landslides.
- Roadblocks caused by debris flow.
- Roadblocks caused by rockfall.
- Roadblocks caused by flooding.
- Roadblocks caused by subsidence.

These were further segregated into one-time roadblocks and multiple-time roadblocks in order to identify the most common geo-hazards affecting the road network and to distinguish the critical road sections prone to such hazards in Bhutan. As the data collection is mostly done based on visual inspection, it was hugely impacted by the pandemic. A more complete data needed to be analyzed and hence, the data from the Financial Year 2019 to 2020 was chosen.

The RAMS of Bhutan is based on the universally accepted definition of risk. It provides a framework for the risk assessment of critical road assets namely the road pavement, bridges, cross drainage structures, and earthworks. To develop a comprehensive framework particularly for geotechnical assets and to determine the possibility of integrating the two systems, it was necessary to study the existing risk assessment methodology adopted by the DoR. As the current risk rating scale adopted by the department has been etched into the system, developing a framework for the geotechnical assets in line with the existing RAMS only makes sense and is economical. However, as the geotechnical assets are mostly associated with natural ground materials, they can be of diverse nature and highly unpredictable.

The biggest questions that now arise are, ‘what are geotechnical assets?’ and ‘how can the conditions of geotechnical assets be measured, and their performance and failure predicted?’. As geotechnical assets are critical for effective functioning of any transportation system, some level of geotechnical asset management is practiced by transportation agencies around the world. There are tools being developed by transportation agencies for data collection, risk-based performance assessment, life-cycle cost analysis and prediction of future conditions for geotechnical assets. The National Cooperative Highway Research Program (NCHRP) Research Report 903 ‘Geotechnical Asset Management for Transportation Agencies’ encourages the inclusion of geotechnical assets into the TAM in the US or any other transportation agency around world. The report provides an overview and guidance on the implementation of a GAM system along with the tools that can be used to do so.

Extensive efforts have been put in place by numerous DOTs and transportation agencies around the world toward risk reduction and proactive risk management against failure of geotechnical assets, especially slopes due to geo-hazards. Realizing the benefits of strategically managing the geotechnical assets, transportation agencies are working toward integrating the geotechnical assets into their Transportation Management Plans. The GAM framework for the DoR, Bhutan is being proposed with the learnings from such best practices adopted by the rest of the world.

The proposed GAM framework will primarily focus on the geotechnical asset that is the most prone to geo-hazards. The most common geo-hazard identified upon analyzing the roadblock data would provide the information on the geotechnical asset affected the most. The framework proposed is then going to be tested on few of the important stretches of highways in Bhutan.

An ideal GAM framework would incorporate inventory of assets, data collection for condition assessment and performance monitoring. Conducting a detailed geotechnical investigation requires resources and ample time making it difficult to implement at every site. In the interest of time and to gather higher frequency of data over larger areas, transportation agencies have been switching to remote sensing techniques and such techniques have been gaining much popularity lately. Such techniques are even deployed at critical sites as early warning systems for cost-effective hazard management (Macciotta et al. 2015). There are multiple locations in Western Canada where similar remote sensing technologies have been used for detection of ground displacements, which indicates the efficacy of such techniques for monitoring performance of geotechnical assets. Data collection, inspection and monitoring, and mitigation of natural and man-made slopes in Bhutan are still mostly based on experienced eye judgements of the local engineers. As the country slowly hopes to delve into the more advanced methods, it is about time to learn about the best practices adopted throughout the world and gradually transition into a more robust system at par with other big nations. Therefore, few case examples from Western Canada are included in this document to illustrate the practicability of using some of the novel technologies in asset monitoring with the aim to create awareness and encourage its use in Bhutan in the coming years. The detailed methodology adopted is illustrated in Figure 2 and the following sections provide an overview of the methodology.

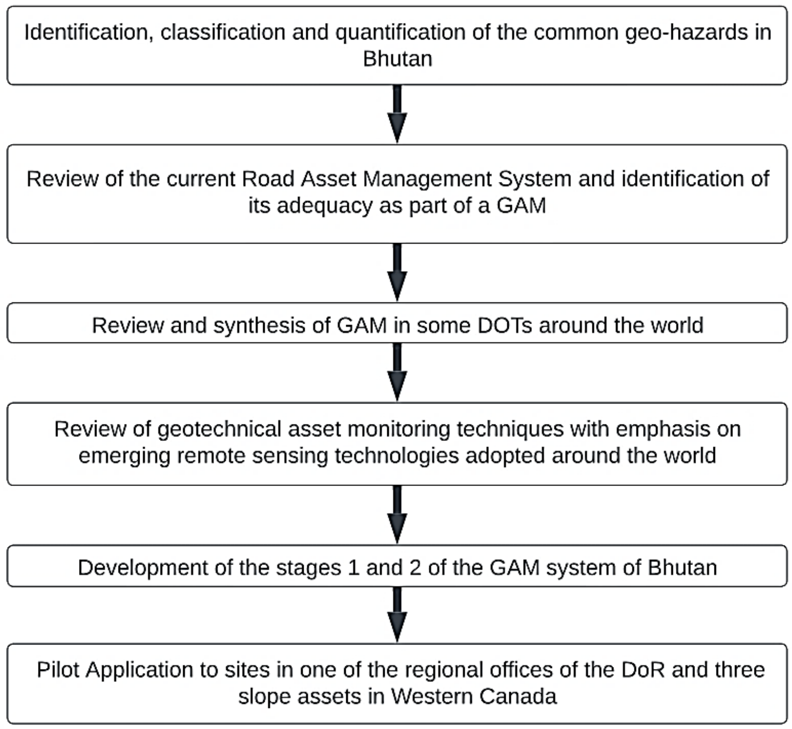


Figure 2: Workflow of the methodology adopted.

The following points briefly describe the content of each chapter in this document:

- Chapter 2 describes the physiographic regions of Bhutan, the occurrences of common geo-hazards in the country, and the link between the two. It further explains the influence of amount of rainfall on slopes along the highways based on the roadblock and rainfall data of 2020 obtained from the DoR and the National Centre for Hydrology and Meteorology (NCHM), Bhutan, respectively.
- Chapter 3 focuses on the risk assessment methodology currently adopted by the DoR in its Road Asset Management System. It comprises an overview of the

methodology backed up by the detailed assessment criterion adopted in the system for common road assets with illustrations for clarity. It further discusses limitations and the way forwards of the system.

- The practice of GAM adopted by various DOTs in the US and around the world is explained in Chapter 4. It describes the methodologies proposed and adopted by the DOTs in managing geotechnical assets against risks posed by geohazards.
- Chapter 5 exclusively discusses the remote sensing techniques adopted for monitoring landslides and rockfalls which can be adopted as a state-of-the-art technology for monitoring of geotechnical assets as a part of the GAMS.
- The framework for the GAM for the DoR, Bhutan, developed based on the best practices adopted by other DOTs, the GRMP of AT, the current practice of RAMS of Bhutan and on the available data from DoR, is explained in Chapter 6.
- The test implementation of the framework is explained in Chapter 7 with example assets from one of the Regional Offices of the DoR, Bhutan and three critical slope assets from Western Canada. Use of remote sensing technologies at the three sites in Western Canada have been presented as case examples of applicability of such technology in the data collection of the proposed GAM. Chapters 8 and 9 include the conclusion and future work of the proposed GAM framework and the references respectively.

2. Geo-hazards in Bhutan

According to the International Centre for Geohazards (ICG), a geo-hazard can be defined as *“a geological state that represents or has the potential to develop further into a situation leading to damage or uncontrolled risk”*. They are related to geological conditions and processes that have occurred in the past and present. Geo-hazards can have a wide range of implications to people and infrastructure. They can even occur naturally in remote areas with no hazardous impacts. Some of the most common and deadly geo-hazards around the world include earthquakes, volcanic eruptions, landslides, avalanches, floods, tsunamis, etc. They can occur in a short period of time or can take thousands of years to surface. They can range from minor to major magnitudes (Ajamee et al. 2022) and severity. Some geo-hazards are triggered by the increasing anthropogenic activities especially construction of roads without sound knowledge of the existing geological terrains.

For a Himalayan country like Bhutan, infrastructures are vulnerable to both tectonic and climate-driven geo-hazards. Some of the most common geo-hazards in Bhutan include the following:

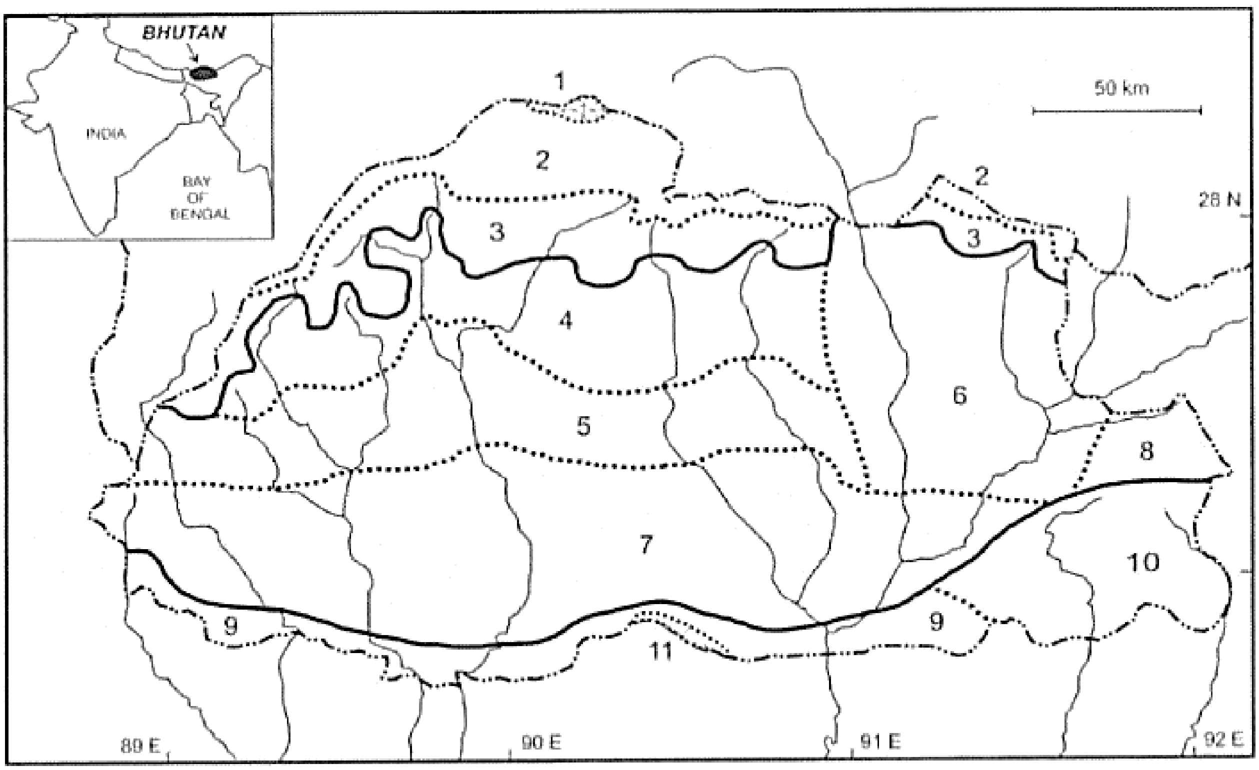
- Landslides
- Debris flow
- Rockfall
- Subsidence
- Flooding
- Scouring

Landslides are geological phenomena where soil masses move from slope surface under the influence of gravity. They are mostly triggered by heavy rainfall or earthquakes. They can occur over time or all at once resulting in various degrees of impacts to the safety of the commuters and economy of the region. Debris flow is an extremely rapid, flow-like mass movement, traveling in a steep, established channel and involving a saturated, unsorted mixture of granular soils, and other debris (Hungr et al., 2001). Debris flow can be responsible for interruption and damage of road infrastructures and lead to fatalities. Rockfall is the phenomenon where rock outcrops or fragments of rock get detached along the existing discontinuities and fall downslope. Depending on the size and magnitude of the rockfall, it can cause varying impacts on the safety and economy of the region. Subsidence is the phenomenon of downward movement of earth's surface which can be caused by inadequate compaction of fill materials or due to natural hazards like earthquakes. It can cause severe damage to road pavements. Flooding in Himalayas is generally caused by the melting of glaciers and due to heavy rainfall during the monsoon season. Scouring is the loss of top bed soil around the bridge piers, abutments, spurs, etc. due to the water flow currents. It can cause failure of bridge foundations.

Heavy monsoon in Bhutan begins from June until the end of August and occurrence of these geohazards are the most prevalent toward the end of the monsoon. It is the riskiest time for travelers to commute and the busiest time for the DoR engineers clearing the roadblocks. Rapid development coupled with unprecedented climate change further triggers the occurrence of such hazards.

2.1 Physiography of Bhutan

The physiographic region of Bhutan can be broadly divided into three regions from north to south: the Greater Himalayas, the Inner Himalayas, and the Southern Foothills. Figure 3 depicts the physiographic regions of Bhutan with different zones as adapted from Chencho Norbu 2003).



Zones 1 – 3 (Greater Himalayas); Zones 4 – 8 (Inner Himalayas); Zones 9 – 11 (Southern Foothills)

Figure 3: Provisional Physiographic Zonation of Bhutan (Adapted from Chencho Norbu 2003)

The Greater Himalayas is a snow-wilderness zone where almost 20% of the land is under perpetual snow with elevation from 3000 metres and above from the mean sea level. Glaciers and barren lands covered with snow are main features of this region. These glaciers are the sources of many rivers in Bhutan. This region comprises the tree line, the area beyond which the vegetation changes from forest to small bushes. This region has a zero to minimal population.

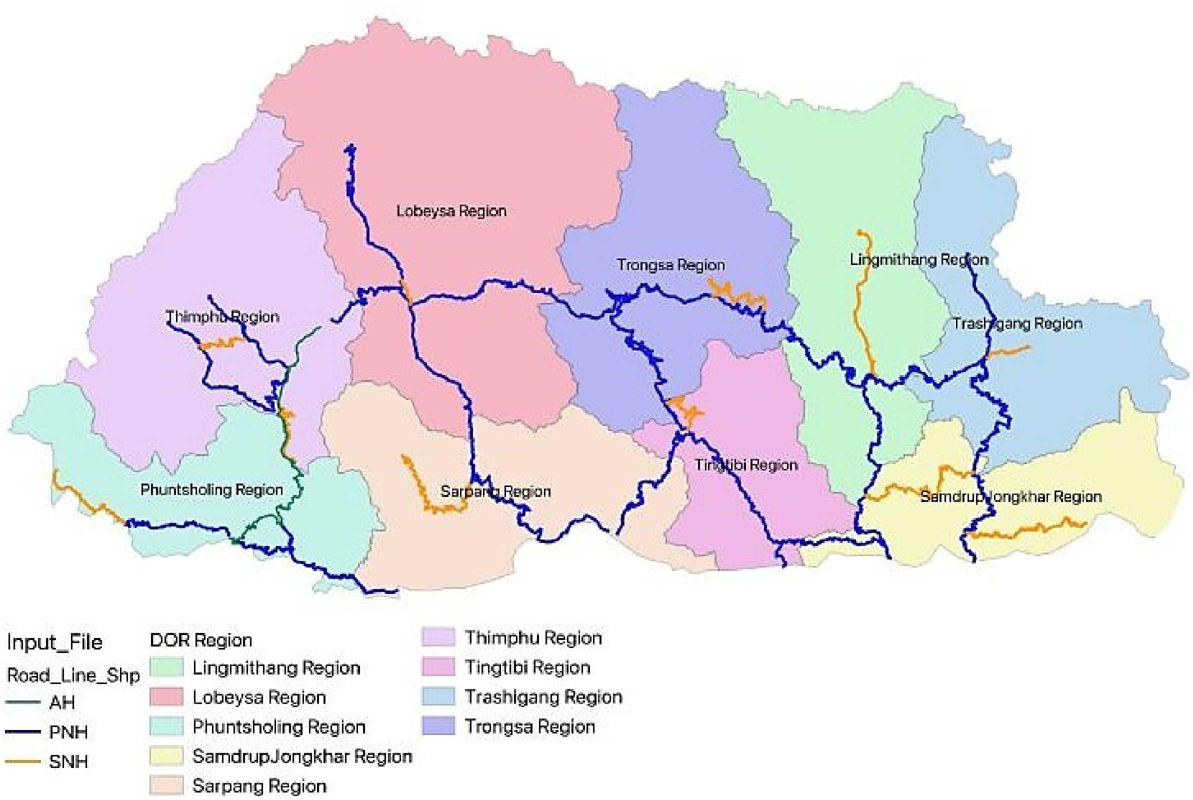
The Inner Himalayas houses all major districts with elevation ranging from 1100 metres to 3000 metres. It is the largest region and the most suitable to live in due to its temperate climatic conditions. The valleys in this region are connected by various passes. The vegetation in this region is characterized by a mixture of broad-leaved and coniferous forest.

The Southern Foothills covers the southernmost part of the country with elevation ranging from 200 metres to 1100 metres. This region receives the highest rainfall. It is known for its dense, lush, and sub-tropical vegetation. It is a habitat for a wide range of wildlife. The population in this region experiences hot and humid sub-tropical climate.

2.2 Geo-hazard Inventory

The nine Regional Offices of the DoR are located throughout the country with multiple districts and roads under the jurisdiction of each RO. These ROs function with the technical support from the Headquarter based in Thimphu, the capital of Bhutan. Figure 4 shows the 9 ROs of the DoR and its major highway network. The highest amount of rainfall is received during the monsoon and the most effort in terms of time and economic resources is spent during this time clearing the roadblocks caused by various geo-hazards triggered by rainfall. The occurrence of such roadblocks directly affects the livelihood of the people as it hinders people from accessing essential services and transport of goods from one region to another; at times it poses a threat to the safety and lives of the commuters.

The occurrence of geo-hazards is measured in terms of the number of roadblocks that occur and are cleared during and after the peak summer seasons. The collection of roadblock data is facilitated using KoBoCollect Mobile Application, which is then transferred onto a masterfile for computation and analysis. This tool has been serving as a reliable source of information for the department in allocating the limited available monsoon restoration budget to the most frequent roadblock locations. The possible causes of roadblocks are scrutinized and identified by site engineers based on visual inspection and experienced judgement. However, due to the lack of monitoring instrumentation at the sites, the identification of the causes of the roadblocks is completely left at the discretion of the site engineers.



*AH – Asian Highway; PNH – Primary National Highway; SNH – Secondary National Highway

Figure 4: 9 Regional Offices of the Department of Roads, Bhutan (Adapted from Maintenance Division, DoR 2019)

The classification of slope movement types as modified from Varnes (1978) given in Figure 5 is used by the DoR as a guide to identify the possible causes of roadblocks. Figure 6 comprises some of the examples of roadblocks caused by different geo-hazards in Bhutan.

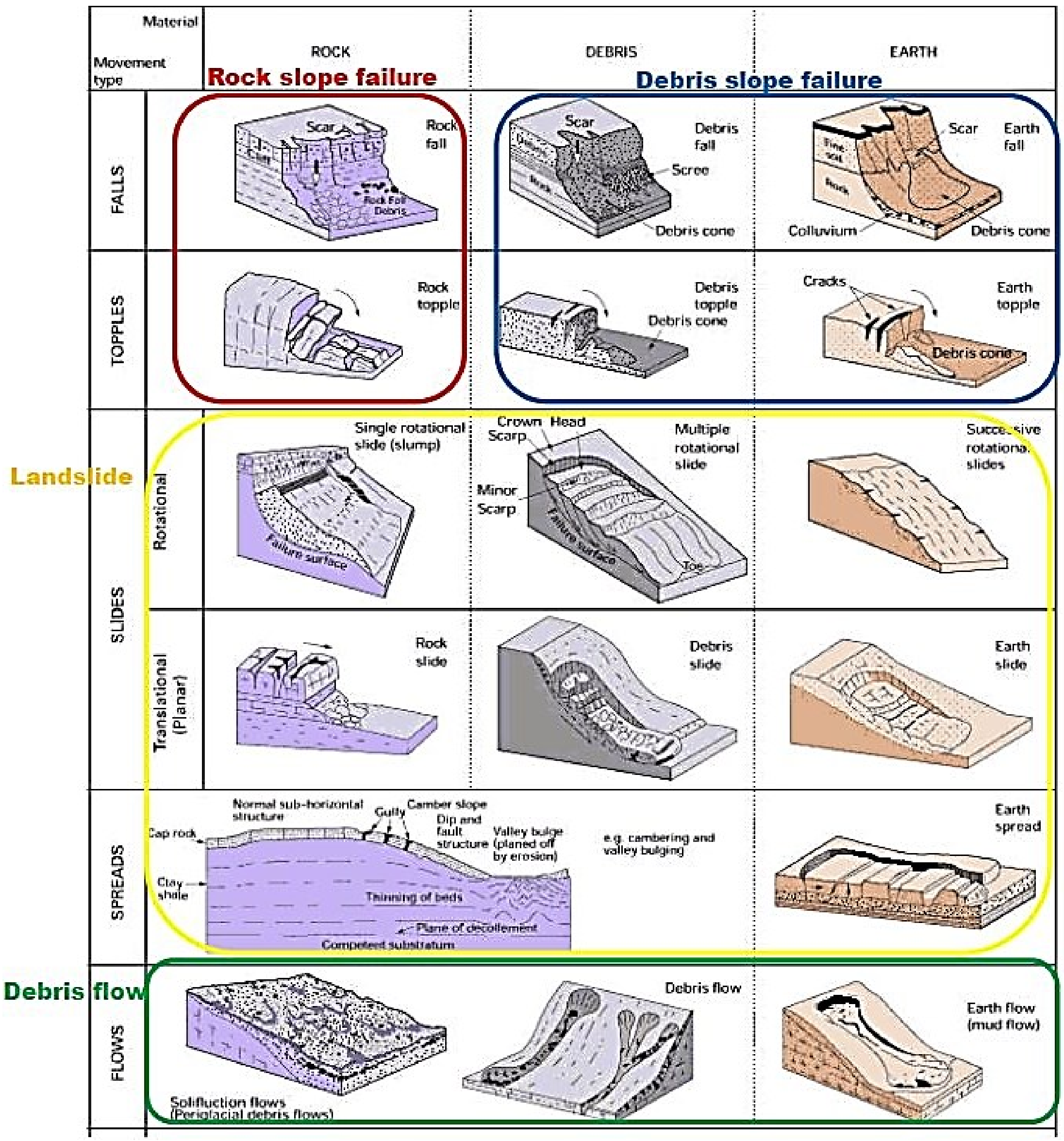


Figure 5: Classification of Types of Slope Disasters (Adapted from Varnes 1978)

Roadblocks are classified into one-time roadblocks and roadblocks that occur multiple times and they are summarized in Table 1 and Table 2 respectively for the year 2020.

Figure 7 and Figure 8 illustrate the percentage of one-time roadblocks and roadblocks that occurred multiple times respectively in 2020.

Roadblocks due to Landslide

Roadblocks due to Rockfall

Roadblocks due to debris flow

Roadblocks due to snowfall

Roadblock due to subsidence/landslide

Figure 6: Examples of Roadblocks in Bhutan due to Various Geo-hazards (Courtesy of DoR)

Table 1: Number and types of one-time roadblocks (Maintenance Division, DoR 2020)

Regional Offices	**Types of Geo-hazards**						
	Landslides	**Debris Flow**	**Rockfall**	**Subsidence**	**Flooding**	**Scouring**	**Snowfall**
Lingmethang	26	0	2	2	1	0	2
Lobeysa	12	5	7	1	1	0	0
Phuentsholing	10	14	3	3	3	1	0
Samdrup Jongkhar	42	1	0	5	0	0	0
Sarpang	125	55	1	4	14	0	0
Thimphu	21	0	0	0	0	0	0
Tingtibi	17	3	8	0	1	0	0
Trashigang	20	1	4	0	2	0	0
Trongsa	79	2	6	1	7	0	0
Total	**352**	**81**	**31**	**16**	**29**	**1**	**2**

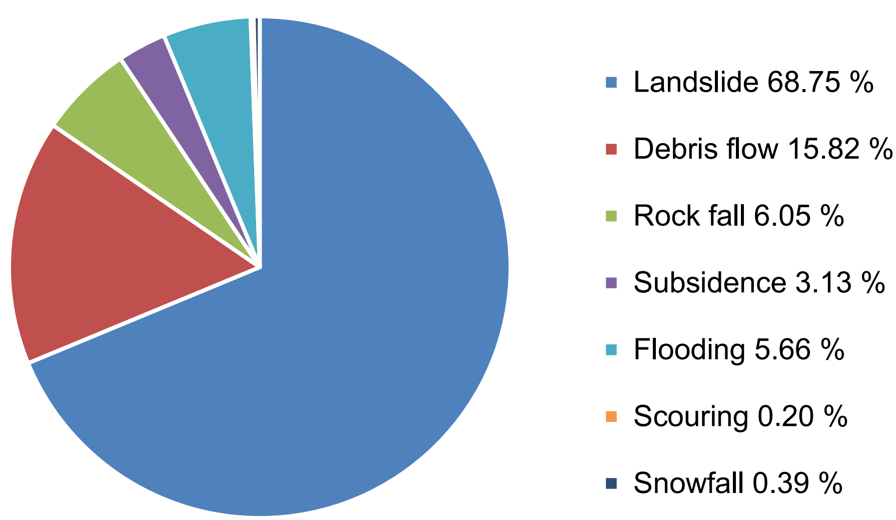


Figure 7: One-time Roadblock Occurrences in 2020 (Maintenance Division, DoR)

Table 2: Number and type of roadblocks that occurred multiple times (Maintenance Division, DoR 2020)

Regional Offices	Types of Geo-hazards						
	Landslides	**Debris Flow**	**Rockfall**	**Subsidence**	**Flooding**	**Scouring**	**Snowfall**
Lingmethang	1	0	0	1	0	0	0
Lobeysa	0	1	1	0	0	0	0
Phuentsholing	16	23	24	2	2	13	0
Samdrup Jongkhar	113	89	13	24	0	2	0
Sarpang	2	1	1	0	0	0	0
Thimphu	1	0	1	0	0	0	0
Tingtibi	28	27	1	0	0	0	0
Trashigang	7	0	7	0	0	0	0
Trongsa	0	1	1	0	0	0	0
Total	**168**	**142**	**49**	**27**	**2**	**15**	**0**

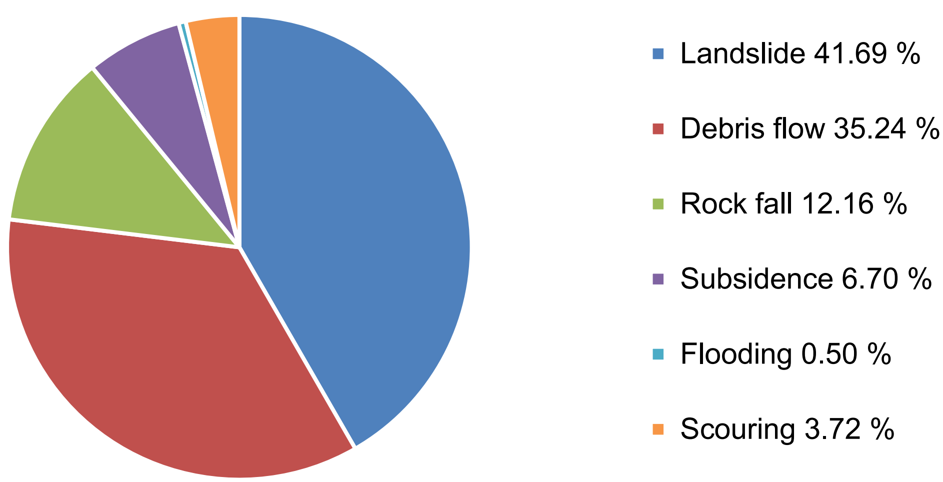


Figure 8: Multiple Roadblock Occurrences in 2020 (Maintenance Division, DoR)

The ROs are located in various physiographic regions of the country and the details can be found in Table 3.

Table 3: Regional Offices and their links to various physiographic zones and regions

Regional Offices	Physiographic Zone*	Physiographic Regions*
Lingmethang	6	Inner Himalayas
Lobeysa	5	Inner Himalayas
Phuentsholing	7 & 9	Inner Himalayas and Southern Foothills
Samdrup Jongkhar	10	Southern Foothills
Sarpang	9	Southern Foothills
Thimphu	4	Inner Himalayas
Tingtibi	7	Inner Himalayas
Trashigang	6	Inner Himalayas
Trongsa	5	Inner Himalayas

*Physiographic zones and regions as shown in Figure 2

ROs comprising districts located in the Southern Foothills tend to receive the highest amount of rainfall and therefore, the majority of roadblocks are witnessed in those regions. Table 4 illustrates the summary of precipitation of various districts under the nine ROs according to the rainfall data of 2020 received from the National Centre for Hydrology and Meteorology, Bhutan. It can clearly be seen from Figure 9; the highest amount of rainfall is received in the months June to August by ROs that have most of its districts in the Southern Foothills region.

Sarpang and Samdrup Jongkhar ROs have the highest number of roadblocks caused by landslides. This contributes to the fact that landslides are the most common cause of roadblocks in Bhutan as illustrated in Tables 1 & 2 and Figures 7 & 8. It can also be deduced that rainfall and sub-tropical climate of the Southern Foothills are the major triggering factors of landslides in those regions.

Table 4: Cumulative precipitation (mm) of different districts under the 9 ROs in 2020

Month	Precipitation amount (mm)								
	1*	**2***	**3***	**4***	**5***	**6***	**7***	**8***	**9***
Jan	26.8	28.3	226.1	23.8	78.3	48.5	12.3	38.1	12.0
Feb	74.9	67.9	124.3	46.9	139.1	38.0	36.4	62.6	35.2
Mar	112.8	143.7	137.5	55.1	105.7	45.6	34.9	114.9	40.0
Apr	193.5	301.6	433.7	193.2	253.9	149.2	177.3	417.7	190.1
May	428.6	434.6	861.5	572.1	1026.3	226.0	140.4	1093.8	440.2
Jun	256.0	546.4	2228.7	991.0	2023.5	368.8	261.1	1324.8	326.8
Jul	337.9	706.8	3756.3	1656.1	3360.9	377.9	373.5	1234.2	427.5
Aug	184.5	703.5	715.0	470.6	1421.2	354.8	185.4	430.4	269.3
Sept	150.3	520.8	1205.6	727.0	1461.8	241.7	191.1	562.2	301.4
Oct	34.4	224.6	553.8	88.8	535.3	86.2	74.0	131.3	76.2
Nov	10.4	10.3	48.2	0.0	17.6	0.6	0.0	28.	10.6
Dec	6.6	15.9	20.4	0.0	20.4	0.3	7.8	15.30	5.3
Total	**1816.7**	**3704.4**	**10311.1**	**4824.6**	**10444.0**	**1937.6**	**1494.2**	**5454.2**	**2134.6**

*1 – Lingmethang, 2 – Lobeysa, 3 – Phuentsholing, 4 – Samdrup Jongkhar, 5 – Sarpang, 6 – Thimphu, 7 – Tingtibi, 8 – Trashigang and 9 – Trongsa

According to the findings from the study of rainfall-induced landslides in Taiwan during 2006 - 2012, extensive landslides usually occurred following long-duration and moderate-intensity rainfall, whereas small and shallow landslides occurred in a wide range of rainfall conditions. Short-duration rainfall can induce shallow landslides as surface materials are easily flushed, however, for deep landslides to occur, high groundwater level, soil moisture, and pore water pressure caused by a prolonged rainfall would be required (Chen et al. 2016). In Bhutan, based on the precipitation data from 2020, the duration of maximum rainfall is from June to August as shown in Figure 9, which could be considered short but a triggering factor to majority of the landslides that cause roadblocks during that time. However, there has been no clear segregation between shallow and deep-seated landslides.

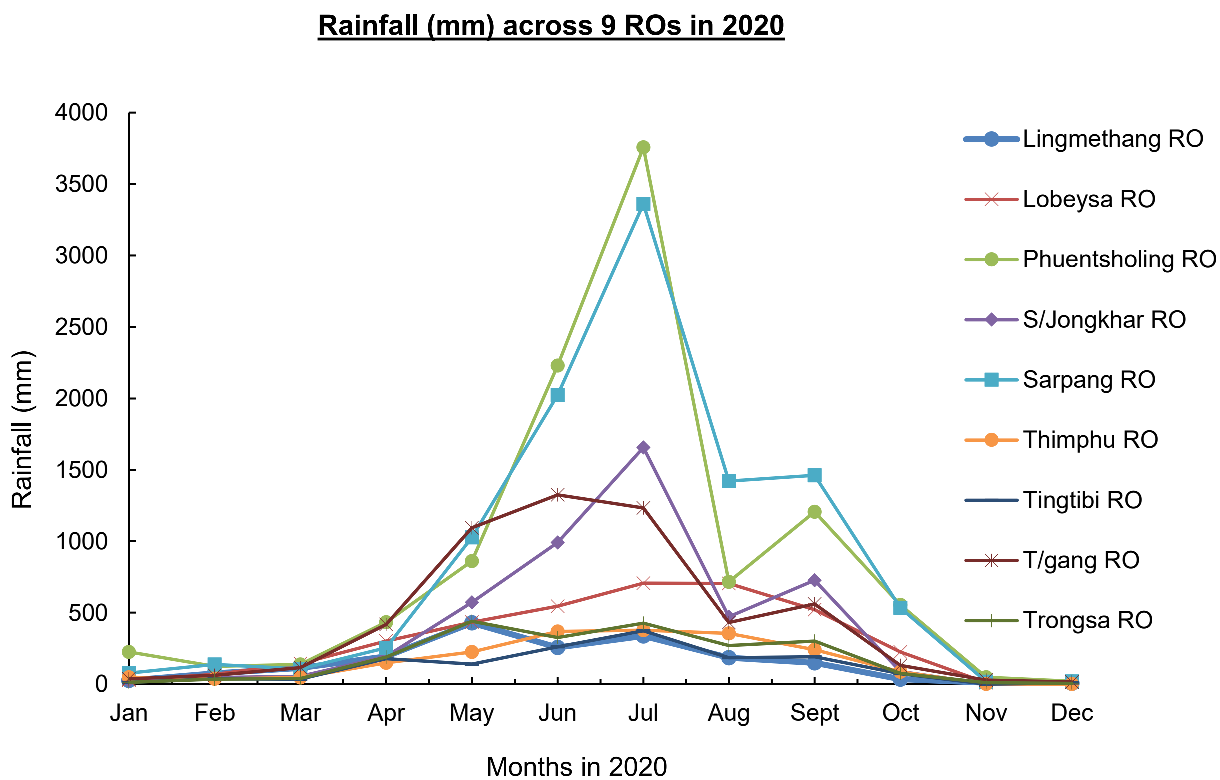


Figure 9: Rainfall (mm) across 9 ROs in 2020

3. Road Asset Management System of Bhutan

3.1 Overview

Developing countries face the brunt of imbalance in funding and developmental activities; funds fall short in numerous construction projects, let alone the maintenance activities. It remains a challenge to provide resilient infrastructure with limited financial and personnel resources for a developing country like Bhutan. Road network of Bhutan has been deteriorating over time due to growing traffic, design or construction deficiencies and inadequate maintenance. The Department of Roads, being the nodal agency responsible for design, construction, and maintenance of important highway networks in the country has been working towards achieving one of its missions of *‘maintaining and ensuring safe and reliable road network through development and use of robust asset management system and innovative road maintenance techniques that are sustainable, economical and environmentally friendly’*. The core reason for the establishment of the Road Asset Management System (RAMS) has been toward fulfilling this mission.

According to the RAMS of Bhutan, asset management is a coordinated approach that seeks to minimize the total cost of acquiring, operating, maintaining, and upgrading or replacing the assets to consistently deliver desired customer satisfaction and the requirements of the government. With technical assistance from the World Bank, the DoR initiated the development of the RAMS with the following objectives:

- Develop a holistic road network inventory.
- Encourage investment and prioritize maintenance interventions depending on the road asset conditions.

- Support funding requirements with concrete facts and facilitate sound decision making.

3.2 Data collection and population

The physical condition and vulnerability survey of the existing road assets was conducted using a video camera and a GPS mounted on a vehicle. The following assets were included in the process:

- Road pavement
- Drainage structures
- Bridges
- Earthworks

The first set of databases for more than 2000 kilometres of National Highways were collected and compiled in 2016 by the department with technical assistance from the consultant INES Ingenieros Consultores S.L. with funding from the World Bank and the Royal Government of Bhutan. The second and third rounds of data collection were undertaken in the years 2017 and 2018 respectively, with the aim to determine deterioration rates of assets and to substantiate investment planning proposals. The inventory and condition assessment data collection for bridges is an on-going project with Japan International Cooperation Agency (JICA) in Bhutan and works are being done to integrate the bridge management system with the RAMS.

The collected data are populated in Excel database, and then exported to Quantum GIS for further analysis and generation of maps. Additionally, Google Earth and AutoCAD are used to facilitate the process.

3.2 Risk Assessment Methodology

The most universally accepted definition of the risk of failure of an asset is the likelihood of failure times the consequence of failure (Macciotta et al. 2018). The same principle has been adopted for the RAMS in Bhutan. Using the available data, it was not possible to mathematically quantify the probability of failure, instead the likelihood of failure has been considered for qualitative evaluation of the risks for each road asset. The following three groups of information have been used for the development of the methodology:

- Asset inventory and condition information
- Natural hazard maps
- Risk assessment factors

The risk score is detailed in Figure 10. It is divided into two components: a numeric component corresponding to the likelihood of failure and an alphabetic component representing the consequences of such failure. This alphanumeric score which is considered a semi-quantitative or a qualitative risk assessment methodology, describes both components of the risk assessment, differentiating between the likelihood of the failure happening and the detrimental effects produced by such failure, which provides a higher degree of information to the decision makers.

The highway networks in Bhutan have been assessed for two possible triggers: the assets' physical deterioration and additionally by the occurrence of natural hazards. The first case is triggered by the inherent conditions of the assets, and it is purely 'internal' whereas the latter case, the cause of potential failure is 'internal' plus 'external', whereby it considers the condition of the asset by the existence of damages and the potential occurrence due to hazard events that would exacerbate the failure. While the risk of physical deterioration enables the department to plan the maintenance activities, the risk of natural hazards highlights the design inadequacies and thus helps introduce design rectifications to mitigate impacts of natural hazards.

Likelihood of failure		**Risk Rating**				
Unlikely	**0 – 20**	0 – 20E	0 – 20D	0 – 20C	0 – 20B	0 – 20A
Possible	**20 – 40**	20 – 40E	20 – 40D	20 – 40C	20 – 40B	20 – 40A
Probable	**40 – 60**	40 – 60E	40 – 60D	40 – 60C	40 – 60B	40 – 60A
Very likely	**60 – 80**	60 – 80E	60 – 80D	60 – 80C	60 – 80B	60 – 80A
Certain	**80 – 100**	80 – 100E	80 – 100D	80 – 100C	80 – 100B	80 – 100A
		E	**D**	**C**	**B**	**A**
		Catastrophic	**Serious**	**Moderate**	**Minor**	**Negligible**
		Consequence of failure				

Figure 10: Risk Rating Scale (Maintenance Division, DoR 2019)

The following relationships are employed for the two categories of risks:

Risk due to Physical Deterioration = *(100 – Asset Condition) x Criticality* ………… [1]

Risk due to Natural Hazards = *Likelihood of Occurrence of Hazard x {100 – [0.85 x Min (Asset Condition; Asset Response) + 0.15 x Max (Asset Condition; Asset Response)]} x Criticality*……………………………………………………………….…… [2]

For the **'risk of failure due to physical deterioration'**, the likelihood of failure is dependent on the condition of the assets, i.e., if there is the existence of intrinsic damages and their nature. The cause of the potential failure is the existence of damage at an advanced level, which reduces the physical condition of the asset. The trigger of failure is therefore ‘internal’ and depends only on the state of preservation of the assets. Risk by physical deterioration enables DoR to plan the maintenance activities. In this case, the likelihood of failure is obtained using the following:

Likelihood of failure = 100 – Asset Condition…………………………………………….…. [3]

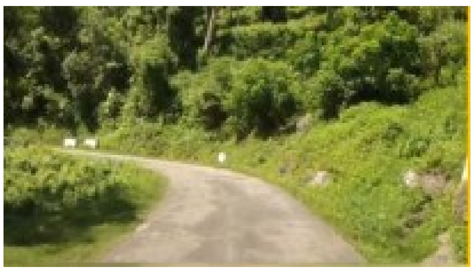
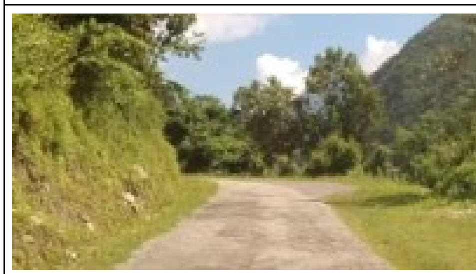
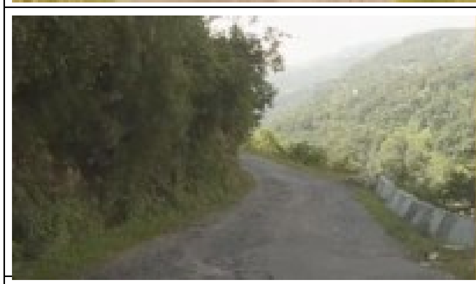
The condition rating follows a scale with 5 different levels with some pre-established criteria for the assessment of each kind of asset. The methodology assigns a range of scoring per condition rate. For instance, Table 5 shows the subjective condition classification for drainage and pavement assets. The asset condition is assessed based on visual assessment and the condition rating follows a scale with five different levels with pre-established criteria for each type of asset.

The present inventory of the assets has a visual condition rating based on letters, and hence the middle value from the provided range is the equivalent score using numbers. For instance, an asset in ‘B’ condition has a 70-condition rating in numbers. The conditions of the assets as mentioned are assigned based on visual assessments, and an example is depicted in Table 6 of the varying conditions of pavement with ‘A’ being the best and ‘E’ the worst.

Table 5: Subjective condition classification for cross drainage structures and pavement (Maintenance Division, DoR 2019)

Rating			Cross Drainage	Pavement
A	80 – 100	Excellent	Newly installed or nearly new condition, correct size, free flowing.	Perfectly smooth without any undulations.
B	60 – 80	Good	Structurally sound, correct size, free flowing.	Good condition with small cracks, thin raveling, and small undulations
C	40 – 60	Fair	Structurally sound, slight siltation and likely to cause drainage problems during times of heavy rain.	Significant cracks such as alligator cracks, longitudinal cracks, transverse cracks, etc.
D	20 – 40	Poor	Signs of deterioration of structure, evidence of silting and likely to cause drainage problems with medium to heavy rain.	Uncomfortable with frequent bumps, depressions, and small potholes.
E	0 – 20	Very poor	Severe structural damage, blocked with silt, vegetation, or other material, inadequate in size and likely to cause flooding even in light rainfall.	Major potholes, large cracks, and undulations.

Table 6: An example of pavement condition ratings (Maintenance Division, DoR 2019)

Asset - Pavement	Pavement Condition	Remarks
	A	Perfectly smooth road pavement without any undulations
	B	Good condition with small cracks, thin raveling, and small undulations
	C	Significant cracks visible (Alligator cracks, longitudinal cracks, transverse cracks, etc.)
	D	Small potholes, rutting and significantly undulating road surfaces.
	E	Major potholes, large cracks, and tremendous undulations; Unpaved roads.

The **consequence** of failure, on the other hand, has been calculated as the criticality of the asset, which is the importance the asset has within the road network, as well as to its economic value. The criticality of assets has been assessed taking into consideration the traffic intensities and the road categories. It further considers the functionality and environmental aspects depending on the location, technical aspects, and economic aspects of each kind of asset which varies according to the asset type. The result is a numeric score that is translated into five level-scale as shown in Table 7.

Table 7: Criticality Classification (Maintenance Division, DoR 2019)

Category	Description		
Very High	5	80 - 100	Would have **catastrophic impact** on the organization's business/services if this asset was not functioning as required.
High	4	60 - 80	Would have a **major impact** on the organization's business/services if this asset was not functioning as required.
Medium	3	40 - 60	Would have a **moderate impact** on the organization's business/services if this asset was not functioning as required.
Low	2	20 - 40	Would have **limited impact** on the organization's business/services if this asset was not functioning as required.
Very Low	1	0 - 20	Would have **negligible impact** on the organization's business/services.

The criticality of assets is further determined by considering the various factors such as the functionality, environmental, technical-economical, etc. which differ for different categories of assets. The factors considered for road pavement assets are as depicted in Table 8, when determining risk caused by physical deterioration.

Table 8: Different criticality factors for road pavement

Criticality Aspect	Weight (%)	Criteria	Weight (%)	Score
Functionality	60	Road Category	50	Primary National Highway (PNH) =1, Secondary National Highway (SNH) = 0.75, District Road (DR) = 0.5, Farm Road (FR) = 0.25
		Traffic	30	Average Daily Traffic (ADT) <100 = 0, 100<ADT<500 = 0.25, 500<ADT<1000 = 0.50, 1000<ADT<2000 = 0.75, ADT>2000 = 1
		Truck Traffic	20	ADT<50 = 0, 50<ADT<100 = 0.25, 100<ADT<200 = 0.50, 200<ADT<500 = 0.75, ADT>500 = 1
Environment	5	Location within a protected area	100	Yes = 1, No = 0
Economic/ Technical	35	Road width	40	Road Width (W) >/= 6 m = 1, 3<W<6 = 0.5, W<= 3 = 0
		Pavement surface material	50	Asphalt = 1, Concrete = 0.75, Gravel surfaces = 0.5, Sand and other surfaces = 0
		Asset location	10	Urban = 1, Rural = 0

An example of application of risk assessment methodology due to physical deterioration is as shown in the Table 9 for a stretch of pavement along Thimphu – Trongsa Highway which is a PNH connecting the capital city Thimphu to the rest of the districts in the central and eastern parts of Bhutan. Criticality is calculated as follows:

Criticality = [(Scoring Subfactor 1 Weight of Subfactor 1 * Weight of Factor 1) + (Scoring Subfactor 2* Weight of Subfactor 2 * Weight of Factor 1) + ... + (Scoring Subfactor n * Weight of Subfactor n * Weight of Factor n)] *100*……………………….[4]

Table 9: An illustration of determination of risk due to physical deterioration for a stretch of pavement asset

Asset (Pavement)	**Likelihood of failure**	**Consequence of Failure**	**Risk Rating**
	Equal to 100 – Asset Condition; Asset Condition in this case is 'A' as the pavement is newly built, with smooth surface, and it corresponds to numerical value '90', which is the mid-value of the range 80-100, hence the likelihood of failure is 100 – 90 = 10A.	It is the criticality of the pavement; *Criticality in terms of i) Functionality – 30+13.5+6 ii) Environment – 0 iii) Technical-Economical - 14+17.5+3.5 Total = 84.5 Consequence 5 *Details in Table 8	Risk level is 10A x 5 = 50 A. It falls in the range of 40-60A of the risk rating scale.

Figure 11 shows the map of Bhutan illustrating the pavements with deteriorating conditions D and E. It was generated using QGIS. The road stretches which are in the worst condition need immediate attention can clearly be observed from the figure.

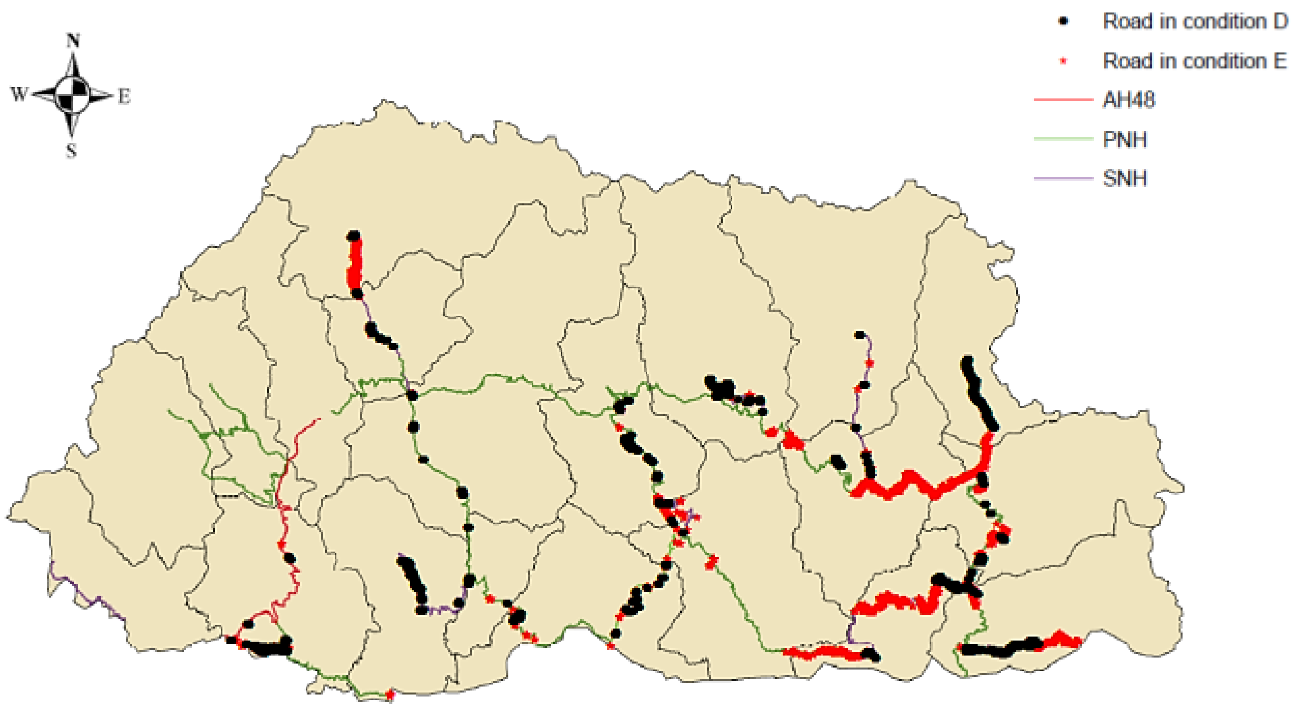


Figure 11:An example showing road pavements in deteriorating conditions (Maintenance Division, DoR 2019)

For the **'risk of failure due to occurrence of natural hazards',** both the condition of the asset and the impact the natural hazards may have, are considered. The cause of potential failure in this case is internal as well as external triggers; it considers the condition of asset i.e., the existence of damages, and the potential occurrence of failure due to the hazard events. The likelihood of failure is given by the following:

Likelihood of failure = Likelihood of occurrence of Hazard x Vulnerability…………… [5]

The likelihood of occurrence of the hazard event is derived from the susceptibility maps which divide the country into areas that have a different spatial likelihood of hazard events occurrence. The susceptibility maps have been generated for the following hazards and return periods:

- Flood susceptibility maps for 5, 20, 100, 200 and 475 years return periods.
- Earthquake susceptibility maps for 50, 100, and 475 years return periods.
- Landslide susceptibility maps for 50, 100 and 475 years return periods triggered by rain and earthquakes.

These susceptibility maps which divide the entire country into five different zones have been used to obtain the likelihood of hazard occurrence factors which corresponds to the location of a particular asset. The likelihood of hazard occurrence factors thus obtained are as shown in Table 10.

Table 10: Likelihood of hazard occurrence factor (Maintenance Division, DoR 2019)

Likelihood of Occurrence		Likelihood of Occurrence Factor
Very High	5	1/1
High	4	1/1.1
Moderate	3	1/1.2
Low	2	1/1.3
Very Low	1	1/1.4

Vulnerability, on the other hand, is the capacity of the assets to respond to a hazard event and it is defined by the combination of two factors: the asset response against hazard and the asset condition. It is an intrinsic property of the asset, regardless of its location. It is determined using the following:

Vulnerability = 100 – [(0.85 x Min (Asset Condition; Asset response)) + (0.15 x Max (Asset Condition; Asset response)] ..……………………………………… ……….. [6]

To address the relationship between asset condition and response, formula 6 ensures the result is not an arithmetic average of both factors but that the weight of each factor depends on its value in such a way that the lowest value of both factors has a higher weight. The asset condition for each type of asset is obtained as previously explained for the case of risk of failure due to physical deterioration.

The four potential hazards to which the road assets in Bhutan are most vulnerable to are determined as flashfloods, earthquakes, landslides triggered by rainfall and landslides triggered by earthquake. Based on the type of hazard and asset, different responses can be expected. To assess the response of assets to the mentioned hazards, it was required to determine which hazard events would affect which asset, as not necessarily all assets are subject to all the four types of hazards. Table 11 illustrates the response scale of the road assets to different hazards.

The consequences of failure, in this case, can be obtained based on asset criticality, which can be obtained as explained in the previous case. An example shown in Table 12 demonstrates how risk can be obtained for the same stretch of pavement as used in the earlier case, but with the consideration of risk due to a hazard event in addition to the risk due to physical deterioration.

Table 11: Asset response scale (Maintenance Division, DoR 2019)

Scale	Score	Description
Very good	80 - 100	Due to the asset's technical and constituent characteristics, the asset is expected to respond greatly against the occurrence of floods/landslides/earthquakes.
Good	60 - 80	The asset's technical and constituent characteristics are enough to make the asset to respond well against the occurrence of floods/landslides/earthquakes.
Medium	40 - 60	The response of the asset against the occurrence of floods/landslides/earthquakes is acceptable, based on the asset's characteristics.
Poor	20 - 40	As a result of the asset's characteristics, its response against hazards is expected to be poor. The asset is more vulnerable to the hazards due to its geometry and constituent materials.
Very Poor	0 - 20	The asset response against hazard is expected to be very poor due to unsuitable characteristics. The asset is highly vulnerable to hazards.

According to the landslide susceptibility map, the given stretch of pavement falls in the jurisdiction of low likelihood of hazard occurrence zone, with the likelihood of occurrence factor of 0.75 as obtained from Table 10. Since the pavement is newly built, it is expected to exhibit sound resilience to any hazard event, hence an asset response factor of 80 is assigned from Table 11. Asset condition, on the other hand, remains the same as the previous example i.e., 'A' which corresponds to the range 80 – 100, and likewise the mid value of 90 is assigned. The consequence of failure is determined based on the criticality of the pavement stretch and the value obtained is the same as in the prior case. However, the risk level is obtained using formula 2, which considers both the asset response and asset condition, and the value thus obtained is 69.4A which falls in the range of 60-80A of the risk rating scale. The risk level has slightly increased in value; however, it remains in the zone of lower risk for this stretch of pavement.

Table 12: An illustration of determination of risk due to natural hazard for a stretch of pavement

Asset (Pavement)	Likelihood of failure			Consequence of Failure	Risk Level
	Likelihood of hazard occurrence factor	Asset Response	Asset Condition		
	0.75	80	90A	It is the criticality of the pavement; *Criticality in terms of i) Functionality – 30+13.5+6 ii) Environment – 0 iii) Technical-Economical - 14+17.5+3.5 Total = 84.5 Consequence 5 *Details in Table 8	RL = [0.75 x (100 – (0.85 x 80) + (0.15 x 90)) x 5] RL = 69.4 A

3.3 Short comings

As much as the system has been simplified for easy understanding and implementation, most of the steps involved in data collection are manual and time consuming. The asset conditions are determined using a simple camera which records videos of the entire stretch of the highway network with GPS coordinates. The conditions of the assets are then assessed manually through visual inspections using recordings. Some of the information is not correctly captured due to the weak GPS reception of the camera, especially in densely vegetated parts of the country. The conditions of the assets are determined purely based on the visual assessment with little or no technical or engineering references. Data population in excel is a tedious task as it requires assessment of individual asset condition through visual inspection of the video recordings analyzed in few seconds interval. Hence, the available data on which the system has been based can be highly subjective.

As RAMS is fairly new to the Department, it is yet to gain popularity among the DoR personnel. Numerous errors have been recorded in data gathering; one reason being a lack of understanding of the importance of adequately following the system. In order to develop deterioration models of the assets for further long-term planning and budget allocation, data collection and population must have minimal errors.

The data collected from the road using GPS and camera, mainly shows the road and limited features outside of the driving lanes. Hence, the system has resulted in substantial prioritization of funding for pavement and rehabilitation; however, it does not currently explicitly consider all geotechnical assets in prioritizing funding. Landslides, debris flows and rockfalls being the main causes of road blockages in the road network, there is an urgent need for a comprehensive and an enhanced system for the management of geotechnical assets.

3.4 Way forwards

Special attention can be placed on data collection, population and management processes which can tremendously reduce the errors and the subjective nature of data interpretation. Use of more robust tools like the Kobocollect Application, that are affordable and effective, could be explored and implemented. Developing a reliable database will be the most critical step for a country like Bhutan; the future of a robust asset management system would largely depend on this database.

To optimize the use of the limited resources, instead of carrying out the data collection survey for the entire assets on an annual basis, it could be carried out every five years; priority can be placed on road stretches that are critical in between. It is critical that the personnel in the field understand the significance of data collection in the overall management of assets and planning. Likewise, more care will be taken in the collection of data if there is adequate awareness among the field staff.

4. Practice of Geotechnical Asset Management

4.1 Overview and taxonomy

In the International Standards Organization (ISO) Standard 55000, asset management is defined as the *'coordinated activity of an organization to realize value from assets. Realization involves the balancing of costs, risks, opportunities, and performance benefits.'* Additionally, the ISO standard states that, *'asset management enables an organization to examine the need for, and performance of, assets and asset systems at different levels. Additionally, it enables the application of analytical approaches towards managing an asset over the different stages of its life cycle (which can start with the conception of the need for the asset, through to its disposal, and includes the managing of any potential post disposal liabilities)'*. (AASHTO TAM Guide 2020)

Transportation agencies around the world have the mandate of safely facilitating the movement of goods and people from one place to another. They also have the goals of being sustainable, minimizing life cycle costs and reducing environmental impacts. Geotechnical assets are the structures composed of soil or rock that help transportation agencies to perform strategic missions (Anderson et al. 2017). Transportation assets like bridges and pavements are given due emphasis in almost every transportation agency. However, geotechnical assets are grouped into the category of unpredictable liabilities, and they may be ignored altogether until failure forces action even though these assets contribute immeasurably to any transportation network (NCHRP 2019). The importance of Geotechnical Asset Management (GAM) was realized by the Transportation Research Board and the National Cooperative Highway Research (NCHRP), and it was conveyed through the NCHRP Research Report 903 titled

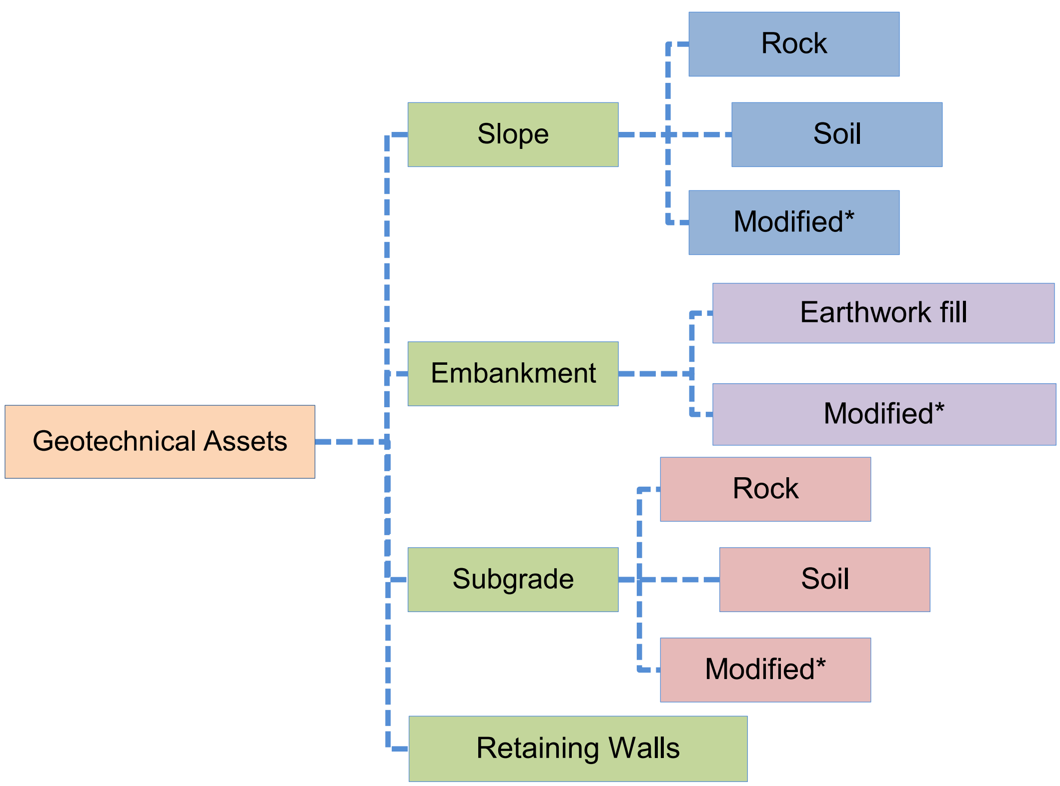
‘Geotechnical Asset Management for Transportation Agencies’. The NCHRP report describes the following benefits of implementing a GAM system:

- Bring about financial savings across the life cycle of geotechnical assets.
- Serve to measure and manage involuntary safety risk exposure across entire asset class.
- Reduce travel delays and road closure times.
- Minimize economic impacts to users, private enterprises, and communities.
- Reduce damage to other transportation assets.
- Improve sustainability of assets, reputation of transportation agencies and optimize resources.
- Facilitate data-driven decision making and help fulfill agency goals and objectives.
- Provide a better understanding of risk exposure levels and help in easy management of those risks.

The Department of Transportation (DOTs) across the United States are required to repair numerous surficial slope failures, referred to as nuisance slides, along with substantial landslides. Though small, these slides cause damage to or loss of pavement sections, reduce effectiveness of safety measures, block drainage channels, and significant damage to bridge piers and other structures. Hence these slides require routine maintenance incurring costs, which may be relatively low for a single slide, but can result in a much higher cumulative cost (Bernhardt et al. 2003).

All in all, the timely and proactive management of geotechnical assets can bring about lifecycle cost savings, help measure, communicate, and manage risks, reduce operational disruptions and lead to a reduction in emergency stabilization projects. According to Anderson et al. (2016), the following assets can be categorized as geotechnical assets (Figure 12 & Table 13):

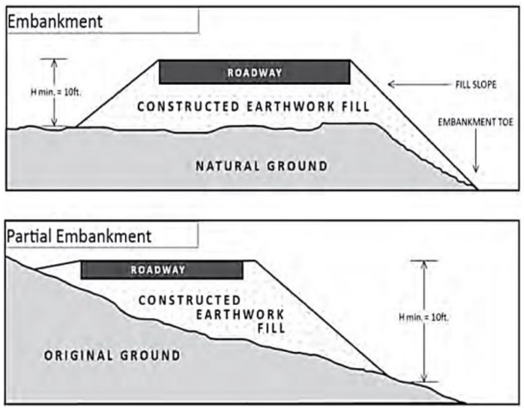
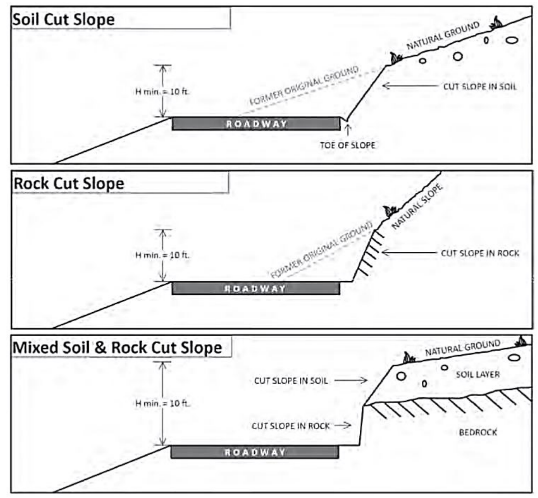
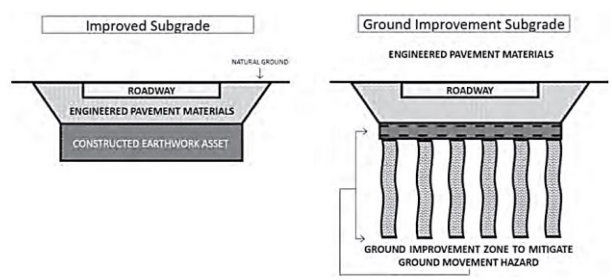
- Slopes
- Embankment
- Retaining Walls
- Subgrade



* Modified slope, embankment, and subgrade contain non-earth inclusions such as anchorages, reinforcements, protection elements, or ground improvements

Figure 12: Recommended Taxonomy for GAM (Adapted from NCHRP 2019)

Table 13: Geotechnical assets according to NCHRP 2019 (With permission from the National Academy of Sciences 10/13/2022)

<table>
<tr><th>Embankment</th><th>Slope</th></tr>
<tr><td>
</td>
<td>
</td></tr>
<tr><th>Retaining Wall</th><th>Subgrade</th></tr>
<tr><td></td>
<td>
</td></tr>
</table>

Bernhardt et al. (2003) discusses the intimate relation between geotechnical assets and other types of assets; that the boundaries between the two types of assets are often blurred. Hence, it was suggested to segregate the geotechnical assets as shown in Table 14. They say it is very likely that assets which fall under the purview of geotechnical assets may vary among organizations according to the organizational structure and history.

Table 14: Highway components that may be considered geotechnical assets (Adapted from Bernhardt et al. 2003)

<table>
<tr><th>Asset</th><th>Asset function category</th><th>Interaction with other assets</th><th>Purpose</th></tr>
<tr><td>Embankments and slopes</td><td>Exclusively geotechnical</td><td>Indirect</td><td>To provide for gradual grade changes in vertical alignment</td></tr>
<tr><td>Tunnels and earth retaining structures</td><td rowspan="2">Partially geotechnical</td><td rowspan="2">Direct</td><td>To retain earthen materials so that highway can be constructed in restricted right-of-way</td></tr>
<tr><td>Culverts and drainage channels foundation</td><td>To provide control of surface waters. To transmit structural loads to supporting ground</td></tr>
<tr><td>Pavement subgrade</td><td>Minimally geotechnical</td><td>Direct</td><td>To serve as foundation for pavement</td></tr>
</table>

Since the embankments and slopes do not directly apply load or support other assets, they are categorized as exclusively geotechnical assets. Partially geotechnical assets like tunnels, earth retaining structures, culverts and drainage channel foundations are tied much more directly to other assets in both physical and conceptual sense. Even if the underlying geologic materials significantly impact the performance of a pavement system, it is the pavement engineers that are primarily responsible for the design and functioning of subgrades, hence the pavement subgrade has been categorized as minimally geotechnical (with the understanding that geotechnical theories and practices are required to the design and maintenance of subgrades, as part of the overall component of the road structure) (Bernhardt et al. 2003)

4.2 Methodologies

GAM proposal for Federal Highway Administration (FHWA) by Bernhardt et al. (2003) – Data base is considered the most crucial source of information, and hence it is advised to store all data in a database that provides valuable information to the users and is easily accessible. Data are segregated into static data that remains unchanged or hardly changes such as location or year of construction, and data that frequently and continuously change like displacements and costs are viewed as dynamic data.

An agency is advised to assign values to its assets and to track the projected maintenance and rehabilitation costs along with budget data and allocation constraints if any. Using the database, algorithms are applied for the analysis of data to generate information that would assist in decision-making. It comprises economic analysis, risk analysis, condition forecasting, cost forecasting, etc.

Finally, the program selection and implementation can include reports that can suit various levels of users and authorities for decision making purposes. It is the ultimate tool that can be used by the management to determine if the data collection practices, and analysis tools are sufficient. The following framework in Figure 13 was suggested by Bernhardt et al. (2003):

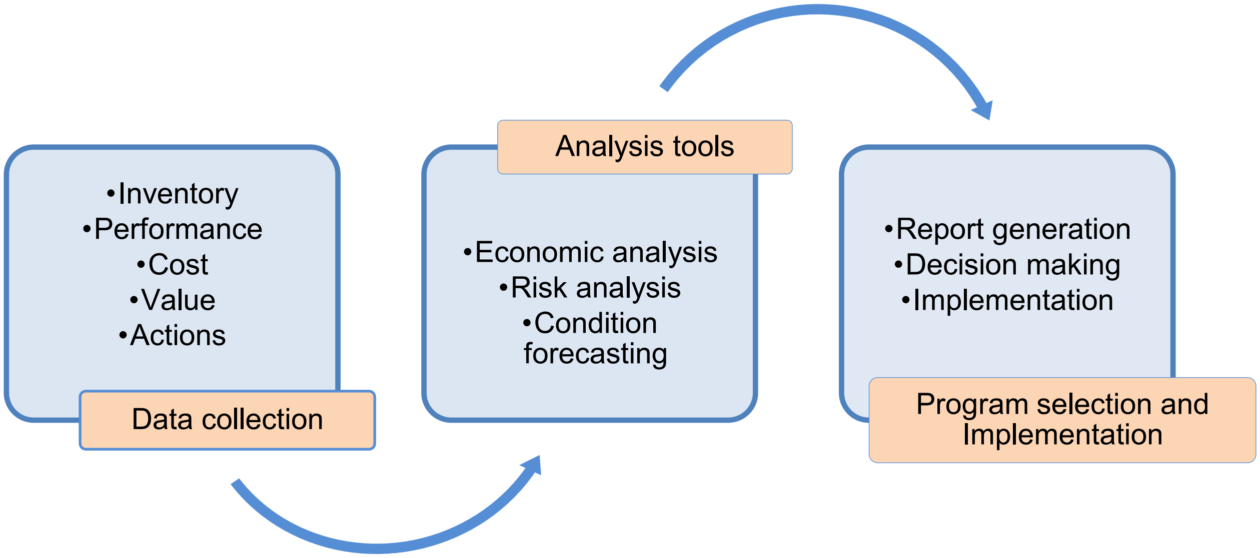


Figure 13: GAM framework suggested by Bernhardt et al. 2003 (modified)

Details of the above can be found in Table 15:

Table 15: Details of the components of GAM framework (Adapted from Bernhardt et al. 2003)

Data Collection	**Description**
Inventory	Location, extent, height of embankment, soil properties, etc.
Performance	Existing erosion, stability, etc.
Cost	Maintenance budget, cost of maintenance actions, etc.
Value	Replacement cost may be the most appropriate option.
Actions	No action, monitor, temporary repair, permanent repair, etc.
Other	Impacts of failure to safety, mobility, etc.
Analysis Tools	**Description**
Economic analysis	Calculation of life-cycle costs to compare impacts of various maintenance and repair options, etc.
Risk analysis	Evaluate risk of repair alternatives as well as risk of no repair, etc.
Condition forecasting	Prediction of future of conditions of geotechnical assets based on current and past information.
Other	Calculate level of hazard and factor of safety, etc.

Program selection and implementation	Description
Report generation	Tables, graphs, charts, etc.
Decision making	Comparison of costs, benefits, and risks of alternatives under different budget scenarios and decide on the course of action.
Implementation	Implement the decision made
Other	Suggest modifications to budget to achieve performance objectives

Transportation Asset Management (TAM) of U.S. State Department of Transportation – Considering the importance of including geotechnical assets in an agency's transportation asset management plan, the NCHRP (2019) Report 903 provides a research overview, the GAM Implementation Manual and the GAM planner tool using which, any agency can kick-start a risk-based asset management program without requiring significant start-up costs or efforts. It can be started simply, even with an incomplete inventory that advances with time. One of the major conclusions drawn from the discussions during the formulation of this GAM Implementation Manual was that a program that is simple to implement would also have the greatest likelihood for adoption and hence considered the following characteristics:

- Relatively simple and easy to implement.
- No requirements for authorization by legislations
- Low cost and resource requirements at initiation

Additionally, as stated in the International Infrastructure Management Manual (IIMM), *"a rule of thumb is often 80 percent of the data can be collected for half the cost of 100 percent. Seeking 100 percent coverage and accuracy may not be justified, except for the most critical assets"* (IPWEA 2016). As data collection for inventory can be a time and cost intensive process, it must be prioritized based on the required level of detail for decision support. Data collection in GAM can deploy the stages as shown in Figure 14.

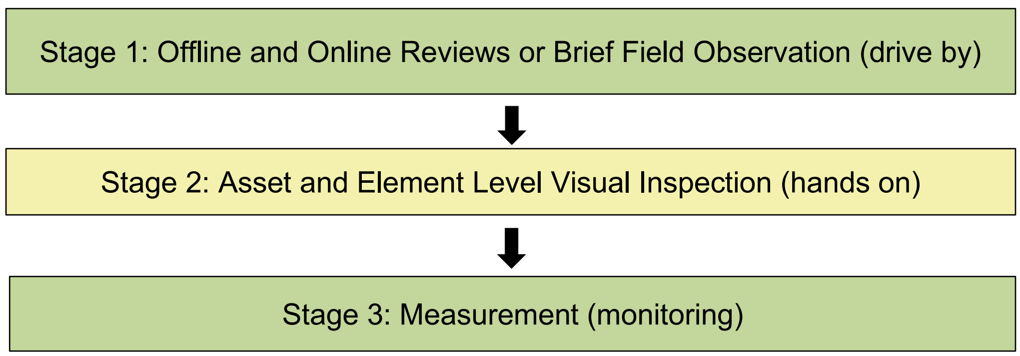


Figure 14: Staged Approach for Data Collection in Asset Management (Adapted from NCHRP 2019)

The proposed implementation process consists of the simplified steps as shown in Figure 15.

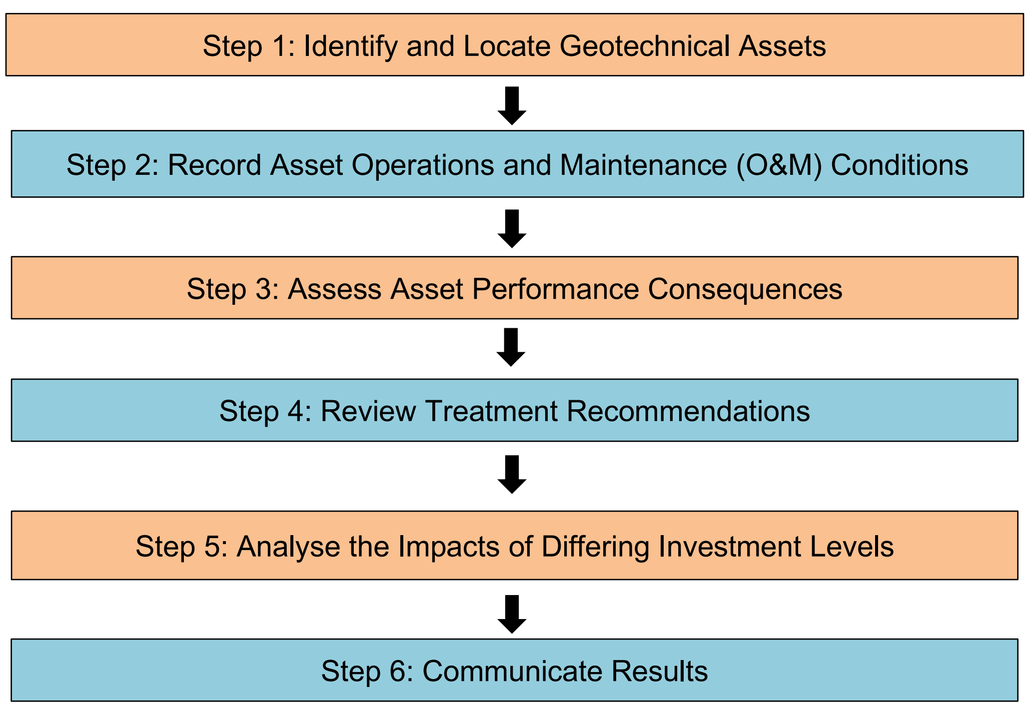


Figure 15: Implementation steps in GAM (Adapted from NCHRP 2019)

Colorado Department of Transportation (CDOT) – Geotechnical assets and hazards have recently been included in the Risk-Based Transportation Asset Management Plan (RB TAMP) aimed to manage multiple hazards linked with slope, embankment, and roadway subgrades. It addresses several performance indicators such as the safety of the commuters, conditions of infrastructure, reliability, traffic, etc. The risk types considered are natural hazards, physical failures, external agency impacts and operational risks.

CDOT calculates the risk as the product of consequence and likelihood, consequences in dollars, and likelihood as an estimated probability. The four asset types considered, four performance goals from the MAP-21 federal highway transportation bill, and four risk types defined by American Association of State Highway Transportation Officials (AASHTO, 2011) are as shown in Figure 16.

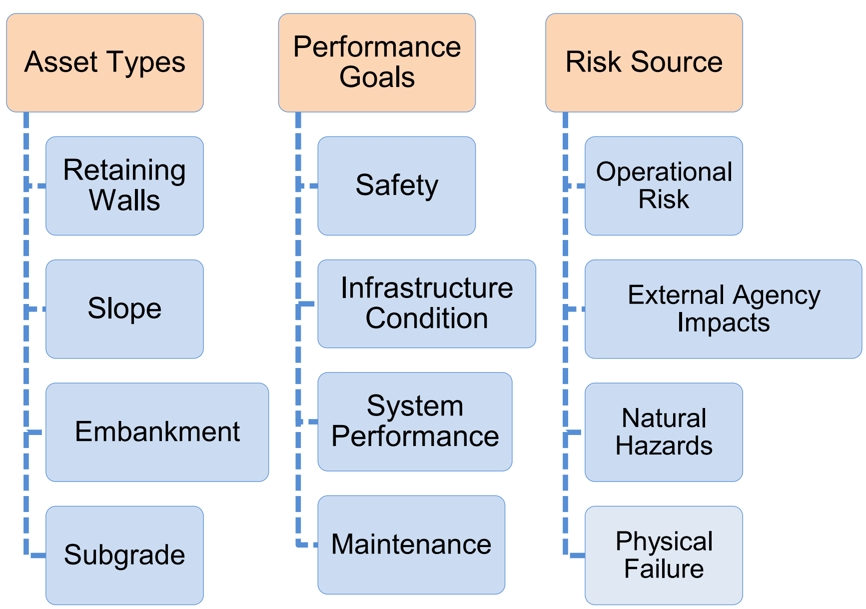


Figure 16: Elements of risk cube of CDOT (Adapted from Anderson et al. 2007)

The retaining wall management plan of CDOT has over 3000 walls and they are assessed against two geotechnical risks namely the maintenance and mobility goal risks. For the maintenance risk, following are the parameters considered:

- Consequence – Quantity of Elements (Unit costs)
- Likelihood – Condition State (Element Type and Element Category whether primary or secondary)

The parameters considered for the mobility risk calculation are as follows:

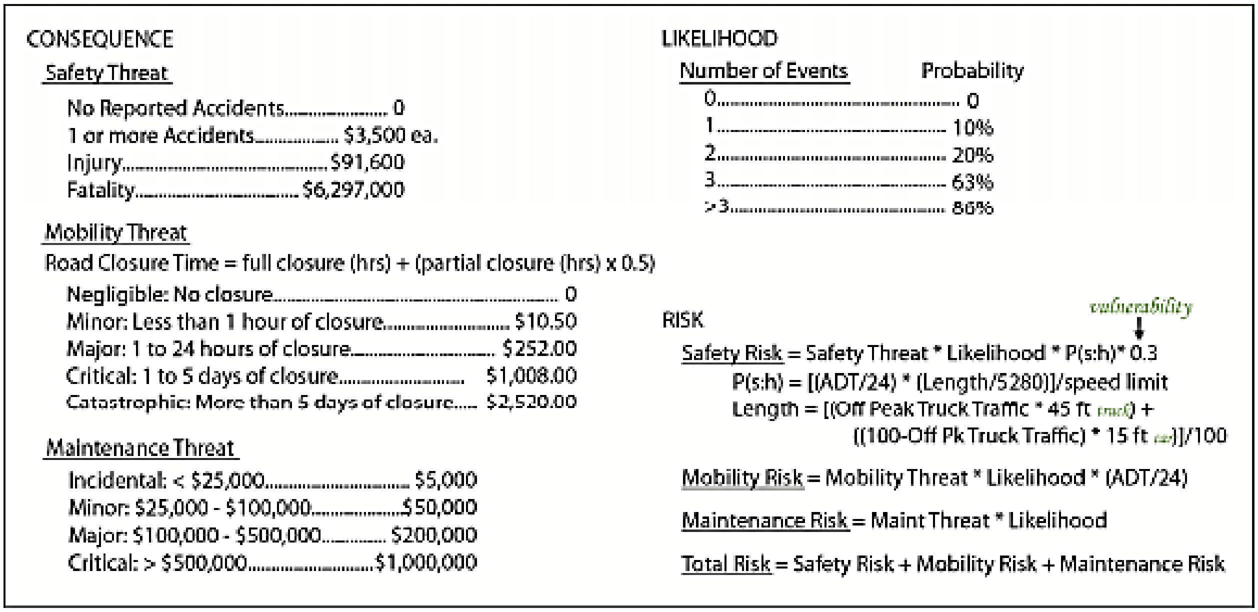
- Consequence – Average wall height, average distance from road in front and road carried, Annual Average Daily Traffic, delay time (2 hours), user value ($ 30.50), occupancy rate (1.67), ADT delay (33 % of actual ADT)
- Likelihood – Main structure condition, foundation condition, scour critical condition.

Following relationships are used to finally obtain the mobility risk:

$$\text{User Costs} = \frac{\text{Delay time}}{3600} \times \frac{(\text{AADT Actual} - \text{AADT Delay})/2}{24} \times \text{User Value} \times \text{Occupancy Rate} \ldots\ldots \quad [7]$$

$$\text{Mobility Risk Exposure} = \text{User Costs} \times \text{Wall Condition} \ldots\ldots \quad [8]$$

However, the other three categories of assets are assessed against all three performance goals and the process as shown in Figure 17.



CONSEQUENCE

Safety Threat

No Reported Accidents...................... 0
1 or more Accidents.................. $3,500 ea.
Injury.. $91,600
Fatality............................... $6,297,000

Mobility Threat

Road Closure Time = full closure (hrs) + (partial closure (hrs) x 0.5)

Negligible: No closure.. 0
Minor: Less than 1 hour of closure.......................... $10.50
Major: 1 to 24 hours of closure.............................. $252.00
Critical: 1 to 5 days of closure.......................... $1,008.00
Catastrophic: More than 5 days of closure..... $2,520.00

Maintenance Threat

Incidental: < $25,000.............................. $5,000
Minor: $25,000 - $100,000.................... $50,000
Major: $100,000 - $500,000............. $200,000
Critical: > $500,000......................... $1,000,000

LIKELIHOOD

Number of Events	Probability
0	0
1	10%
2	20%
3	63%
>3	86%

RISK

Safety Risk = Safety Threat * Likelihood * P(s:h)* 0.3 (vulnerability)
P(s:h) = [(ADT/24) * (Length/5280)]/speed limit
Length = [(Off Peak Truck Traffic * 45 ft truck) + ((100-Off Pk Truck Traffic) * 15 ft car)]/100

Mobility Risk = Mobility Threat * Likelihood * (ADT/24)

Maintenance Risk = Maint Threat * Likelihood

Total Risk = Safety Risk + Mobility Risk + Maintenance Risk

Figure 17: Calculation of total annual geo-hazard risk exposure of CDOT (Anderson et al 2007)

4.3 Discussion

The study of practices of GAM at different DOTs emphasizes a need to develop better management practices that are tailored to the specific needs of geotechnical assets; an integrated GAMS, which includes the development of data-driven decision-making process essential to ensure the long-term success of GAM programs. These practices should include the use of appropriate monitoring and assessment techniques, as well as the development of effective life-cycle management plans. It is necessary for agencies to develop and implement GAMS to ensure the safety and performance of their infrastructure, and to be able to achieve this, agencies must integrate various technologies, data management, and planning processes. Not a lot of work has been done in the field of GAM and hence it further highlights the need for more research into the development of effective decision support systems and the use of advanced analytics to better understand the condition of geotechnical assets.

The GAM Implementation Manual by NCHRP provides guidance and information for an agency to realize the benefits of GAM and it has been purposely developed for adoption by any agency irrespective of the stage of their GAMS. It can be simply and easily implemented without substantial resources involved in its initiation. Most importantly, it lays out the basics of GAM through step-by-step instructions to initiate its implementation and provides supporting information and guidance on integration of GAM with TAM as the level of GAM matures over time. The most critical component of an effective GAM is the management of risks to traveller and worker safety, mobility, and economic vitality.

The RB TAMP of CDOT considers the external agency impacts as one of the risk sources, however, for DoR, as GAM is yet to be implemented, it can be a challenge to involve different stakeholders, citizens, and private sector organisations due to their lack of knowledge about GAM and its importance. The consequences in terms of safety, mobility, and maintenance threats are obtained in terms of monetary values (dollars) which ultimately results in risk values in terms of dollars. This would require acquisition of data such as the direct and indirect costs of various components of the mentioned threats to obtain the consequences and hence the risk levels. Such a level of data collection can be tedious and resource intensive, and it might take extra effort to convince the decision makers into making investments.

Some of the issues the DoR or many other transportation agencies are likely to face in implementation of a GAMS are:

- Insufficient data as most agencies neither maintain a complete inventory of geotechnical assets nor do they track maintenance costs at the level of detail required to ascertain costs for geotechnical repairs. Additionally, most agencies do not assess the condition of geotechnical assets on a routine basis, hence making it difficult to determine deterioration models.

- The need to identify and address the potential impacts of poor performance of geotechnical assets such as the safety and mobility of the commuters, which could be, as stated earlier, time and resource intensive.
- The uncertainty in carrying out the risk-based analysis on geotechnical assets as the performance of such assets are often dominated by random events, like heavy rainfall, earthquake, etc. which would lead to changing conditions of the assets.

5. Asset Inspection and Monitoring

Asset inspection and monitoring are usually perceived as a reactive approach and are conducted only after the asset has undergone considerable damage and needs evaluation for either repair or replacement. For the data collection purposes, asset condition inspections are done through visual inspections backed up by displacement measurements and use of GPS mounted cameras, GIS tools, etc. It may not be feasible to conduct detailed monitoring and inspection of all sites given the costs and resources associated with it. A detailed hands-on inspection is the most apt and accurate for determining risks and mitigation measures, however this type of inspection is more expensive and may not be required for every asset (Alaska DOT&PF GAMP 2017). A simple rule of thumb for data collection and the threshold criterion for different stages of data collection are consolidated in Figure 18.

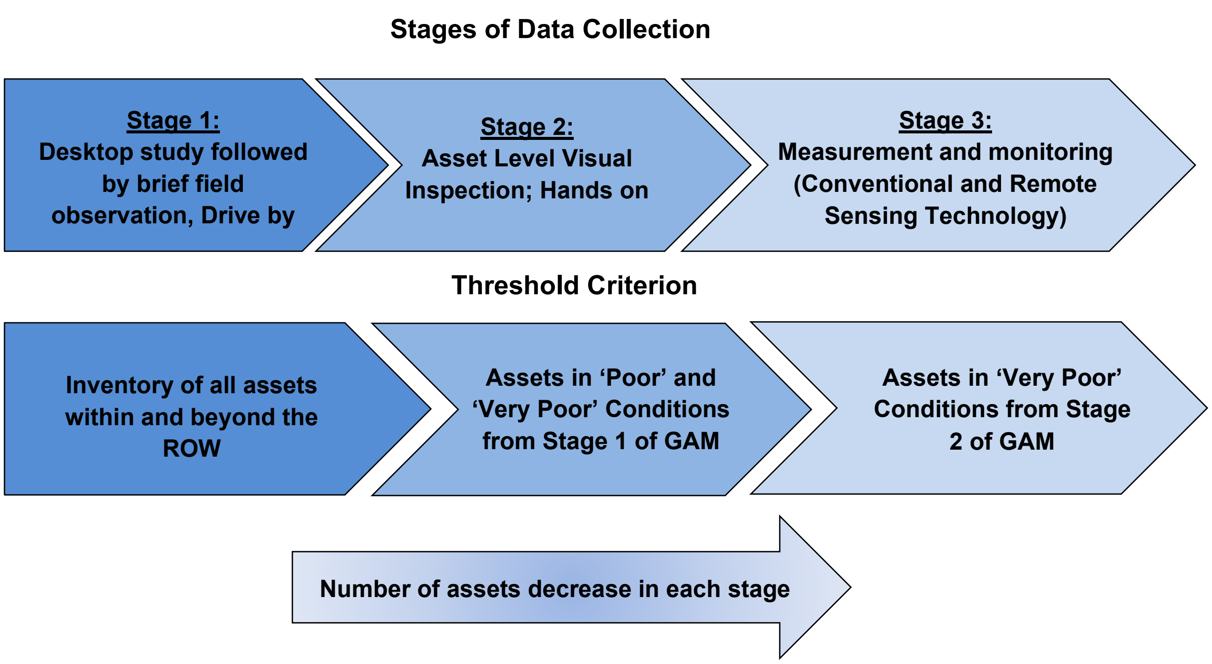


Figure 18: Rule of Thumb for Data Collection, Inspection and Monitoring and Threshold Criterion (Adapted from NCHRP 2019)

This chapter focuses on the monitoring and measurement of various parameters of geotechnical assets using conventional methods as well as remote sensing techniques, with more emphasis on the latter. It provides an overview of the state of technology that can be used to better manage geotechnical assets. Some of the important geotechnical parameters for an effective and useful monitoring plan are displacement or deformation, pore water pressure, stress, load and strain, temperature, vibration and acoustic, etc. (Dunnicliff J. 1995, Dunnicliff J. et al. 2012). A detailed geotechnical inspection should generally comprise the following:

- Site investigation comprising field investigation (drilling, sampling, in-situ testing, etc.) and laboratory testing.
- Data analyses
- Risk assessment and management
- Identification and design of mitigation measures

Asset monitoring has a pivotal role to play in the risk management of assets. Although there is extensive work being done in understanding the landslide characteristics and monitoring using in situ testing, instrumentation, and remote sensing techniques, there are more advancements in such technologies which are more precise and reliable. In fact, remote sensing technologies are gradually becoming a routine practice in the fields of landslide hazard and risk assessments and management (Macciotta and Hendry 2021).

5.1 Use of Conventional Methods

The knowledge of geotechnical assets is inherently lower than that available for engineered slopes due to the amount of uncertainty and complexities associated with them. However, monitoring of the key geotechnical parameters can provide substantial information for any GAMS. Rapid developments of geotechnical monitoring took place in the late 1990s. Some of the key parameters that can be measured by various monitoring techniques summarized by Mazzanti P. et al. 2017 are shown in Table 16.

Table 16: Some of the common geotechnical monitoring equipment and the parameters (Adapted from Mazzanti P. et al. 2017)

Equipment	**Parameters**
Surface and probe tiltmeter	Displacement/Deformation
Inclinometer	Displacement/Deformation
Piezometer	Groundwater pressure
Load cell and strain gauge	Load and strain
Earth pressure cell	Stress
Extensometer	Displacement/Deformation
Observation well	Groundwater pressure
Thermometer/Thermocouple	Temperature

The method of monitoring using such instruments can be referred to as 'contact method' and it can be characterized by higher accuracy but reduced spatial information density and limited size of the monitored area (Mazzanti P. et al. 2017).

5.2 Use of Remote Sensing Technology

Even though asset inspection through visual inspection is the most practiced and the most affordable means of inspection, it may not be adequate for some of the critical sites that are not accessible for either hands-on or visual inspections and may pose safety threat if attempted to access. Doing a detailed geotechnical inspection, on the other hand, is resource intensive and may not be necessary for all sites. Remote sensing techniques can be used to obtain intermediate level of information between each site investigation. Such technology can be used for inaccessible assets to obtain accurate and reliable data about the surface characteristics, topography, and geotechnical properties of the site to better understand the subsurface conditions. Most importantly, it can be used to accurately measure surface deformation, a key parameter to determine the criticality of an asset. Hence, it is essential to acquire knowledge about the functioning, their advantages and limitations, and the applicability of such technologies to risk assessment and management of geotechnical assets.

Remote sensing is defined as methods that make use of electromagnetic energy to detect, record, and measure the characteristics of a target, such as the earth's surface (Sabins 1987). The two types of remote sensing systems are passive and active systems. Two examples of passive remote sensing systems are multispectral and hyperspectral remote sensing systems; they measure reflected solar radiation in visible, near infrared, and mid-infrared wavelengths, or absorbed and then reemitted solar radiation in thermal infrared wavelengths. Active systems on the other hand, emit radiation toward target using their own source of energy and detect the radiation reflected from that target, and examples of this system include radar remote sensing and light detection and ranging (LiDAR) remote sensing (LiDAR Remote Sensing and Applications, Pinliang Dong and Qi Chen 2018). Some of the common applications of remote sensing in geotechnical engineering include the following:

- Generation of Digital Elevation Models (DEM)

- Detection of change in terrains
- Generation of geological maps
- Generation of geohazard maps
- Hazard assessment
- Monitoring

Remote sensing facilitates higher frequency data collection over large areas that is economically efficient and requires lesser amount of time. Use of such technology has contributed tremendously to identifying, assessing, and monitoring of geohazards, especially landslides, making such technology much more popular in the modern era of geotechnical engineering. It is, therefore, vital to understand the concept of such technology, its applicability, advantages, and disadvantages.

For a small developing country like Bhutan, concept of geotechnical asset monitoring using remote sensing technology is new, first reason being the resource constraints and secondly the minimal exposure to use of such technologies. For the same reason, even asset monitoring using conventional methods is rarely practiced. It is about time the nodal agencies like DoR in Bhutan develop an understanding of remote sensing technologies and their applicability to geotechnical assets in Bhutan. The following remote sensing technologies are discussed in detail with their example applications in different parts of Western Canada:

- LiDAR
- Unmanned Aerial Vehicle (UAV) Photogrammetry
- Interferometric Synthetic Aperture (InSAR)

- Global Positioning System (GPS)
- Global Navigation Satellite System (GNSS)

5.2.1 LiDAR

LiDAR, otherwise known as laser scanner, emits a beam of highly paralleled, directional, and coherent electromagnetic radiation and it is based on the measure of time required for the radiations to travel from a light source to the object being scanned and back. Following formula is used to measure the distance between the sensor and the object:

$$d = \frac{c \times t}{2} \text{.................................[9]}$$

Where c is the speed of light and t is the time required for light to travel from a light source to the object being scanned and back (Macciotta CIV E 683 notes 2021). Depending on the position of the sensor, two ways laser scanning developed are Airborne Laser Scanning (ALS) and Terrestrial Land Scanning (TLS), both of which send out laser pulses that get back-scattered by objects such as ground surface, vegetation, etc. and record the returning signal. The direction of Line of Sight (LOS) and the attitude of the device enables to determine the position Δx, Δy and Δz of a reflective surface with respect to the device. An ALS sensor position is defined by a GPS and the point cloud coordinates are estimated as $x + \Delta x$, $y + \Delta y$ and $z + \Delta z$, whereas on the other hand, the position and orientation of TLS are determined in the field (Jaboyedoff et. Al 2012). Figure 19 shows a TLS LiDAR used for Frank Slide in Southern Alberta.

Figure 19:Use of TLS LiDAR at Frank Slide in Southern Alberta

The point density generally ranges from 0.5 to 100 points per m^2 for ALS and 50 to 10,000 points per m^2 for TLS (Jaboyedoff et al. 2012). The minimum scale in which change detection can be performed will depend on the point density, it would be impossible to identify smaller scale movements with larger point spacings (Deane E. 2019). A lower point density, on the other hand, can help reduce potential point errors which would impact results (Lato et al. 2009). The points thus obtained are analyzed using opensource software like CloudCompare. The following two-step procedures are usually used to align the point cloud (Besl and McKay 1992; Chen and Medioni 1992; Jaboyedoff et al. 2012):

- Visual identification of homogenous points

- Optimization of the alignment using an Iterative Closest Points (ICP) procedure

According to Jaboyedoff et al. (2012), ALS and TLS LiDAR technologies can be used for many applications including the following:

- Mapping of geomorphic features
- Rock face imaging and characterization
- Calculation of discontinuity orientation of rocks
- Detection of mobilizable volumes of debris
- Hydromorphic characterization
- Monitoring of surface displacements in landslide and rockfall
- Determination of landslide and rockfall volumes
- Monitoring of morphological changes in debris flow channels

With the advent of time, more accurate ALS and TLS devices are likely to be developed, that would allow generation of better DEMs and more accurate change detections. However, more powerful computers would need to be developed to facilitate increasing data acquisition (Jaboyedoff et. al 2012). Vegetation hinders the accurate measurement of surface movements, however, there are means to reduce or remove the vegetation by deploying several methods within the scanner such as use of CANUPO classification, which is a tool that uses various scales and dimensionality observations to classify local cloud geometry (Brodu and Lague 2012, as cited in Deane E. 2019). Moreover, LiDAR has seen plenty of successful applications in unvegetated surfaces and bare rockfaces (Lato 2010, as cited in Deane E. 2019).

5.2.2 UAV Photogrammetry

UAV stands for Unmanned Aerial Vehicle; it is a photogrammetric measurement tool, the use of which is increasingly gaining popularity in the field of monitoring of slopes that are extended over large areas and are inaccessible. The device is equipped with a photogrammetric measurement system and a camera system, that allow for the registration and tracking of the position and orientation of the implemented sensors in a local or global coordinate system (Eisenbeiß 2009). Figure 20 shows one type of drone being used for a site in Drumheller, Alberta.

One of the biggest advantages of using UAV is its applicability in inaccessible and high-risk areas which would otherwise be impossible to reach and where manned systems cannot be flown. Data acquisition using UAVs is even possible in cloudy and drizzly weather conditions, provided the distance to the object permits flying below the clouds unlike in the case of manned aircrafts, which require larger flight altitude above ground in such weather conditions. It is highly commendable for its real-time ability and the capacity for fast data acquisition, transmission of images, videos, and orientation data in real time to the ground control stations. Implementing navigation and stabilization units in the UAV allows accurate flights resulting in sufficient image coverage and overlap (Eisenbeiß 2009).

Figure 20:UAV/Drone DJI Phantom 4 with 12 MP camera and 3-axis stabilizer used for CO18 site.

Some of the downsides of using UAVs include having to acquire a larger number of images, especially, in the low-cost UAVs with lower resolution cameras. For successful operation and to make optimum use of the system, trained pilots are required who can maneuver and interact with the system at any time or without any obstacle (Eisenbeiß 2009).

UAV photogrammetry requires a set of images with enough overlap to reconstruct the terrain and to produce a point cloud of enough resolution to capture the scale of prominent features of the ground. This can be achieved using three images captured using high resolution cameras (12-MP or 17-MP) and allowing an overlap of 60% between images. Different software such as the Pix4Dcapture can be used to create automatic flight plans to optimize collecting photos. Parameters namely the grid pattern, flight height, flight speed, and camera angle are established for the drone being used (Rodriguez et al. 2020). Some of the following can be deduced as tips while capturing UAV images (Rodriguez et al. 2020):

- High speeds can reduce the flight time and battery consumption; however, care must be taken in order not to capture blurry images.
- Photos captured at oblique angles allow adequate coverage of steep slopes.
- Care must be taken to avoid angles and orientations that result in direct sunlight on the lens which could result in the overexposure of the images.
- There could be the need to establish Ground Control Points (GCPs) if the internal GPS system of UAV has low precision.
- A visual inspection is recommended for the captured photos from the site to remove low-quality photos which would ultimately reduce errors in the point cloud reconstruction.

The images thus obtained from the scan are used to generate point clouds, which are then compared and analyzed for changes in the ground features. The UAV photos are reconstructed into the topography using software such as Pix4Dmapper Pro, which divides the process into internal and external parameters for the calibration of camera. The sample key points automatically generated from each photo are matched to other overlapping photos. GCPs, if installed, improve georeferencing and scale of the point clouds in calibration. This is followed by densification of the point cloud based on the key points calibrated using GCPs (Rodriguez et al. 2020).

Once the densification of each point is achieved, outlier points are filtered using software such as CloudCompare (open source) without changing the overall roughness of the point cloud. Ultimately, change detection is obtained by aligning the point clouds from different surveys and it is crucial the alignments are accurate for accurate change detection. Precise alignments of the point clouds can be obtained by using known stable areas outside of the area of analysis; the alignment and cloud to cloud comparisons can be computed using the CloudCompare software. Of the many methods available to evaluate the differences between point clouds, one is the closest point method (C2C) that provides a first estimate with lower computational requirements (Girardeau-Montaut et al. 2013, as cited in Rodriguez et al 2020); and the multi-scale model-to-model cloud comparison (M3C2) based on a more robust statistical analysis (Lague et al. 2013, as cited in Rodriguez et al. 2020). Change in C2C is computed as the absolute distance from a point on the first point cloud to the nearest point on the next point cloud (Girardeau-Montaut et al. 2013, as cited in Rodriguez et al. 2020); whereas the change in M3C2 considers the total displacement of two point clouds in a positive (material gain) or negative (material loss) directions. The direction for the latter is quantified using the triangulation model of the software based on the calculation of the normal vector on the reference cloud (Rodriguez et al. 2020).

5.2.3 InSAR

Interferometry of Synthetic Aperture Radar (InSAR) measures displacements of the earth surface or its objects on it using the electromagnetic wave signal emitted by radars shipped in satellites orbiting in quasi polar orbits (Raventos and Arroyo 2017). InSAR can be used to gain a better understanding of landslides as it can generate ground displacement measurements of centimeter or millimeter accuracy. It has the ability to capture all-day or all-weather images with high spatial-temporal resolutions (Massonnet and Feigl 1998, as cited in Jia et al. 2022).

One main reason for InSAR to gain popularity in the last decade is the development of D-InSAR (Differential Interferometry) techniques which is based on the analysis of a couple of radar images acquired by a SAR sensor, and which derive an interferogram that expresses the phase difference for each image pixel between two passages of the satellite on the same area. Temporal evolution of ground displacements can be achieved over time using multiple SAR images and the interferograms. Based on how stable the signal is, the time series of deformation are extracted from those signals during the monitoring period. Algorithms grouped in Point-like or Persistent Scatterers Interferometry (PSI) and Distributed Scatterers Interferometry (DSI) approaches can be used to select those pixels which are stable. The final output is a deformation map comprising thousands/millions of points, each one with a value of annual velocity and a time series of displacement (Ferretti et al. 2001, Berardino et al. 2002, Crosetto et al. 2016, as cited in Solari et al. 2020).

Solari et al. 2020 stated some of the following advantages and limitations of using InSAR:

<u>Advantages</u>

- Great cost-benefit ratio
- Wide area coverage with millimeter accuracy
- Temporal repetitiveness of up to 6-days with Sentinel-1 images
- All-weather and day or night data acquisition
- Data coverage in inaccessible areas
- Possibility of back analyzing phenomena from 1992, the first year of acquisition of the C-band satellite ERS 1

- Launch of the Sentinel-1 constellation, granted free access to radar images.

Limitations

- Geometrical effects
- Snow cover
- Phase aliasing
- Presence of vegetation or variable land cover

One such type of InSAR remote sensing technology is the Ground-Based InSAR (GB-InSAR), which has been used in the mining industry for monitoring of open pit mine slopes across Canada and around the world (Dick et al. 2014, Severin et al. 2014, as cited in Wood et al. 2019). It has even been successfully implemented for landslide monitoring and assessment (Barla et al. 2011, as cited in Woods et al. 2020). Since the conventional methods of geotechnical investigation have the potential to provide sub-surface data at depth which would allow for the identification of distinct failure planes and increased understanding of potential landslide failure mechanisms, GB-InSAR is unable to completely replace all in-ground instrumentation for many projects but may be able to supplement such data and reduce the number of total drillholes required (Wood et al. 2019).

Compared to other remote-sensing technologies such as LiDAR and UAV photogrammetry, GB-InSAR can cover a much larger study area ranging from tens to hundreds of kilometers depending on the dataset used (Wood et al, 2019). Unlike LiDAR, GB-InSAR can be used in all weather conditions as the wavelength from LiDAR is highly sensitive to atmospheric conditions (Luiz et al. 2009, Kromer et al. 2017, as cited in Wood et al. 2019). GB-InSAR can cover large areas with a map of dense continuous data, 24 hours a day, in all weather conditions, making it highly suitable for densely vegetated locations (Wood et al. 2019) with proper measures taken to remove vegetation. Figure 21 from Wood et al. 2019 shows a GB-InSAR components:

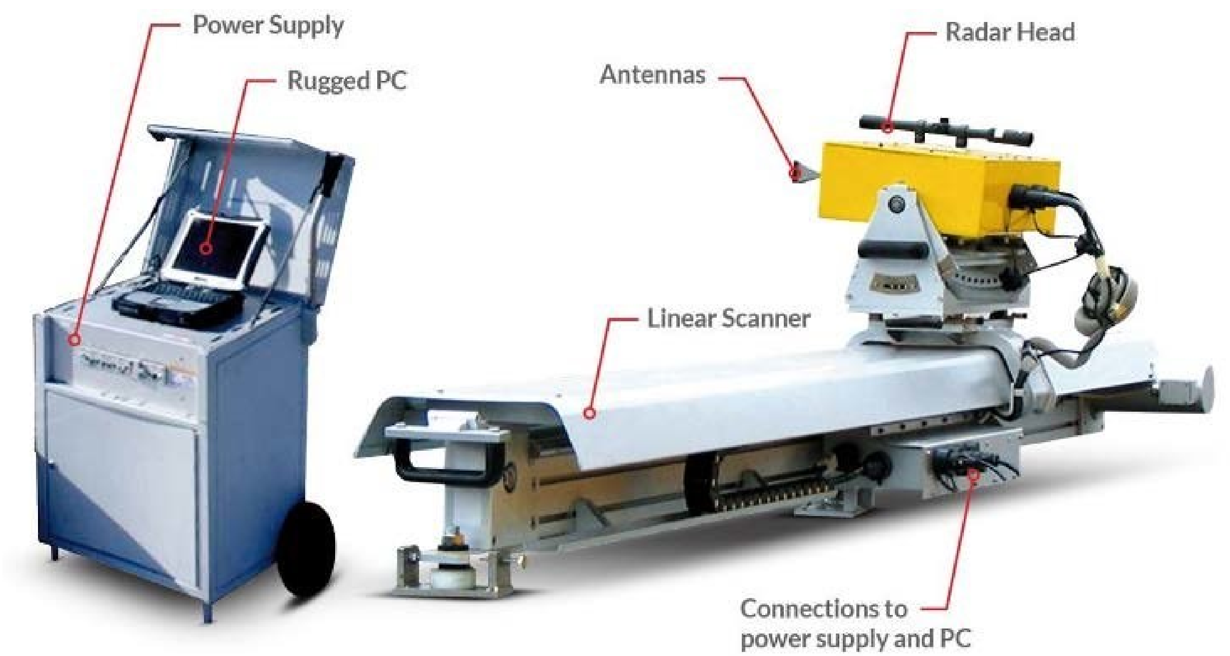


Figure 21: GB-InSAR Components (IDS Georadar, 2019 from Wood et al. 2019)

Although GB-InSAR facilitate data acquisition of higher spatial resolution, it involves a much higher initial investment (Travelletti et al. 2012, as cited in Wood et al. 2019) along with several other challenges and their available solutions as summarized below:

- It is only able to provide displacement values along Line of Sight (LoS), so it might be required to deploy two or more GB-InSAR systems to capture displacement values of a steep uneven terrain (Severin et al. 2014, Wood et al. 2019). A more cost-effective solution is to choose the installation location directly opposite the estimated direction of movement.

- Special interventions must be incorporated into achieving higher coherence between GB-InSAR images for removing noises due to presence of dense vegetation, and one such intervention could be the use of radar corner reflectors (Wood et al. 2019)
- The typical components of GB-InSAR include the radar head, linear scanner rail, a weatherized laptop, connecting cables, associated power supply and telecommunication equipment. It might be a challenge, both financially and logistically, to transport GB-InSAR equipment and its parts to remote inaccessible locations. This can be eased with the use of trailers for sites accessible by vehicle and exploring options of using more portable GB-InSAR units such as IDS Hydra, which are much smaller and can be mounted on a typical tripod like TLS LiDAR (Wood et al. 2019).
- Remote connectivity to the monitoring software can reduce the need for site visits; instead, data can be transmitted via virtual private network (VPN) and processed offsite to allow early warning if increased displacements are detected. However, in remote regions, such communication may not be feasible due to poor internet connectivity. This can be overcome by using external directional antennas, cellular signal boosters, and satellite communication links (Wood et al. 2019).
- It is crucial to have a reliable power source for the functioning of GB-InSAR components; installing alternative power sources like solar energy can be expensive and can be hindered at locations with deep, steep-sided mountain valleys with overcast weather and snow cover. Other options could be the use of

small gas generators attached to battery banks, and the use of wind turbines and fuel cells. Provided the place has enough sunlight, solar power systems are highly recommended as it can operate with little requirement of regular site visits (Wood et al. 2019).

5.2.4 Differential Global Positioning System (dGPS) or differential Global Navigation Satellite System (dGNSS)

In order to improve the positioning accuracy of a moving GPS receiver, differential techniques can be used and in case of real time data collection, a datalink has to be established between the moving GPS receiver and a fixed reference station (Langley 1993). An appropriate radio communications link must be selected and have it interfaced with the GPS receivers at the reference and user stations (Langley 1994). Application of differential GPS comprises a fixed-point which is placed in a stable non-moving area to facilitate acquiring and correcting for errors present within the system due to atmospheric conditions (Deane E. et al. 2019). A dGPS or dGNSS can be used for obtaining high frequency measurements and can be adequately used for developing early warning systems (Macciotta et al. 2016, as cited by Rodriguez et al. 2021). The use of this technology was hindered due to the high cost of equipment and requirement of power associated with the system (Hendry et al. 2015, Woods et al. 2020, as cited in Rodriguez et al. 2021). Hence, continuous efforts are being made in developing low-cost GNSS tools and techniques, which include advances in both positioning and processing methods as well as less expensive highway components (Takasu and Yasuda 2009, Eyo et al. 2014, as cited in Rodriguez et al. 2021). One such technology is the Geocube™ by Ophelia Sensors or previously by GeoKylia™ (Rodriguez et al.

2021). Technology like that has a great potential for use in monitoring of landslides especially in areas with constraints related to budget and/or available power (Benoit et al. 2015, as cited in Rodriguez et al. 2021).

The geocube system comprises a network of GPS units, each with a radio frequency antenna that facilitates communication with other units and a data logger. A schematic of the working of a differential system is shown in

Figure 22. The system measures the relative distance between the reference unit and other units and allows for millimeter accuracy and high temporal resolution. Data is collected for the movement in the x, y and z directions. Such systems allow monitoring of large areas with one network system or for monitoring a localized area with high density of units. For instance, the system from Kylia offered up to 100 units over a maximum span of 15 km with one data logger. Under ideal weather conditions free from obstructions, the maximum spacing between the units is up to 200 m with the use of an internal antenna, and 1000 m with an external antenna (Kylia, 2016b, Kylia 2016c, as cited in Rodriguez et al. 2018). Environmental sensors such as meteorological sensors, soil humidity probes, pore fluid pressure sensors, seismometers can be attached directly to the geocube or outside (Benoit L. et al. 2015).

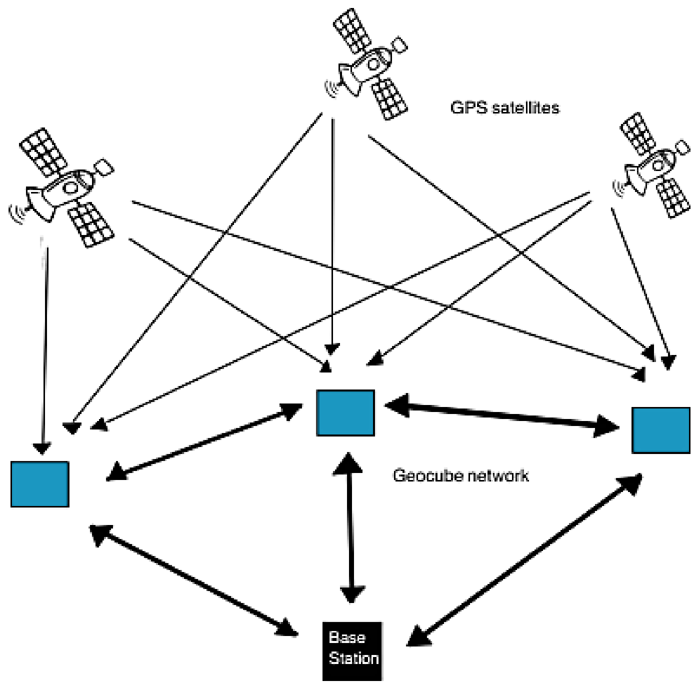


Figure 22: Schematic of a geocube system (Adapted from Rodriguez et al. 2019)

Benoit L. et al. (2015) highlighted the following advantages of using differential GPS especially the geocube system:

- It enables monitoring of landslide behavior at high spatial density, high time resolution as well as with multiple sensors.
- Where precise deformation measurement is needed, receivers can be deployed relatively quickly due to the low cost of receivers and ease of deployment. It can be installed by two people without heavy equipment and can be redeployed to other sites on a requirement basis.
- It can function with low power consumption and by using small solar panels.

It is possible to capture spatial heterogeneity of the displacement field and obtain advanced information such as variation in strain rates through dense spatial sampling of the deformation.

6. A Proposed Geotechnical Asset Management Framework for Bhutan

6.1 Overview

The mission of formulating a robust transportation asset management strategy for the country led to the start and implementation of the very useful RAMS. Since then, the RAMS, Bhutan has greatly benefitted the DoR in strategic allocation of the limited resources available to the department for maintenance and restoration purposes. Since the conception of this system, the department has been successful in emphasizing the need for often less emphasized road maintenance activities, in addition to capital construction projects. Like many other TAM systems around the world, RAMS places emphasis on the management of road pavements over any other asset. Even though geotechnical assets play a major role in the successful operation of transportation corridors, they are often overlooked, the reason being mostly the uncertainty of soil and rock conditions as well as the availability of limited resources. As the importance of managing geotechnical assets in concert with the overall roadway network is increasingly understood, it is about time the DoR considered implementing a comprehensive risk-based GAMS which can be envisioned as a detailed geotechnical component of the RAMS. A GAMS would provide the framework to guide the department in measuring and managing life-cycle investments in natural and constructed geotechnical assets, with the objectives of reducing risk to public safety while benefitting the country's economy through provision of a safe and resilient road network.

One of the main objectives of the DoR is to achieve the national goal of poverty reduction and economic growth through provision of reliable and resilient road infrastructure. However, for a small developing country like Bhutan, resources are limited and hence it is crucial to make optimum use of whatever is available at the disposal of the department. Therefore, it makes complete sense to aim for a system that can be simply started using the available data and with minimal investment. One of the distinct characteristics of the NCHRP Implementation Manual 2019 is the requirement of low cost and resources in its initiation with its open availability of GAM Planner tools. The framework for GAMS Bhutan shall closely follow the NCHRP Implementation Manual 2019 along with some of the other best practices of risk-based GAM programs adopted by various agencies around the world.

6.2 Proposed Geotechnical Asset Management Framework for the DoR

A geohazard risk management framework focuses on identifying and assessing potential risks associated with potentially occurring geological hazards; it can help identify the risks, evaluate their severity and likelihood, and develop strategies to manage the risks. Further it can help develop plans to mitigate and respond to the risks. A GAM framework, on the other hand, will focus on the management of physical assets namely roadside slopes, embankments, retaining walls and subgrades, in order to ensure their safety and longevity. It can help identify any potential risks associated with the physical assets, evaluate the severity and likelihood of failure, and develop strategies to mitigate and respond to the risks. It can further help develop plans for maintenance and monitoring of the assets. Geohazard risk management is an important component of GAM, as it helps to identify, assess, and manage the risks associated with geological hazards. The steps involved in geohazard risk management including gathering data on the geologic characteristics of a site, developing hazard maps, and conducting risk assessments, can facilitate strategic decision-making processes and implement appropriate mitigation measures.

The proposed GAM framework for the DoR comprises two stages: stage 1 is aimed to identify the geotechnical assets and perform a preliminary risk assessment to filter the assets that are in more critical condition. As stated in the International Infrastructure Management Manual (IIMM), *"a rule of thumb is often 80 percent of the data can be collected for half the cost of 100 percent. Seeking 100 percent coverage and accuracy may not be justified, except for the most critical assets"* (IPWEA 2016). A developing nation like Bhutan, cannot afford to achieve 100 percent coverage of geotechnical assets. Hence, it is only justifiable to take into consideration the assets in a more critical condition for further assessment. Stage 2, on the other hand, is aimed to assess the critical assets identified in the first stage, based on the likelihood of failure and consequences in terms of safety, mobility, and economic consequences. However, the objective of this framework is to kickstart a GAM program in the department; the risk assessment method is a semi-quantitative method. Figure 23 illustrates the proposed GAM framework for the DoR.

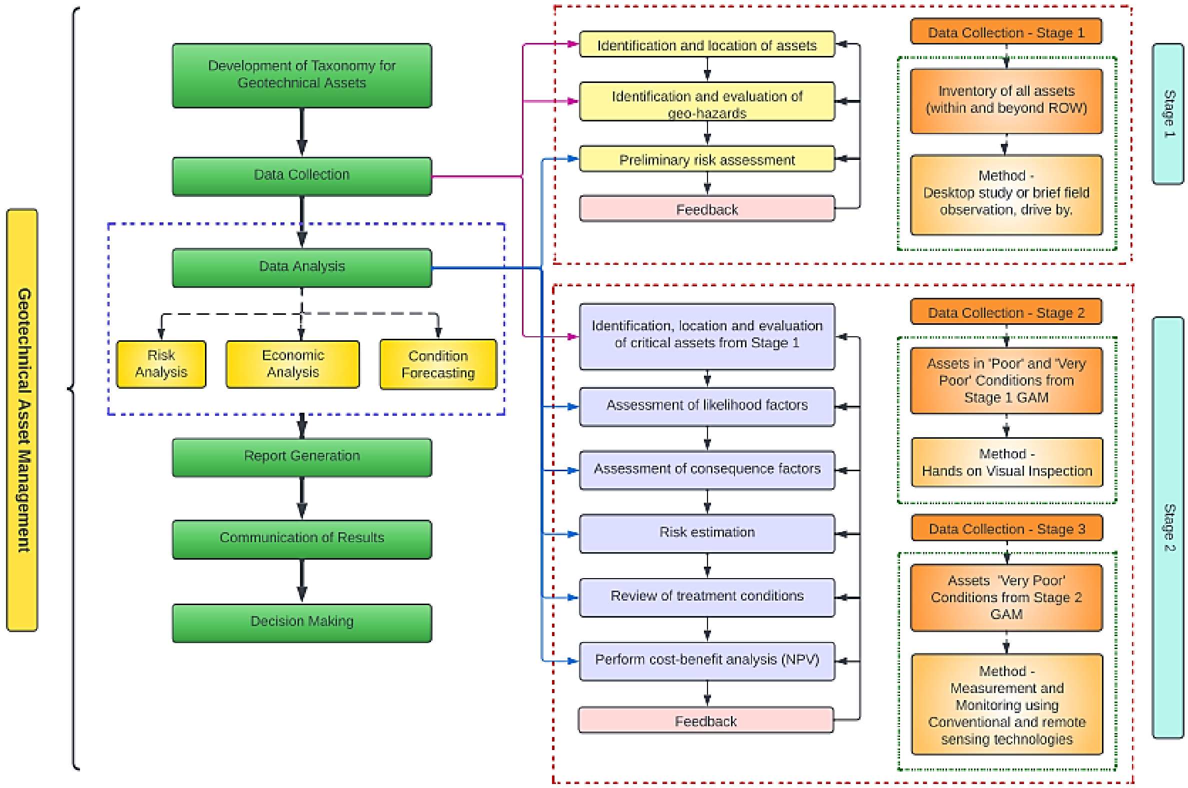


Figure 23: Proposed Geotechnical Asset Management (GAM) framework for DoR, Bhutan

6.2.1 Taxonomy of Geotechnical Assets

It is very likely that assets which fall under the purview of geotechnical assets may vary among organizations according to the organizational structure and history (Bernhardt et al. 2003). However, some of the widely accepted assets as geotechnical assets are slopes, embankments, retaining walls and subgrades. Among these assets, subgrades are being considered a part of the road pavement asset as pavement engineers are primarily responsible for the design and functioning of subgrades (Bernhardt et al. 2003). Hence this brings the need to explicitly consider slopes as well as the other two groups of geotechnical assets namely the embankments and retaining walls in the system. Since the existing inventory has been collected entirely through visual inspection, the first and the most important step would be to modify the data collection strategy. Visual inspections must be supported by expert site inspections and, in some cases, instrumentation readings. The Geohazard Risk Management Program (GRMP) of Alberta Transportation (AT) includes annual and semi-annual field inspections and instrumentation readings at all the active sites (Tappenden and Skirrow 2020). The frequency of re-inspection for the geo-hazard sites is dependent upon the risk posed to the highway network. As practiced by AT, the field-level inspections and instrumentation readings can be outsourced to geotechnical consultants. The rule of thumb for data collection, as stated in the IIMM, can be prioritized for the critical sites rather than on the entire data as data collection can be a time and cost intensive process.

Since it is hard to completely distinguish the subgrade from the pavement (Bernhardt et al. 2003) and as pavement is extensively considered in the RAMS, the taxonomy for geotechnical assets for GAM in Bhutan is proposed as shown in Figure 24.

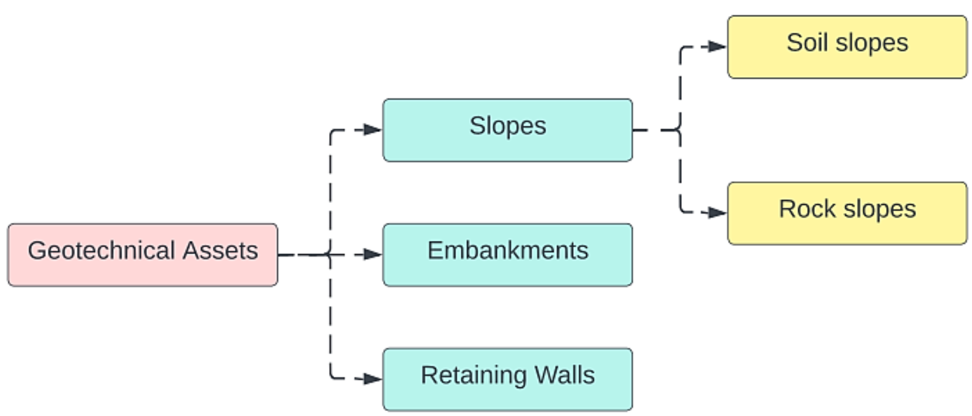


Figure 24: Recommended Taxonomy for GAM Bhutan

6.2.2 Stage 1 of the Proposed GAM Framework

For an agency with limited resources, it is only valid to invest the scarce funds and attention to the assets that are more critical and are likely to deteriorate over time. With the objective of filtering the data, Stage 1 of the proposed GAM for the DoR would constitute the steps shown in Figure 25.

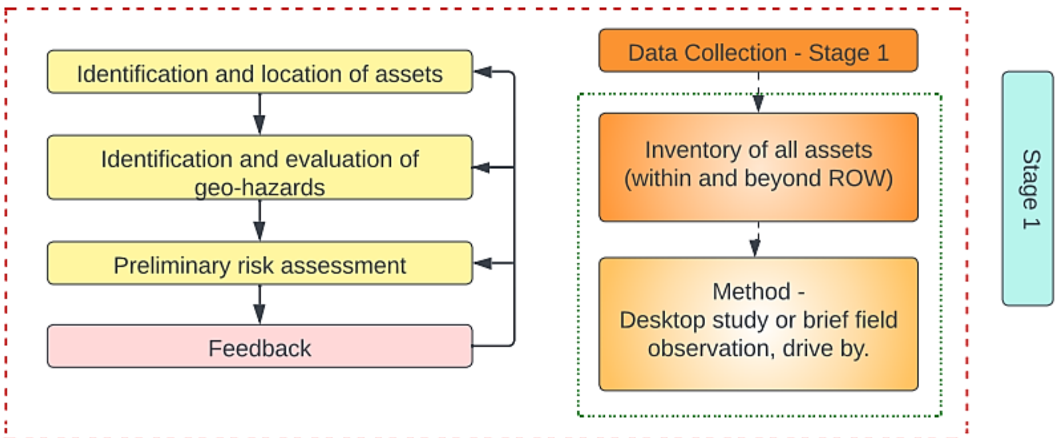


Figure 25: Stage 1 of the Proposed GAM Framework

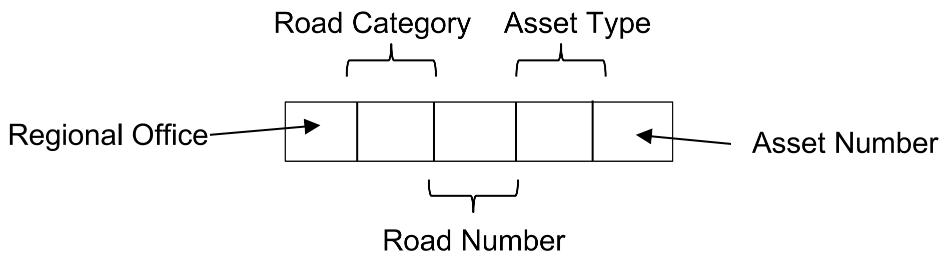
Step 1: Identify and locate assets.

Embankment assets are a type of geotechnical assets comprising fill materials such as rock, soil, or other materials that help elevate a stretch of road from a lower ground to meet design requirements. The NCHRP GAM Implementation manual (2019) suggests a threshold embankment height of **3 m** as delineation between a minor earthwork and an embankment asset.

Slope assets can be composed of soil or rock or a mixture of the two in most cases in Bhutan. According to the GAM Implementation Manual, a **3 m** height threshold is recommended for slopes, however for a country like Bhutan, where roads meander along the mountainous terrains, it can be based on whether the slope is going to create an unacceptable hazard to the safety of the users and maintenance personnel from the history of roadblocks. Slope assets considered are the cut-slopes along the road network and within the right of way (ROW). However, there are slopes beyond the ROW that can threaten the transportation assets or disrupt the free flow of traffic. Such features include natural rockfalls from geologic outcrops, landslides or debris flow that occur beyond the ROW and enter the ROW causing disruptions to traffic and threat to commuter safety.

Retaining wall assets retain soil or rock materials in place to support a roadway. It could be a gravity retaining wall, mechanically stabilized earth (MSE) walls, etc. The recommended wall height in the GAM Implementation Manual is 1.2 m.

The actual age of the asset or an estimated age must be included in the inventory and for the asset identification, each asset will be assigned an identification number. Each asset will have a unique location which is required to be included in the inventory. Each asset must be assigned a unique identity using the nomenclature shown in Figure 26.



1. Regional Office: Lobeysa (LO), Lingmethang (LT), Phuentsholing (PL), Samdrup Jongkhar (SJ), Sarpang (SP), Thimphu (TP), Tingtibi (TT), Trashigang (TG), Trongsa (TR)
2. Road category: Primary National Highway (P), Secondary National Highway (S), District Road (D), Farm Road (F)
3. Road number: 01, 02, ..… according to the Road Classification and Network Information of Bhutan 2020
4. Asset type: Soil Slope (SS), Rock Slope (RS), Embankment (E), Retaining Wall (RW)
5. Asset number: 001, 002, ……, etc.

Figure 26: Nomenclature for Asset ID for the inventory

Step 2: Identification and evaluation of geo-hazards affecting the geotechnical assets.

Geo-hazards likely to affect the geotechnical assets are to be identified using the same classification of geo-hazards as discussed in chapter 2. The knowledge of geo-hazards enables the risks associated with the geotechnical assets to be assessed, reduced, and managed, and therefore it is crucial to recognize and identify hazards. The classification chart is reiterated as Figure 27. Additionally, referring the landslide hazard map of Bhutan with 50 years return period shown in Figure 28 can provide better insights into identification and categorization of geo-hazards likely to affect the given asset.

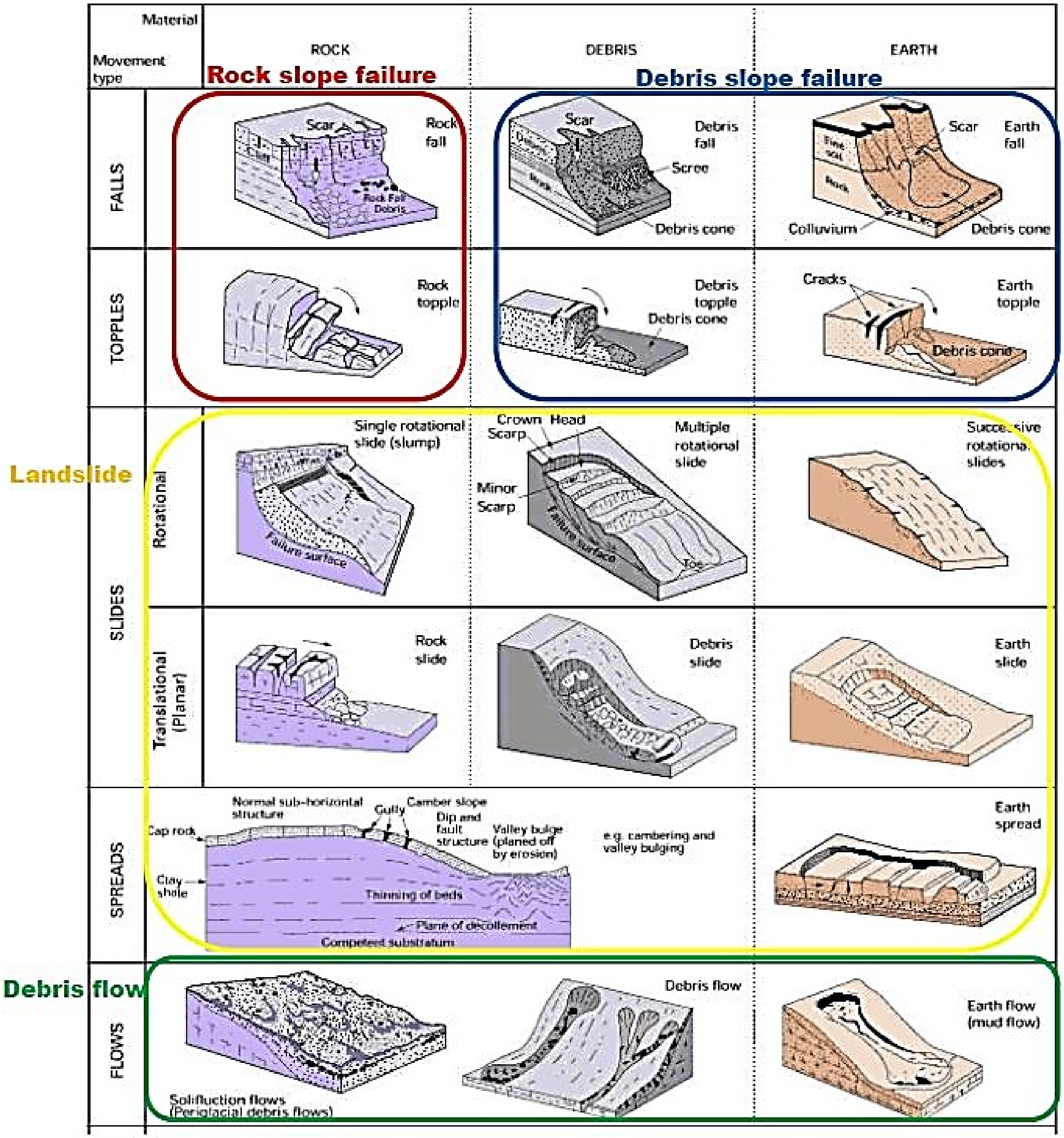


Figure 27:Chart for classification of geo-hazards (Adapted from Varnes 1997)

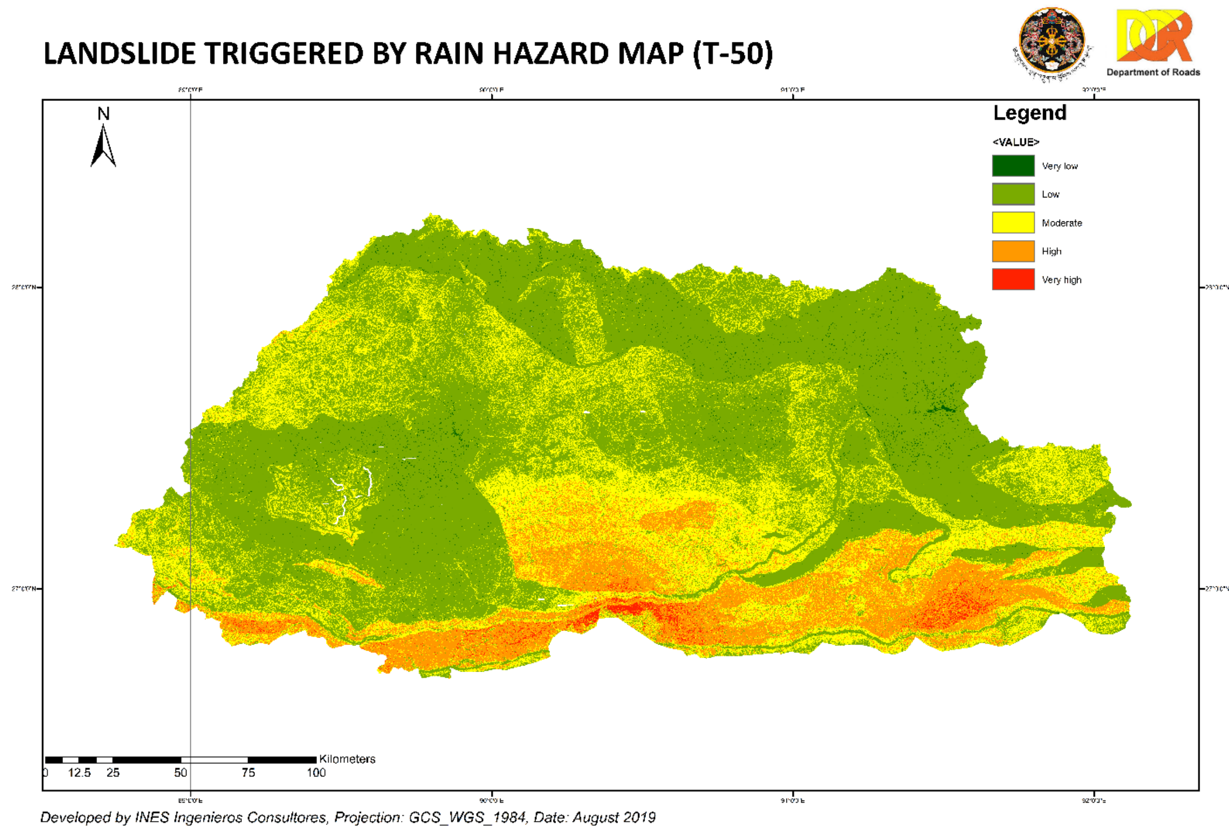


Figure 28: Landslide Triggered by Rain Hazard Map with a Return Period of 50 years (RAMS of DoR)

Geotechnical assets including the engineered slopes within the agency ROW are within the control of the agency; they are built, maintained, managed and the agency has full access rights to them. On the other hand, geotechnical assets located outside of ROW can include natural hazard features that may pose threat to the assets within the ROW, and they are not owned by the agency. Some of these assets located beyond the ROW can be a source of larger risk and hence having an inventory can prove beneficial in developing resilience strategies. Although the assets beyond the ROW can affect the assets within the ROW, the NCHRP GAM Implementation Manual (2019) suggests that during the initial stages of implementation, focus should be given on assets within the

ROW and defer the assessment and management of geotechnical assets outside of the ROW to a later stage, when the agency would have gained some years of experience in GAM implementation. However, an inventory of geotechnical assets beyond the ROW is recommended in the NCHRP GAM Implementation Manual (2019) and it shall be an aspect of the GAMS for Bhutan given the landslide activity in the region.

Step 3: Determine condition states and deterioration.

The condition states of the assets can be determined in accordance with the criterion shown in Table 17 while collecting the inventory of the geotechnical assets. The Markov model is one of the simplest deterioration models using condition state; it expresses deterioration rates as probabilities of transitions among different condition states each year. These models are increasingly being adopted in geotechnical asset management and are more commonly adopted when the available data is limited. Markov deterioration models are based on the concept of a Markov chain, which is a mathematical tool that models the probability of a certain event occurring, given the current condition state of the system. This can be used to model the probability of a certain deterioration state occurring, given the current state of the asset. The transition time shown in Table 18 is the number of years it takes for 50% of a population of assets to deteriorate from the current condition to the next worse condition, for example from condition state 1 to 2. The probability that an asset remains in the same condition state after a year is the same-state probability; the next-state probability, on the other hand is the probability that an asset will deteriorate to the next worse condition state.

Table 17: Condition states from the inventory (Adapted from Thompson 2017)

Condition States		Description
Very poor	5	Asset has completely failed causing other assets to be out of service requiring major mitigation.
Poor	4	Deterioration is advanced requiring repairs to restore full functionality.
Fair	3	Significant deterioration but corrective measures can extend asset life.
Good	2	Minor defects but do not require corrective action.
Excellent	1	Asset is in excellent condition with no action needed.

Table 18: Markov Deterioration model for different geotechnical assets (Adapted from Thompson 2017 & Tappenden and Skirrow 2020)

Asset type	Deterioration model	Markov model – starting condition state				
		1	2	3	4	5
Soil Slopes	Transition time (years)	55	23.1	12.6	7.6	
	Same-state probability (%)	98.8	97.0	94.7	91.2	100.0
	Next-state probability (%)	1.8	2.2	3.3	4.9	0.0
Rock Slopes	Transition time (years)	38.3	32.5	21.2	13.7	
	Same-state probability (%)	98.2	97.9	96.8	95.1	100.0
	Next-state probability (%)	1.8	2.1	3.2	4.9	0.0
Retaining Walls	Transition time (years)	25.2	20.8	8.3	7.2	
	Same-state probability (%)	97.3	96.7	92.0	90.8	100.0
	Next-state probability (%)	2.7	3.3	8.0	9.2	0.0

Markov deterioration models are frequently used in bridge and pavement management systems. Table 18 summarizes the deterioration models for soil slopes, rock slopes, and retaining walls developed by the Alaska Department of Transportation (Waseem et. al 2022). With the known or estimated transition time, the same-state probability can be computed as follows (Thompson, 2017):

$$p_{jj} = 0.5^{\frac{1}{t}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [10]$$

Where:

j = condition state (before and after 1 year)

t = transition time in years

p_{jj} = same-state probability one year later in state *j*

According to Thompson, 2017, this calculation can be repeated as many times as possible to extend the inventory condition forecast into the future. However, this simple deterioration model is dependent only on the type and current condition of the asset and it limits the transition of an asset in any given year from one state to the next worse one. As a part of the ongoing GAM program development, AT proposes to use the Markov deterioration models against the growing inventory of slopes, embankments, retaining walls and subgrades (Waseem et al. 2022). In order to apply the model, at least a first set of data for each geotechnical asset specifying the current condition state is required, which can be modified as the GAM plan matures over time. This process can be applied once a complete set of data is obtained but considering the importance of deterioration models, it has been discussed in this section.

Step 4: Preliminary risk assessment

The risk assessment in Stage 1 of the proposed GAM framework is aimed at segregating the more critical data from the inventory of geotechnical assets. It is proposed to be conducted based on the existing road category of Bhutan using the risk assessment methodology adapted from AT (Tappenden and Skirrow, 2020) and the risk rating scale of RAMS Bhutan as shown in Table 19.

The road category of Bhutan according to the Road Classification and Network Information of Bhutan 2020 are as follows:

- Primary National Highway (PNH), as the name suggests, are roads of highest strategic and economic importance. They can cater to traffic volume of over 200 commercial vehicles per day (CVPD). Such roads usually comprise two lanes and are made smooth and pliable throughout the year.
- SNH, on the other hand are roads that connect a district centre to a road of same or higher classification or are roads that connect two district centres. Such roads can cater to traffic volume of around 100 – 200 CVPD.
- District roads are all internal roads within a District Centre. These are roads of much lesser importance compared to the other two mentioned above.
- Farm roads are those that link farmlands or villages to a road of equal or higher classification.

The assets in the 'Poor' and 'Very Poor' categories along PNH and SNH, and the assets in the 'Very Poor' category along the district roads and farm roads are deemed more critical and are suggested to be carried forward to Stage 2 of the GAM for further assessment.

Table 19: Preliminary risk assessment based on road category for GAM (Adapted from Tappenden and Skirrow 2020)

<table>
<tr><th rowspan="2">Preliminary risk rating</th><th rowspan="2">Performance/ Condition</th><th colspan="4">Road Category</th></tr>
<tr><th>PNH</th><th>SNH</th><th>District Road</th><th>Farm Road</th></tr>
<tr><td>0 – 20</td><td>Excellent</td><td colspan="2" rowspan="2">Acceptable performance</td><td colspan="2" rowspan="3">Acceptable performance</td></tr>
<tr><td>20 – 40</td><td>Good</td></tr>
<tr><td>40 – 60</td><td>Fair</td><td colspan="2">Intermediate level of performance</td></tr>
<tr><td>60 – 80</td><td>Poor</td><td colspan="2" rowspan="2">Immediate Action for Mitigation</td><td colspan="2">Intermediate level of performance</td></tr>
<tr><td>80 – 100</td><td>Very poor</td><td colspan="2">Immediate Action for mitigation</td></tr>
</table>

6.2.3 Stage 2 of the Proposed GAM Framework

The assets carried forward from stage 1 are assessed for their likelihood of failure and consequence of failure expressed in terms of safety, mobility, and economic consequences. Figure 29 illustrates the steps involved in stage 2. Expressing consequence in terms of safety, mobility, and economic vitality will ensure the road users and workers stay safe, experience undisturbed flow of traffic, and ensure effective use of resources. These consequence aspects have been determined based on the NCHRP GAM Implementation Manual 2019 as well as from the RB TAMP of Colorado DOT; additionally, AT in its approach to develop the GAM Program, consequence of failure is being expressed in terms of safety, mobility, and economic consequences. Based on the estimated risk tolerance range (the risk rating scale of the RAMS Bhutan), treatment options will be reviewed, and recommendations made. Further, a simple cost-benefit analysis using the net present value (NPV) analysis shall be performed to check the costs likely to be incurred to fulfill the different alternatives.

The risk assessment methodology is inspired from the GRMP of AT and the NCHRP GAM Implementation Manual (2019), both of which involve qualitative assessment of asset condition and performance consequences. The NCHRP GAM Implementation Manual (2019) suggests ‘Starting Simply’ a GAM plan without a large investment, especially for an agency like the DoR, where the concept of GAM is new, and resources are constraint.

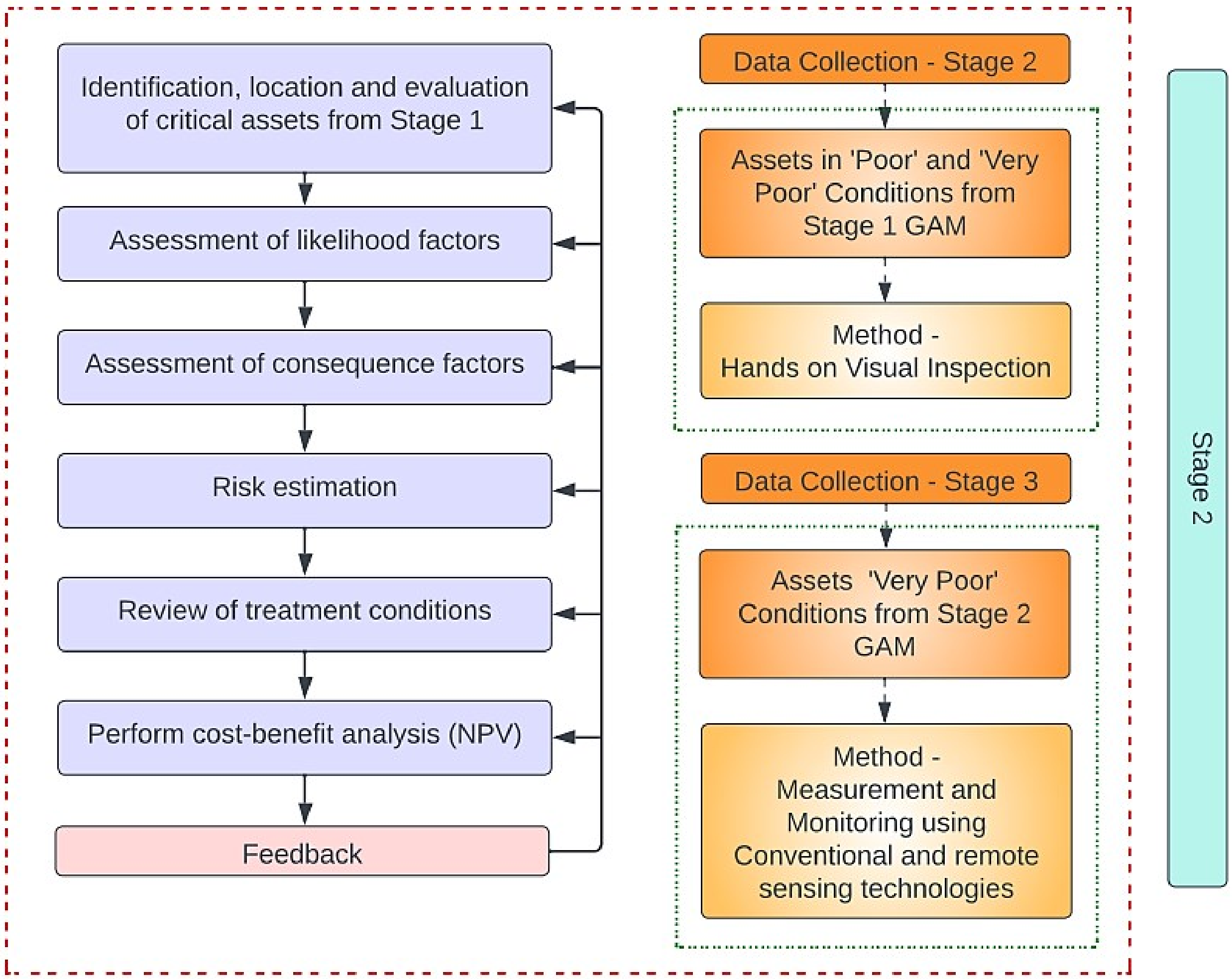


Figure 29: Stage 2 of the proposed GAM framework

Step 1: Identify critical assets from Stage 1

The assets in the 'Poor' and 'Very Poor' categories along PNH and SNH, and the assets in the 'Very Poor' category along the district roads and farm roads are deemed more critical and are filtered in stage 2 for further assessment. The data collection method can range from hands on visual inspection based on experience to methods involving detailed measurements or monitoring based on the feasibility and criticality of the assets. For the more critical geotechnical assets, additional data should be collected as shown in Table 20.

Table 20: Asset Parameters for Data Collection as part of Stage 2 of GAMS of Bhutan (Adapted from Unstable Slope Rating System of Washington DOT)

Asset Type	Parameters
Soil and Rock Slope (Along a road network)	Slope Age
	Slope Height
	Slope length
	Slope Angle
	ADT
	Sight Distance
	Ditch Effectiveness
	Roadblock Clearance or Maintenance Cost per Year
	Impact of roadblock by slide or rockfall to roadway width and Pavement
	Accidents (in last 10 years)
	Rockfall/slide history
	Presence of Water on Slope
	Discontinuity Characteristics

Retaining Wall	Wall Age
	Wall height
	Wall length
	Presence of Cracks or failures
	Wall Maintenance Cost per Year
	Impact to Traffic
Embankment	Embankment Age
	Embankment Material
	Embankment Length
	Embankment Height
	Embankment Angle
	ADT
	Impact to Traffic

Step 2: Assess the likelihood factors.

The GRMP of AT is used to assess the risk-based performance of the geotechnical assets particularly the earth slides, debris flow, rockfall and erosion sites (Tappenden and Skirrow 2020); the likelihood factors listed in Table 21 and Table 23 have been adapted from the GRMP of AT. The likelihood factors are, however, represented as a range of values to fit the risk rating scale of the already existing RAMS of Bhutan. The middle value from the provided range can be used for scoring as the assessment is qualitative and mostly based on hands on visual inspection.

Table 21: Likelihood factors for Stage 1 of GAM framework, Bhutan for soil slope, embankment and retaining wall (Adapted from GRMP of AT and RAMS of Bhutan)

Likelihood Factor (0 – 100)	
0 – 20	Very low likelihood of slide occurrence/low likelihood of embankment or wall failure
20 – 40	Moderate likelihood of remobilization or active but very slow rate of movement or indeterminate movement pattern/moderate likelihood of remobilization of embankment/moderate likelihood of wall failure with very slow rate of movement with a few hairline cracks
40 – 60	Likely with steady rate of movement/ likely failure of embankment or wall with steady rate of movement with several hairline cracks
60 – 80	Very likely with higher rates of movement/ failure of embankment or wall very likely with noticeable settlement or formation of wide horizontal or stepped cracks
80 – 100	Occurrence of major slide/Occurrence of failure of embankment or wall

Table 22:Likelihood factors for Stage 1 of GAM framework, Bhutan for rock slope (Adapted from GRMP of AT and RAMS of Bhutan)

Likelihood Factor (0 – 100)	
0 – 20	Very low likelihood of fall occurrence, inactive; geological conditions for failure (rock mass, discontinuity orientation) have not been identified.
20 – 40	Moderate likelihood of fall occurrence, inactive; geological conditions for failure (rock mass, discontinuities) are possible given the geology and morphology of the area.
40 – 60	Fall occurs after exceptional weather (intense precipitation), active with fall frequency in the order of once a decade; geological conditions for failure (rock mass, discontinuities) have been identified.
60 – 80	Several falls occur each year and the frequency increasing in comparison to previous years.
80 – 100	Toppling or sliding of large volume of rockfall, displacing mass accelerating.

Step 3: Assess the consequence factors.

Mobility and economic vitality consequences can be measured in terms of the categories of road, whether a Primary National Highway (PNH) or a Secondary National Highway (SNH) or a District Road (DR) which would have varying levels of economic consequences as each type of road has different functions. This can even be measured using the delays and closures due to roadblocks in addition to the expenditure incurred in clearing those roadblocks. It will rely on user judgement to assess the relationship between different factors to the magnitude of consequence.

An annual routine maintenance budget of Nu. 5,000,000 which is equivalent to CAD 83,000 based on the current exchange rate (CAD 1 = Nu. 61) is allocated to every RO for roadblock clearance and maintenance purposes irrespective of the number and magnitude of roadblocks in each RO. This maintenance budget for every RO has been used to determine the consequence factors as shown in Table 23. The mobility consequence factor, on the other hand, is based on the number of road closure hours adapted from NCHRP 2019 and Thompson 2017 as depicted in Table 24. The safety consequence can either be based on the possibility of vehicle crash or injury or fatality to commuters as shown in Table 25 and the decision sight distances as stipulated by AASHTO (Table 26 & Table 27).

Table 23: Proposed economic vitality consequence for GAM (Adapted from NCHRP 2019 and Maintenance Division, DoR 2019)

Consequence Factor (A – E) (Economic consequence)	
A	No impact or negligible impact to the economy; disruption confined to the shoulder or right-of-way; roadblock clearance or wall repair expenditure amounting to 0 – 5 % of CAD 82,000.
B	Minor consequence with the possibility of small volume of slide falling on the pavement, partially blocking the roadway but does not require closure of the road therefore, producing minor impacts to the economy; roadblock clearance expenditure amounting to 5 – 15 % of CAD 82,000.
C	Moderate consequence or moderate delay (one lane closure); sites where partial closure of the road or significant detours will be required due to slide occurrence or failure of wall; roadblock clearance expenditure amounting to 15 – 30 % of CAD 82,000.
D	Sites where clearance of roadblocks takes more than a day and closure of road is unavoidable bringing about serious impacts to the economy; roadblock clearance expenditure amounting to 30 – 70 % of CAD 82,000.
E	Sites where clearance of roadblocks takes days and closure of road is unavoidable bringing about catastrophic impacts to the economy; roadblock clearance expenditure amounting to 70 – 100 % of CAD 82,000 or more.

Table 24: Mobility consequence factors from GAM Implementation Manual (Adapted from NCHRP, 2019 and Thompson, 2017)

Consequence Factor (A – E) (Mobility)	
A	Negligible impact to traffic, no closure or impact on traffic (0 hours)
B	Minor impact to traffic; less than 1 hour of road closure
C	Major impact to traffic; 1 – 24 hours of road closure
D	Critical impact to traffic; 1 – 4 days of road closure
E	Catastrophic impact to traffic; more than 4 days of road closure

Safety consequences can be proposed as shown in Table 25 based on the crash history and threat to the safety of the commuters.

Table 25: Safety consequence for GAM (Adapted from NCHRP 2019)

Consequence Factor (A – E) (Safety)	
A	Negligible impact to the safety of commuters; no known crash history or crash event not likely to occur.
B	The possibility of impact only on hard shoulder and not the road pavement producing minor impacts to the safety of the commuters; impact only to shoulder and does not reach travel lanes.
C	Sites where partial closure of the road will be required because of slide occurrence or failure of retaining wall or embankment but are avoidable or limited to driver distraction.
D	Collision with asset related debris possible damaging vehicle or cause slight threat of injury.
E	Sites where clearance of roadblocks takes days and closure of road is unavoidable likely to bring catastrophic impacts to the safety of the commuters; fatality or injury possible.

Safety consequence is measured based on the decision sight distance (DSD) obtained based on the methods adopted by Tennessee DOT. DSD is the maximum road length that a driver has to identify and avoid a rockfall/landslide; it is measured in the direction of the oncoming traffic along the edge of the pavement. It is the distance from the pavement edge to where an object of 6 inch disappears while viewing at a height of 3.5 ft above the ground. In case both directions of traffic are likely to be affected by the slope failure, distance is measured in both directions, however the shorter distance is recorded. Table 26 shows the standard DSD, recommended by AASHTO (1984) for different speed limits. Based on the recommended DSD by AASHTO, the scoring of the safety consequence based on DSD is proposed as shown in Table 27. More critical of the two safety consequence factors – history/possibility of accidents and DSD, must be considered for the final risk estimation.

Table 26:AASHTO recommended Decision Sight Distance

Posted Speed Limit (kmph*)	Decision Sight Distance (m*)
40	114
48	137
56	160
64	183
72	206
80	229
89	267
97	305
105	320

*Units were mentioned in mph and ft in the AASHTO Green Book.

Table 27:Safety consequence factor in terms of % DSD

Consequence Factor (A – E) (Safety)	
A	Design sight distance 70 – 100 % or more than recommended by AASHTO
B	Design sight distance 30 – 70 % of the recommended distance by AASHTO
C	Design sight distance 15 – 30 % of the recommended distance by AASHTO
D	Design sight distance 5 – 15 % of the recommended distance by AASHTO
E	Design sight distance 0 – 5 % of the recommended distance by AASHTO

Step 4: Estimate risk.

Risk is estimated using the following relationship:

Risk = Likelihood x Consequence…………………………………………………………..[11]

The recommended risk rating scale to be adopted for the GAM is the one available in the RAMS of Bhutan reiterated as Figure 30. The implementation of GAM should eventually be incorporated into an agency-wide TAM (RAMS Bhutan in this case), and it can be made easier if the same risk rating methodology, already in place, is applied to the geotechnical assets as well.

			Risk rating				
Likelihood of Failure	Certain	80 - 100	80 - 100A	80 - 100B	80 - 100C	80 - 100D	80 - 100E
	Very Likely	60 - 80	60 - 80A	60 - 80B	60 - 80C	60 - 80D	60 - 80E
	Probable	40 - 60	40 - 60A	40 - 60B	40 - 60C	40 - 60D	40 - 60E
	Possible	20 - 40	20 - 40A	20 - 40B	20 - 40C	20 - 40D	20 - 40E
	Unlikely	0 - 20	0 - 20A	0 - 20B	0 - 20C	0 - 20D	0 - 20E
			A	B	C	D	E
			Negligible	Minor	Moderate	Serious	Catastrophic
			Consequences				

Figure 30: Risk Rating Scale (Adapted from Maintenance Division, DoR 2019)

Step 5: Review treatment recommendation

NCHRP GAM Implementation Manual 2019 and Waseem et. al 2022 suggest the following:

- Do minimum – The option of doing minimum involves performing only the minimum level of work needed to keep the asset in a condition that enables unobstructed traffic flow. It could be as simple as the activities shown in Table 28.

- Maintain (Routine maintenance) – This option involves routine maintenance treatments that are regular, frequent, but short activities done on a biannual or annual basis. Some of the routine maintenance activities are listed in Table 29.
- Rehabilitate – This option can include activities that will improve the asset condition to at least the next higher condition level and can eventually extend the life of the asset. Some such activities are listed in Table 30.
- Reconstruct – This option of treatment will consist of actions that will result in a tremendous improvement in the condition of the asset and likely reset the service life of the asset. Some examples are listed in Table 31.
- Restore – This category of treatment is recommended only upon the failure of the asset. Few activities listed in Table 32 are examples of such a treatment.

Table 28:Suggested maintenance activities (Adapted from NCHRP, 2019 and Waseem et al., 2022)

Do minimum
Installing signage
Patching pavement
Undertaking inspection
Removing debris and rocks from the road or ditches
Replace or reset damaged fences and railings

Table 29: Suggested maintenance activities (Adapted from NCHRP GAM Manual Vol.2)

Maintenance
Frequent cleaning of roadside ditch
Management of vegetation on slopes or embankments
Repair erosion scar by conducting minor earthwork activities
Cleaning drainage features on slopes or embankments or walls
Using instrumentation and monitoring
Crack sealing and removal of vegetation on retaining walls
Replacing damaged drainage structures or wall elements

Table 30: Suggested rehabilitation activities (Adapted from NCHRP GAM Manual Vol. 2)

Rehabilitate
Installation of drainage features underneath or into a geotechnical asset
Installation of anchor or draped mesh or other barriers on slopes
Excavation of larger catchment ditches
Replacement or improvement of a significant quantity of retaining wall facing elements
Conducting heavy scaling and slope modifications
Implementing vegetation or hydroseeding
Installing reinforcements and/or groundwater drainage in embankment
Conducting a partial reconstruction of the embankment

Table 31:Suggested reconstruction activities (Adapted from NCHRP GAM Manual Vol. 2)

Reconstruct
Flattening the slope inclination
Rebuilding a retaining wall
Realigning a roadway
Placing ground reinforcements to stabilize a slope or embankment
Reconstructing an embankment that is distressed beyond repair

Table 32: Suggested restoration activities (Adapted from NCHRP GAM Manual Vol. 2)

Restore
Replacing the asset with another asset
Developing alternative routes to detour the failure site

Though the risk assessment and management of geotechnical assets beyond the ROW is out of scope of this study, some generic treatment options are reflected in Table 33. The geotechnical assets beyond the ROW which includes natural hazard sites beyond the ROW such as natural rockfalls from geologic outcrops and landslides/debris flows way beyond the ROW can eventually affect the assets within the ROW and disrupt their operations. GAM framework encourages to maintain a separate inventory of slopes that originate as natural hazards beyond the ROW so as to facilitate the development of differing treatment plans, investment and resilience strategies, and risk management plans as the GAM matures over time within the DoR.

Table 33: Treatment options for geotechnical assets beyond the ROW (Adapted from NCHRP GAM Manual Vol. 2)

Treatment Options for Geotechnical Assets beyond the ROW
Grouting
Soil Nailing
Rockfall protection using anchors and meshes
Detailed study of geohazards and monitoring using advanced technologies

Step 6: Perform simple cost-benefit analysis.

NCHRP GAM Implementation Manual 2019, suggests incorporating basic life-cycle cost analyses (LCCA) in design and operation for an agency in the early stages of GAM; this would enable a systematic and defensible approach to making decisions which can be later updated as the system matures. The main objective of this step is to enable DoR to decide what specific treatment options will result in the least life-cycle cost over a period. The technique to be adopted for the LCCA will depend on the availability of data and the context for the decision. It could either be a simple summary of costs for each major activity or phase of the life cycle or each year of service or it could incorporate both direct and indirect costs. One such method is the net present value (NPV) analysis, which is especially useful when the data available is mostly related to the direct-cost impacts. Hence, for the GAMS, Bhutan, NPV analysis is suggested to be adopted to perform cost-benefit analysis.

The NPV analysis will help identify the best treatment alternative which will result in the least life-cycle cost and the greatest benefit over the stipulated design life of an asset. Detailed information, such as the indirect costs related to users can be incorporated with the advancement of the GAMS. Table 34 is a typical NPV analysis, according to the NCHRP 2019, and it consists of the components shown.

Table 34: Components of a typical NPV analysis for GAM Bhutan (Adapted from NCHRP 2019)

Sl. No	Cost type	Activity	Recommendation Options	
			Alternative 1	Alternative 2
1	Initial Cost	Design		
		Right of Way Purchase		
		Construction		
		Total Initial Cost		
2	Maintenance Cost	Annual Maintenance		
3	Present Worth Value of Annual Maintenance Cost (50 years)	Annual maintenance using a 4% discount rate over 50 years		
4	**Net Present Value**	**Initial + annual maintenance costs**	**1 + 3**	**1 + 3**

7. Test Implementation of the Proposed GAM Framework and Examples of Asset Monitoring Techniques

7.1 Test Implementation for Assets in Trashigang Regional Office

The Regional Offices constitute an important part of the DoR and are mandated to oversee construction, maintenance, and improvement works of roads and bridges under their jurisdiction. The 9 ROs are in various parts of the country, and they function with assistance from the head office. RO Trashigang is located in the eastern part of Bhutan. The proposed GAM framework is applied to 10 pilot sites within the jurisdiction of the RO Trashigang of the DoR; however, the 10 pilot sites are mainly soil and rock slopes as limited data was available for embankments and retaining walls. The assets are located at the vicinity of various highways connecting numerous districts within the purview of Trashigang RO as shown in Figure 31. The information on these assets have been generated from the KoboToolbox, which the department uses to manage the roadblocks within the country. Engineers of the RO's collect the data based on their field observations and the details comprise the exact locations of assets, triggering factor of the roadblock, time it took to clear the roadblock, costs incurred in doing so, etc.

A template for asset inventory has been prepared in Excel, which includes information such as the Asset ID, Asset Type, Route, Type of Road, Chainage, Preliminary Risk Level and Performance for Stage 1 of the GAMS. Further, details such as the Likelihood factors, Consequence factors in terms of economic consequences, safety and mobility consequences, risk level and treatment recommendations for Stage 2 of the GAMS.

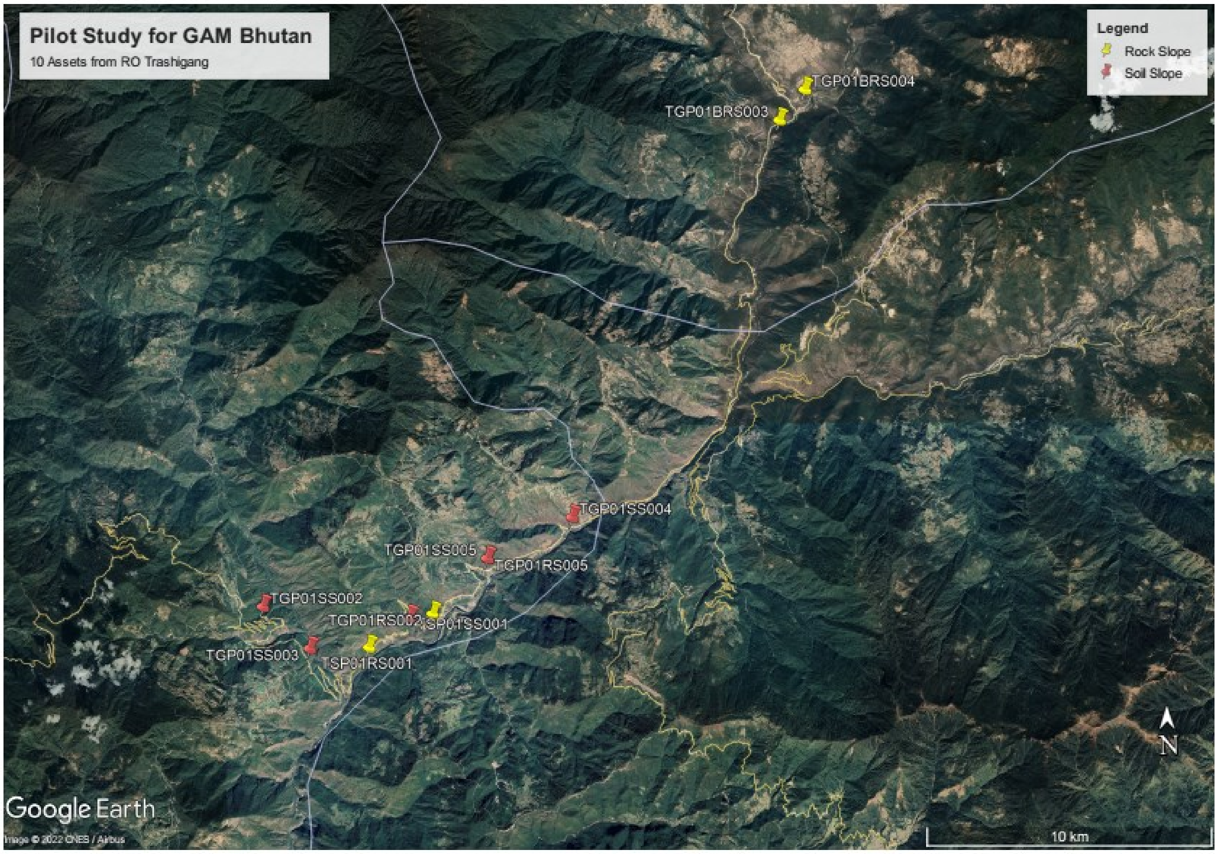


Figure 31: 10 Assets from RO Trashigang for the Pilot Study

The 10 assets are shown in Figure 32 with their IDs according to the nomenclature described in Chapter 6.

TGP01RS001	TGP01SS001
	

TGP01RS002	TGP01SS002
	
TGP01SS003	TGP01BRS003
	
TGP01BRS004	TGP01SS004
	

TGP01SS005	TGP01RS005
	

Figure 32: 10 Assets for Pilot Application of GAM Framework (Courtesy of DoR)

The ten assets have been assessed for Stages 1 and 2 as shown in Table 35 and Table 36. The asset with identity TGP01RS001 shown as the first asset in Figure 32 is a rock slope along Thimphu – Trashigang Highway (P01), located in Trashigang RO (TG). Rockfall at the given location has almost occupied half of the highway lane, however the volume is not as massive. Therefore, a preliminary risk rating, based on the criticality of the road stretch and on visual inspection, is assigned the range '60 – 80' which corresponds to 'Poor' performance or condition based on the preliminary risk category of stage 1 of GAMS stipulated in Table 19. The soil slope asset (TGP01SS001), on the other hand, shows some evidence of debris flow, hence a preliminary risk rating of '40 – 60' corresponding to 'Fair' performance or condition, is assigned based on visual inspection and criticality of the road stretch along which the asset exists. The soil slope (TGP01SS002) along the same highway, is assigned a preliminary risk rating of '20 –

40' which corresponds to 'Good' performance or condition as no debris can be observed on the pavement, except for a small volume in the ditch, which can be cleared during routine maintenance. The rock slope asset (TGP01BRS003) is assigned a preliminary risk rating of '80 – 100' which corresponds to 'Very Poor' performance or condition as the rockfall has completely blocked the highway and given the size and volume of boulders, it could have led to serious injury or even fatality and serious damage to the road pavement. The remaining six assets have been assessed in a similar manner and the results are presented in Table 35.

Assets being evaluated as 'Poor' and 'Very Poor' from stage 1 are further assessed in stage 2 against economic, mobility and safety consequences as stated in chapter 6. The rock slope asset (TGP01RS001) has been assigned a likelihood factor range of '40 – 60' in accordance with Table 22 as the rockfall occurred after intense rainfall and additionally geological conditions (rock mass discontinuities) for failure were identified. The expenditure incurred to clear the road from rockfall was recorded as CAD 300 which corresponds to consequence factor 'A' (Table 23); the stretch of road remained partially closed for 8 hours which corresponds to mobility consequence factor 'C' (Table 24), and finally as the site was partially closed and the rockfall is avoidable or limited to driver distraction (Table 25), the safety consequence assigned is 'C'. Among the three consequence factors, the most critical is adopted for risk estimation, which in this case is '40 – 60 C' which corresponds to moderate level of risk. Against the risk levels, are the recommended treatments for each asset. Various treatment options under the different treatment categories are mentioned in chapter 6 under treatment recommendations.

Similarly, for soil slope asset (TGP01SS003), likelihood factor of range ’60 – 80’ is assigned as higher rates of movement of debris were observed at the site based on visual inspection. The expenditure incurred to clear the road from debris was recorded as CAD 3000 which corresponds to consequence factor ‘A’, the stretch of road remained partially closed to traffic for 32 hours which corresponds to mobility consequence factor ‘D’, and finally as the landslide could have caused collision leading to vehicle damage or even cause threat of injury, the safety consequence assigned is ‘D’. Among the three consequence factors, the most critical is adopted for risk estimation, which in this case is ’60 - 80 D’. Likewise, the remaining assets have been assessed considering various likelihood and consequence factors.

Table 35: Stage 1 for the 10 Assets for the Pilot Study

Asset ID	Type	Route	Type of Road	Chainage (km)	Preliminary Risk Rating	Performance
TGP01RS001	Rock Slope	Thimphu - Trashigang	PNH	29.15	60 – 80	Poor
TGP01SS001	Soil Slope	Thimphu - Trashigang	PNH	26.88	40 – 60	Fair
TGP01RS002	Rock Slope	Thimphu - Trashigang	PNH	24.10	60 – 80	Poor
TGP01SS002	Soil Slope	Thimphu - Trashigang	PNH	42.00	20 – 40	Good
TGP01SS003	Soil Slope	Thimphu - Trashigang	PNH	37.26	60 – 80	Poor
TGP01BRS003	Rock Slope	Chazam - Trashiyangtse	PNH	9.00	80 – 100	Very Poor
TGP01BRS004	Rock Slope	Chazam - Trashiyangtse	PNH	5.00	40 – 60	Fair
TGP01SS004	Soil Slope	Thimphu - Trashigang	PNH	15.70	60 – 80	Poor
TGP01SS005	Soil Slope	Thimphu - Trashigang	PNH	19.60	80 – 100	Very Poor
TGP01RS005	Rock Slope	Thimphu - Trashigang	PNH	19.60	60 – 80	Poor

Table 36: Stage 2 for the 'Poor' and 'Very Poor' Categories from Stage 1 among the 10 Assets

Asset ID	Likelihood Factor	Economic Consequence Factor	Mobility Consequence Factor	Safety Consequence	Risk Level	Treatment Recommendations
TGP01RS001	40 – 60	A	C	C	40 - 60C	Do minimum
TGP01RS002	60 – 80	B	C	C	60 - 80D	Do minimum
TGP01SS003	60 – 80	A	D	D	60 - 80D	Rehabilitate
TGP01BRS003	80 – 100	B	D	E	80 - 100E	Reconstruct
TGP01SS004	40 – 60	A	C	C	40 - 60C	Do minimum
TGP01SS005	80 – 100	B	D	E	80 - 100E	Reconstruct
TGP01RS005	40 - 60	A	C	C	40 - 60C	Do minimum

Table 37 is the NPV analysis carried out for the two assets in the 'Very Poor' Categories from the risk assessment as shown above; the recommendation options for both being 'Reconstruct', an alternative could be flattening the slope angle and increasing the ditch dimensions and the other could be realigning the highway to another route. Design of highway geometry including the roadside slopes are carried out in-house by the department (DoR) and hence, the costs considered for design are staff salary and allowances based on the current pay scales of the staffs likely to be involved in the survey and design processes. Construction of roadside slopes and highways, on the other hand, are outsourced to eligible contractors based on the cost estimates prepared by the department using the Bhutan Schedule of Rates (BSR), which is updated every year with change in market prices. The estimates have been obtained using the unit costs developed by the department based on the BSR 2021.

Table 37: NPV Analysis of the Soil Slope (TGP01SS005) based on unit costs from DoR, Bhutan

Sl. No	Cost type	Activity	Recommendation Options	
			Alternative 1: Flattening of side slope to 1:0.5	**Alternative 2: Realigning the highway to another route**
1	Initial Cost	Design	$4300*	$7000*
		Construction	$75,000	$1,500,000**
		Total Initial Cost	**$79,300**	$1,507,000
2	Maintenance Cost	Annual Maintenance	$700	$3500
3	Present Worth Value of Annual Maintenance Cost (50 years)	Annual maintenance using a 4% discount rate over 50 years	$15,200	$76,100
4	**Net Present Value**	**Initial + annual maintenance costs**	**$94,500**	**$1,583,100**

*Design of highway geometry including slope flattening and new highway designs are done in-house, hence the costs only include the staff salary and daily allowances.

**Considered increased length (5 km) after rerouting the highway

7.2 Test Implementation of Proposed GAM Framework and Asset Monitoring using Remote Sensing Techniques for Sites in Western Canada

The GAM Framework has been developed based on the GAM Implementation Manual released by NCHRP in 2019 designed to provide guidance on the management of geotechnical assets irrespective of the stage of GAM the agency is at, practices adopted by various DoTs in the U.S., and it has been customized in accordance to the risk assessment methodology adopted by the RAMS of Bhutan, with the aim to eventually integrate the two systems when the GAM matures. The risk assessment methodology further takes inspiration from the current GRMP risk rating system adopted by AT, designed to reduce, and manage the risks associated with geological hazards which potentially impact roadways, railway lines, and other transportation infrastructure within Alberta. Though the framework is explicitly applicable to geotechnical assets within Bhutan, an attempt has been made to apply the two stages of the framework to some of the sites in Western Canada as some aspects of the risk assessment methodology are based on the GRMP of AT. For the most critical assets, the framework recommends using detailed monitoring and measurement either using conventional methods or remote sensing technology or a hybrid of the two methods. Likewise, different remote sensing technologies described in chapter 5 have the potential to be used for monitoring and assessment purposes within a geotechnical asset management system. Being able to accurately monitor surface deformation makes such techniques particularly relevant. The following sections describe application of the two stages of the proposed GAM to three sites in Western Canada and various cases of remote sensing applications as case studies present practicable examples for how the information can be captured using remote sensing techniques.

7.2.1 Chin Coulee Landslide in Southern Alberta, Canada

The Chin Coulee landslide is located adjacent to Highway 36, near the town of Taber in southern Alberta as shown in Figure 33. The landslide is believed to have been caused by the works required to relocate Highway 36 and fill the reservoir. Highway 36 is a provincial highway in Alberta, and it is a part of a trade corridor linking Canada, U.S., and Mexico. It passes through the cities of Cardston, Stirling, and Red Deer. This highway can be considered equivalent to a SNH in Bhutan, which connects different district centers. The local stratigraphy comprises a medium plasticity clay toward the scarp and a silty clay till of low to medium plasticity with traces of fine gravel in the valley slope. The thickness of the latter ranges from 20 m at the toe to 35 m near the head scarp. The average reservoir elevation is at about 838 m.a.s.l. and the elevation of Highway 36 is at about 887 m.a.s.l. This information has been obtained and interpreted based on borehole logs, inclinometer readings and piezometric readings as shown in Figure 34 (Deane E. et al. 2019, Deane E. et al. 2020, as cited in Macciotta R. and Hendry M. 2021).

Based on the field and photographic mapping, the landslide is about 200 m long, 350 m wide and 45 m deep; the volume of the landslide is estimated to be 2 million cubic meters. The toe of the landslide is within the reservoir. The failure surface, as shown in the figure below, is based on the location of the head scarp, the shear zones identified in the slope inclinometers, and the location of the coal seam. The landslide has been categorized as a translational retrogressive landslide and the displacement rates vary between 10 and 50 mm per year (Macciotta R. and Hendry M. 2021). Given the history of the slide, criticality of the highway and based on the visual inspection of the site, the slope asset can be assessed for stage 1 of the GAM framework as shown in Table 38. Figure 35 is the snapshot showing the head scarp cracking captured by KCB during the annual routine inspection of the site carried out on May 9, 2019.

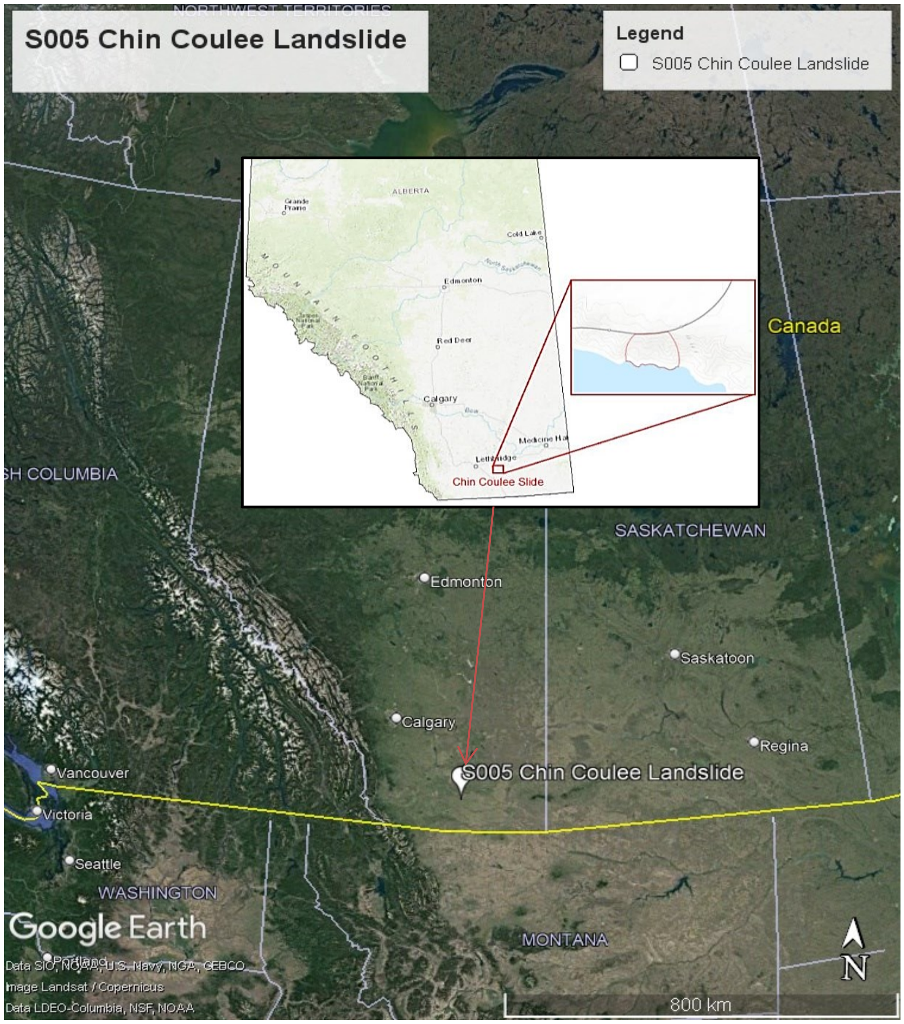


Figure 33: Location of Chin Coulee landslide (Adapted from Deane E. et al. 2019)

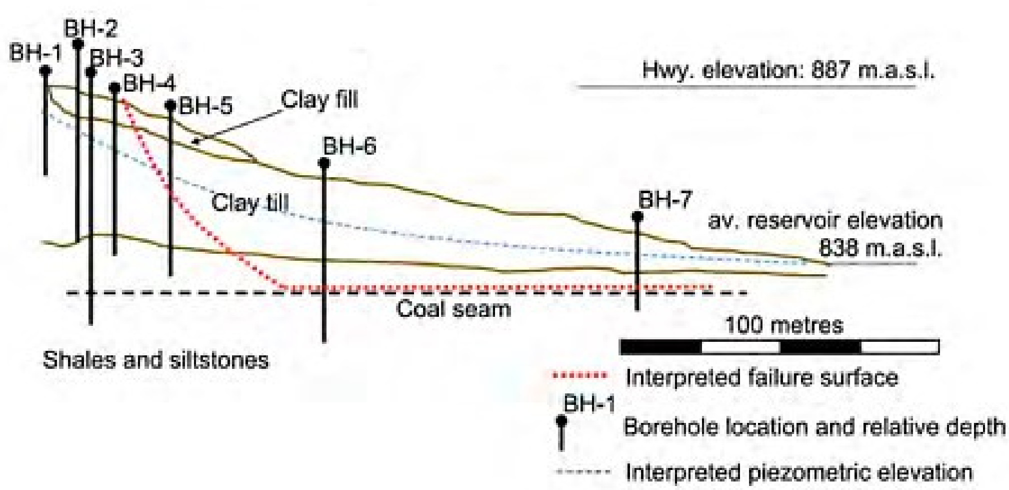


Figure 34: Typical cross section of Chin Coulee landslide (Macciotta R. and Hendry M. 2021 Licensed under [CC BY 4.0](CC BY 4.0))

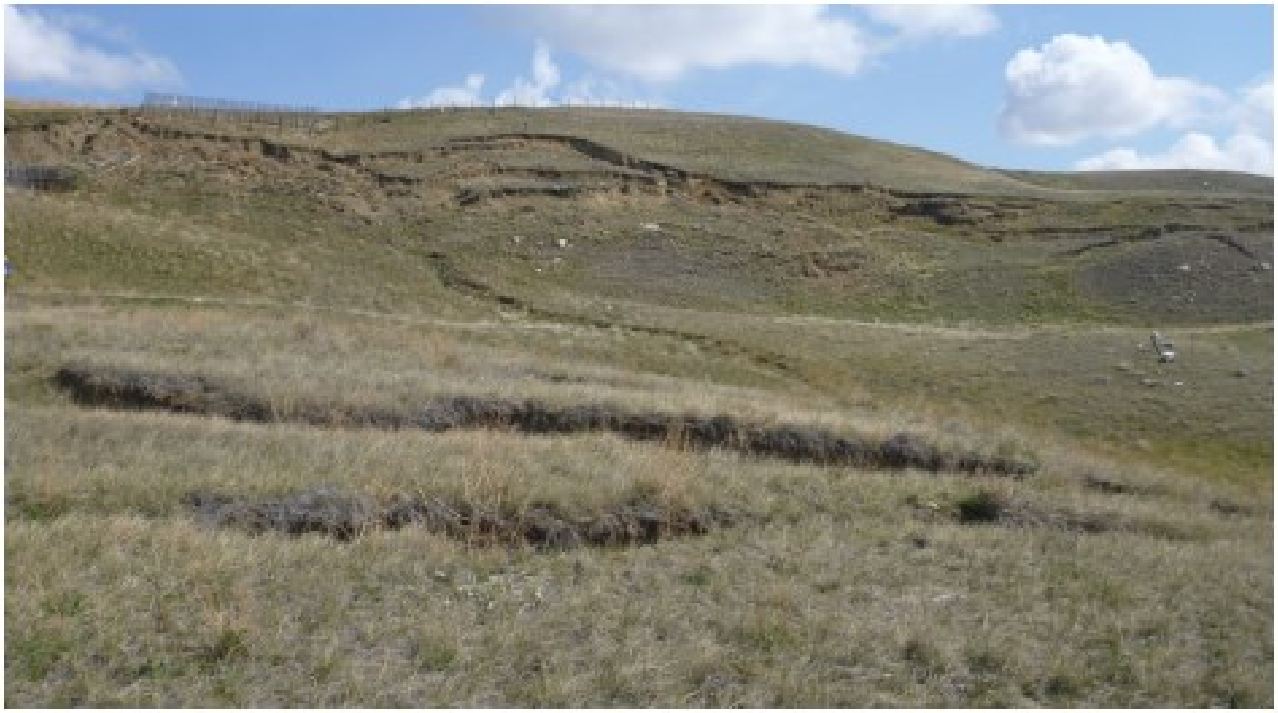


Figure 35: Head scarp cracking at S005 Chin Coulee Slide Captured on May 9, 2019, as a part of annual inspection by KCB (Accessed on 01/17/23)

Table 38: Preliminary Risk Rating for S005 Chin Coulee Slide

Asset ID	Type	Route	Type of Road	Preliminary Risk Rating	Performance/ Condition
S005	Soil Slope	Highway 36	Provincial Highway	60 – 80	Poor

Highway 36 is a provincial highway equivalent to a SNH of Bhutan and hence, considering the criticality of the highway and based on the head scarps observed upon visual inspection, a preliminary risk rating of '60 – 80' which corresponds to 'Poor' performance or condition, is assigned to this asset. As a result of this, asset S005 is carried forward to be assessed for stage 2 of the GAM. During the last annual slope inspection conducted by KCB for AT on May 9, 2019, using the GRMP, a probability factor of '9' and a consequence factor '2' were assigned to the asset. This likelihood factor corresponds to the range ’40 – 60’ in the criteria of likelihood factor of the proposed GAMS (Table 21). Based on the consequence factor of ‘2’, loss of portion of slide onto road would have been possible which could have affected the use of the highway and safety of motorists; however, it would not have required closure of the highway. Hence, mobility and economic consequence factors of ‘A’, and as there is the possibility of affecting the safety of the motorists, a safety consequence factor of ‘C’ is assigned to the asset as illustrated in Table 39. This is supported by the extremely slow movement of the landslide (~50 mm/year) which implies gradual deterioration of the road however, a very low likelihood of harm to highway users.

Table 39: Risk Assessment of the Slope Asset (S005) for Stage 2 of GAM Framework

Asset ID	Likelihood Factor	Economic Consequence Factor	Mobility Consequence Factor	Safety Consequence	Risk Level	Treatment Recommendations
S005	40 – 60	A	A	C	40 - 60C	Do minimum

The risk level obtained as a result of the assessment is ’40 – 60 C’ which corresponds to ‘Fair’ performance or condition based on the risk rating scale of GAMS. Treatment recommendation suggested for this level of risk is to ‘Do minimum’. The annual inspection team recommended visiting the site once every two years, however, the long-term plan suggests rerouting the road several hundred metres to the west. Even though the risk of failure of the asset obtained is moderate, AT has been actively monitoring the site using both conventional and remote sensing technologies. The following sections describe the two remote sensing techniques implemented at the site for continuous and more accurate monitoring of surface displacements at the site.

7.2.1.1 Differential GPS system at Chin Coulee

A differential GPS system comprising 10 Geocubes™ was installed at the Chin Coulee landslide in July 2018 as shown in Figure 36, with the aim to obtain continuous movement data for targeted regions in the landslide (Deane E. et al 2019). The movement data acquisition included the following major steps:

- Installation of Geocubes™
- Continuous movement data acquisition
- Analysis of data

Installation of Geocubes™ (Deane E. et al. 2019)

The Geocubes™ were installed using hand augered deck screw piles, the embedment depth of which was limited to 0.8 – 0.9 m due to the presence of gravel; each unit was equipped with a 10-Watt solar panel and two 12-Volt, 100 Ah batteries which provided continuous power to the system as shown in Figure 37. Some of the GPS units had to be raised almost 1 m above the ground to achieve communication; the installation height, however, increased the amount of error.

Figure 36: GPS Unit Location on Chin Coulee (Deane E. et al. 2019)

Figure 37:GPS and Battery Box Setup on Chin Coulee (Deane E. et al. 2019)

Continuous movement data acquisition (Deane E. et al. 2019)

The data acquisition was done using a mobile data plan, which facilitated remote data acquisition without having to go to the site regularly.

Analysis of data (Deane E. et al. 2019)

The Chin Coulee landslide using the differential GPS system was monitored for 9 months from July 2019 to April 2019. The displacement values were determined by computing the Euclidean distance from the initial position to the current position. Since some of the GPS units had to be raised above the ground and due to some cases of vandalism at site, there were some unrealistic movement data captured by those units, for instance some showed uphill movements, and some showed sudden jumps. Data analyses involved removal of such jumps and fitting the remaining data to the same value, the resultant thereafter is as shown in Figure 38. Therefore, upon removal of sudden movements or jumps in the movement data, a yearly moving rate for the Chin Coulee landslide corresponded to 20-40 mm per year.

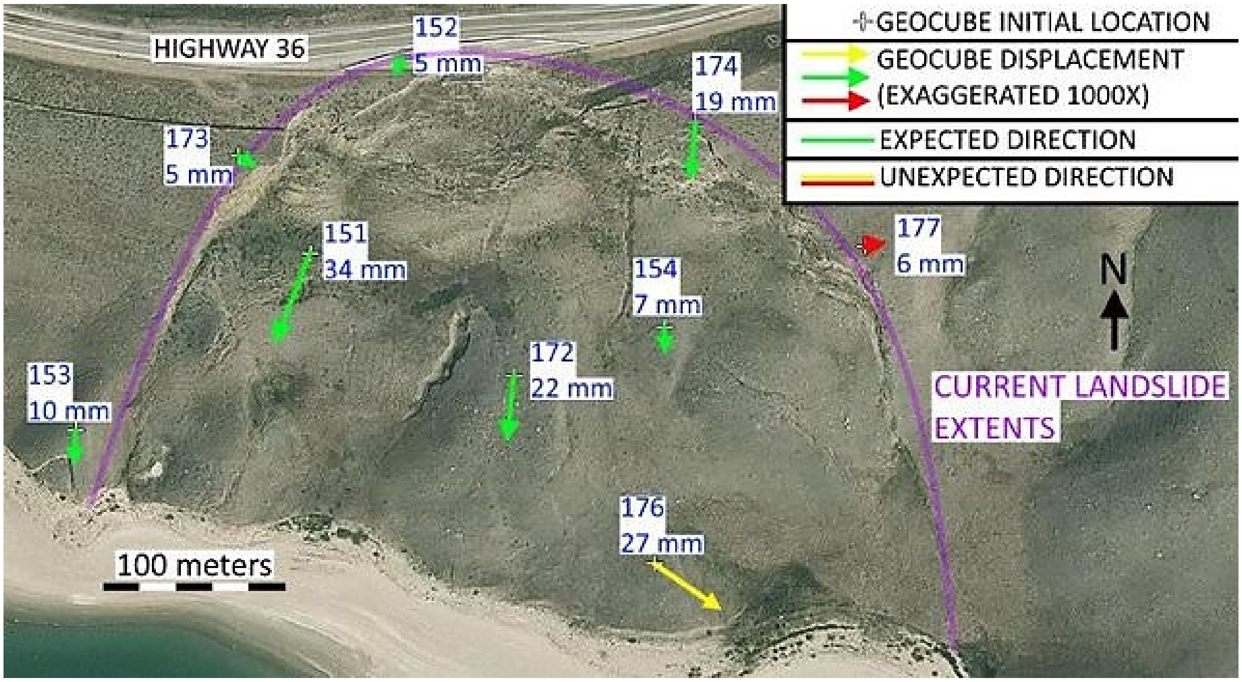


Figure 38: GPS Unit Movements on Chin Coulee from July 11, 2018, to April 6, 2019 (Deane E. et al. 2019)

7.2.1.2 Terrestrial LiDAR at Chin Coulee

The primary reason for deploying terrestrial LiDAR system at the Chin Coulee site was to obtain complete spatial monitoring coverage of the slide. The first scan performed in July 2018 was projected from two locations which hindered the absolute coverage of the slide; hence the scans thereafter were captured from three locations as shown in Figure 39. The LiDAR system used an Optech ILRIS-LR laser scanner with the features as shown in Table 40 with an average scan distance of 950 m (Deane et al. 2019, Macciotta R. and Hendry M. 2021).

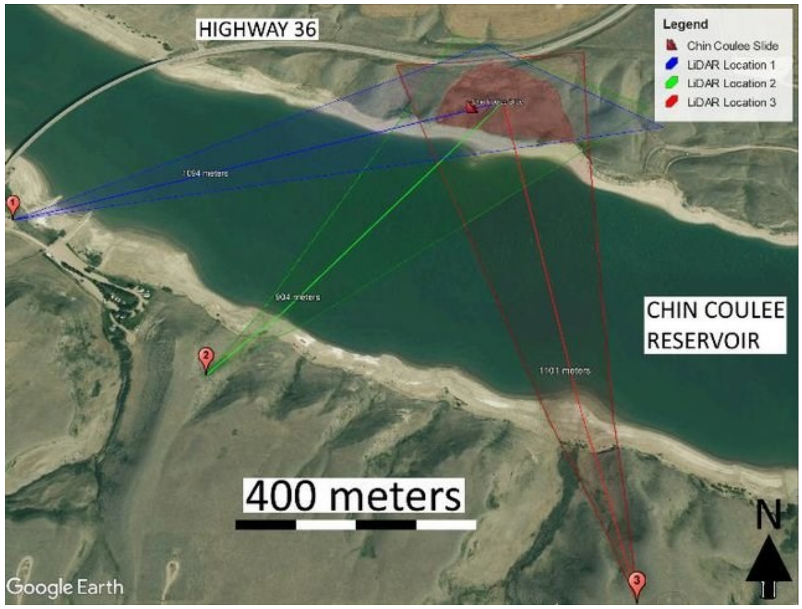


Figure 39: LiDAR scan locations at Chin Coulee slide (Deane et al. 2019)

Table 40: Specifications of the laser used in the LiDAR system (Adapted from Deane et al. 2019, Macciotta R. and Hendry M. 2021)

Features	Specifics
Laser wavelength	1064 nm
Pulse frequency	10 kHz
Beam divergence	0.014324°

<u>Change Detection</u>

Using the scans captured on July 10, 2018, and August 23, 2018, change detection was performed. Due to its superior performance for distance calculation, M3C2 was used to perform the change detection. This method averages the distance between points that fall within a user defined size of cylinder, normal to the surface of one point cloud. CloudCompare^{TM} was used to conduct the point cloud analysis. The level of detection (LOD) was calculated as 80 mm and upon removing points below this threshold, resulted in 87% of the points being removed within the active landslide region. The result of the change detection is as shown in Figure 40 (Deane et al. 2019, Macciotta R. and Hendry M. 2021).

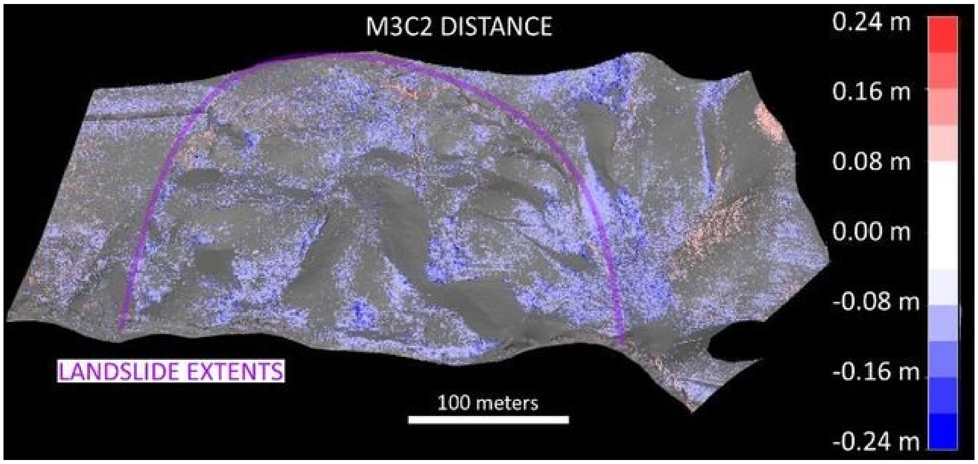


Figure 40: Change detection between July 10 and August 23, 2018, using LiDAR scanning (Deane et al. 2019)

One of the pertinent limitations of LiDAR scanning is the LOD; if the movement between the scans is lower than the LOD, it is not detected by the system. Sites with dense vegetation cover will likely result in worse levels of detection because of poor point cloud registration and bare earth model generation. It can however be improved by methods such using the 'last reflection' options made available for a lot of LiDAR systems, using vegetation classification tools found within point cloud software, using CANUPO classifier, using GCPs, etc. (Alba et al., 2006, Deane et al. 2019).

7.2.1.3 Applicability in Bhutan

Differential GPS is a reliable and cost-effective method that can measure the position of individual geotechnical assets, as well as monitor the displacement of these assets over time. Geocube^{TM} by Ophelia deployed at the Chin Coulee slide is a type of differential GPS technology designed to be used by agencies with budget constraints. It can function with low power consumption and by using small solar panels. Receivers can be deployed relatively quickly due to the low cost of receivers and ease of deployment without having to use heavy equipment. These very facts make it an ideal choice for monitoring of geotechnical assets in a country like Bhutan, where resources are scare and number of geotechnical assets to be monitored are plenty. However, care must be taken while embedding the receivers at appropriate installation heights to ensure proper reception of signals and to minimize error during data analysis. It is very likely to face similar issues of vandalism of equipment at site which can be minimized by enhanced protection of equipment and by having the equipment monitored by a site office in the vicinity, on a regular basis.

LiDAR is a powerful remote sensing tool that has the ability to capture data from a wide range of distances and detect changes in terrain features over time. It can be used to monitor displacements with high surface point densities and hence, can be applicable for less extensive regions and focus on the most critical assets identified through risk assessment. Vegetation hinders the accurate measurement of surface movements, however, there are means to reduce or remove the vegetation with the use of appropriate tools such as the CANUPO classification. For unvegetated surfaces and bare rock faces, LiDAR can generate highly accurate measurements. Hence, this technology can be considered for use in the southern parts of Bhutan, where the slope assets are mostly with scare vegetation and gentle terrains.

7.2.2 C018 Landslide in Drumheller, Alberta

C018 landslide is in southeastern Alberta (region known as Badlands) adjacent to Highway 837 approximately 10 km northwest of the town Drumheller (Figure 41).

Highway 837 is an important route in the region, connecting the towns of Bow Island and Burdett to the rest of the region and it also serves as an important link between Highway 836 and Highway 589, which provide access to the nearby cities of Medicine Hat and Lethbridge. This highway, as it links two important highways and few cities, it can be considered of equivalent importance to a SNH of Bhutan. The site is alongside the Red Deer River, the landscape of which has little vegetation cover and is highly eroded and weathered. Glaciation deposition followed by erosion from melted water and the Red Deer River led to the formation of interbedded sedimentary rocks composed of fine-grained sandstone, bentonitic mudstone, and carbonaceous mudstone, with coal seams and bentonite beds (Borneuf 1972, Stalker 1973, Prior et al. 2013, as cited in Rodriguez et al. 2020). Figure 42 shows the geology of a site located close to the C018 landslide.

The slide is about 520 m long and 90 m high (Macciotta R. and Hendry M. 2021). The geology of the site causes Highway 837 to be vulnerable to different instability processes especially during precipitation events (Rodriguez et al. 2020). For instance, a large rockfall and debris flow event on May 23, 2018, following a 15-mm rainfall event which occurred 6 days prior to the event, blocked the highway. AT, then had to partially close one lane of the road by installing concrete barriers known as Jersey barriers of almost 90 m along the highway as shown in Figure 43.

Figure 41: Location and aerial view of CO18 landslide (Adapted from Macciotta R. and Hendry M. 2021)

Given the history of the slide, criticality of the highway and based on the visual inspection of the site, the slope asset can be assessed for stage 1 of the GAM framework as shown in Table 41.

Figure 42: View of the sedimentary geology at C018 slide consisting of interbedded sandstone, siltstone, and mudstone.

Figure 43: Jersey barriers partially closing one lane of Highway 837 at C018 site.

Continuous movement of debris has been observed at the site, in fact the highway has be partially closed to traffic following a large rockfall and debris flow event of May 23, 2018. Given the history and based on visual inspection of the site, a preliminary risk rating of ’80 -100’ is assigned. Since this range of rating corresponds to ‘Very Poor’ performance or condition, the asset is carried forward to be assessed for stage 2 of GAM in accordance with the framework. During the last annual slope inspection conducted by KCB for AT on May 30, 2022, using the GRMP, a probability factor of ‘16’ and a consequence factor ‘9’ were assigned to the asset, based on debris flow of 0.5 cubic meters or more, which resulted in the highest risk level (RL) of 144. Values have been assigned for debris flow less than 0.5 cubic metres (RL = 90) as well as for earth slide (RL = 60). The highest of the three is being considered for assessment of the asset in stage 2 of GAM. This likelihood factor corresponds to the range ’60 – 80’ in the likelihood factor stipulated in Table 21 of the GAMS. Based on the consequence factor of ‘9’, which indicates the safety of the public could be compromised, and a significant loss of infrastructure would occur if additional sliding occurred. The highway has been partially closed since May 2018 and it continues to pose a threat to the safety of motorists. Hence, a consequence factors of ‘E’ is assigned to all three consequence factors as illustrated in Table 42.

Table 41: Preliminary risk rating (Stage 1 of GAM) for C018 slide

Asset ID	Type	Route	Type of Road	Preliminary Risk Rating	Performance/ Condition
C018	Soil and Rock Slope	Highway 837	Provincial Highway	80 – 100	Very Poor

Table 42:Risk Assessment of the Slope Asset (C018) for Stage 2 of GAM

Asset ID	Likelihood Factor	Economic Consequence Factor	Mobility Consequence Factor	Safety Consequence	Risk Level	Treatment Recommendations
C018	60 – 80	E	E	E	60 – 80 E	Reconstruct

The risk level thus obtained is '60 – 80 E' which corresponds to 'Very Poor' performance or condition based on the risk rating scale of GAMS (Figure 30). Treatment recommendation suggested for this level of risk is to 'reconstruct' which includes flattening slope inclination and highway realignment among many others. According to the annual inspection report, AT's consultant, KCB in their Conceptual Engineering Assessment (CEA) included options of re-routing the highway, installing rock shed, installing a barrier wall in the upslope ditch, re-aligning the highway, and implementing automatic monitoring at the site. The risk of failure of the asset obtained is severe and the monitoring measures being implemented agrees with the GAMS as AT has been actively monitoring the site using different remote sensing technologies. The following section describes the use of UAV photogrammetry at site for continuous and more accurate monitoring of surface displacements.

7.2.2.1 UAV Photogrammetry at C018

UAV technology was adopted for this site as the location and geometry of the slope posed a challenge to observe the conditions of the slope. The implementation of this technology involved following steps (Rodriguez et al. 2020):

- Capturing UAV photos
- Digital photogrammetric reconstruction
- Change detection.

<u>Capturing UAV photos</u>

The UAV photos were captured in December 2017, May 2018, and November 2018; a UAV of 12-MP camera was used for the first and third flights and a UAV of 17-MP was used for the second flight (Rodriguez et al. 2020). The cameras had the following properties as shown in Table 43.

The photographs had a minimum overlap of 60%, and required 655, 600 and 910 photographs respectively for the three surveys in chronological order (Macciotta R. and Hendry M. 2021). The UAVs were equipped with GPS+GLONASS dual positioning module to obtain precise location, and the flight path was created using Pix4DCapture.

Table 43: Features of the UAVs used for C018 (Macciotta R. and Hendry M. 2021)

Features	**12-MP Camera**	**17-MP Camera**
Sensor	1/ 2.3” CMOS (6.3 mm width and 4.7 mm height)	1/ 2.3” CMOS (6.3 mm width and 4.7 mm height)
Field of view	94°	82°
Focal length	20 mm	44 mm
Aperture	F 1:2.8	F 1:3.3

To optimize the accuracy of point cloud reference, ground control points (GCPs) were distributed; the first two surveys had 5 GCPs and the last survey had 10 GCPs. Photos captured were then checked for quality and the ones with poor quality were removed (Rodriguez et al. 2020).

<u>Digital photogrammetric reconstruction</u>

The UAV photos were reconstructed into topography using the Pix4Dmapper. Upon densifying each point cloud, filtering of outlier points (points identified outside the confidence interval defined by the average distance to a point of 10 neighboring points plus ‘n’ standard deviations of the distance) were done using the open-source software

CloudCompare V2.9 (Rodriguez et al. 2020). Figure 44 from Rodriguez et al. 2020 shows the point clouds for the largest active zone on the slope.

Figure 44: Point clouds for the most active zone a) UAV photo taken after May event b) point cloud from first UAV survey c) from second UAV survey d) from third UAV survey (Rodriguez et al. 2020 licensed under CC BY 4.0)

<u>Change Detection</u>

The first survey was used as a reference point for alignment of the point clouds (Rodriguez et al. 2020). The surface model was converted to a point cloud having a minimum density of 500 points/m^2. This surface model was used for change detection using the M3C2 method (Macciotta R. and Hendry M. 2021). This method allowed for computing the total displacement of two point clouds, the direction of which was quantified based on the calculation of normal vector using the point cloud from the first survey. The points on the second point cloud were those located within a circular projection of 0.3 m in diameter (Rodriguez et al. 2020). The change detection analysis using M3C2 resulted in significant change of 8.5% of the points in the reference point cloud at 95% confidence level, and the result is as shown in Figure 45 and Figure 46 analyzed by Rodriguez et al. 2020. Part a) shows the comparison between the first and the second surveys. Whereas the part b) shows the resultant change between the second and the third surveys.

The change detection analysis showed an average material loss of 0.18 to 0.58 m depth on the upper and middle sections of the slope. This occurred in May 2018 followed by gradual accumulation of materials along the ditch of the highway. The changes after November 2018 corresponded to a loss of 738 m^3 and a gain of 323 m^3 materials at the toe of the slope in the northern region. The change detection showed three modes of failure namely the development of debris flows, rockfalls and detachment and falling of blocks of frozen soil from the surface of the slope (Rodriguez et al. 2020).

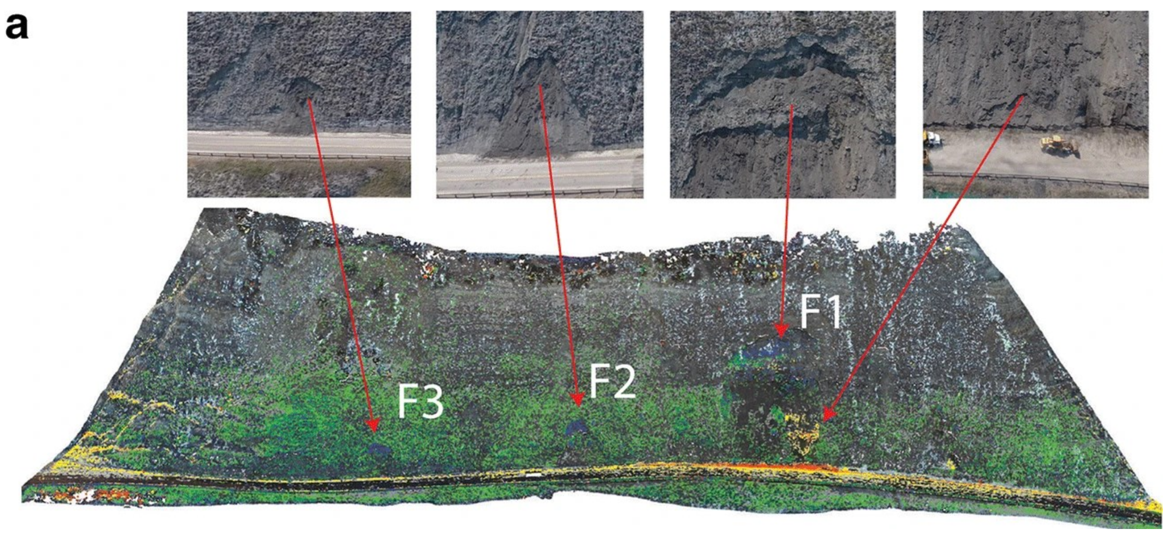


Figure 45: Change detection based on the first and the second survey (Rodriguez et al. 2020 licensed under [CC BY 4.0](CC BY 4.0))

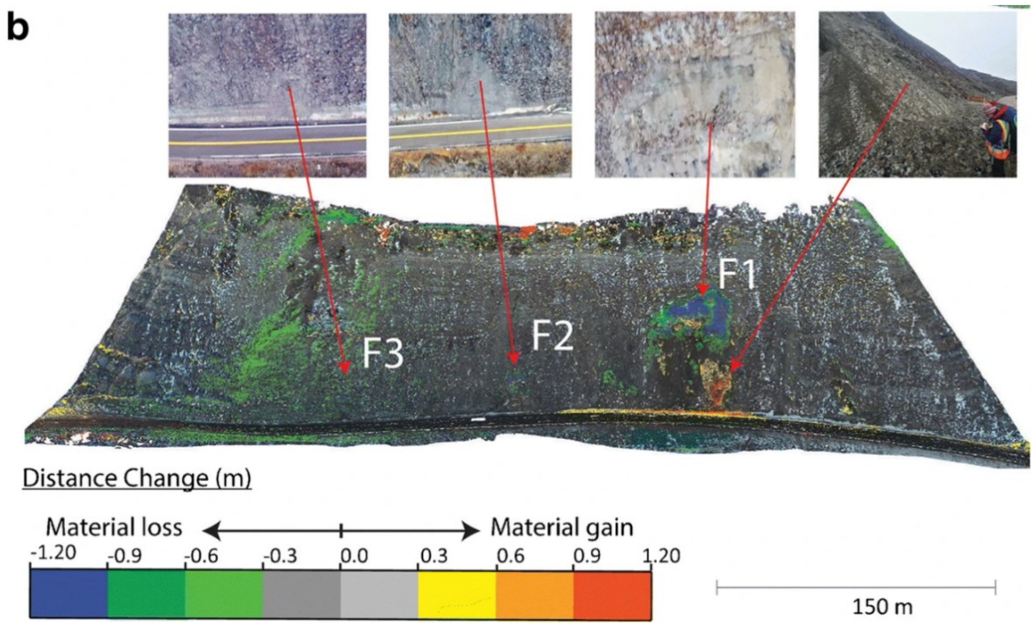


Figure 46: Change detection based on the second and the third surveys (Rodriguez et al. 2020 licensed under CC BY 4.0)

7.2.2.2 Applicability in Bhutan

UAV photogrammetry can be used for monitoring geotechnical assets in mountainous terrains, providing detailed information about the deformation of the terrain and its characteristics. This method of geotechnical asset monitoring for use in GAMS can help obtain information about the assets that are not accessible for hands-on inspection and monitoring using site instrumentation. Being located in the terrains of the Himalayas, a major portion of the slope assets in Bhutan, remain inaccessible for monitoring and detailed site investigations. It would be wise for the DoR to invest in UAVs with high resolution cameras and have the staff trained in operating the equipment and for analyzing the data. This technology can be effectively used for determining conditions of assets that are inaccessible for visual or hands-on inspection and facilitate fast data acquisition. Further, UAVs equipped with high resolution cameras can provide detailed aerial maps of the terrain, allowing for the assembly of high-resolution DEMs, which can then be used to compare changes in the terrain over time and to generate more accurate hazard maps. It is yet another cost-effective method and for a resource constrained agency like the DoR, this technology can be a great start of delving into the world of remote sensing and efficient data collection and asset monitoring.

7.2.3 Checkerboard Creek Rock Slope in Revelstoke, British Columbia, Canada

The Checkerboard Creek slope is located 1.5 km upstream of the Revelstoke Dam structure along Highway 23 in Revelstoke, BC (Figure 47). Highway 23 in this location provides an important link to local forestry industry and access to two major hydroelectric projects and their reservoirs. The dam is a part of a hydroelectric project operated by BC Hydro along Columbia River (Macciotta R. and Martin D. 2018, Woods et al. 2019). Tension cracks define the upper boundary of the slope; the active deformation zone has an average slope angle of 45°, at a depth of about 50-60 m, and an estimated volume of about 2 to 3 million m^3. The slope comprises massive to weakly foliated granodiorite overlying the gneiss and schist of Columbia River fault dipping towards east. The primary joint set dips more than 80° and parallel to the slope contours, whereas the secondary joint set dips perpendicular to the slope (Macciotta R. and Martin D. 2018, Woods et al. 2019).

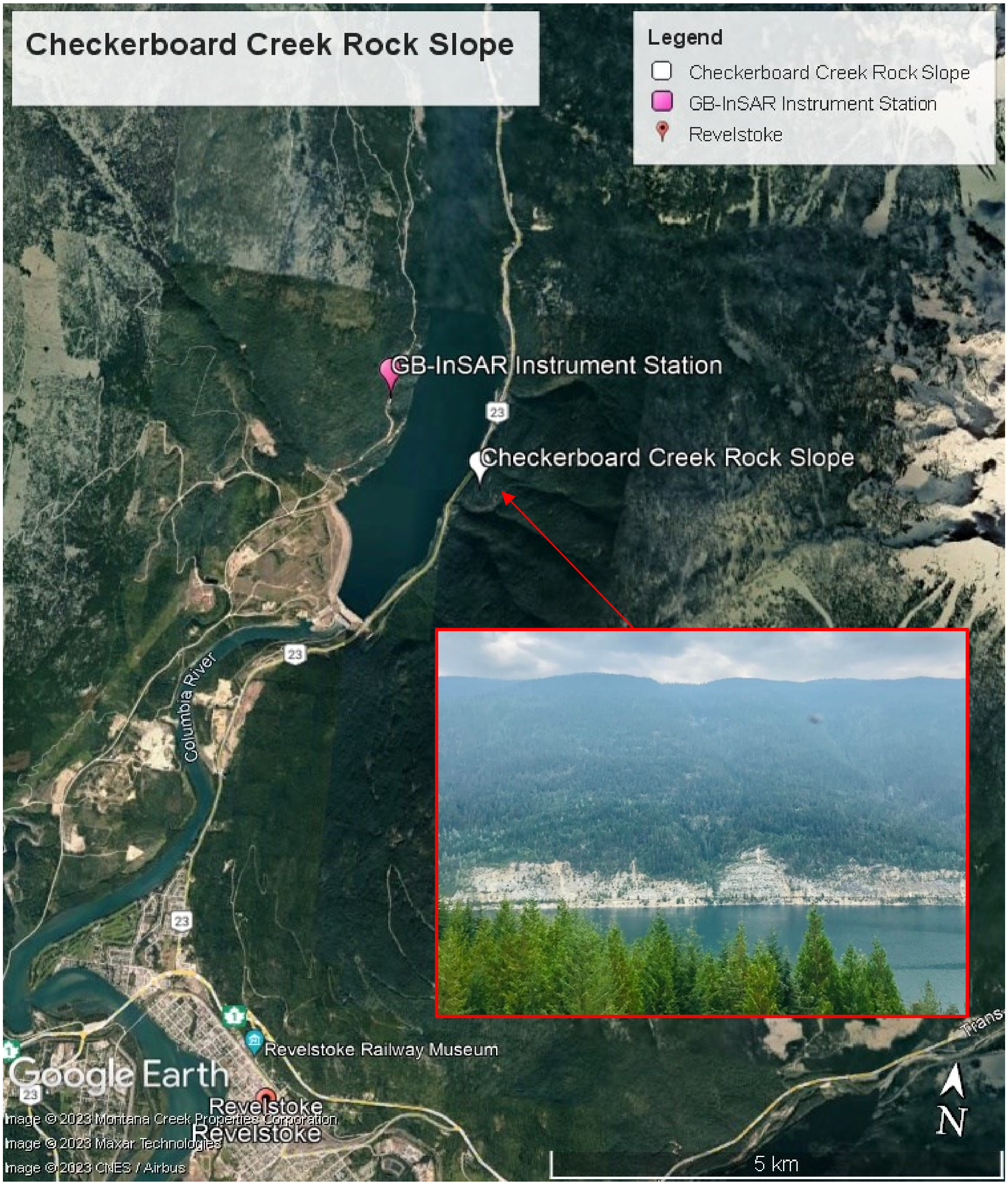


Figure 47: Location of Checkerboard Creek Rock Slope in Revelstoke, BC

The slide is about 600 m wide with a slope angle of 30° on average; it is steeper at the toe of about 45° slope angle and gentler in the upper area of about 25° slope angle. The toe of the slope is at an elevation of 260 m and that of the crest is 590 m at Highway 23 (Macciotta R. and Martin D. 2018, Woods et al. 2019). The quality of rock mass ranges from very strong, fresh, undisturbed, and blocky to highly weathered, altered, weak and disturbed.

Highway 23 is a significant route for Revelstoke, and it is an important economic driver for the region, hence, it can be considered equivalent to a SNH of Bhutan. Given the criticality of the highway and the magnitude of the slope, the rock slope has been assessed as shown in Table 44 for stage 1 of GAM. Since the site is in BC, it is not under the jurisdiction of AT and hence it is not being inspected and assessed using GRMP of AT. Therefore, the risk assessment for both stage 1 and 2 of GAM are based on assumptions and on already existing data of the rock slope. An asset identity of 'CB01' is assigned to the Checkerboard Creek rock slope. The presence of fresh scars on the slope face can indicate minor rock falls, however, there have been no signs of significant rapid mass movements (falls) in the area of the slope based on visual inspections undertaken by many researchers. Since the beginning of monitoring, an average annual displacement rate of 10 mm/year was observed and has remained consistent. Despite the low annual displacement rate, the rock slope asset holds significant value to the highway as well as to BC Hydro; there would be major consequences in terms of safety, mobility and economy should there be a major rockslide at the site. Therefore, a preliminary risk rating of '60 – 80' is assigned to the rock slope which corresponds to 'Poor' performance or condition.

Table 44: Preliminary risk rating of Checkerboard Creek Rock Slope (Stage 1 of GAM)

Asset ID	Type	Route	Type of Road	Preliminary Risk Rating	Performance/ Condition
CB01	Rock Slope	Highway 23	Provincial Highway (BC)	60 – 80	Poor

The Checkerboard Creek rock slope has been categorized into 'Poor' condition; thus, it becomes eligible to be assessed for stage 2 of GAM as shown in Table 45. In accordance with the likelihood of failure factor of rock slope of GAMS, a range of '20 – 40' is assigned to the site, as there is a moderate likelihood of fall occurrence, even though the slope is inactive; the site is further characterized with the presence of geological conditions for failure such as the distinct head scarp and rock discontinuities. Should a major rock fall occur, there will be enormous economic, mobility and safety consequences due to the vicinity of the site to the reservoir of BC Hydro and therefore, the consequence factor of 'E' is assigned to all three aspects. The risk level thus obtained is '20 – 40 E' which corresponds to 'Fair' condition or performance. The treatment recommendation suggested for this level of risk is to 'Do minimum' in the proposed GAMS. Even though the risk of failure of the asset obtained is moderate according to the proposed GAM, the rock slope is being continuously monitored using both conventional and remote sensing technologies taking into consideration the likely consequences in case the asset fails.

Table 45: Risk Assessment of Checkerboard Creek Rock slope for Stage 2 of GAM

Asset ID	Likelihood Factor	Economic Consequence Factor	Mobility Consequence Factor	Safety Consequence	Risk Level	Treatment Recommendations
CB01	20 – 40	E	E	E	20 – 40 E	Do minimum

The following sections describe the application of GB-InSAR at the site for continuous and more accurate monitoring of rock falls:

7.2.3.1 Application of GB-InSAR at Checkerboard Creek Rock Slope

The site was chosen for application of GB-InSAR remote sensing technique because of the following reasons:

- The amount of precipitation and overcast days the site is subjected to.
- The presence of dense vegetation cover.
- Exposure of rock face at the toe of the slide.
- Easy access to the site due to its proximity to Revelstoke town and the dam.

GB-InSAR was installed to obtain further insights into the deformation mechanism of Checkerboard Creek Rockslide, and it involved the following major steps (Macciotta R. and Martin D. 2018, Woods et al. 2019):

- GB-InSAR installation
- Data collection

<u>GB-InSAR installation</u>

A GB-InSAR system (IBIS-L by IDS Georadar) was installed in October 2016 on the opposite side of the Checkerboard Creek Rock slope on the west bank of the Revelstoke Reservoir. The instrument system was protected within a small timber-frame shelter and the instrument has been installed as shown in the figure below. The system has a radar head mounted and travels along a 2-m long linear rail. Figure 48 shows the GB-InSAR components for monitoring of Checkerboard Creek rock slope.

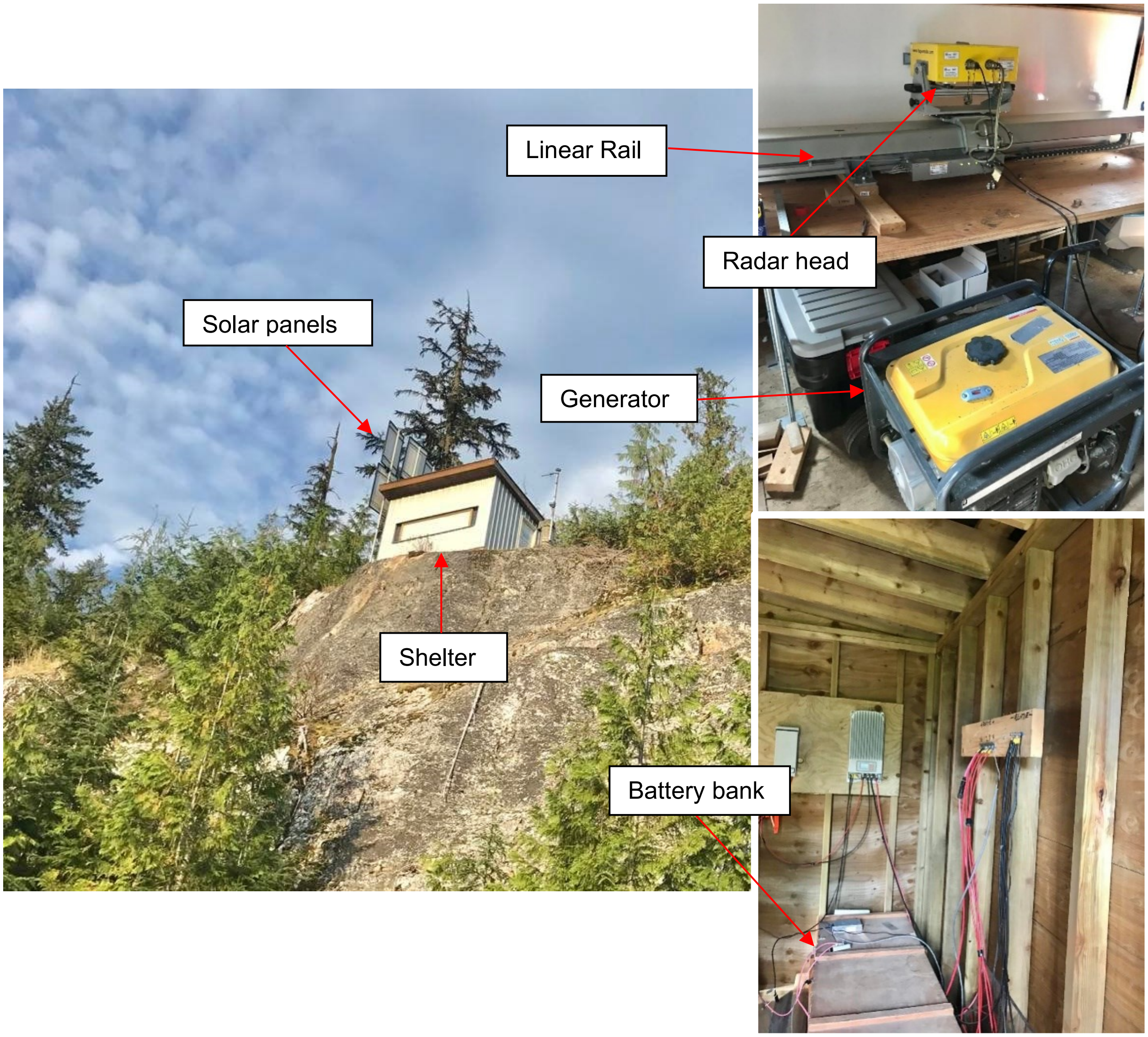


Figure 48: GB-InSAR components for monitoring of Checkerboard Creek Rock Slope

The radar head captures data to obtain 2-D images from the area of interest. The resolution of the image is dependent on the distance between the target and the radar head. The availability of limited sunlight was one of the biggest challenges encountered at the site which led to uncertainty and limited periods of continuous monitoring. Inadequacy of power supply for the system was addressed soon after and it was continuously monitored from March to June 2019 and was made accessible remotely using VPN. The entire installation and establishment of the GB-InSAR system incurred significant costs (Macciotta R. and Hendry M. 2021, Woods et al. 2019).

Data Collection

The data acquisition mode used for the Checkerboard Creek rock slope was discontinuous (D-InSAR) mainly due to restrictions on solar power generation. The monitoring campaigns of 1 to 2 weeks long with an average of 6 images per hour were acquired. The average deformations obtained using the GB-InSAR system agreed with the measurements obtained using in-place instruments and it is as shown in the figure below. In fact, the results from this system facilitated an enhanced understanding of the active portions of the rock slope. An important finding was the presence of a potential unstable block that appeared to be sliding on a ledge dipping 15° to 20° out of the slope with persistent discontinuity. The block did not show increased movement after September 2017 however, it is being continuously monitored (Macciotta R. and Hendry M. 2021, Woods et al. 2019).

Figure 49 shows the outcome of monitoring the Checkerboard Creek rock slope using GB-InSAR.

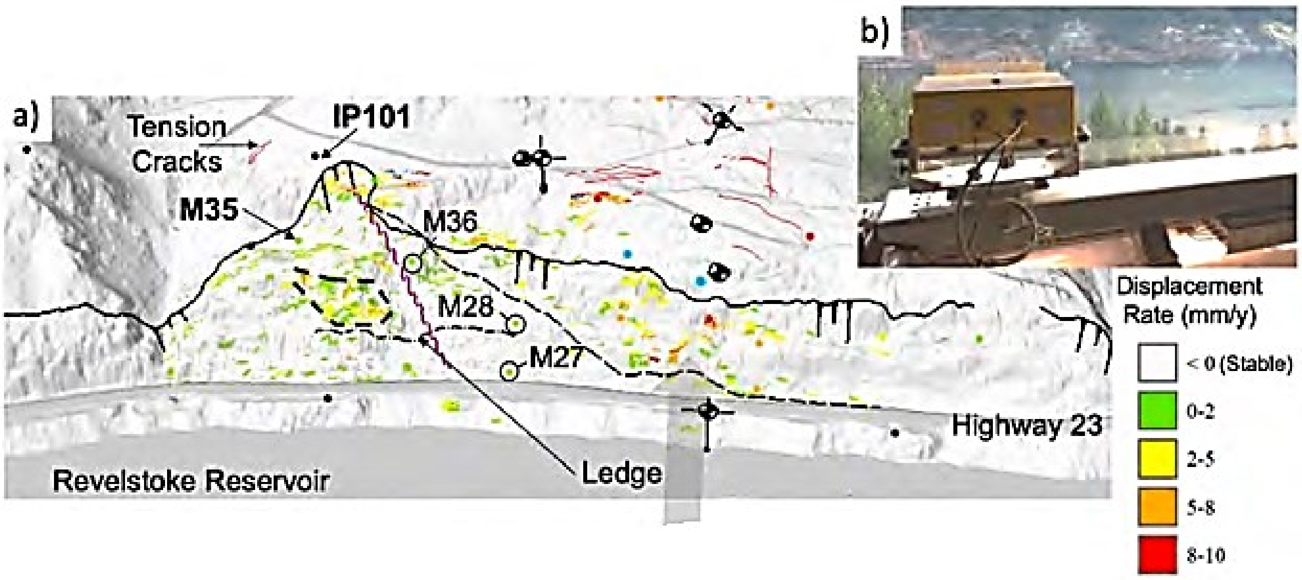


Figure 49: a) The displacement rate in the LOS shown by GB-InSAR at Checkerboard Creek rock slope, solid dark line shows the crest of exposed rock face, and the dashed line shows the boundary of active deformation b) View of radar system facing the slope (Macciotta R. and Hendry M. 2021, Woods et al. 2019 licensed under [CC BY 4.0](CC BY 4.0))

7.2.3.2 Applicability of GB-InSAR to geotechnical assets in Bhutan

For an extensive asset corridor that shows very small displacement rates such as in the order of mm/year, use of general InSAR technology may be the most beneficial due to its high level of accuracy. GB-InSAR is a type of InSAR technology capable of providing continuous monitoring of slopes and identifying areas of potential instability, allowing for early warning, and enabling timely response. It can capture all-day or all-weather images with high spatial resolutions. It can return promising results for rock slope assets with exposed faces in a country like Bhutan if budget allows, as establishment of this equipment and its operation can involve a much higher initial investment. Since it is only able to provide displacement values along LoS, two or more systems might have to be deployed for steep uneven terrain which can further add to the costs of establishment and have the instrument running. Though this technology can effectively monitor the geotechnical assets with increased accuracy of measurements, it might not be preferred over other cost-effective technologies for use as an asset monitoring option in the GAMS, as the DoR will not likely be able to afford it. However, it can always be an alternative monitoring technology for geotechnical assets as the system matures over time.

8. Conclusion

The road network system of Bhutan plays a pivotal role in enhancing the livelihood of its citizens and in all its developmental activities. Being a mountainous and a landlocked nation, roads are used as the primary mode of transportation. Department of Roads, the nodal agency in the country responsible for design, construction, and maintenance of road networks, has been instituted with an objective to achieve the national goal of poverty reduction and economic growth through provision of reliable and resilient road infrastructures. However, the road network of Bhutan remains vulnerable to various kinds of geohazards, most commonly the landslides. DoR has recorded over 300 landslides post monsoon in 2020 alone, having recorded the highest number in a region located in the Southern Foothills, one of the three physiographic regions of Bhutan, which receives the highest amount of rainfall. Such geohazards can potentially lead to loss of human lives and significant economic and financial damages. The study of geohazards in Bhutan has provided a comprehensive understanding of their prevalence, classification, and quantification. It has further provided a clearer picture of how the prevalent geohazards are linked to the three physiographic regions of the country and the direct influence of precipitation on the occurrences of the geohazards. Understanding the prevalence, classification, and quantification of geohazards, further emphasizes the importance of geohazard risk management to ensure safety and well-being of the community.

The review of the existing asset management literature emphasizes the importance of geotechnical assets in a transportation network, assists in developing the taxonomy of geotechnical assets and reinforces the criterions established for the risk assessment of the geotechnical assets. The Road Asset Management System of Bhutan has greatly benefited the DoR in strategic allocation of the limited resources. Since the conception of this system, the DoR could place emphasis on road maintenance projects alongside the construction projects which was otherwise not given the required attention it deserved. Like many other Transportation Asset Management systems around the world, RAMS places more emphasis on the management of road pavements, bridges, and cross drainage structures. Though geotechnical assets play a major role in successful operation of transportation corridors, it is merely highlighted. As the management of geotechnical assets is increasingly seen important, it is about time the DoR equally considers implementing a holistic risk-based Geotechnical Asset Management system that would help the department measure and manage the life-cycle investments at reduced risk to the public as well as to the economy. The GAM framework is thus being proposed to fulfill this objective.

The proposed GAM framework adopts the risk assessment methodology of the existing asset management system as the goal is to have the GAMS as one of the integral components of the RAMS at a later stage. The framework proposed can be a valuable tool that ensures the DoR is able to prioritize geotechnical assets and balance hazard and risk with available resources. The framework can be adopted right away without incurring huge initial investment. Stages 1 and 2 of the GAMS provide a structured and consistent approach in assessing the risks of the assets and prioritizing the assets based on their criticality. The two stages distinctly stipulate the varied steps of data collection that are clear and applicable to the current GAM as well as to its advanced stages in the future. The framework additionally lays out recommendation options against different outcomes of the risk assessment and performance and is supported by simple cost-benefit analysis to facilitate the decision makers toward making informed choices of investment. The framework has been illustrated through case examples from Bhutan and Western Canada to showcase its clarity and applicability.

The framework developed can be customized for use by any other agency at a similar stage of GAM maturity level as the DoR or any agency wanting to start a similar program. The system is flexible so that it can continuously be adapted and enhanced to fit its purposes in an effective and efficient manner. It can be especially beneficial for transportation agencies in developing countries as it has been developed with the following distinct features to reflect resource constraints:

- Cost-effective
- Simple and implementable right away
- Adaptable
- Flexibility as it can customized for use by any agency.

A simple GAMS can help identify cost-effective solutions for addressing geotechnical risks and prioritize maintenance and repair activities based on the available resources especially for developing countries. Such countries have limited access to advanced technology and software tools and hence a simple GAMS can be implemented using readily available and affordable tools.

An important component of the GAMS is to track and monitor the performance of geotechnical assets. Asset monitoring can help identify changes in the condition of the asset, such as surface displacement or settlement or even provide an early warning system for potential problems. These methods may include conventional methods as well as remote sensing techniques. The review of the existing literature on application of remote sensing to geohazards emphasizes the methodology, applicability and the advantages and limitations of some of the emerging remote sensing technologies used in Canada and around the world. The final stage of data collection in the GAMS recommends the use of conventional or remote sensing techniques to closely monitor those assets that have been categorized as the most critical. Stages 1 and 2 of the GAMS applied to the three sites in Western Canada resulted in some assets requiring remote sensing technology for monitoring; it has been supported by presenting the cases of actual applications of some of the state-of-the-art remote sensing technologies at the three sites. Finally, the applicability of those techniques for geotechnical assets in Bhutan have been discussed.

8.1 Future Work

Some of the ways in which the proposed GAMS can be enhanced are as follows:

- One of the distinct features of the proposed GAMS for Bhutan is its ability to be implemented simply by any agency irrespective of their GAM maturity level. However, it is also one of its drawbacks as the risk rating system adopted in the GAMS is based on qualitative and subjective criterion of risk assessments. Future modifications to the proposed system could include detailed rating criteria and scores based on more quantifiable aspects such as the average vehicle risk using the average daily traffic, geologic characteristics of rock and soil slopes, quantity of rockfall per event, rate of displacement in roadway, and more.

- The taxonomy of the proposed GAMS does not emphasize the geotechnical assets located beyond the ROW which includes natural hazard sites, therefore, future modifications to the system should include guidelines of risk assessment and management of those assets.
- Once a complete set of asset condition state data is obtained, specific life-cycle deterioration models for geotechnical assets such as the simple Markov deterioration model developed by Alaska DOT must be adopted to forecast future deteriorations of the assets.
- AT, in their effort to develop a holistic GAM program, are adopting the concept of monetizing the consequences of unsatisfactory performance and expressing losses in terms of financial values. In a similar manner, the DoR, in their effort to shift to a quantitative risk assessment, should base their probability of failure on deterioration models and monetize their consequence factors. In order to monetize the consequences, detailed unit cost analyses must be carried out for different treatment measures.
- As the GAM matures, DoR should explore methods to modernize the data management system from using simple excel to a GIS centric cloud-based platform for improved data collection and management.
- Along with the known risks associated with geotechnical assets, climate change increases the uncertainty with regards to the rates of deterioration of geotechnical assets. Future modifications to the system could include evaluating the risk profile of geotechnical assets taking into account the effects of climate change.

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