Geohazard vulnerability and condition assessment of the Asian highway AH-48 in Bhutan

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ABSTRACT

Transport networks are frequently exposed to geohazards, and losses can be observed frequently by notable disaster incidents such as landslides, earthquakes, and floods. Although losses due to natural disasters are frequently reported, limited attention is paid to assess the condition of strategic road networks in the Himalayas. Thus, to fulfill this gap, this study performs condition assessment of Asian Highway AH-48 in Bhutan and develops a system to rate the performance level of road assets. The assessment is conducted along a 157.6 km stretch of AH-48. The sum of findings highlights that about 55% of the road assets along the AH-48 are highly vulnerable to geohazards. Drains are observed to be the most vulnerable, with 52% drains lying below the standard rating among the considered assets followed by retaining walls and pavement. Landslide vulnerability function for highways that are situated in mountain regions is developed using the newly proposed landslide intensity scale. The sum of findings highlights that the Himalayan roads will be affected mostly by landslides and the drainage system is the most affected road asset showing the least serviceability among the common road assets.

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1. Introduction

Asset management is a systematic process of maintaining, upgrading, and operating assets, combining engineering principles with sound business practice, and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public’s expectations (OECD 2001). The occurrence of geohazards along the road corridor is a serious threat to the
functionality of road condition and can also deprive the quality and timeliness of driving. The impacts of such disaster incidents on roads and bridges range from temporary traffic disruption to major calamities resulting in deaths, long-term loss of access to major economic corridors, interruption in development activities, and direct and indirect economic losses. The occurrence of landslides is governed by several factors, such as tectonic activities, torrential rainfall, anthropogenic activity-based slope destabilization such as infrastructure construction in hill slopes, among others (Gautam 2017; Santo et al. 2018; Forte et al. 2019). The slope along the highway varies between 15° and 75° with the majority of the area having a slope greater than 35%. Roads are not only important paths for development; they are critical to poverty reduction (Choden et al. 2017). Generally, landslides are natural events, it can be instigated by deforestation, unplanned development, and expansion of human settlements and infrastructure development in landslide prone areas. In most of the developing countries, the construction of local roads and highways in mountainous areas are the most important triggering factor for landslides. Such construction can lead to higher rates of erosion and sedimentation. The situation is particularly aggravated when the roads are unpaved. Therefore, construction and maintenance of transport infrastructures must always consider the possibility of landslides and slope failures. Bhutan faces difficult challenges managing landslide risks due to challenging terrain, young geology, steep Himalayan mountains, and annual torrential precipitation. In addition, deteriorations of transport infrastructure are contributed by aging, exposure to weather and traffic, and to the growing maintenance backlog (Marcelino et al. 2018).

The construction of the Thimphu-Phuentsholing Highway started in the early 1960s as the primary national highway (PNH) and was officially inaugurated in 1968 (MOWHS 2017). Later, several road widening and improvement works were carried out assisted by the Border Road Organization (BRO) that became Bhutan’s first Asian Highway connecting Bhutan with India. The road network in Bhutan can be divided into seven categories and the total length of roads in Bhutan is 18,362.69 km. Agricultural roads comprise the majority of the road networks in Bhutan, with 11,353.99 km length accounting for 62% of total road length in the country. This is followed by Dzongkhag Road/Gewog Connectivity roads (district/village roads) with 2115.66 km (12%) of the total road length. The total length of the PNH and Secondary National Highway (SNH) is 1788.18 km (10%) and 1012.72 km (5%), respectively followed by the access road with 1668.86 km (9%) length (MOWHS, Annual Information Bulletin 2019). The road classification refers to Bhutan Road Classification System 2017 (MOWHS 2019). The development of efficient and safe road connectivity is vital to Bhutan’s socio-economic growth, especially in the regional mountainous areas where the movement of the tourists, merchants, and farmers is greatly supported by the road network. The framework for national development activities; Bhutan 2020, Eleventh Five-Year Plan (2013–2018), Road Sector Master Plan (2007–2027), and Bhutan Transport 2040 Integrated Strategic Vision provide the basis for national development goals in the road sector (Tozawa 2015). Given the critical geographic location of Bhutan, serviceability and performance assurance of the transport sector is pivotal not only for daily use but also for
economic activities, search and rescue efforts after natural hazards are converted to disasters. Replacing damaged structures in the aftermath of disasters is often beyond the resources of local governments and are economically and environmentally costly. Although natural disasters are very prominent in Bhutan, very few studies are conducted and particularly along the AH-48. The best examples can be considered the 2009 Mongar and the 2011 Sikkim-Nepal border earthquakes that caused severe loss to the economy of the country. During these earthquakes, numerous rockfalls and landslides along the highway due to earthquake shaking and caused economic losses of around US$52 million and US$24.46 million respectively in the infrastructure sector (Chettri et al. 2021). In conjunction with this, flash floods, stray catchments, and streams along highway corridors have been predominant agents imposing threat to road infrastructures, particularly during monsoon season. Such events occur frequently along Phuentsholing – Thimphu Road section and severely affect transportation sector. Therefore, considering Bhutan’s peculiar vulnerability to disasters, quantification of the level of vulnerability under each level of geophysical disaster is the prime challenge of now. For these reasons, in current research, to lessen the ambiguity resulting from phenomenal causes of landslides, geohazards relating earthquake-induced landslides and stream flash floods along the road corridor are accumulated simply as landslide hazard. To this end, we considered aggregated landslide hazard as the recurrent monsoon phenomenon and the focus is inclined to exposure of the road asset condition and their vulnerability. This study pertains to develop a landslide vulnerability model for road infrastructure using the empirical databases.
from notable historical landslides. Apart from the vulnerability model, landslide vulnerability is hinged with physical parameters, road condition assessment scenario, rating systems, and repair and maintenance scenarios.

2. Geohazards along the Asian highway AH-48

The AH-48 stretches between two major districts connecting the capital city of Bhutan, Thimphu and Phuentsholing, with 174 km in length (MOWHS 2017). The Thimphu-Phuentsholing Highway passes through challenging geographical terrain features ranging from steep to very steep slopes having slope gradient 40°–60° and more than 60° respectively with the altitude ranging between 800 m and 2500 m.
approximately from sea level (Figure 1). The area is sparsely populated mainly due to adverse geographical conditions. The AH-48 passes through some of the major fault lines and critical slopes, for example at Jumja, Sorchen, Kamji, Wangkha, etc. The road connects many pockets of villages together with clustered settlements at various locations and provides access to a number of people in the area.

The Department of Geology and Mines (DGM) is one of the core agencies responsible for maintaining a database on geological characteristics of Bhutan and also on aspects of exploring the issues related to disaster scenarios in the country. Similar studies in some part of the southern Himalayan region exploring the soil and rock strata properties are also reported in (Tempa et al. 2020). As shown in Figure 2 geology of the study area stretches along the Buxa group of Lesser Himalaya towards the Greater Himalayan rocks. In the south, lesser Himalayan rocks are separated from the structurally higher Greater Himalaya by the Main Central Thrust (MCT). The MCT dips to the north and divides the high-grade gneiss of the Higher Himalayan crystalline (HHC) into the hanging wall, from the greenschist metamorphic rocks of the Lesser Himalaya (Kuenza et al. 1994).

The rocks of Phuentsholing formation belonging to Buxa group are exposed quartzite, and greenish-grey, variegated, and carbonaceous phyllite. Carbonaceous phyllite is the dominant type in the area, followed by variegated phyllite and a thin band of grey quartzite that gives rise to reddish-brown togreyish brown residual soil (Department of Geology and Mines 2009; Tempa and Chettri 2021). The southern belt is characterized by deep-seated slides in rocks of moderate to highly weathered phyllite. The areas that are most prone to rainfall-induced slope failures are heavily fractured and weathered rocks of phyllite, slates, and schists that contain high amounts of clay minerals.

Due to highly tectonized fragile sedimentary and low-grade metamorphic formations along with the heavy precipitation cause several slope failures in Phuentsholing–Thimphu highway. The stretch along Phuentsholing to Thimphu is geologically weak, marked by several shear zones as well as weathered and folded phyllite rocks turning into clay (Chettri et al. 2019a, 2019b; Tempa et al. 2021a, 2021b, 2014). Usually, the AH-48 experiences numerous transport disruptions due to rainfall-induced slope failures that trigger major landslides.

A landslide inventory map of the study area indicates that the AH-48 is highly prone to landslides, and the susceptibility is classified as high, especially in Chhukha region usually triggered by heavy monsoon rainfall. This region receives one of the highest rainfalls starting early to the late monsoon of the year. In 2020, the annual cumulative rainfall was 3988.10 mm with the highest in July, amounting to 1620 mm of rainfall (NCHM 2021). Some studies conducted in the Himalayan region including Bhutan demonstrate that most landslide scenarios are induced by rainfall and corresponding threshold (e.g. Regmi et al. 2013; Devkota et al. 2013; Gautam and Dong 2018; Gariano et al. 2019; Dikshit et al. 2019); however, very few studies are conducted to incorporate landslide risk and management (Cheki and Shibayama 2008; Dawson et al. 2018). Globally, the situations are very similar (e.g. Kanungo et al. 2008; Lee et al. 2016; Lazzari and Piccarreta 2018; Xiao et al. 2020; Wang et al. 2020; Thakur et al. 2020; Mallick et al. 2021; Meena et al. 2021). In reality, the exposure
Table 1. Landslide occurrences and impact in AH-48.

| Year | Location(s)                          | Impact                                                                 |
|------|--------------------------------------|------------------------------------------------------------------------|
| 1993 | Chhukha area                         | Two houses in Genju village damaged, killing a 65-year-old woman and a 26-year-old man |
| 2000 | Sorchen, Jumja, Chhukha              | Phuentsholing-Thimphu highway severely disrupted by numerous major landslides. Highways and roads between and within districts are blocked due to landslides, most of the feeder roads were reported as blocked |
| 2002 | Jumga, Shorchen, Phuentsholing       | Road blocked                                                           |
| 2003 | Phuentsholing                         | Road blocked                                                           |
| 2005 | Shorchen, Phuentsholing              | Damaged road infrastructures causing road blockage                     |
| 02/07/2006 | Bemisisi, Thimphu and Chhukha | A total of 7,150.9 square meters of wetland affected by the landslide. |
| 2011 | Chhukha                              | Road blocked                                                           |
| 2012 | Damchu-Chhukha                       | Sequential landslides occurred damaging road infrastructures           |
| 2013 | Phuentsholing-Kharbandi              | Affected nearby settlements, caused cracks in nearby houses            |
| 2013 | Rinchening check post                | Major landslide, affected nearby settlements, caused cracks in nearby houses |
| 2013 | Thimphu-Phuentsholing highway        | Series of slide, affected road networks, blockage, and damaged road infrastructures |
| 2014-2015 | Tsimasham landslide | Affected Thimphu-Phuentsholing Highway                                |
| 2016-2017 | Phuentsholing–Thimphu highway in Chhukha | Road blocked, damages to road infrastructures                      |
| 2018 | Sorchen and Jumja                    | Series of slides, rock fall, bailey bridge totally damaged, road blocked, nearby settlement affected |
| 2018 | Rinchening slide below CST, Phuentsholing | Road blocked                                                   |
| 2019 | Series of slides along Thimphu-Phuentsholing highway | Damages to road infrastructures                                      |
| 2019 | Rinchening slide below CST, Phuentsholing | Road blocked                                                   |
| 2019 | Sorchen, Kamji and Jumja and other segments of Thimphu-Phuentsholing highway | Series of slides. Damages to road infrastructures, road blocked |
| 2020 | Kamji, Takikoti and Wangkha area     | Road blocked                                                           |

The level of the AH-48 assets is highly vulnerable due to recurrent landslide phenomenon that cause continuous damage to the structures of the highway. The landslide inventory reproduced from the report prepared by the Royal Government of Bhutan is exclusively referred to identify the past landslides scenario and their damageability scenario. The inventory comprises landslides documentation between 1993 and 2020, as shown in Table 1. The amount loss encompasses losses due to damage to the transport infrastructures.

The landslide rating on the map was prepared qualitatively based on the history, magnitude or intensity, and frequency of occurrence in particular locations. Chhukha district observes a greater number of landslide events than any other district. The AH-48 caters to 19 local regions in Thimphu and Chhukha districts, which has a population of approximately 80,000 (~12% of the total population of Bhutan) and 6000 households in total. The services rendered by these pools of population are often associated with the degradation of the condition of road assets. The AH-48 is characterized by 19 historical landslides that affect the service condition of the road assets every monsoon (June to September). The slope and proximity of geologically fragile
areas characterize frequent landslide scenarios that damage road infrastructures, nearby settlements, and also disrupt mobility from hours to the extent of months. A study in 2018 figures out that 269 landslides had occurred between 1998 and 2015 along the 90 km highway stretch between Phuentsholing and Chhukha (Gariano et al. 2019). Often, these statistics are not conscientiously available in finer details from the relevant organization. This is mainly because several minor slides and rockfall are never documented.

Active earth slopes and major landslides were mapped in the current study, which endangers the road assets. Active slopes indicate both earth and rock slopes that are active during the time of survey, including the historical landslides, and are perceived to cause threat to the road asset in the future as well. These slopes extend between

Figure 3. Active slopes and historical landslide inventory plotted together with settlements and population distribution along the AH-48.
200 and 400 m in length along the highway. Chhukha has all active slopes and those are characterized as major landslides. The proximity and association of population and settlement distribution to active slopes, and the historical landslide inventory of the study area are presented in Figure 3.

3. Materials and method

To assess the geohazard vulnerability along the AH-48, field data was collected through a video-based survey with the Global Positioning System (GPS). The instrumentation setup is simple and capable of recording geographical coordinates and altitudes that can provide moving distance with video runtime. These data are exported and further visually investigated based on the point of location, media runtime, and corresponding chainage. Hence, the length of pavement, retaining walls, safety barriers, drains, and number of the cross-drainage systems, and bridges can be obtained. This method is suitable and is found applicable in terms of economy, as data collection in the pavement management process is one of the expensive activities (Marcelino et al. 2018). A part of the database for the AH-48 was used for the current study to evaluate and assess the condition of each road asset. The condition assessment was carried out in segmented zones corresponding to strategic locations or towns, i.e., Thimphu-Chuzom-Damchu-Chapcha-Jumja-Phuentsholing chainage. This allows relevant stakeholders, the department of roads (DOR) to comprehend the condition of each asset to make an informed decision on infrastructure development and maintenance planning from both short and long-term perspectives. Currently, there is a limited tally of these road asset conditions in Bhutan.

3.1. Field survey

Condition of road assets along the AH-48 was obtained using video recordings (see e.g., Figure 4). Such a method of image and video-based framework has achieved more than 85% recall and is suggested as an applicable, reliable, and accurate to localize technique for pavement condition (Jog et al. 2011). The field video recordings were visually investigated for each road asset and populated in a database indicating
details such as location, altitude, chainage, conditions, and physical parameters of each asset.

3.2. Asset attributes

Pavements in Bhutan are characterized by narrow carriageway, basically with 3.5 m pavement width. In the last decade, the majority of stretches along AH-48 were improved by reconstructing the road to road widening projects and currently the AH-48 comprises double lanes in most sections such as Thimphu to Damchu, Chhukha to Gedu, and Gedu to Phuentsholing segment. Commonly, pavement distresses such as longitudinal and transverse cracks, potholes, peeling off wearing surface, degradation of subgrade strength are observed. Random rubble masonry (RRM) walls dominate the retaining structures along the AH-48 with a few gabion walls. Reinforced concrete (RC) walls exist only in a few pocketed areas. The RRM walls are widely used in mountain roads due to the fact that it can be constructed rapidly, have an ability to retain the slopes under gravity and are cost-effective for new construction if immediate replacement is needed when slope failure occurs.

Road signals and road markings used in the study area are in accordance with the Bhutan Standard Road Safety Signs and Symbols 2017 (Ministry of Works and Transport 1997). Commonly, road signs and symbols are located at intersections, junctions, and curves. The signs are assigned to alignment, width, warning, obstacles, hazard, advance direction, reassurance, services, informatory, overhead signs, and kilometer post (milestones). Pavement or road marking, and longitudinal center lines are also supplemented to guide and control vehicles and pedestrians. Road signs or symbols, road delineators, and markings are considered essential communication strategies to prevent road disasters. This not only contributed to comfort driving but also substantially enhanced the overall safety. Road safety barriers are perceived as guiding structures for the users and practically play an important role in preventing vehicles from running off the roadway (Ministry of Works and Transport 1997).

Similarly, road safety barriers not only serve as a barrier to road accidents but also greatly help in lowering the severity of accidents (Butans et al. 2015). Often, it is a priority concern in terms of public health, which may result due to traffic accident injuries and road crashes, which are the major causes of loss of life every year. Safety barrier can be found in different forms such as drum, concrete, and steel barriers. Steel barriers are commonly employed along the AH-48, so their condition was assessed in this study.

The performance and durability of pavement largely depend on the drainage system and its condition. Drainage is considered as the main factor in road design, construction, and maintenance to provide long-term serviceability (Warati and Demissie 2015). Drainage is designed to protect from flooding and is required to function at the designed peak discharge within the particular catchment area. Inadequate or poor drainage system leads to seepage from adjacent hill slope, wearing and tearing of the pavement surface, percolation of water through pavement surfaces, among others. So, the base and sub-base components of the pavement become soft and susceptible to
overall pavement damage and distress. The pictorial representation of road assets along the AH-48 is shown in Figure 5.

The annotations used in the database are presented in Table 2. The database used by the DOR is grouped into three asset categories as Road (R), Earthworks (E), and Drainages (D), and each category was described by two sub-attributes comprising general data and operation. In the road category, under the general dataset, the database houses road name, type, rank, material type, longitude, latitude, altitude, and media time. Similarly, under operation, the dataset comprises road conditions, damages by flood and landslide, crash barriers, and road signals. General data for the earthworks category indicates types, position, material, width, and height and in
operation, the condition of the earthwork is indicated. In the drainage category, the information is defined by types, position, material, and date of construction under general data and condition under operation. Type of roads, bridges, materials, earthwork, drainage, and physical dimension range were predefined in the library and were assigned during the data management phase.

3.3. Data population

The actual process of data population includes extraction of GPS data from media clips using Contour Storyteller software (https://store.contour.com/). The coordinates were further converted to UTMlong and UTMlat format. The UTM coordinates, UTMalt, and media runtime were transferred to the data population sheet in excel format and the corresponding KmPoint were generated. The road assets were then entered from the video in the datasheet with reference to the media time and the road asset database was created. These data were validated by carrying out ground-truthing for a randomly selected stretch of highway to validate physical parameters. The populated datasheet represents the physical existence of particular road assets along the AH-48. The asset location was well defined by the GPS coordinates and distance from the chainage point (KmPoint). The process of ground-truthing supplements the accuracy of assets presented in the field. The data population process is shown in Figure 6. Such a method of landslide data collection is efficient to cover the large length of the road network and is user-friendly; similar to CitSci app used by some researchers nowadays (Kocaman and Gokceoglu 2019). Common road assets encountered are breast walls, retaining walls, cross drainage, drains, road signals, and safety barriers. The datasheet also represents the critical slope or landslide locations.

3.4. Ground-truthing

Ground-truthing plays important role in validating the asset attributes that represent the real-time scenario. Validation was carried out to check the physical characteristics

| Type of assets | General data | Operation |
|----------------|--------------|-----------|
| Roads (R)      | RName, RType of Road, RRank, RMaterial, RLongitude, RLatitude, RAltitude, RMovie time | Condition, RCondition, Rdamagesflood, Rdamageslandslide, RCrash barrier, RRoad signal | |
| Earthworks (E) | E1, E2, E3, EType, EPosition, EMaterial, EW1, EW2, EW3, EHeight, EType, EM1, EM2, EM3 | Condition, EC1, EC2, EC3 |
| Drainages (D)  | Dtype, DPosition, DMaterial, DYear construct | Condition, DCondition |
of the road assets, such as the width of the pavement, dimensions of the retaining structures, condition verification, and length of the barriers and walls (Figure 6). Validation was carried at Chuzom-Damchu and two stretches at Chapcha-Jumja segment. Ground-truthing for risk assessment was also carried out at various locations prone to landslide and flood, for e.g., Sorchen, Kamji, Jumja, and Wangkha in Chhukha region. The ground-truthing indicated acceptance of the data populated through video recording in terms of attributes of field measurements with an accuracy more than of 80 to 90%. The accuracy was checked based on the comparison between measured data at the site, such as height, width, and length of the assets to the data populated in the database. For example, in ground-truthing, dimensions of road pavement, retaining walls and drains are easily accessible, which make verifications feasible. However, some discrepancies still exist, such as the height of the walls at steep slopes (rock or cliff) below the roads was often higher compared to visual approximation. Such realization was considered by re-visiting the video records and site condition. Similarly, observations were made in a few pocketed areas in which old retaining walls were often buried that may not have been accounted for in the database.

3.5. Asset condition rating

The ranking system of rating was used to define the condition of the assets. Type of roads, bridges, materials, earthwork, drainage, and physical dimension range were defined in the library and assigned during data population. The ranking class refers to a qualitative evaluation of road asset conditions usually divided into five classes that are used in developing countries by the World Bank group owing to its
economic benefit as well as its efficiency in rapid data collection ability. The ranking system is classified to define the condition of the assets as A: good, B: satisfactory, C: fair, D: poor, and E: very poor. In recent years, this system has been initiated with technical assistance (TA) from the World Bank group in Bhutan and has been implemented for road asset management system by the Department of Roads, DOR (www.mowhs.gov.bt) and is presented in Table 3.

Furthermore, the repair requirement index (RRI) was also evaluated for the entire pavement in the AH-48. The RRI is primarily computed to evaluate the severity and to identify the locations that require repair and maintenance. Based on the pavement inspection guideline (JICA 2016), the RRI was evaluated for the segmented length of AH-48 to indicate the requirements for repair, pavement condition, surface condition, driving condition, and method of repair per Table 3. The RRI is related to surface smoothness expressed in terms of international roughness index (IRI) and structural condition expressed in crack rate coefficient and pothole rank coefficient, as shown in Equation 1.

### Table 3. Condition rating system for road assets.

| Rating | Condition | Pavement | Retaining structures | Barriers/signals | Drains |
|--------|-----------|----------|----------------------|-----------------|--------|
| A Good | Smooth surfaces, no physical distress, structurally sound, repair and maintenance are not required | Structurally sound | Well intact in position, rigid | Structurally sound and fully functional |
| B Satisfactory | Smooth surfaces, minor physical distress, structurally sound, minor maintenance required | Structurally sound | Rigid and in position, minor displacement in alignment | Functional but minor physical deteriorations |
| C Fair | Moderately rough surfaces, noticeable physical distress such as cracks, potholes, surface discontinuity, sub-base exposed partially, repair and maintenance are required frequently | Minor damage, bulging, failure in some parts | Displaced from original position | Functional but minor physical deteriorations and structural components |
| D Poor | Rough surfaces, large cracks and potholes, partial structural failures, surface discontinuity and discomfort, sub-base fully exposed and major maintenance or restoration are required | Structurally unstable and not functional | Structurally distorted due to external forces | Completely damaged, not functional |
| E Very poor | Structural failure due to excessive service load or external calamities, complete restoration is required | Completely damaged due to external forces | Completely damaged | Structural components do not exist |
where IRI is the international roughness index that ranges between 1 to 20, $\alpha$ is the crack rate coefficient, and $\beta$ is the pothole rank coefficient. The details of RRI and schedule of crack rate coefficient are presented in Tables 4–6.

4. Results and discussions

4.1. Pavement

AH-48 pavement is composed of dense bituminous macadam (DBM) and asphalt concrete (AC) layers. The road condition along the AH-48 was first assessed and categorized using the rating system implemented by the DOR in four different segmented zones of the study area, covering a total road length of 157.60 km. The results provide primary condition information under each rating system to the corresponding segmented length in a particular region. The study area shows pavement segmented distribution as Thimphu-Damchu segment (31.75 km), Damchu-Chapcha (10.73 km), Chapcha-Jumja (76.33 km), Jumja-Phuentsholing (38.79 km). It is obtained that condition B was the most prevalent scenario with 45.94% with the results showing 19.73% of road is in conditions C and D that need immediate attention especially in terms of repair and maintenance (Figure 7(a)).

The RRI value calculated using the road surface smoothness, crack rate, and pothole rank yielded a value that falls within the rating criteria adopted by the DOR. A summary of the pavement condition evaluation matrix applying both the rating systems is presented in Table 7 for the AH-48. In few stretches, pavement condition category C exhibited bad surface leading to a moderate driving condition that was contributed by higher crack rate (50–70%) in pocketed areas between Chapcha-Jumja segment. The RRI results show that around 31.09 km road is near the end of service life and needs routine repair immediately. The pavement in conditions A and B having the RRI between 0–7 are within the service life. However, minor crack and pothole sealing (patchworks approximating up to 2 m²) in road condition category A and B are also found, which led to RRI between 5–7; however, the overall condition remains unaltered. In some locations, pavement condition C is observed to have noticeable potholes (surface area between 0.4–0.6 m²) in some stretches, which resulted in the RRI value of 10–12. The road condition category D that has the RRI
between 10–12 is out of condition, which is validated at the critical landslide locations. Hence, the road segment falling in this category was washed away without any pavement components. Pavement in condition E is usually damaged due to extreme events of rainfall-induced landslide or flood or due to excessive service disorder and this category is incorporated within condition D.

4.2. Road signs and symbols

The AH-48 is assigned with a total of 363 road signals at various strategic locations, as shown in Figure 7(b). Landslide area, sharp curves, chainage points, and rockfall area are prominent locations for road signals. Condition of these road signals depicts that 278 in signals were in condition category A, 60 were in B, 18 were in C, and seven were in D. The majority of road signals exist between Chapcha and Jumja segmented zone and were in fairly good condition.

4.3. Safety barrier

In general, the steel crash barrier has performed well. Barriers were mostly damaged due to collisions at the time of accidents, landslides, and floods that deteriorate the overall functionality due to damage in the structural system. The current study indicates the existence of 30.64 km of steel barriers (Figure 7(c)), approximately 20% of the total road length. Steel crash barrier consists of 28.44 km under condition A, which is 18.05% of the total road length.

4.4. Drains, culverts, and bridges

L and V-shaped and box drains were commonly found along the AH-48. The majority of drain types were V or L-drains with a total 97.07 km length (61.80% of the total road length). About 5.44 km (3.45% of the total road length) was found to be provided with box drains and the rest of the sections were having natural drains (34.75% of total road length). The majority of the drain conditions fall in the B and C category for the Chapcha to Jumja section with 21.44 and 20.64 km lengths of each category respectively. Also indicating 9.72 km of condition B in Thimphu to Chuzom

| Table 5. Schedule for crack rate coefficient. |
|---------------------------------------------|
| Pothole rank | Condition | Criteria | α     |
|--------|-----------|----------|--------|
| A      | No pothole| No pothole neither no repair patching| 1.0    |
| B      | Few potholes| 1–5 potholes or patching per 100 m| 1.0    |
| C      | Several potholes| 5–20 potholes or patching per 100 m| 1.1    |
| D      | Many potholes| More than 20 potholes or patching per 100 m| 1.2    |

| Table 6. Schedule for Pothole rank coefficient. |
|-----------------------------------------------|
| Crack rate (%) | Typical condition | β     |
|----------------|-------------------|------|
| 0–30           | New pavement      | 1.0  |
| 30–50          | Partial crack (longitudinal or transverse cracks) | 1.0  |
| 50–70          | Jointed partial crack (longitudinal and transverse crack joins and covers whole surface) | 1.1  |
| 70–100         | Dense alligator cracks | 1.2  |
and 13.78 km in condition C in Jumja to Phuentsholing segment, respectively. Drains having condition D were found significantly in Jumja to Phuentsholing and Chuzom to Chapcha, with at least 5.43 and 1.25 km, respectively that was completely damaged.

Figure 7. Spatial distribution of road assets and conditions in AH-48.
and out of service. The overall condition of drainage system was rated poor indicating immediate attention for repair and maintenance. Figure 7(d) represents the spatial distribution of the drain and the corresponding condition. The AH-48 consists of 364 cross drainage structures (culverts) and five bridges with two causeways in Chhukha area. All the cross drainage and bridges were in condition A.

### 4.5. Retaining walls

The condition evaluation of retaining walls was carried out in four segmented zones which show most of the retaining structures along the AH-48 to be random rubble masonry (RRM) walls with varying height up to 8 m as shown in Figure 8. The total length of the RRM wall as per the investigation was 54.50 km, which is 34.58% of the total road length of the entire road corridor. Gabion walls were found in small stretches that consist of 0.363 km in total length. Thimphu to Damchu possesses the greatest length of retaining wall in condition B, i.e., 19.047 km among 31.75 km total road length. Damchu to Chapcha (10.73 km) segment consists of 3.542 km retaining walls with most of the section under A condition. The average condition of the retaining walls is satisfactory in these two segments. Approximately 22 km length of retaining walls exists between Chapcha to Jumja in which the majority of the section falls under B condition followed by C and D conditions. The Jumja to Phuentsholing segment indicates a majority of the retaining wall in conditions B and C. The total length of retaining walls is 9 km in this section. The average condition of retaining walls in this segment can be rated as fair.

Figure 9 presents the overall condition rating of all assets in the AH-48. The results indicate that road assets, such as pavement, retaining walls, and drains suffer more compared to road signals and steel barriers. The condition corresponds to B, C, and D, with the majority of conditions clustered to B and C. At least 66% of pavement, 88% of retaining walls, and 52% of drains need attention for repair and maintenance. Only about 7% of steel barriers and 23% of road signals fall into this category. Figure 9 shows that 55% of the overall asset condition was found to be needing immediate attention, while 45% were performing well.

### 4.6. Vulnerability function

Based on the historical damageability, a suitable scale is assigned from 1 to 10 in the order of least damage to the maximum, respectively. The landslide events of the last 27 years indicate that a relatively lesser number of landslides of severe damageability occurred within this period. The damageability scenario leading to casualties and total collapse of infrastructures is assigned with intensity 10. The plot depicts that such a
scenario is very rarely experienced in the last 27 years. On the contrary, the minor slides capable enough to cause traffic disruptions and local hazards were frequently felt across the highway over time.

Ground-truthing and physical verification of highway assets such as pavement, retaining wall, bridges, culverts, and drains collected sufficient features to quantify the losses due to landslide hazards. The damage to the road assets was estimated using the Bhutan Schedule of Rates (Department of Engineering Services 2020). The results were also validated with the data from the DOR and Border Road Organization (BRO). Historical damages were converted to damageability, losses, and landslide scenarios. The damage analysis and cost categorization provide an approximate loss, as depicted in Table 8, and are used to develop the landslide vulnerability curve for transport infrastructures. The vulnerability function depicts the susceptibility of particular or more damage when exposed to the level of intensity measures, landslide intensity in this case. A logit function was fitted between the newly proposed landslide intensity scale and total economic loss, as shown in Figure 10. To fit the logit function, we collected average damage to each landslide intensity first. Thereafter, the vulnerability function was plotted considering landslide intensity as the intensity measure and economic loss. It is pertinent to note that a system level vulnerability function is constructed in this study. Although landslide vulnerability functions are rare worldwide, we deployed the data available in Bhutan to construct one, which could be insightful to other Asian Highways especially passing through mountainous terrains. The worst-case scenario (intensity 8) corresponds to extensive damages such as total damage of pavement, bridges, loss of lives, and other infrastructures. In this case, the contribution of the capital loss is very high although the frequency of such events is relatively low. Landslides of average intensity (6+) have a

Figure 8. Condition of retaining walls corresponding to different heights in AH-48.
capacity to cause the total loss of US$50,000 (1 US$ = 72.5 BTN, Bhutanese currency) or more. In unstable regions, loss of ~US$20,000 is expected annually due to minor landslides (intensity <4).

Figure 9. Condition rating of all the road assets and overall condition rating in AH-48: (a) pavement condition, (b) Retaining wall condition, (c) road signal condition, (d) safety barrier condition, (e) drainage condition, (f) overall asset condition rating in AH-48.
4.7. Geohazard risk assessment

Some of the fundamental aspects from ISO/IEC 27005, International Standard on Information Security and Risk Management (ISO/IEC 2018), and ISO 31000 Risk Management Guidelines (ISO 2018) were considered interlinking the data obtained from condition assessment to risk assessment. The ISO/IEC 27005 defines risk as follows:

\[
\text{Risk} = \text{Asset value (AV)} \times \text{Threat value (TV)} \times \text{Vulnerability value (VV)} \tag{2}
\]

Asset value (AV) refers to the capital status of the existing infrastructures. Initial road asset condition assessment provides the quantity of each asset under corresponding condition rating. Overall, the AH-48 consists of 157.60 km road pavement,
54.50 km retaining walls, 363 road signals, 30.64 km length of side drains, and 364 culverts. The capital value of each asset in segmented zones was obtained using the Bhutan Schedule of Rates (Department of Engineering Services, Bhutan Schedule of Rates (Civil) 2020). The evaluation of asset value excludes the capital status of five bridges along the AH-48. The capital values of corresponding sections were then correlated to the suitable scale of AV grade and rating according to the ISO/IGE 27005 and ISO 31000, as shown in Table 9. The segmented study area was rated on the scale of AV grade 1 to 4 that defines: 1: low, 2: medium, 3: high, and 4: critical corresponding to the evaluated asset conditions D and E, C, B, and A, respectively. The maximum grade value from all the asset types in particular section was taken as the AV grade and subsequent AV ratings are assigned. The consideration of a higher value of AV grade is to maintain unbiased judgment and avoid under-estimation of the particular AV, especially when a large quantity of assets is to be assessed. These AV ratings indicate the severity of loss due to damage with grade 1 as the lowest loss and grade 4 as the highest loss. As per this rating system, assets in Thimphu-Damchu and Chapcha-Jumja segments will observe the highest damage loss due to geohazards which reveal critical AV ratings while Damchu-Chapcha and Jumja-Phuentsholing segments would be subjected to lesser loss with high AV ratings when compared. This conceptual framework is valid as infrastructures along the Thimphu-Damchu segment are newly constructed and geohazard susceptibility is comparatively low in Thimphu region, but the impending geohazards are likely to cause higher losses and therefore have the highest AV grade and rating. Similar arguments can be applied to Chapcha-Jumja, which is the longest segment having the highest number of assets. On the contrary, Damchu-Chapcha, which is the shortest segment among others, and Jumja-Phuentsholing segments still demonstrate high AV
grade and ratings since the latter is located along the fault lines and massive slope failures can be observed annually.

Road assets are exposed to numerous threats during their service life. For the current study, the inclusive action of likelihood or frequency of hazard and impact is considered as the governing parameter to represent a threat. Landslide inventory and damageability loss plot are extensively used to interject these two parameters that influence threat. The TV and corresponding ratings are presented in Table 10. For example, the study zone comprising Jumja–Phuentsholing segment experiences frequent landslides along the fringe of unstable Buxa formation, thus the rating is assigned as critical with the threat value 4. On the contrary, Thimphu-Damchu experiences less slope movement and as a result placed under a medium rating with the threat value 2. However, the intensity of impact would be high due to the presence of newly constructed infrastructures. The maximum value of likelihood of landslide occurrence or intensity of impact, whichever is higher, is accounted as the influencing parameter and is considered as the TV.

The landslide inventory clearly indicates that landslide activities are evident along the highway under investigation. The segmented zone from Chapcha-Jumja-Phuentsholing is observed to have a greater number of active slopes or landslides compared to any other segment. This segment thus has a higher score in terms of vulnerability. The maximum value of hazard and infrastructure presence provides the VV. The vulnerability score is shown in Table 11.

The product of AV, TV, and VV depicts the measure of risk (MOR) as highlighted by Equation 1. The qualitative scoring system indicates that the MOR values 1–12, 13–24, 25–36, and greater than 36, respectively represent low, medium, high, and critical scenarios. The results obtained thus accentuate the physical damage to the assets exacerbated by the recurrent hazards. It can be concluded that the technique is simple and can be suitably implemented for other locations in Bhutan or similar highway segments.

The results shown in Table 12 provide the basic insight into the measure of risk without considering the effectiveness of the control measures. To account for the significance of the control measures, we explored the risk reduction scheme along the study area under suitable consideration of effectiveness of the control measures and mitigation, such as providing better retaining walls and drainage and other slope failure control mechanisms. In Table 13, we provide effectiveness factors that can assist decision-makers and relevant stakeholders to comprehend and implement the risk management plans. The idea of the effectiveness of control measures attributed mainly to the natural hazards such as landslides and floods or flash floods induced by heavy rainfall events, geology of the area (topography, slope, aspect, and vegetation), and other related factors are considered in this study. Through the segmented

| Zone                     | Pavement | Retaining wall | Barrier/Signals | Drains/culverts | AV grade | AV rating |
|--------------------------|----------|----------------|-----------------|-----------------|-----------|-----------|
| Thimphu-Damchu           | 4        | 4              | 4               | 3               | 4         | Critical  |
| Damchu-Chapcha           | 2        | 2              | 3               | 3               | 3         | High      |
| Chapcha-Jumja            | 4        | 3              | 3               | 3               | 4         | Critical  |
| Jumja-Phuentsholing      | 2        | 3              | 3               | 2               | 3         | High      |
videographic investigation in each zone of the AH-48 corridor and ground-truthing process, the rating of the effectiveness of control measures was deduced. The personal communication with officials from DOR and BRO substantiated this effort, which allowed validation of the results by cross-checking the control measures being practiced. Some of the highlights to control effectiveness rating indicate placement of the retaining walls in the superfluous stretch. The issues such as unfitting retaining structures are very common in certain stretches e.g., in Damchu-Jumja segment, several stretches of stone masonry walls exist but are inefficient. Their performance can be increased by replacement with reinforced concrete walls. In Table 13, control effectiveness indexes 1, 1.5, 2, and 3, respectively indicate ineffective, partially effective, limited, and matured.

The comparative plots of asset risk integrated with influential hazards in each segmented zone are shown in Figure 11. The measure of the risk of a consolidated asset is segregated without the control, with existing control, and with planned control schemes. The range of values to depict the efficacies of the level of control are based on a year of record after the control measures were instigated in situ. Based on the field evaluation of the performance and reduction of the failures, the points for different performance levels were assigned. For the planned perspective, the same factor as used in the existing control was enabled to check the decrease in the risk under appropriate planning and implementation. The MOR of Thimphu-Damchu segment without control indicates critical (36) risk to the asset, whereas in the case of the suitable existing control being in proper implementation, the MOR drops to low (12). The controls are more effective for this segment as it is situated along the stable region. Hence, with control effectiveness factor 3, the risk is further reduced if planned control is enabled in the future. On the contrary, the segment along Jumja-Phuentsholing denotes no reduction in the MOR as the zone is predominantly susceptible to high-frequency landslides every year.

5. Conclusions

The AH-48 is one of the most critical lifelines in Bhutan, as it is the only Asian Highway that extends north to south in Bhutan. However, geohazard risks along the highway were seldom quantified, and thus the geohazard events that occurred in the past disrupted the operation of the highway for a considerable time. Aiming to quantify the scenarios of geohazard risks integrated with condition assessment along with four segments of the highway, we developed a condition rating system, implemented the same, and depicted landslide vulnerability of the transport network. Based on field investigation, ground-truthing, videographic records, and historical reviews, we assigned a rating to each asset and found that the performance of road assets will be

| Zone                  | Likelihood | Impact  | TV  | TV rating |
|-----------------------|------------|---------|-----|-----------|
| Thimphu-Damchu        | 1          | Low     | 3   | High      |
| Damchu-Chapcha        | 1          | Low     | 2   | Medium    |
| Chapcha-Jumja         | 3          | High    | 3   | High      |
| Jumja-Phuentsholing   | 4          | Critical| 2   | Medium    |

Table 10. Asset threat value and ratings.
gravely affected by the occurrence of landslides or other types of mass movements. This study sets out to optimize the condition assessment system and incorporate the same in geohazard risk assessment. Thus, the findings of the study will be helpful, especially in geohazard planning across mountainous terrains where landslide is the major geohazard that causes annual disruptions and loss of functionality. Approximately 55% of the road assets along the AH-48 are highly vulnerable to geo-hazards, which require urgent attention. Drains reflect the poorest performance

| Zone                      | Hazard (as per past disaster assessment) | Capital value of infrastructure | VV | Rating |
|---------------------------|-----------------------------------------|---------------------------------|----|--------|
| Thimphu-Damchu            | 2                                        | Medium                          | 3  | High   |
| Damchu-Chapcha            | 2                                        | Medium                          | 2  | Medium |
| Chapcha-Jumja             | 3                                        | High                            | 3  | High   |
| Jumja-Phuentsholing       | 4                                        | Critical                        | 3  | Critical |

Table 11. Vulnerability rating of asset in different zones.

| Zone                      | Asset value | Threat value | Vulnerability value | Measure of risk |
|---------------------------|-------------|--------------|---------------------|-----------------|
| Thimphu-Damchu            | 4           | 3            | 3                   | 36              |
| Damchu-Chapcha            | 3           | 2            | 2                   | 12              |
| Chapcha-Jumja             | 4           | 3            | 3                   | 36              |
| Jumja-Phuentsholing       | 3           | 4            | 4                   | 48              |

Table 12. Measure of risk for asset in different segmented zones.

Table 13. Measure of risk with control measures and insights for risk management.

Figure 11. Measure of risk (MOR) under control measure schemes.
among the considered assets, followed by retaining walls and pavement. The condition of safety barriers, road signals, and cross drainage systems is found to be satisfactory. The landslide vulnerability function developed in this study highlights that significant landslides will cause enormous losses to road networks, although the frequency of such a high intensity landslides is low even in the Himalayan region. Although this comprises field verifications and field investigations, quantitative assessments of geohazards and their associated impacts will further enhance the understanding regarding geohazard risk of road networks. Future studies can incorporate quantitative assessment of multiple hazards to depict the independent as well as cascaded scenarios to effectively assign the overall risk level.

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Data availability statement
All data used in this study are reported in the paper.

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