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Investigating probable causes for predicting catastrophic landslides along NH-60 excavated through semi-arid basaltic terrain of Chandanapuri Ghat, Maharashtra, India

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Abstract

Road Cut Slope Catastrophe (RCSC) is a recent menace threatening vehicular traffic and commuter safety in hilly tracts. Reduction of risk along Road Cut Hill Slope (RCHS) needs to be tackled on priority. National Highway (NH) 60 (formerly NH-50) situated in semi-arid basaltic tract within Chandanapuri Ghat (hill) in Maharashtra is being expanded to enhance economic activity in the allied region. To predict RCSC or landslide activity across the Ghat stretch, eleven ($n = 11$) road cut slopes were investigated by collecting data regarding (1) slope, (2) RCHS height, (3) distance from road, (4) rock composition, (5) soil structure, and (6) mass movement. Traffic survey was also carried out to understand the vehicular frequency. Survey of India (SOI) 1:50,000 scale toposheet (47/I/3) and LISS-III satellite imagery were used to identify the pre-expansion road situation of the area. Mean rainfall and temperature data were collected from TRMM data, and worldclime grid, respectively, to evaluate climatic nature of the area. Satellite-derived ASTER GDEM data were used to prepare the topographic information. Field investigations, GPS data and traffic survey, space-based remote sensing (RS) satellite-derived data were all integrated in ArcGIS V.9.2 software to produce the composite spatial database of all samples. After that, RCHS site weighting and weighted factor combination (WFC) were carried out to form the Landslide Risk Intensity (LRI), i.e., Low risk (LR), Moderate Risk (MR), High risk (HR), and Very High risk (VHR). Results indicate that out of 11 samples, 2 (P3, P11) are prone to VHR, 3 (P2, P9, P10) prone to HR, 3 (P5, P7, P8) prone to MR, and 3 (P1, P4, P6) prone to RCSC. The results were validated from rock fall activity even though the cut slopes are protected with security net, confirmed by field visit. Thus, investigated RCSC will be useful to evaluate the risk intensity and help evolve suitable remedial measures for RCSC or landslide reduction in the present and other similar areas. It is also recommended to make highway slope maintenance an integral part of highway management.

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Keywords Landslide risk intensity · RCSC · RS-GIS · Slope site weighting

1 Introduction

The economic well-being of modern world is highly dependent on spatial connectivity achieved through raising roads and highways that increases the frequency of vehicular traffic on a given stretch of road. The increased road cutting, especially through difficult terrain, changes the physical and cultural landscape of the area. Alteration to extant geomorphology, especially in the hilly terrain, increases the risk of slope failure, rock fall, and debris/soil slide (Varol et al., 2019). It also increases the risk of landslide and rotational failure of weathered material due to loss of the base or cutting of hilly tracts without providing support to the exposed walls of the hills. The degree of uncertainty is further exacerbated by prolonged rainfall, even of normal intensity, and also by vibrations created by traversing of heavy vehicles through the steep hill road cut tracts. The basic ingredients required for initiating landslides in such regions are anomalously high rainfall in a small duration of period, high-temperature gradient, the pervasive pull of gravity, susceptibility of soil or rock to erosion and weathering, sloping ground, active mass movement (Ahmed, 2015; Gawali et al., 2017; Kansas Geological Survey [KGS], 1999) and massive highway building leading to RCSC in hilly areas (Jangpangi et al., 2019; Kainthola et al., 2015). A large part of the allocated budget is spent on just the restoration of highways damaged from repeatedly recurring landslides.

Economic development of a state or nation is dependent upon resources and their timely and targeted mobility, achieved through transportation nodes. The excavation of highways is through and along the hill slopes; thus, the strength of slopes becomes a primary concern for road developers and engineers from economic, risk and public safety point of view (Hoek et al., 2000). Mega highway projects in hilly tracts regularly undergo slope failure and experience RCHS occurrence leading to economic and human suffering. The stability of RCHS is generally dependent upon the geotechnical characteristics of slope geo-material (soil and rocks), and the manifestation of geological deformations. Thus, geotechnical characterization of slopes and their stability detection is of significant concern (Nanda, 2020; Sharma et al., 2016) for RCSC or landslide risk assessment. Moreover, texture, permeability, porosity, water holding capacity, etc., are some of characteristics that determine the nature of land sliding along the slopes. Normally, falling of rock, sliding of debris, collapsing, and rotational failure of wet material are some of the regular mass movement or non-stability causes (Ayalew & Yamagishi, 2003). Large columnar jointed basalt, surface overflow, joints or cracks of rocks, and the presence of marl and shale inside the compact rigid rocks also are the main causes of slope instability (Ayele et al., 2014). Landslides are common in young mountainous terrain like the Himalayas. However, the Deccan Trap region is experiencing increased landslide activity due to increased road laying episodes.

Landslide analysis or RCSC hazard in road cut hilly tracts is being carried out to deal with the ensuing catastrophes. To tackle this problem, different analytical methods and approaches like analog, experiential, numerical, programming (Alavi & Gandomi, 2012; Efdal et al., 2019) field-based inventory (Kainthola et al., 2012a, 2012b; Verma et al., 2013), computer-based Geographical Information System (GIS), and RS (Pradhan, 2011; Ramakrishnan et al., 2013) are used to detect landslide susceptible areas. Andrea et al. (2016), Aher et al. (2017), Sharma et al. (2017), Gawali et al. (2017); and some others applied these methods to assess landslide risk. Kveldsvik et al. (2009), Lin et al. (2012);

and Khamkar and Mhaske (2018) consider conventional techniques are inadequate to study the complex interconnectedness of rock behavior. Thus, in the present attempt for precise analysis of landslide and allied mass movement, composite data were integrated in GIS software containing primary (field-based) and secondary (satellite-derived) data to generate composite spatial database with highest accuracy possible (Aher et al., 2012; Deshmukh et al., 2017). Advanced RS-GIS computer-based techniques are now used to monitor landslide-prone locations to plan mitigation measures (Aher et al., 2014; Barbara et al., 2016; Deshmukh & Aher, 2016; Gawali et al., 2017; Kantamaneni et al., 2017; Kilicoglu et al., 2020). Siddique and Pradhan (2018) assessed the stability of road cut slopes along India's NH-7 at different sites with different geological features.

Recently, NH-60 has been converted into a 4-lane highway by cutting down multiple hilly tracts, leading to steep unnatural slopes initiating multiple deformations and cracks due to blasting activity. The hills along NH-60 are composed of loose material that are seen to cap the jointed basaltic rock mass. They have now become more susceptible to slope-induced catastrophic landslides. Moreover, an external triggering mechanism like traffic flow and continuous rainfall in rainy season may also accelerate the slope failure. The slope deformation, at the time of blasting, has led to rock fall activity along this highway. These are, anyway, some of the obvious indicators of the RCSC. Furthermore, field visits to the area have revealed high-density presence of horizontal and vertical crosscutting cracks along road cuts. This jointing has the potential to create huge rock blocks with weak planes. In surveyed area, for the present study contains a simple dike having chilled margins. For better spatial analyses and to identify the dominant geological features, extensive fieldwork with primary, secondary, and space-based satellite imagery and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) data was carried out. In the present attempt, collected primary field information, GPS and traffic survey, and then secondary and space-based RS satellite-derived data were integrated in GIS software to produce composite spatial database. This was done to obtain precise LRI in the selected area. In a geologically stable region like the Deccan Traps there have been instances of landslides along some of the hilly regions in places like Konkan and Lonavala. These have been attributed to different reasons, most commonly the breakdown of the local rock mass. With the excavation initiated and throwing open of NH-60 we recognized the possible danger of landslide in the selected area of study. We have surveyed the area quite closely and tried to understand how the different rock cut segments will behave in different anthropogenic and meteorological conditions. Moreover, the hilly transect under study is quite newly dissected and it will be interesting to monitor the changes it undergoes. The efficacy and reliability of our proposed approach to understanding landslides will also be tested. It will also act as a baseline for any future study in areas of similar geotectonics of transportation corridors developed for roadways and railways anywhere in the world.

2 Morphologic arrangement of study area

The study focused its attention on the current NH-60 of Maharashtra, India, which is a national highway between Pune and Nashik that traverses through the Chandanapuri hill section. This highway connects to major cities and industrial zones. The road widening activity was initiated a few years back and completed in 2017. The geographical extent of the selected area is 19° 25′ 44.79″ to 19°27′ 58.42″ N latitude and 74°11′8.22″ to 74°

12′ 27.63″ E longitude (Fig. 1). The selected area is toward south of Sangamner city and is placed at about 17 km distance from it. This area consists of rigid basaltic structure which belongs to the Thakurvadi Formation, a part of the Kalsubai Subdivision (Khadri et al., 1988; Subbarao & Hooper, 1988). According to District Resource Map (2001), geologically, the present area is part of the upper Ratangad formation, mainly of compound pahoehoe flows and some Aa flows. The Chandanapuri Ghat area depicts step-like and plateau-type geometry. Topographically, this area is marked by mixed hilly and plateau geomorphology, which is drained by tributaries of the Pravara River. According to Koppen-Geiger climatic classification (Peel et al., 2007), this area lies in warm semi-arid climate (BSh) which tends to be hot. The summers are warm and winters cool (mean temperature~19.2 °C), with low to very low precipitation. The orographic gradient effect of Western hill (located in western direction of study area), is felt on the precipitation, because of which the observed mean annual precipitation is around 500 mm indicating BSh climate in the area. The annual range of rainfall is between 500 and 700 mm, with maximum rains during June to September month, which is then followed by a lengthy dry climate. Scant rainfall in the region has laid barren the soil in this region where only rare Acacia trees are seen to flourish. Thus, this overall climatic environment is classified to be of semi-arid type. In the higher reaches of the Ghat, edges of hilly tracks separated by badlands are seen, while the foothill zone is marked by presence of gently sloping fertile soil. Earlier, geological, hydrological, and geomorphological background of Chandanapuri valley and surrounding area was investigated by Rajaguru et al. (1993), Bondre et al. (2000, 2004, 2006), Aher et al. (2012), Joshi et al. (2013), Deshmukh et al. (2017).

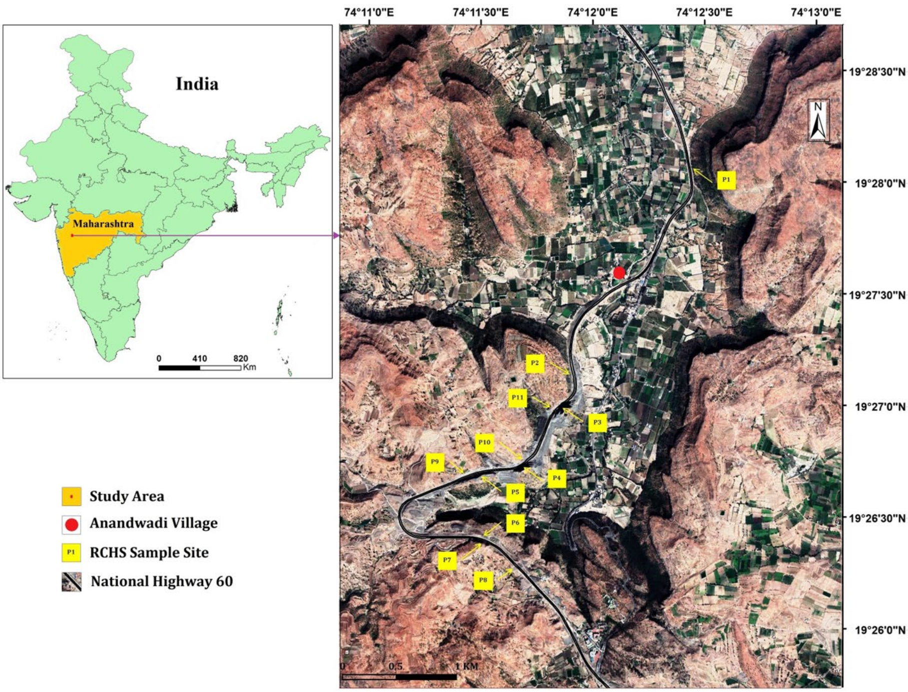

Fig. 1 Location map of NH-60 traversing through Chandanapuri Ghat section

3 Materials and method

The basaltic rocks and soil within the study region exhibit complex geotechnical behavior because of which it is felt understanding geotechnical characteristics from just one site sample, might not be adequate for classification of entire RCHS section (Sharma et al., 2016). Landslides are a modern menace, and it needs to be tackled in a systematic manner. The novelty of our work lies in the selection of the site itself, which is quite virgin and untested. Thus, extensive field investigations were carried out to collect representative RCHS site samples from eleven ($n = 11$) locations along NH-60 at the Chandanapuri hill section, Maharashtra, India. Each sample site's (1) slope, (2) RCHS height, (3) distance from road, (4) rock composition, (5) soil structure, and (6) mass movement pattern were identified and later quantified by field investigation to verify the composite impact on the RCSC or landslide risk possibility. The assessment was based primarily on estimated potential of rock fall and its impact on the vehicular mobility.

3.1 Field survey

Slope instability leads to slow slide in the Deccan Trap region and is one of the common causes for initiating hilly region instability. The slope failure possibility increases substantially due to combined effect of slope geometry, strength of slope, mechanical break, expansion of fragile areas, lithological trouble, and continuous rainfall (Ahmad et al., 2013; Bhasin & Kaynia, 2004; Souley & Homand, 1996; Umrao et al., 2011). Based on these parameters and approaches, Abney-level instrument was used to measure slope of the hill cut site (Table 2). Strength and durability of rock structure were assessed to primarily understand different rock properties (Ahmad et al., 2017). Large highway schemes in undulating hilly tracks can lead to growth in RCHS frequency, where the stability depends upon the geotechnical characterization of slope forming geomaterials. The physical and geotechnical behavior of geo-materials predominantly controls catastrophic mechanism and stability of hill slopes (Sharma et al., 2016). Thus, RCHS height (Fig. 2e) and its distance from the road were measured (Table 2), to understand and evaluate road cut slope stability within the selected area. Rock lithology determines the weathering process, and sliding down of weathered material depends on angle of slope. The rock composition (Fig. 2d) of RCHS sample was also identified (Table 2). Weathered soil bands or mass, deposited on the slopes, is most prone to landslides, especially in rainy seasons. Therefore, soil tracks were identified (Table 2) and evaluated carefully to assess the composite impact in a probable landslide scenario (Fig. 2h). The stability of rock or soil mass depends upon the deposited debris mass, its slope angle, and active mass movement process. Hence, mass movement status in the area was verified from the tilt angle of local trees (Table 2, Fig. 2g).

3.2 Use of RS-GIS techniques

Garmin GPS receiver (12 channel) was used to register latitude, longitude, and elevation from mean sea level (MSL) of each site studied (Table 1) to establish spatial database. Mean rainfall data were collected from Tropical Rainfall Measurement Mission (TRMM) and worldclime grid, respectively, to determine the semi-arid climatic nature of the area (Table 1). TRMM data are available with 4 k horizontal and 250 m vertical resolutions at http://www.geog.ucsb.edu/~bodo/TRMM/ website. It is a freely disseminated precipitation data from tropical regions (Hunink et al., 2014) providing a distinctive idea of

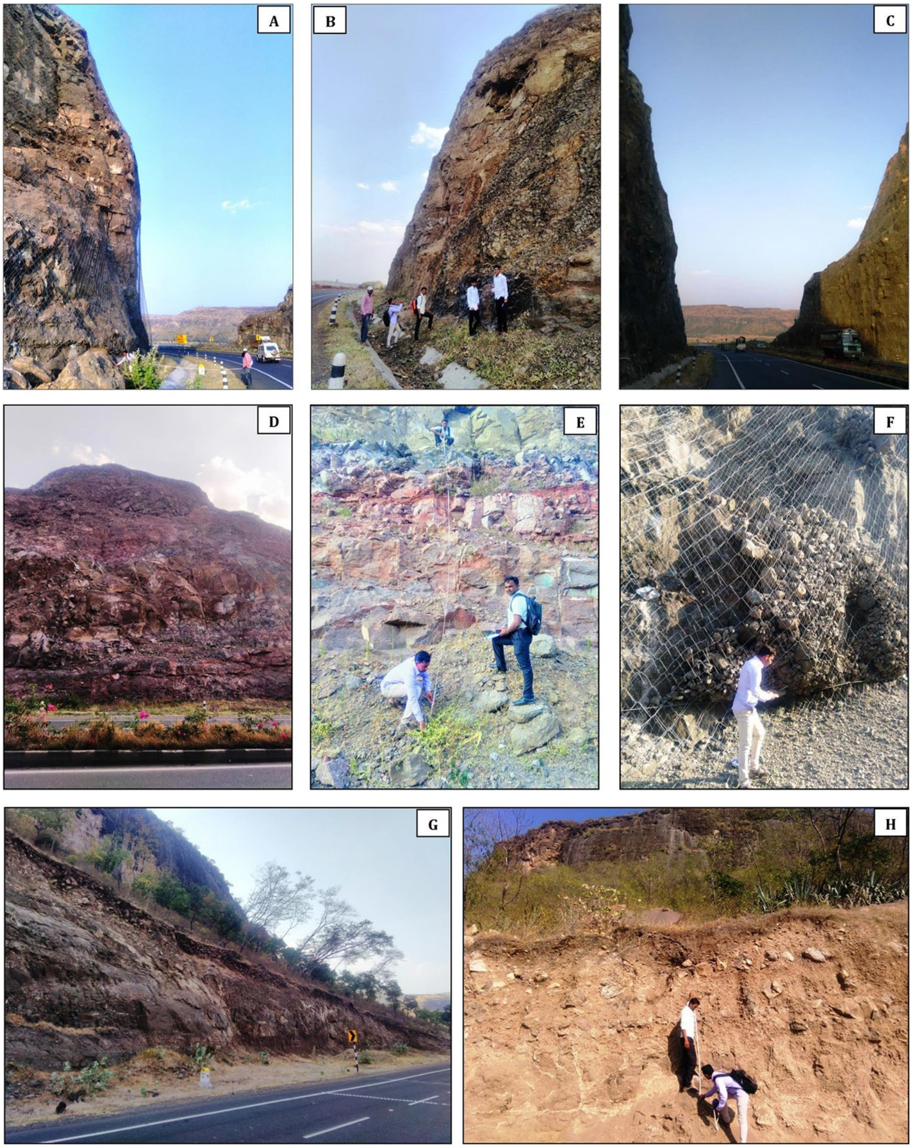

Fig. 2 **A**) RCHS, **B**) Dyke line cut during highway development, **C**) RCHS along NH-60, **D**) deformations due to blasting, **E**) red bole and rock fall, **F**) rock fall in the inner part of metallic net, **G**) base cutting of hill slope, **H**) cutting of deposited soil tracks

rainfall distribution, especially in the remote and mountainous region. The two lanes that were newly laid out on NH-60 were imported from high-resolution satellite imagery, using web-based Google Earth, and superimposed over satellite-derived ASTER GDEM data. This was done to decipher the spatial arrangement of highway with respect to topographic relief (Fig. 5). In ASTER DEM the highest resolution, 30 m (1 arc second) spacing is suggested (Guth, 2010), which refers to a three-dimensional model of area. As compared to

Table 1 Spatial information of surveyed RCHS sample sites

RCHS sample site	Latitude	Longitude	Elevation (MSL)	Aspect (slope direction)	Mean rainfall (mm)	Mean temp. (°C)
P1	19° 28′ 0.08″ N	74° 12′ 26.71″ E	649	West	520	20
P2	19° 27′ 8.92″ N	74° 11′ 54.57″ E	693	East	520	20
P3	19° 26′ 57.61″ N	74° 11′ 53.19″ E	703	North-West	520	20
P4	19° 26′ 42.58″ N	74° 11′ 42.05″E	749	North-West	520	20
P5	19° 26′ 40.69″ N	74° 11′ 30.28″ E	751	North	520	20
P6	19° 26′ 25.38″ N	74° 11′ 29.16″ E	790	South	520	20
P7	19° 26′ 24.38″ N	74°11′ 29.97″ E	789	North	520	20
P8	19° 26′ 23.27″ N	74° 11′ 32.96″ E	790	North-East	520	20
P9	19° 26′ 41.20″ N	74° 11′ 28.04″ E	761	South	520	20
P10	19°26′43.23″N	74°11′40.77″E	746	South-East	520	20
P11	19° 26′ 57.51″ N	74° 11′ 51.21″ E	720	South-East	520	20
					Warm semi-arid climates (BSh)	

traditional methods, satellite data give extraordinary benefits, especially for remote and unreachable terrains. Currently, it can be easily acquired, is very close to reality, and can be worked in a comparatively short time, at quite a low cost (Jiang et al., 2014) and reasonably high accuracy (Aher et al., 2017). Aspect information (slope direction) of all samples was collected (Table 1), and contours produced from ASTER DEM to identify the slope gradient (Fig. 5). Collected field data, SOI 1:50,00 scale Toposheet (47/I/2), Linear Imaging Self-Scanning Sensor (LISS-III) satellite imagery, DEM and GPS data were incorporated in the ArcGIS V.9.2 software to produce multi-thematic spatial information of selected sample (Tables 1, 2). The LISS-III image with 24 m spatial resolution, captured at Feb 16, 2018, was downloaded from Indian Space Research Organizations (ISRO's) Geoportal Bhuvan https://bhuvan-app3.nrsc.gov.in/data/download/index.php?c=s&s=L3. Satellite data and its incorporation in GIS platform make the spatial analysis easy (Ganapuram et al., 2009) when are deployed in consonance with other traditional methods, such as field measurement and observations (Das et al., 2018; Deshmukh et al., 2017).

3.3 RCHS site weighting and landslide risk intensity

Collected field data and RS-GIS based inputs were integrated to form the relative RCHS site weighting. All samples were assigned 1–11 scale weights with respect to selected five factors, viz., (1) slope, (2) RCHS height, (3) distance from road, (4) soil structure, and (5) mass movement (Table 2). RCSC or landslide is the combined effect of natural and man-induced factors. Thus, WFC technique was used to prepare the LRI along selected road (Table 3). With WFC technique, each factors weight was combined to produce the LRI using Eq. 1. The ratings have been assigned based on Pierson et al. (1992) and Pierson (1991). The vertical height of a slope is an important factor. Higher slope and height has more potential energy than lower slope and height. Hence, the steep slope and height is more hazardous because of which they receive higher rating. The distance from road, soil structure and mass movement has low impact on rock fall and hence is rated lower.

Table 2 Field survey with geological and geomorphic characteristic of surveyed RCHS sites

RCHS site	Slope°	RCHS height (m)	Dist. from road (m)	Rock composition	Soil structure	Mass movement	Risk intensity
P1	47 (01)	04 (01)	11.5 (01)	The compact basalt at the top has a high degree of slope. Though it looks compact, there are many weak zones within the central and left part, whereas the right end of the formation is seen to be highly weathered. This weathered material can be prone to landslides, if and when there is heavy and continuous rainfall. The gravity can also lead to its downfall. The clay portion, at the bottom of this site, is more susceptible to the mass movement in the eventuality of heavy rainfall since it can retain water and in the process increases the load. The overburden can cascade down very heavily onto the area below	Mixed with slided rocks and clay, debris types, deposited in the foot hill (05)	*T*1 Angel—38° = Active mass movement (05)	13 (Low)
P2	63 (04)	22 (03)	06.0 (05)	The rock cutting for road construction has increased the vulnerability of this area to landslides. The slope angle also makes it amenable to such an activity. This site also reveals some weak planes through which the rainwater can percolate and the temperature difference can launch an assault on these rocks, further breaking them up and making them more susceptible to landslide activity	Deposited at slope, part of active mass movement (06)	*T*2 Angel—43° = Active mass movement (06)	24 (High)

Table 2 (continued)

RCHS site	Slope°	RCHS height (m)	Dist. from road (m)	Rock composition	Soil structure	Mass movement	Risk intensity
P3	73 (08)	55 (09)	04.8 (11)	The mass movement and the breakage of basaltic blocks can well be identified from this site. Though the falling boulders have been tightly leashed by metal mesh. These are highly weathered and are likely to give in to the force of gravity. These rocks are highly prone to sliding, due to the force of gravity and high angle of slope as well	–	–	28 (very high)
P4	62 (03)	52 (08)	06.1 (04)	At this site block of basalt is highly weathered and brecciated with pockets of calcite encrustations. There are many weak planes, and these, over a period of time, will give in to the forces of gravity. The weathering processes can weaken these rocks	–	–	15 (Low)
P5	80 (11)	29 (04)	10.2 (02)	This exposed rock cut exhibits weathered material which can tumble down in the form of blocks cut along the weaker planes. The high slope angle will aid in sliding due to gravity	–	–	17 (Moderate)

Table 2 (continued)

RCHS site	Slope°	RCHS height (m)	Dist. from road (m)	Rock composition	Soil structure	Mass movement	Risk intensity
P6	55 (02)	16 (02)	05.7 (07)	The chemical weathering seen in the form of bole activity can indicate the strength of the physical and chemical processes that acted on these rocks in the past. It can be seen that the basalt is highly weathered and jointed. In the top right-hand corner of the site, high angle of slope and lack of downward support can trigger a major landslide in this terrain	Placed on top, formed due to physical weathering (04)	–	11 (Low)
P7	65 (05)	30 (05)	05.0 (10)	This is a highly weathered and jointed basaltic rock, and the high angle of slope can trigger gravity induced landslide. The mass movement may start in the form of trickle, which can attain a massive form of destruction in coming years and decades	–	–	20 (Moderate)

Table 2 (continued)

RCHS site	Slope°	RCHS height (m)	Dist. from road (m)	Rock composition	Soil structure	Mass movement	Risk intensity
P8	72 (07)	40 (06)	05.8 (06)	This region is highly prone to sliding of the rocks. The basalt is highly weathered and brecciated on the right of the site. The high angle of slope and lack of support to the top of the hillock basalt is an invitation to a major accident. Gravity will play a major role in the sliding of the top rocks. But, if there is continuous and heavy rainfall on this formation, the percolated water will increase the load and hasten the action of sliding. Metal meshing can reduce or slow down the impact of sliding	–	–	19 (Moderate)
P9	70 (06)	42 (07)	05.2 (09)	This region is highly prone to sliding of the rocks. The basalt is highly weathered and brecciated. Gravity will play a major role in the sliding of the top rocks. But, if there is continuous and heavy rainfall on this formation, the percolated water will increase the load and hasten the action of sliding. Metal meshing, seen in the photograph, can reduce or slow down the impact of sliding in this area. It can give some time to mitigate the impact of landslides	–	–	22 (High)

Table 2 (continued)

RCHS site	Slope°	RCHS height (m)	Dist. from road (m)	Rock composition	Soil structure	Mass movement	Risk intensity
P10	76 (09)	56 (10)	06.9 (03)	This region is highly prone to sliding of the rocks. The basalt is highly weathered and brecciated. The high angle of slope and lack of support to the top of the hillock basalt is an invitation to a major accident. Gravity will play a major role in the sliding of the top rocks. But, if there is continuous and heavy rainfall, the percolated water will increase the load and hasten the action of sliding. Metal meshing can reduce or slow down the impact of sliding. However, the top of the hillock is totally neglected and is devoid of any meshes. The highly weathered and jointed formation can trickle down due to a high degree of slope	–	–	21 (High)

Table 2 (continued)

RCHS site	Slope°	RCHS height (m)	Dist. from road (m)	Rock composition	Soil structure	Mass movement	Risk intensity
P11	77 (10)	57 (11)	05.3 (08)	This road is highly prone to experiencing deleterious effects of sliding of the rocks on either side. The basalt is highly weathered on both sides of the road. The high angle of slope and lack of support is an invitation to a major accident. Gravity will play a major role in the sliding of the top rocks. But, if there is continuous and heavy rainfall on this formation, the percolated water will increase the load and hasten the action of sliding. Metal meshing can reduce or slow down the impact of sliding in this area	–	–	27 (Very high)

*Values in bracket are assigned weights to the RCHS sample site

*Abney-level instrument height: 1.6 m

Table 3 LRI and possible RCSC

Sr. no.	LRI	RCSC possibility	Possible RCHS site
1	10–15	Low risk (LR)	P1, P4, P6
2	16–20	Moderate risk (MR)	P5, P7, P8
3	21–25	High risk (HR)	P2, P9, P10
4	26–30	Very high risk (VHR)	P3, P11

$$\text{LRI} = \text{Slope}^{\text{rw}} + \text{RCHSHeight}^{\text{rw}} + \text{Dist from Road}^{\text{rw}} + \text{Soil Structure}^{\text{rw}} + \text{Mass Movement}^{\text{rw}} \tag{1}$$

The RCHS site weighting, WFC and LRI techniques help to handle the problematic issues of incorporation of various data series, which is significantly important in integrating the combined maps with one another and thus to produce multi-objective maps (Ayele et al., 2014). Finally, the possible RCSC grid was produced with the help of 15 m buffer (Fig. 6) technique in ArcGIS V.9.2 software along the selected highway to determine the LRI, i.e., (1) VHR, (2) HR, (3) MR, and (4) LR in thematic form (Fig. 6).

3.4 Possible RCSC or landslide risk

Slope failure, landslide risk, and RCSC are always a threat to natural, as well as man-induced environment. Possible RCSC or slope failure along NH-60 is a continuous risk for commuters and vehicular traffic. It also poses a big challenge to highway planners to find ways and means to annihilate dangers to human life and property. NH-60 running through Chandanapuri Ghat section of Maharashtra is an important national highway. Because of the commercial importance of this highway a large number of vehicular traffic comprising two-, four-wheeler, loaded, and heavy-loaded vehicles are seen to travel. The loaded and heavy-loaded vehicles plying on the road produce robust vibrations along the highway, which may be responsible for the increase in the cracks and slope failure activity. Quantitative analysis of traffic flow can help assess the frequency of all types of vehicles. Hence, traffic survey was carried out in vacation and non-vacation days to identify the traffic volume on the NH-60 (Table 4).

Table 4 Traffic survey (July 29 and 30, 2018)

Day	Two wheeler	Four wheeler	Loaded	Heavy loaded	Total
Sunday (29/7)	5297	5160	2589	694	13,740
Monday (30/7)	6220	4462	1859	725	13,266
Mean	5758.5	4811	2224	709.5	13,503

4 Results and discussion

4.1 Field investigation

Maximum RCHS height of slope site was recorded at 57 m above the highway where the angle of slope was more than 77° for the P11 slope site (Table 2). Generally, the maximum cutting height, cliff-like structure, is more susceptible to slope failure and the outcome could be hugely disturbing. At many sampled places in the area, distance of slope cutting to the road was very close. Minimum distance of about 5.0 m was seen to be present at P7, whereas maximum, i.e., 11.5 m, was measured at P1 (Table 2). Landslide or RCSC is likely to damage the infrastructural property because of closeness of cutting face of mountain to road, and presence of steep slope (Fig. 4f). The rock formation observed in the area is mainly basalts which are in a massive compact form. However, some small tracks of shale, limestone, and sandstone are seen to be present along the excavated highway in the study area (Fig. 2d). The presence of these sedimentary entities is quite critical since clay and silt-sized grains are more often seen to be associated with slope failure. Clay and silt-sized shale constituents have revealed high possibility of slumps, block slides, and earth flow. The sedimentary limestone terrain is typically solid and quite adequately seen to provide support to the slopes. These hard rock bands create the barrier to weathering because of competent nature of rocks (KGS, 1999).

In the area, sandstone and limestone are seen to be exposed in highway cuttings. Hence, it is inferred these places can potentially pose a risk of rock fall, especially in rainy season. During the field survey, active weathering was observed to be taking place, which is altering the rocks from hard to soft. It is also giving rise to the formation of soils as well. At site P1, P2 and P6 can be seen weathered soil layers (Figs. 2g, h and 4d) above the slope (Table 2), which will be more prone to water holding, permeability, porosity actions during rainy seasons. Such properties of soils can increase the load on soil mass when it becomes wet, especially in rainy season, and can be prone to sliding under the effect of gravity (Fig. 3).

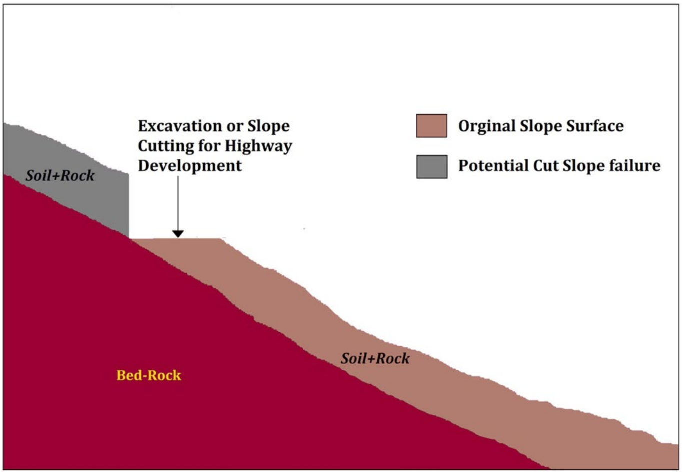

Fig. 3 Modeled geological and morphological geometry with RCHS

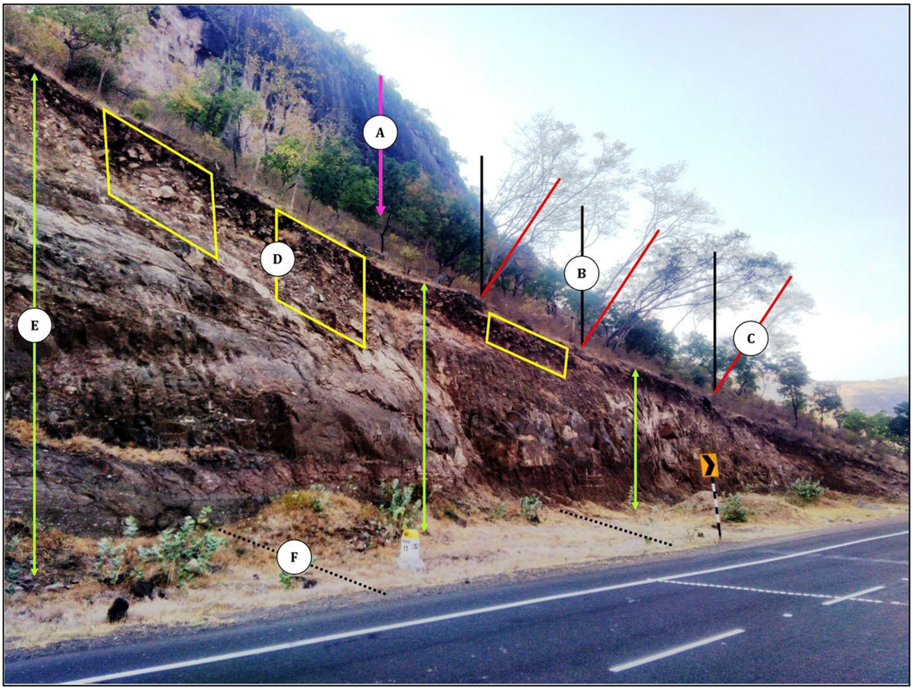

Fig. 4 Alterations and evidence of active mass movement. **A**) Massive basaltic layer, **B**) original tree angle, **C**) tilted tree angle, **D**) deposited soil bands, **E**) slope cutting, and **F**) distance of the cut slope from RCHS

The present area is in the semi-arid climatic zone where maximum temperature has been observed in dry spells (Fig. 4). Due to this reason, physical weathering and associated loosening of materials is seen to be very active. Maximum RCHS angle along the road was measured at P5 (80°) and minimum at P1 (47°). To summarize, of the total, 6 sites' slope was more than 70° at P3-73°, P5-80°, P8-72°, P9-70°, P10-76°, and P11-77° (Table 2). Gravity and mass movement is found to be higher at steep hill slopes. Due to this reason, rock fall or slope failure is likely to occur in the present study area. Rock fall studies carried in high hill slopes (Ahmad et al., 2013) reveal the main cause of rock fall to be high amount of rainfall during monsoon season and occurrence of nearly parallel joints to the slope face. In this area, large cutting of hill has increased the slope angle at the base, which is now more susceptible to slope failure (Fig. 2a, c, f). The maximum safe slope angle for any hillside is a function of the category, thickness, and proportion of water content in the rock and soil (KGS, 1999; Chang and Wan 2015). Accordingly, rain water acts as a lubricant in the associated rock and soil. Therefore, if the content of water increases, the capacity of the rock and soil is observed to decrease. We propose this mechanism can lead to slope failure or landslides in the area.

During the field survey, rock fall at different road cut slopes, and tilting of old trees were observed. These are important evidence of active mass movement process. Uprooted trees were also observed along the rock fall along a steep road cut cliff or steep slope. Due to base cutting, the soil bands become prone to sliding, or it may initiate debris fall once the weight of the soil bands increase due to rainfall. Thus, in this area due to RCHS, there is a risk of slope failure catastrophe or landslide, especially in

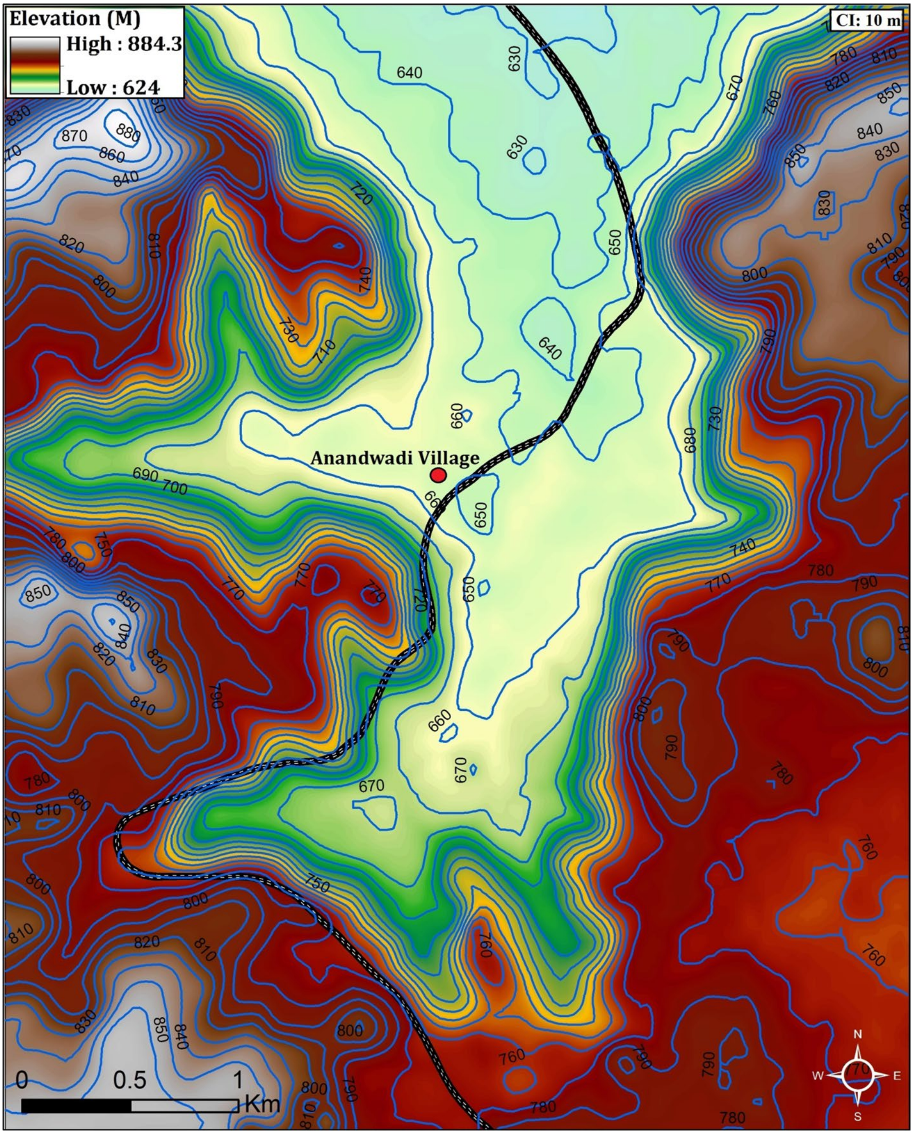

Fig. 5 Contour map shows the gradient direction and path of highway passing exactly through steep gradient (CI: contour interval)

the monsoon season (June–October). Though the relevant highway construction company has provided protective nets along RCHS zone, there may still be a possibility of RCSC or landslides when there will be an increase in the mass of disintegrated material within the net cover (Fig. 2f). The alterations of present highway and increasing traffic frequency on it, there may be a possibility of RCSC or landslide in the Chandanapuri Ghat section area.

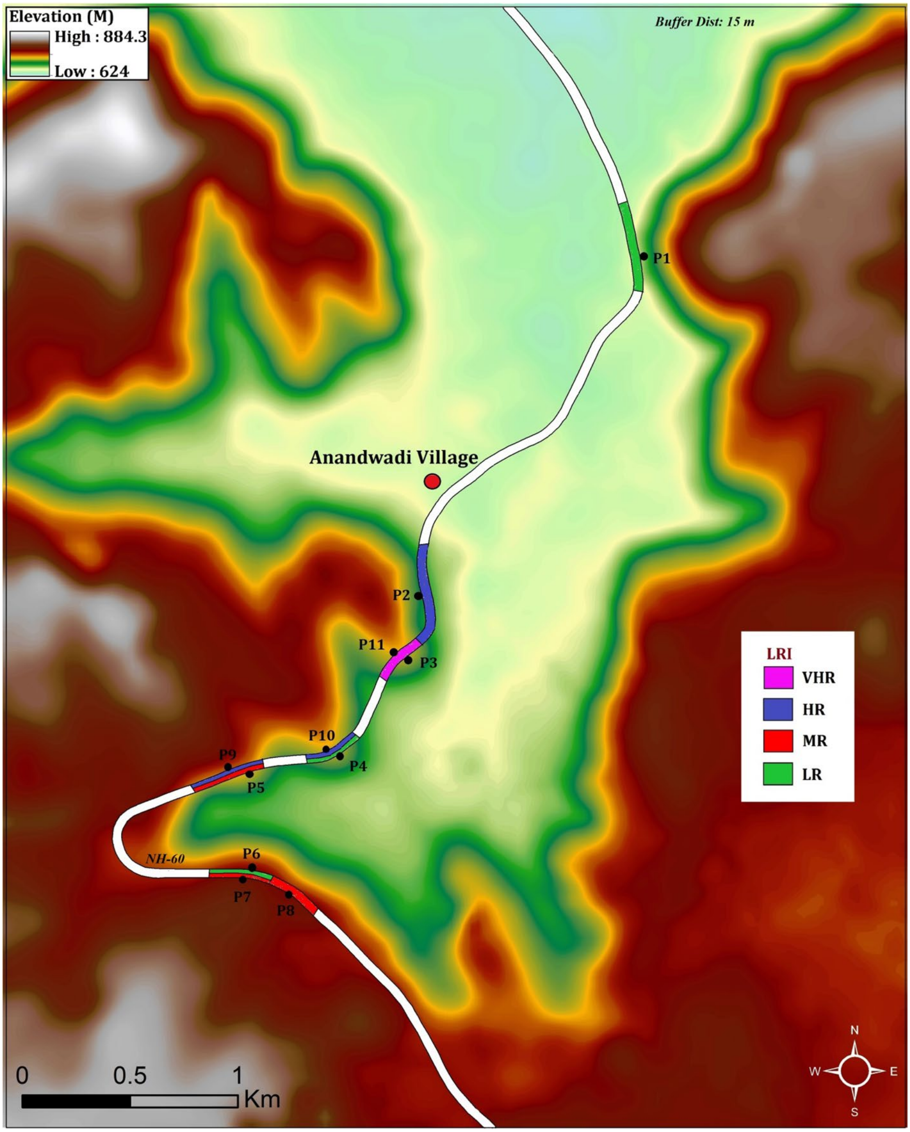

Fig. 6 Predicted LRI within 11 grid zones

4.2 RS and GIS database

GPS survey has unraveled sharp gradient of the present track of NH, and it may suffer from RCSC or slope failure. On this track, maximum recorded GPS height was 790 m and minimum 649 m from MSL (Table 1). This means the relative height of lacerated hill section tracks was around 140 m. Such gradients may induce speeding leading to road accidents. Some information on the frequency of accidents on this road sector was collected via interaction with local and road transport authorities of the area. The TRMM rainfall data (mean

520 mm) and worldclime temperature data (mean 20°) highlighted the semi-arid characteristic of the area. These factors are quite relevant to understanding landslide and mass movement activity. RS satellite-derived ASTER GDEM has shown the relief and the nature of the selected study area to be of mixed hilly, plateau, and valley topography. It indicated foot-hill zones with all the directional slopes (Aspect). Generated contours from ASTER DEM (Fig. 5) have validated field observation that the highway has been developed at the foot-hill zone, where steep gradient is present. This in itself could be one of the possible reasons of slope failure at this juncture. Advanced space-based RS data, toposheet, geology map, field-surveyed data, and its integration and superimposing process with unique projection in GIS software have produced the highest resolution spatial information of the area (Table 2) helpful to predict LRI (Table 3). Out of the total 11 grid zones, P3 and P11 grid fall in VHR; P2, P9, and P10 are in HR of RCSC in selected area. It means that middle portion of selected tracks is highly prone to possible RCSC or landslide activity (Fig. 6).

4.3 RCHS weighting and LRI

The slopes formed at the site were weighted to detect the WFC and LRI. This helps to tackle points of improbability by incorporating heterogeneous databases. Advance multi-thematic map/data can be produced by integrating various layered maps with one another (Figs. 5, 6). This model needs input of multiple primary and secondary data, along with space-based inputs, and its integration in a GIS environment to form precise spatial data of a planned study region. This can then be included into large types of area according to stated purpose and requirement. Based on slope site weighting and WFC in the area, possibly 4 LRI relative classes, i.e., LR, MR, HR, and VHR were considered (Table 3). The results have shown that out of 11 RCHS site samples, 2 (P3, P11) are prone to VHR, 3 (P2, P9, P10) are prone to HR, 3 (P5, P7, P8) are prone to MR, and 3 (P1, P4, P6) are prone to LR in the selected area (Figs. 6, 7).

Curiously, during the preparation of this manuscript, rock fall activity occurred which was confirmed by field visit. This happened despite RCHS being covered and protected by a security net. Thus, the results that were obtained during the course of our analysis confirmed our rationality for considering factors like slope failure, their sample site weighting, adopted methodology, tools and techniques, primary, secondary, and space-based inputs used, along with the GIS environment in preparing LRI map of the study area (Fig. 6). The Radar diagram (Fig. 7) succinctly summarizes all the RCHS sites' sample comparison with aggregate values of slope, RCHS height, distance from road and LRI.

4.4 Possible RCSC or landslide risk

The present study has brought to the fore the heightened geological instability brought about by construction of NH 60. In the study area heavy traffic was noticed. More than 13,000 vehicles per day traveled along this route during the period of survey. Out of that, on an average 2224 loaded and an average of 709 heavy-loaded vehicles comprised the traffic (Table 4). Loaded and heavy-loaded vehicle traffic also produces robust vibrations while chugging along the highway. These vibrations can increase width of the cracks and joints within the rock formations leading to enhanced slope failure possibility. Such a slope failure or landslide possibility will threaten natural and man-induced environment in the area. The possible slope failure along this NH-60 cut slope is a continuous risk for all types of vehicles and commuter life which may keep human life in danger. There is a huge density of horizontal and vertical cracks

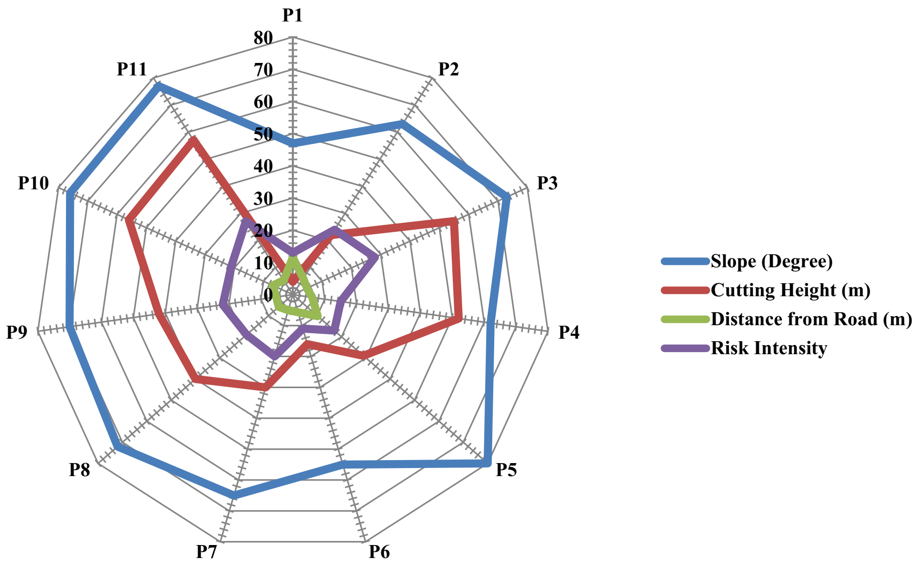

Fig. 7 Radar diagram showing the RCHS sitewise LRI

within the cut sides which are difficult to measure. During the road development, steep cutting of the hilly track was carried out by blasting, which has also formed multiple horizontal and vertical cracks (Fig. 8). Due to the heavy vehicle transportation and discontinuity in rock mass a soil band was formed which may increase the risk of probable RCSC or landslide. In rainy season, rainfall may act as a lubricant in rock and soil mass which can lead to slope failure.

The expansion of NH-60 has been carried out through this complex geological and hydro-geomorphic track. Here, massive basalts are seen to be interlayered with red bole, dykes, and weathered soil bands at some places where excavation has been carried out. Moreover, massive lava flows are been altered with allied structures by construction activity carried during this highway expansion. The area is very vulnerable to weathering, susceptible to dissimilar notches of Land Use and Land Cover (LULC) alteration, formation of soils, and mass movement. Normally, surface joints, sub-vertical to vertical slopes, semi-arid nature, and associated geological alterations play a crucial role in slope instability (Ahmad et al. 2013). Thus, hill slope cutting for NH-60 expansion in this area is one of most impelling factors for landslide or relevant rock falls.

Unfortunately, but coincidently for this study, ground truthing did occur naturally when a landslide did take place on July 14, 2019 (Fig. 9) at a site which was earmarked by this study as highly prone to landslide. One lane closer to the excavation completely blocked the traffic for hours. Fortunately, there was not any loss of human life or vehicles. But we cannot always get away so lightly.

5 Conclusion

The entire input database acquired from the primary field survey, secondary space-based inputs, and its integrations in GIS environment was found to be effective to investigate precise LRI and its hazard identifications. Measured, prepared, and investigated composite

Fig. 8 Discontinuous orientation through horizontal, vertical, and diagonal cracks produced during the blasting activity for NH-60 development

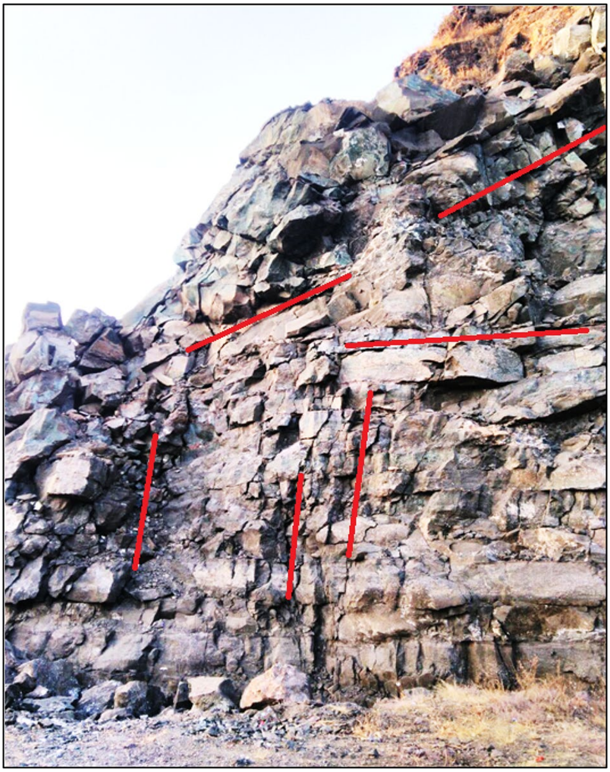

Fig. 9 Landslide occurrence at P11 site on July 14, 2019

databases and its analyses provide an accurate understanding of the RCHS behavior and illustrate that P3 and P11 are at VHR, P2, P9, and P10 are at HR, P5, P7, and P8 at MR, and P1, P4, and P6 are at LR in the selected area. In this area RCSC, slope failure or landslide activity may be possible due to altered geological, morphological, hydrological, and LULC environment. This study emphatically predicts possibility of RCSC or landslide, especially in rainy season in the Chandanapuri Ghat section. Such kind of hazards may be associated with shale rock tracks within the basalt formations. Moreover, limestone layers that occur between these shale tracks may cause landslides as well. Rock fall hazards may be occurring at the slope site where nearly higher vertical slopes along developed highways and limestone tracks are exposed. Possibility of HR will be threatened with natural and man-induced environment in the area where steep slope, higher RCHS height, and distance from road are closer. Semi-arid nature and massive alterations of LULC, especially for NH-60, can trigger the landslide activity in near future. Few road accidents and rock fall activity are quite visible on and along highway in spite of cut slopes are covered with security net. The failed blocks range in size from 1 to 3 feet. The growing cracks on steep walls due to blasting are likely to move down through the landslide. Increase in vehicular traffic at this NH-60 node will increase vibrations exacerbating vertical and horizontal cracks, faults, etc. It could also initiate water percolation through these cracks aiding in mass movement. The results obtained were validated by rock fall event predicted for a high-risk site. To minimize the rock fall or landslide risk it is proposed to immediately initiate precautionary procedures to prevent another big catastrophe. Slope reduction at suggested VHR, HR, and MR site and monitoring of security net, especially prior to rainy season, could be initiated right away. This will help control the next RCSC in the selected area and in other areas, around the world, which may be facing similar climatic and morphological characteristics. The study has universal appeal and application.

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Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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