Geotechnical and Geological Investigation of Critical Slopes along Balipara-Charduar-Tawang Road in Vartak area, Arunachal Pradesh, India

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Abstract
Landslides are a significant concern in the Himalayan region of India, particularly affecting large areas along the Balipara-Chardwar-Tawang (BCT) road. This study presents a comprehensive study involving field and laboratory investigations for slope stability analysis for two critical slopes between the Tippi and Sessa villages. Field investigations, such as electrical resistivity and standard penetration tests, were conducted while laboratory experiments were conducted to determine the engineering properties of soil and rocks following standard codes. Geological mapping of these two BCT road slopes revealed steep slopes ranging from 35° to 60°. The strata primarily consist of silty sand overlying bedrock, with the rock's uniaxial compressive strength (UCS) value of more than 20.0 MPa.

Slope stability analysis indicated that both slopes are vulnerable to landslides, with the factor of safety less than the required thresholds for both static and seismic conditions. Detailed mitigation measures are proposed, including the design of soil nails and anchors. Numerical analysis post-installation of these mitigation measures shows an improvement in the factor of safety, surpassing the recommended value of 1.05 for seismic and 1.30 for static conditions.

Introduction

Landslides are natural disasters characterized by rock, earth, or debris movement down the slope. They occur due to various factors including heavy rainfall, earthquakes, volcanic activity and human activities like deforestation and construction[32,38]. The impact of landslides can be devastating, causing loss of life, destruction of property and disruption of transportation and communication networks. Understanding landslides' causes and potential risks is crucial for developing effective prevention and mitigation strategies to protect communities and infrastructure[28,35]. According to a database released by EM-DAT[4], landslides accounted for an economic loss of 0.9 billion US$ in 2018.

The Indian subcontinent is highly vulnerable to natural hazards. Based on a database of the Indian Space Research Organisation (ISRO 2023)[6] risk assessment report, about 80,000 landslides occurred between 1998 and 2022. The report also suggests the claim that India is among the top five landslide-prone countries globally, where at least one death per 100 sq km is reported yearly due to a landslide event. Approximately 3985 death occurred due to landslides in India between 2010-2020[22]. The economic loss due to landslides may amount to as much as 1% to 2% of the Gross National Product. The number of casualties reported during 2010-2021 is presented in fig. 1. Arunachal Pradesh is one of the most challenging hilly terrains, prone to landslides. Hence, slopes along the highways must be protected/ stabilized to ensure stability throughout the year.

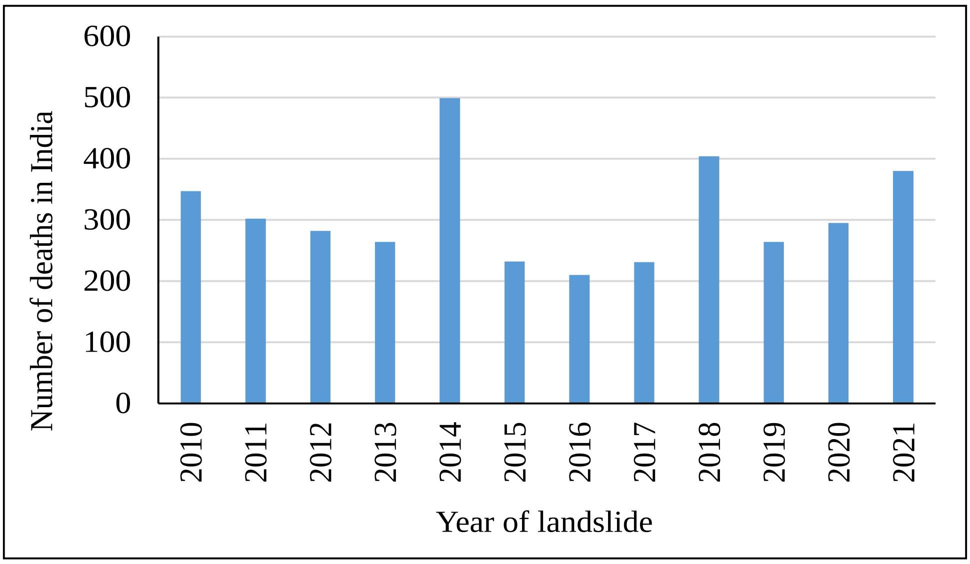

Fig. 1: Casualties in India due to landslides during 2010-2021

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Geological Survey of India (GSI) has carried out the National Landslide Susceptibility Mapping (NLSM 2023) of the total area of 4.3 lakh sq. km in different landslide-prone states/U.T. of India. The largest covered mapping area under NLSM (2023) was 71,228 sq. km in Arunachal Pradesh. Every year, with the onset of monsoon, landslides and floods cause havoc to the lives and properties of the people.

Numerous studies have been conducted on the triggering mechanisms of landslides worldwide. The causes of different landslides may be the same or different regions with comparable geological setups. Several empirical techniques exist in the scientific literature for evaluating the condition of slopes, but rock slope instability score (RSIS) proposed by Jaiswal et al[23] assesses the effect of rainfall on the stability of rock slopes. Various approaches have been adopted by several workers to study slope instability in Himalaya[22-27,40,41].

This study presents a detailed investigation of the two slopes at Balipara-Chardwar-Tawang (BCT) road under Border Roads Organisation (BRO) Vartak at chainage 50.7 and chainage 55.9 in the State of Arunachal Pradesh, India. The study includes field, laboratory and numerical investigations. The field investigation comprises of geological mapping, standard penetration tests and an electrical resistivity survey conducted on the slope strata up to 20m depth. The samples were collected using a double tube sampler through drilling. Laboratory investigations were conducted on the obtained samples to determine the engineering and index properties of the rocks and soils. The slope stability analysis was conducted using slide software based on the data obtained. Apart from the slope stability investigation, various mitigation measures were suggested for slope stabilization.

Study Area

Arunachal Himalaya is the easternmost region of the Himalayan mountain range with an extension of 91°30' E to 96°0' E and 26°28' N to 29°30' N. The study was conducted on the Balipara-Chardwar-Tawang (BCT) road, which has been constructed by Border Roads Organisation (BRO) Vartak. Two critical slopes of this road section at chainage Km 50.700 (27° 06'49"N, 92°32'14"E) and Km 55.900 (27°14'44"N, 92°25'04"E) have been studied in detail through different type of geological, geophysical and geotechnical investigations (Fig. 2). Fig. 3 shows the google earth and drone image of two studied critical slopes. BCT Road section is a critical road as it connects three districts East Kameng, West Kameng and Tawang of Arunachal Pradesh. BCT road is located in a tough climatic and high rainfall region.

Material and Methods

The methodology involves detailed field investigation through various geological, geophysical and geotechnical investigations of two critical slopes. Laboratory investigations were performed to determine the strength properties of the slope materials. The data gathered from these field and laboratory investigations were then used in numerical modelling to evaluate the slope stability conditions.

Field investigations

Geological mapping: The field investigation comprised of different types of investigations. The first topography and contour survey was conducted to find out the details of the terrain to prepare topographical and contour maps of both slopes. Through geological mapping, lithology and structures present in the region were identified, which were further used during numerical modelling.

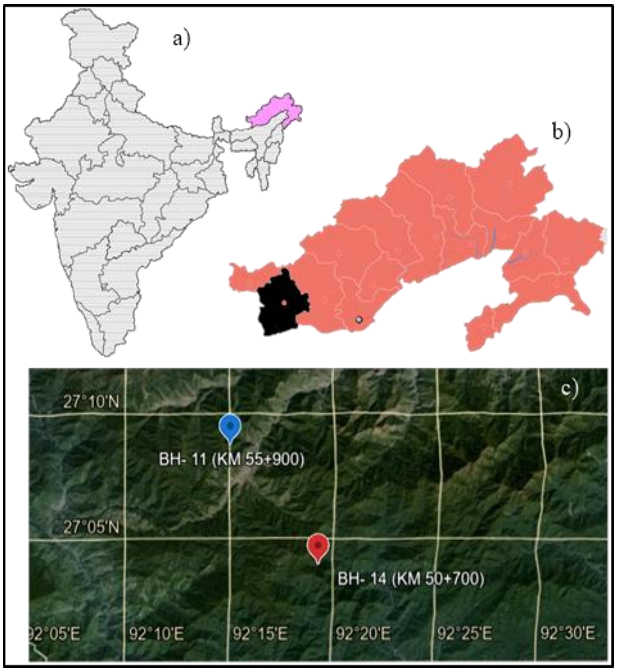

Fig. 2: Location map of studied slopes a) map of India, b) map of Arunachal Pradesh and c) slope locations

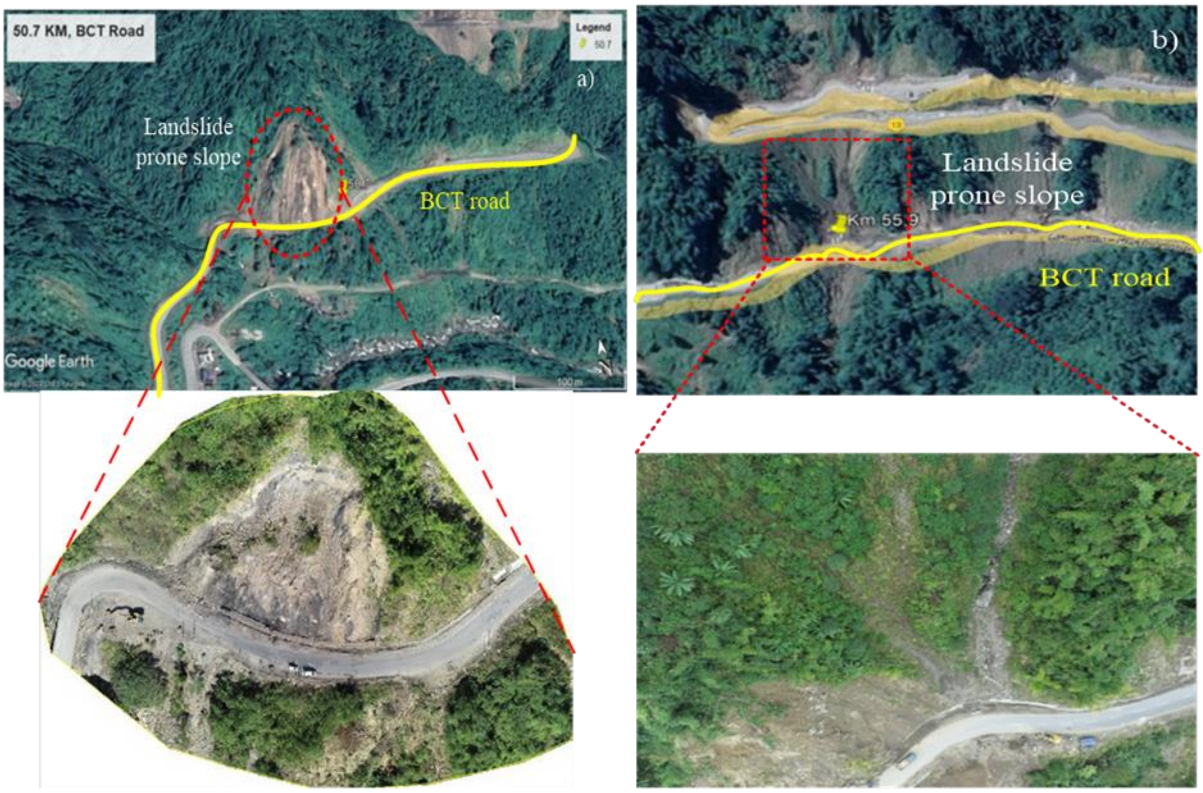

Fig. 3: Google Earth images of critical slopes at a) 50.7 KM chainage and b) 55.9 KM chainage

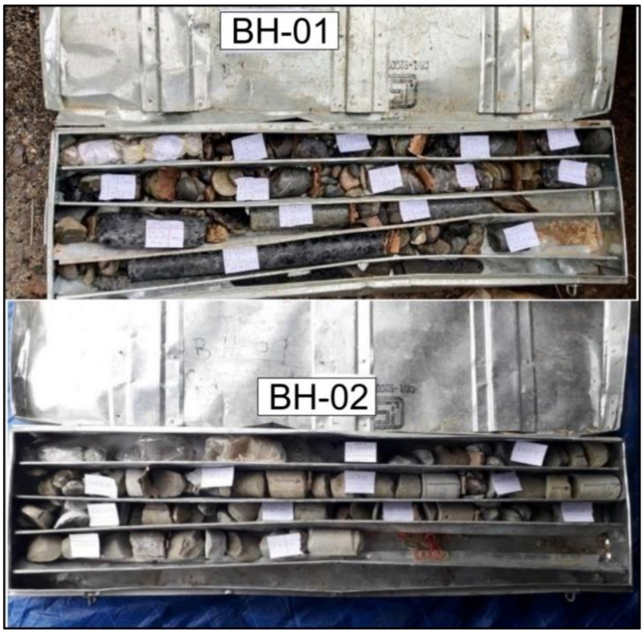

Fig. 4: Core boxes of two drill holes

Borehole investigation: Geotechnical borehole investigations were conducted to establish the lithology of both slopes. Soil samples were obtained using a split spoon sampler through the standard penetration test (SPT) at intervals of 1.50 m as per codal provisions. Diamond coring with a double-core barrel was used when formations were encountered in the borehole. Two boreholes were drilled on the landslide's surface and complete cores were extracted. These boreholes were drilled at specific locations, 15.0 m below the average existing ground level. Core logging (Fig. 4) and various laboratory tests were conducted on rock and soil samples. A single borehole of 15 m depth was drilled at each slope to ascertain the lithology.

Geophysical investigation: Geophysical investigations are highly effective and convenient for detecting subsurface structures in earth materials[1,36,42]. Resistivity is the most essential feature in a geophysical investigation where a constant voltage is applied to an object and the current flowing through it is calculated using the Schlumberger configuration. An electrical resistivity test was conducted at both locations and data were recorded as per standard IS 15736 (2007). The standard values of resistivity for different materials are given in table 1.

Laboratory investigations: Laboratory tests were conducted on soil and rock samples obtained from two boreholes following the relevant Indian standard codes (Table 2). The purpose of the test was to determine various engineering properties. The soil analysis encompassed grain size analysis, specific gravity determination, natural density assessment, dry density measurement, natural moisture content determination, cohesion evaluation, friction angle determination and Atterberg's limit tests including plastic and liquid limits. Meanwhile, rock sample analysis involves UCS (Fig. 5), specific gravity, point load and tensile strength.

Numerical analysis: Based on the field and laboratory investigations, the stability for the two critical slopes was analyzed using the software 'SLIDE2' of Rocscience Inc., USA. SLIDE2 is a 2D slope stability program for evaluating the stability of circular or non-circular failure surfaces in soil or rock slopes. External loading, groundwater and support can also be modelled in various ways. SLIDE2 analyses the stability of slip surfaces using vertical slice limit equilibrium methods. Individual slip surfaces can be analyzed, or the critical slip surface can be located at a given slope. Bishop's simplified method (circular slip circles method) was used during modelling.

Table 1
Resistivity values for common geological formations (Peck et al., 1974)

Materials	Resistivity (Ω-M)
Clay and saturated silt	0 – 100
Sandy clay and wet silty sand	100 – 250
Clayey sand and saturated sand	250 – 500
Sand	500 – 1500
Gravel	1500 – 5000
Weathered rock	1000 – 2000

Fig. 5: Uniaxial compressive strength testing setup for rock and soil samples.

Table 2
Description of code followed for laboratory tests for different materials

Material	Test	Code followed
Soil samples	Grain size distribution	IS 2720: Part 4 (1985)
	Atterberg's limits	IS 2720: Part 5 (1985)
	Shear strength parameters	IS 2720: Part 13 (1986)
	Specific gravity	IS 2720: Part 3 (1980)
Rock samples	Unconfined compressive strength	IS 9143 (1979)
	Specific gravity	IS 1122 (1974)
	Point Load	IS 8764 (1998)
	Tensile Strength	IS 10082 (1981)

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Results and Discussion

Geology of slope: Both critical slopes are along BCT Road, in a harsh climatic and high rainfall region. During the field investigation, it was observed that the upper strata are primarily composed of overburdened, weathered material and soil-mixed boulders (SMB). At 50.7 KM chainage, the maximum slope height and angle were 76 m and 60° respectively while at 55.9 KM chainage, slope height and angle were roughly 74 m and 55°.

The geotechnical investigation at 50.7 KM chainage revealed three layers of strata. The first layer consists of gravel of phyllite, granite gneissic rock, fine to medium-grained sandy clay and soil that extends up to 6 m below ground level. The second layer consists of unweathered phyllite and granite gneiss up to a depth of 10 m from the existing ground level, while the third layer consists of mostly intact granite gneissic rock up to the borehole's termination depth, which is 15 m from the existing ground level. While at 55.9 KM chainage, two layers of strata were found. The first layer is medium-dense fine to medium-grained silty clay with gravels up to 7 m depth from the existing ground level. In contrast, the second layer is gneissic rock up to termination depth, which is 15 m from the existing ground level.

Geotechnical characteristics: Geotechnical properties determined from borehole investigations at two different locations along a specific road section (K.M. 50+700 and K.M. 55+900) identified as borehole (B.H.) no. 1 and borehole (B.H.) no. 2 respectively, are given in table 3. The boreholes were drilled to varying depths, ranging from 1.00 to 5.00 meters. The grain size analysis soil composition found in boreholes predominantly consists of sand, with a percentage ranging from 75.7% to 79.0%, followed by silt content between 17.8% and 21.3%. Gravel content is minimal, ranging from 2.6% to 3.4%. The unit weight of the soil samples remains consistent across both boreholes, approximately 1.9 to 1.904 gm/cc. The soils in these boreholes are classified as non-plastic.

According to the Indian Standard (I.S.) classification, all samples fall under the S.M. category, indicating silty sand. Direct shear tests (D.S.) were conducted on the samples and the results show angles of friction ranging from 24° to 27°. The specific gravity of the soil is relatively uniform, approximately 2.67 to 2.68. The laboratory investigation showed that the soil primarily consists of silty sand with relatively good shear strength, making it moderately stable. However, the low clay content and non-plastic nature may infer limited cohesion.

Table 4 shows the mechanical parameters of rock samples from two boreholes, borehole no. 1 (K.M. 50+700) and borehole no. 2 (K.M. 55+900), located at depths of 12.00 m and 13.00 m. In B.H. 1, as the depth increases from 12.00 m to 13.00 m, so does the unit weight (from 2.670 to 2.680 gm/cc), unconfined compressive strength (UCS) (from 21.0 to 23.5 MPa), tensile strength (from 7.46 to 8.66 MPa) and point load strength (from 0.86 to 0.97 MPa), indicating that the rock strengthens with depth. The specific gravity is steady at 2.72, indicating a continuous mineral composition. In contrast, B.H. 2 at 13.00 m depth has somewhat lower values in unit weight (2.650 gm/cc), UCS (21.2 MPa), tensile strength (7.05 MPa) and point load strength (0.88 MPa), indicating that the rock in B.H. 2 is somewhat weaker compared to B.H. 1 at the same depth.

Geophysical Investigation: The electrical resistivity (ERT) test showed that the resistivity value is between 46 to 614 ohm-m at KM 50.7 and 5 to 63 ohm-m at KM 55.9 (Fig. 6). ERT results validated that the top strata mostly comprise of overburdened soil and some portions show soil-boulder (weathered rock) mix strata. At the 50.7 KM chainage, the resistivity is 97 ohm-m up to a depth of 6 meters, indicating the presence of fine sandy clay.

Following this, the resistivity increases, revealing weathered rock up to a depth of 11 meters. Beyond the depth of 11 m, the resistivity values are inconsistent, attributed to the presence of non-uniform rock strata. However, this rock stratum is non-uniform, as the higher resistivity values are not observed at the centre and right side of the borehole. Below this layer, fragments of weathered rock or granite gneiss are identified, as reflected by the resistivity values. The resistivity in the uppermost layers indicates a mixture of soil and gravel, with some fines present (Fig. 6a to 6c). While at the 55.9 KM chainage, resistivity values ranging from 5 to 30 ohm-meters are observed up to a depth of 7 meters, indicating the presence of fine soil mixed with some gravel.

Table 3
Properties of soil samples

Material	Test	Code followed
Soil samples	Grain size distribution	IS 2720: Part 4 (1985)
	Atterberg's limits	IS 2720: Part 5 (1985)
	Shear strength parameters	IS 2720: Part 13 (1986)
	Specific gravity	IS 2720: Part 3 (1980)
Rock samples	Unconfined compressive strength	IS 9143 (1979)
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	Tensile Strength	IS 10082 (1981)

Beyond this depth, a resistivity value of 10,000 ohm-meters suggests the presence of solid rock. The depths at which the resistivity value exceeds 10,000, vary for three testing points along the bore location. This observation indicates that the rock is non-uniform along the slope. The depth at which this rock stratum is encountered varies across the three testing points, indicating non-uniformity in the rock layer's location (Fig. 6d to 6f).

Numerical analysis and mitigation measures: The stability of both critical slopes was evaluated through a numerical modelling technique. The grids of global minimum using the Bishop method are plotted with colour contours. The required factors of safety (FOS) are 1.05 and 1.30 for the seismic and static cases respectively as per WSDOT- geotechnical design manual of Allen[2] and IRC landslide correction techniques IRC: SP:106 (2015). In the static case, gravity load on the whole model and a uniform load of 24 kN/m were applied on the road line. At the same time, the acceleration of 0.18g in the horizontal and 0.12g in the vertical direction is applied for seismic case analysis. The soil and rock properties used during SLIDE2 modelling are determined from the different geotechnical laboratory testing (Table 5).

Figures 7a, c and figures 8a and c show the factor of safety for the critical slope sections under static and dynamic conditions respectively. The FOS value for slope 55.7 KM chainage in static conditions is 0.99, while in dynamic conditions, it is 0.78 and for chainage 55.9 KM, it is 0.833 in static conditions and 0.638 in dynamic conditions. The numerical analysis results show that the FOS for both slopes at present conditions is less than the minimum required value. So, the reinforcement measures were used to stabilise the slopes.

However, after installing soil nails, the FOS achieves the minimum required value (Fig. 7b, d and Fig. 8b, d). Without any mitigation methods, FOS reveals that slopes are unstable. Bond strength for nails and anchorages is given based on *in situ* material properties (Table 5).

Table 4
Properties of rock samples

Bore Hole No.	Depth (m)	Unit Weight (gm/cc)	UCS (MPa)	Sp. Gravity	Tensile Strength (MPa)	Point Load (MPa)
B.H.- 1 (KM 50+700)	12.00	2.670	21.0	2.72	7.46	0.86
BH- 1 (KM 50+700)	13.00	2.680	23.5	2.72	8.66	0.97
BH- 2 (KM 55+900)	13.00	2.650	21.2	2.72	7.05	0.88

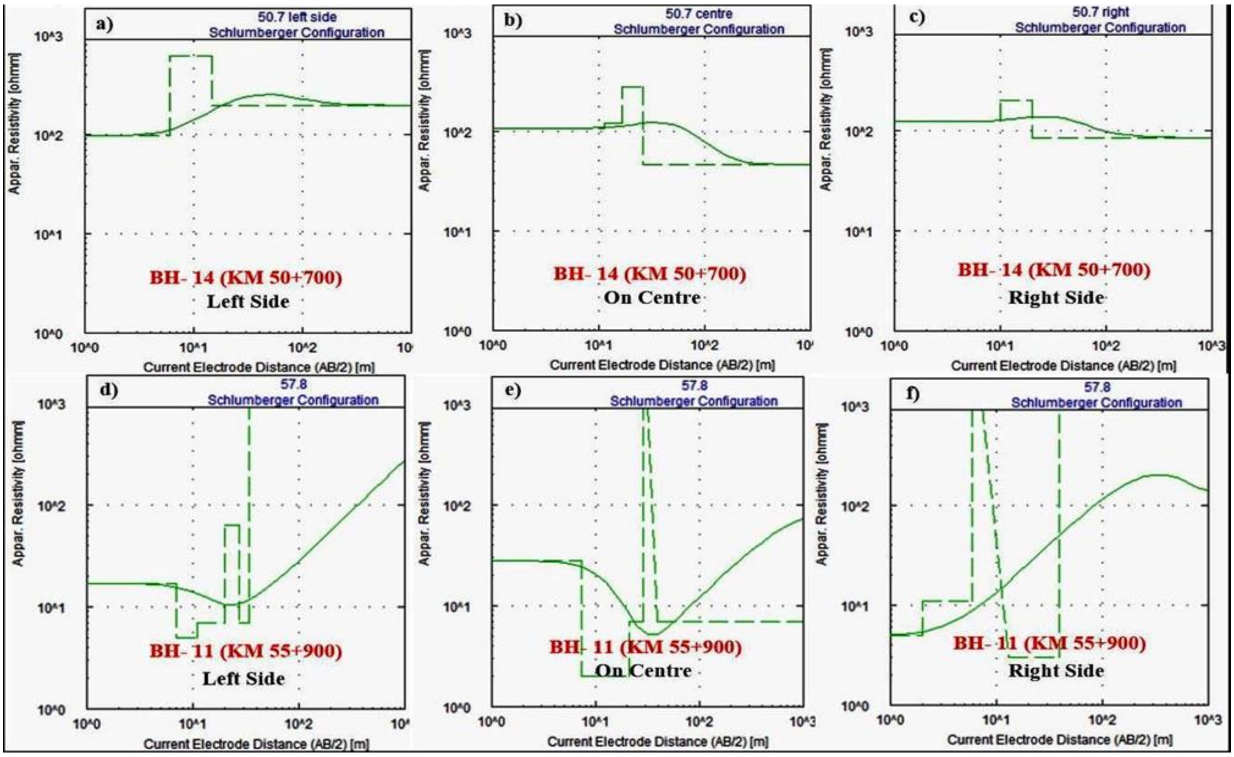

Fig. 6: ERT outcome a) to c) at 50.7 KM chainage and d) to f) at 55.9 KM chainage

The soil nails' tensile capacity is 230 kN and the plate capacity is 5 kN. The diameter of self-driven anchors is chosen to be 32 mm with a minimum hole diameter of 90 mm. However, the prestressed anchorages are provided as active members with tensile and plate capacities of 1094 kN and 547 kN respectively. The percentage of bond length is set as 30% of the anchor length. A numerical analysis shows that the proposed mitigation methods provide the minimum requirement FOS for a stable slope (Table 7).

Conclusion

The Vartak region is prone to frequent slope instabilities. The present study focuses on the comprehensive geotechnical characterisation of subsoil and rock. In addition, an electrical resistivity test of the slope surface was conducted, along with a numerical analysis of two critical slopes located along the BCT road section at two different chainages. The key findings from field, laboratory and numerical studies include:

1. The topographical survey of the slopes reveals details about the slope geometry. At the 50.7 KM chainage, the slope height ranges from 24 to 76 meters, with the slope angle in the critical section varying from approximately 35° to 60°. Similarly, at the 55.9 KM chainage, the slope height ranges from 60° to 74 meters, with the slope angle in the critical section varying from approximately 35° to 55°.
2. The field study results including borehole and geophysical investigations, were used to characterize the subsurface stratigraphy. Laboratory analysis identified the soil as silty sand (S.M.) overlaying bedrock. An electrical resistivity test showed that the resistivity is 46 to 614 ohm-m at KM 50.7 and 5 to 63 ohm-m at KM 55.9. Both field and laboratory findings indicated that the primary source of debris flow was a loose and soft soil layer characterized by low permeability and plasticity interspersed with boulders.
3. Slope stabilization and erosion control measures for cut slopes on the hillside and drainage techniques are proposed to avoid any incidents during the rainfall season.

Table 5
Material properties used during SLIDE2 modelling.

Chainage	Layer	Material type	Unit weight (kN/m3)	Cohesion (kPa)	Angle of friction (°)	Bond strength for drill hole dia of 90mm (kN/m)
95+580 KM	*In situ* -1	Soil	18	12	21	24
	In situ -2	Soil	19	14	21	24
	Bedrock	Rock	24	100	35	48
95+600 KM	*In situ* -1	Soil	18.6	23	25	24
	In situ -2	Soil	18.6	23	27	25
	Bedrock	Rock	26	200	40	46

Table 6
Bond strength property for different strata

Chainage	Material/ layer	Bond strength for drill hole dia of 90mm (kN/m)
50.7 KM	*In situ* -1	24
	In situ - 2	25
	Bedrock	42
55.9 KM	*In situ* - 1	29
	Bedrock	51

Table 7
Summary of factors of safety after remedial measures for different cases

Chainage	Remedy material	No.	Location	Length (m)	Spacing (m)	FOS without remedy		FOS with remedy	
						Static	Seismic	Static	Seismic
50.7 KM	Soil nail	22	From top	16	2	0.990	0.780	1.312	1.088
		23		18	2				
	Prestressed anchors	5	At toe	25	3				
55.9 KM	Soil nail	8	From top	11	2	0.833	0.638	1.312	1.090
		35		9	2				
		7		8	2				

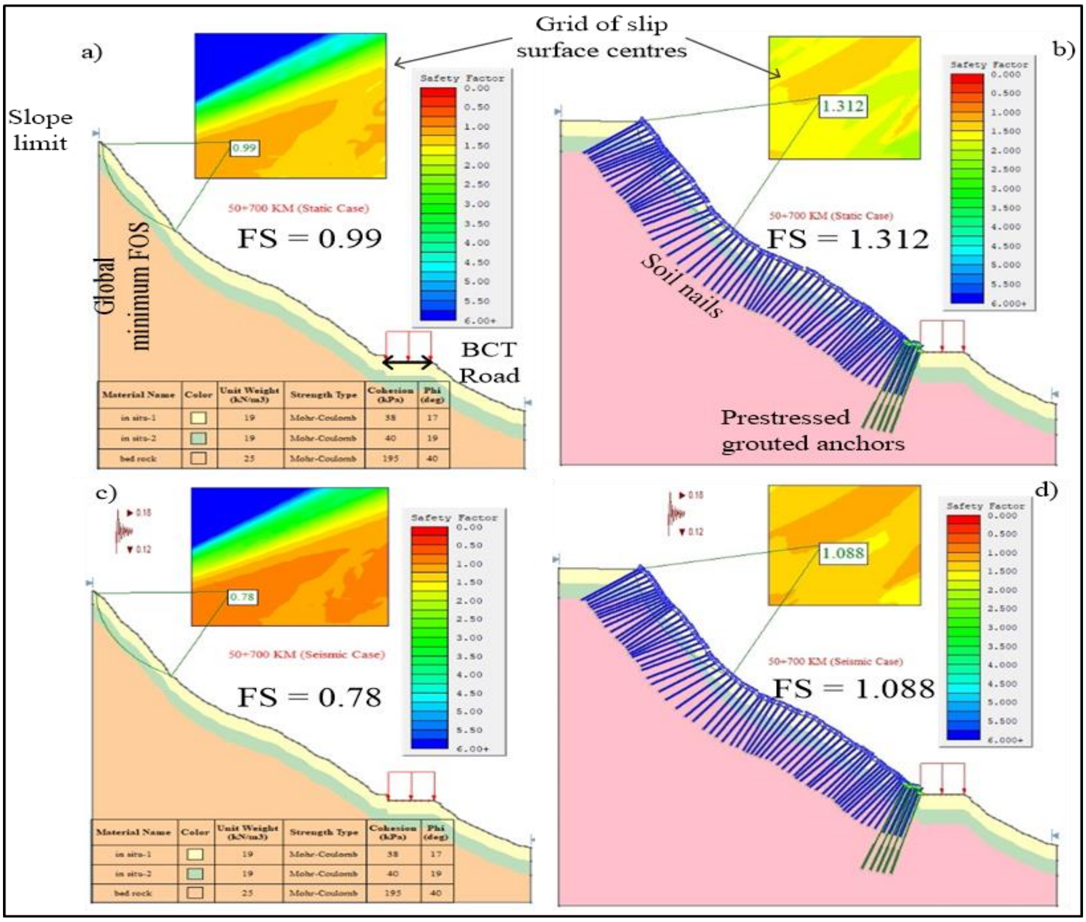

Fig. 7: Numerical analysis of slope section at 50+700 K.M. chainage for a) static loading without mitigation, b) static loading with mitigation, c) seismic loading without mitigation and d) seismic loading with mitigation

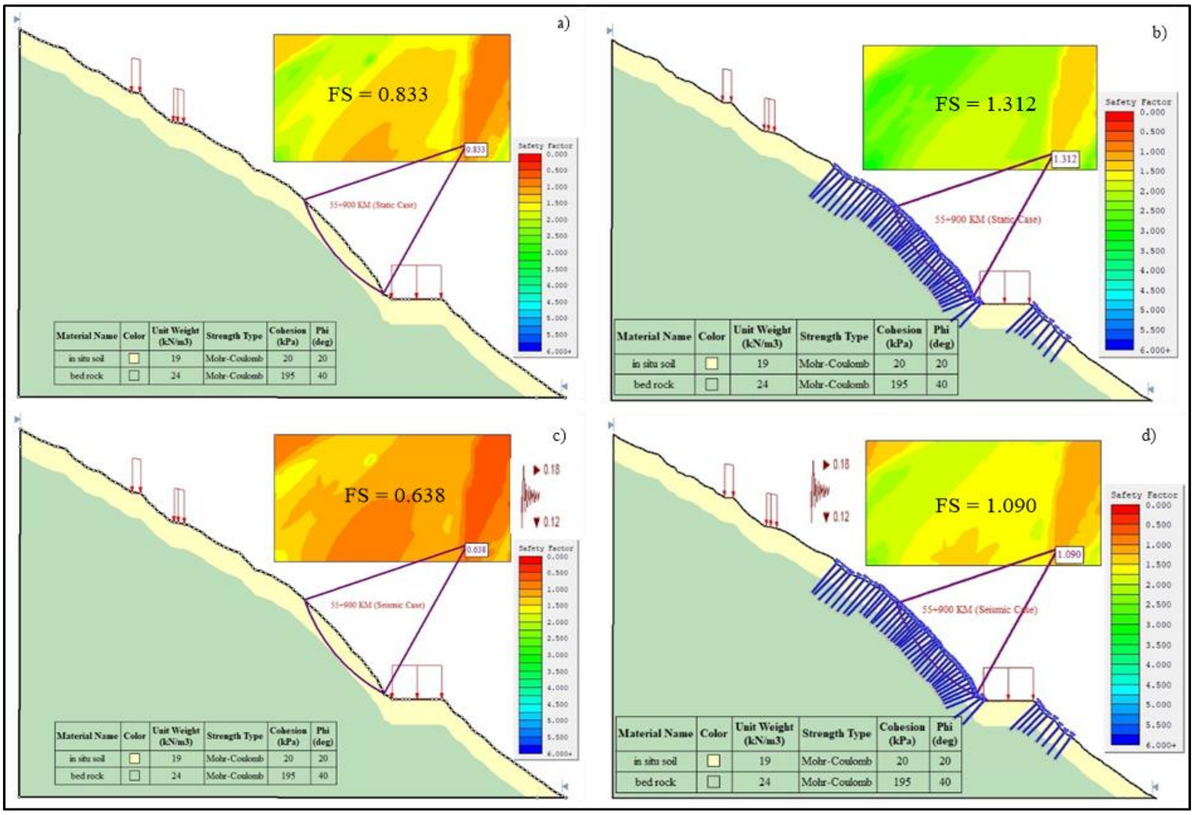

Fig. 8: Numerical analysis of slope section at 55+900 K.M. chainage for a) static loading without mitigation, b) static loading with mitigation, c) seismic loading without mitigation and d) seismic loading with mitigation

4. The factor of safety (FOS) without any mitigation measures indicates that the slopes are susceptible to landslides. However, a numerical analysis demonstrates that the proposed mitigation methods meet the minimum safety requirements for stabilizing the slope.

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