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Landslide hazard zonation mapping and cut slope stability analyses along Yercaud ghat road (Kuppanur–Yercaud) section, Tamil Nadu, India

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Abstract

In the present study, the macro landslide hazard zonation (LHZ) mapping and slope stability analyses of selected rock slope (RS) sections were carried out along Kuppanur–Yercaud ghat road section. The macro LHZ map was prepared on 1:50,000 scale using landslide hazard evaluation factor (LHEF) rating scheme proposed by Bureau of Indian Standard IS 14496 (Part-2) 1998. The study incorporated predefined ratings for different causative factors viz. lithology, structure, slope morphometry, relative relief, land use and land cover, and hydrogeological condition as well as triggering factors like seismicity and rainfall. The total estimated hazard (TEHD) was evaluated by adding ratings of all the causative factors. On the basis of TEHD values, the facet 3 with TEHD value 6.25 was classified as high hazard zone (HHZ). The facet 2 and 4 with TEHD values 5.50 and 5.40 respectively was classified as moderate hazard zones (MHZ). The facet 1 and 5 with TEHD values 2.20 and 3.15 was categorized as very low hazard zone (VLHZ). The slope stability analyses were carried out in six RS sections using rock mass rating (RMR) and slope mass rating (SMR) systems and the factor of safety (FOS) was evaluated for critical discontinuity sets. The results of RMR show that RS sections 1, 2, 4, 5, and 6 fall in class-III fair rock category, whereas the RS section 3 falls in class-IV poor rock category. The SMR method involves field measurement of slope and discontinuity orientation. These structural values were plotted in the stereonet and identified possible direction and mode of failure. The results of SMR show that the rock sections 1, 2, 4, 5, and 6 falls under partially stable condition, while the rock section 3 comes under unstable condition. The FOS of the critical discontinuity sections was evaluated for planar as well as wedge failure modes. The results based on planar failure analysis, the RS-2 and RS-3 having FOS < 1 are more unstable for slope failure. The wedge failure analysis shows that all the RS sections having FOS > 1 fall in safe conditions.

Keywords: Landslide hazard zonation, Slope stability analyses, LHEF rating scheme, Rock mass rating (RMR), Slope mass rating (SMR), Factor of safety (FOS)

Background

Landslide is an important natural calamity, which frequently occurs on natural slopes as well as cut slopes of ghat roads in mountainous region, causing risk to human life and properties each year [2, 45]. The occurrence of landslides in mountainous regions is

subjected to influence of different causative factors and are triggered by rainfall, earthquake shaking, water level change, storm waves and rapid stream erosion etc. [18, 46]. In addition, the anthropogenic activities on hill slope such as construction of roads, urban expansion, deforestation, and changes on land use practices increases the landslide occurrences [19]. The discrimination and mitigation of landslide prone areas in a region are essential for future planning and developmental activities. Globally, the governments as well as several research institutions have been spending significant resources to assess the landslide hazards and their spatial distribution [26]. The evaluation of landslide hazard is a vital task for different interest groups such as geoscientists, planners and local administrations, because of the situation of increased awareness and the socio-economic impact of landslides [21]. Landslide hazard refers to the possibility of occurrence of certain type and magnitude of landslide at a particular location within a specified period of time. LHZ mapping involves the discrimination of identical areas of varying hazard levels based on degrees of actual or potential damage [77]. LHZ map shows probable areas of landslide occurrence and useful for better land use planning and the progress of suitable remedial measures. The LHZ map can be used for developmental activities and management of natural resources in an area [76].

Landslide hazard and susceptibility zonation mapping have been carried out by using various methods and techniques using different scales based on the requirement of the end user and the rationale of the investigation [26]. Different landslide hazards and susceptibility mapping methods described by Mantovani et al. [39] include distribution analysis [16, 22, 78], qualitative analysis [17, 41, 43], statistical analysis [53, 55, 67], deterministic analysis [1, 6, 44, 68], landslide frequency analysis [12, 32, 40, 42], and distribution-free methods such as fuzzy logic [34, 36, 52–54, 69] and artificial neural network (ANN) models [13, 15, 51, 80]. Many researchers adopted the Bureau of Indian Standard [BIS 14496 (Part 2): 1998] guidelines to prepare the landslide hazard zonation mapping [5]. The BIS guidelines [11] were originally proposed by Anbalagan [3], which suggest a quantitative method based on conventional field surveys called landslide hazard evaluation factor (LHEF) rating scheme for Himalaya region. Number of researchers have carried out the landslide hazard zonation mapping based on LHEF rating scheme on different scales using varying number of parameters with some revision for different terrains [4, 5, 33, 35, 60–62, 65].

In mountainous region, the inappropriate modification adopted on natural slope condition for the purpose of construction and widening of the transportation network affects the stability of the cut slope [68]. The understanding and analyses of geotechnical characteristics of soil and rock give the possibility of occurrence of landslide in a specific site. The stability of a required and existing rock slope can evaluate rapidly and reliably using rock mass classification systems [70] on the basis of structural and other geotechnical parameters [49]. The geomechanical classification or the RMR system was first proposed by Bieniawski [8] for the application of stability assessment for designing tunnels, mine, dam, and underground excavations. The RMR system in the evaluation of slope stability was introduced by Bieniawski [9]. Different geomechanical classification systems have been proposed to assess the slope stability of a rock mass [73] which includes, rock mass strength [63], slope mass rating system [57], slope rock mass rating [56], rock mass rating [10], mining rock mass rating [37], mining rock mass rating modified [29], natural slope methodology [66], chinese slope mass rating [14], modified rock mass rating [75], slope

stability probability classification [27, 28], slope stability probability classification modified [38], continuous rock mass rating [64], continuous slope mass rating [72, 74] and an alternative rock mass classification system proposed by Pantelidis [50]. The SMR is the commonly used classification system globally [59] and can be derived from the RMR_{basic} [10]. The RMR_{basic} and SMR classifications system provides a specific rating for individual parameter and describes the slope stability in terms of total RMR_{basic} and SMR values.

The BIS guidelines [11] for LHZ mapping in mountainous terrain at medium scale (1:50,000) were used in the present study. The LHZ map was prepared for the Kuppanur–Yercaud ghat road section using LHEF rating scheme [11], which suggests indirect heuristic (knowledge-driven) method to LHZ mapping without taking into consideration of landslide inventory data [23]. The ghat road section covers small aerial extent, hence the technique is more appropriate to evaluate the causative factors through field surveys. The cut slope stability assessment of rock slopes was also assessed along this ghat road section at selected locations using RMR system [10] and SMR system [58]. The FOS for the critical rock slope sections was calculated by using Hoek and Bray [31] method.

Study area

Yercaud hill is one of the important tourist spots in Tamil Nadu, situated in Shervaroy's hills of Salem district, Tamil Nadu. The hilly region is connected by ghat road section constructed with minor hairpin bends. The length of the ghat road is 27 km, which connects the foot hills at Kuppanur to Yercaud at top of the hill. This 27 km ghat road crosses the settlements Kotanchedu, Kirakadu, and Sengadu. The general relief of the Yercaud (Alternate) ghat section is ranges from 400 to 1450 m above mean sea level (AMSL). The lowest altitude of 400 m is present near the Yercaud foothills (Kuppanur Village). The highest altitude of 1450 m is present near the Longlipettai area. The annual rainfall ranges between 1500 and 2000 mm. The 12 km ghat road sections from Kuppanur to Kottanchedu have many vertical rock and soil slopes with considerable slope height has chosen for the present study. The remaining section of the road constructed nearly parallel to the contour and drainage, hence there are no cut slopes found. The area falls in between $11^{\circ}44'31''$ N and $11^{\circ}47'2''$ N latitudes and $78^{\circ}15'28''$ E and $78^{\circ}16'39''$ E longitudes. The Survey of India (SOI) topographical map series numbers 58 I/5 and 58 I/6 is covering the study area (Fig. 1). This ghat road section is an alternative route to reach the Yercaud hills. The geological setting in the study area has shown that highly fissile charnockite and gneiss with area covered by smaller ultramafic rock of serpentine-dunite in the southwestern part (GSI [25]). The hill top is a plateau region marked by high peaks and undulating terrain. In addition, the hill comprises of steep slopes, gullies, valleys and fractures.

Methods and parameters

LHEF rating scheme

The LHZ map was prepared based on the guidelines of BIS code [IS 14496 (Part 2): 1998]. The BIS guidelines is a Indian standard developed for the purpose of preparation of LHZ maps in mountainous terrains. The method and procedure described in BIS guidelines is LHEF rating scheme. The LHEF rating scheme is a numerical system, which

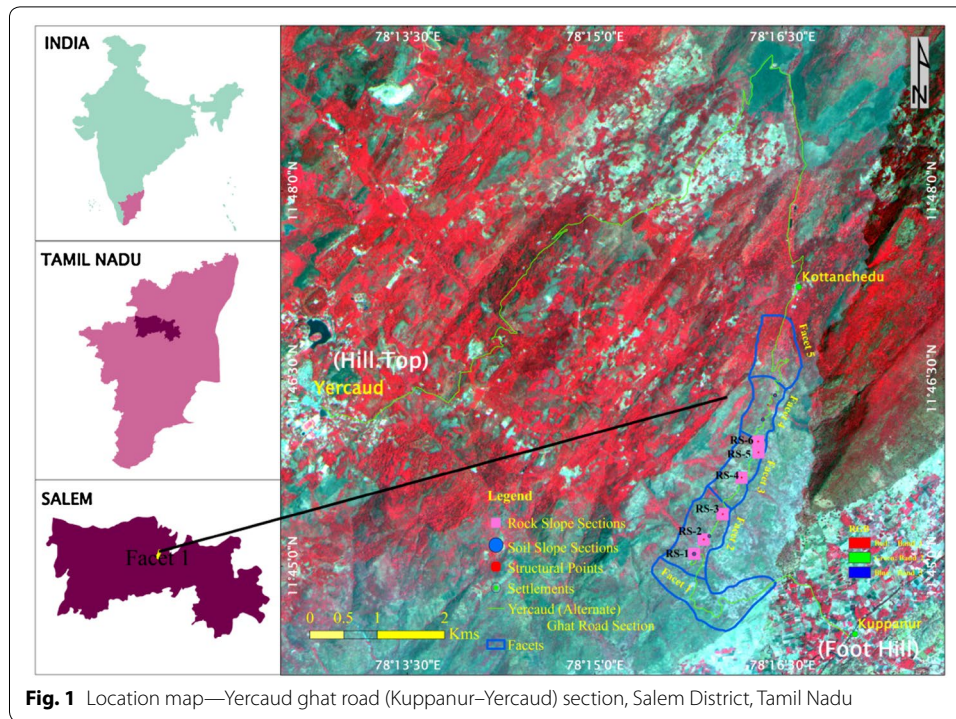


Fig. 1 Location map—Yercaud ghat road (Kuppanur–Yercaud) section, Salem District, Tamil Nadu

describes the slope instability in terms of cumulative effect of the major causative factors of the slope instability [11]. The lithology, structure, slope morphometry, relative relief, land use and land cover, and hydrogeological condition are the major parameters considered in the LHEF rating scheme. Apart from six in-built causative factors, the triggering factors like seismicity and rainfall were also included in LHEF rating scheme [4]. The facet-wise analyses were carried out on causative factors according to the maximum LHEF rating given in Table 1. The ratings for the sub-categories in each causative factor were assigned using the LHEF rating scheme given in BIS guidelines (Table 2).

A slope facet is the smallest section which is divided using ridges, spurs, gullies and rivers for the analysis of each causative factor in LHEF rating scheme. It is a part of hill slope which has more or less identical characteristics of slope, showing regular slope

Table 1 Maximum LHEF rating for causative factors (source: [4, 11])

Causative factor	Maximum
Lithology	2.0
Structure	2.0
Slope morphometry	2.0
Relative relief	0.5
Land use and land cover	2.0
Hydrogeological condition	1.5
Correction due to triggering factors (to be added separately to the total of LHEF)	
a) Seismicity	0.5
b) Rainfall	0.5
Corrected LHEF rating	11.0

Table 2 Landslide hazard evaluation factor (LHEF) rating scheme (Source: [5, 11])

Contributory factor	Category	Rating	
A. Lithology			
(i) Rock type	Type-I		
	Quartzite and limestone	0.20	
	Granite and gabbro	0.30	
	Gneiss	0.40	
	Type-II		
	Well cemented sedimentary rock dominantly sandstone with minor beds of clay stone	1.00	
	Poorly cemented terrigenous sedimentary rock dominantly sandstone with minor clay shale beds	1.30	
	Type-III		
	Slate and phyllite	1.20	
	Schist	1.30	
	Shale with interbedded clayey and non-clayey rocks	1.80	
	Highly weathered shale, phyllite and schist	2.00	
	(ii) Soil type	Older well compacted alluvial fill material	0.80
		Clayey soil with naturally formed surface	1.00
Sandy soil with naturally formed surface (alluvial)		1.40	
Debris comprising mostly rock pieces mixed with clayey/sandy soil (colluvial)			
Older well compacted		1.20	
Younger loose material		2.00	
Remarks —correction factor for weathering of rock			
Highly weathered—rock discoloured, joints open with weathered products, rock fabric altered to a large extent—correction factors C1			
Moderately weathered—rock discoloured with fresh rock patches, weathering more around joint planes, but rock in-tact in nature—correction factor C2			
Slightly weathered—rock slightly discoloured along joint planes, which may be moderately tight to open, intact rock—correction factor C3			
The correction factor for weathering to be multiplied with the fresh rock rating			
For rock type 1: $C_1 = 4, C_2 = 3, C_3 = 2$			
For rock type 2: $C_1 = 1.5, C_2 = 1.25, C_3 = 1.0$			
B. Structure			
(i) Relationship of parallelism between the slope and the discontinuity			
Planar ($\alpha_1 - \alpha_2$)	I	>30° 0.20	
Wedge ($\alpha_1 - \alpha_2$)	II	21°–30° 0.25	
	III	11°–20° 0.30	
	IV	6°–10° 0.40	
	V	<5° 0.50	
	(ii) Relationship of dip of discontinuity and inclination of slope		
Planar ($\beta_1 - \beta_2$)	I	>10° 0.30	
Wedge ($\beta_1 - \beta_2$)	II	0°–10° 0.50	
	III	0° 0.70	
	IV	0°–(–)10° 0.80	
	V	>(–) 10° 1.00	
	(iii) Dip of discontinuity		
Planar ($\beta_1 - \beta_2$)	I	<15° 0.20	
Wedge ($\beta_1 - \beta_2$)	II	16°–25° 0.25	
	III	26°–35° 0.30	
	IV	36°–45° 0.40	
	V	>45° 0.50	

Table 2 continued

Contributory factor	Category		Rating
(iv) Depth of soil cover		<5 m	0.65
		6–10 m	0.85
		11–15 m	1.30
		16–20 m	2.00
		>20 m	1.20
Remarks —discontinuity refers to the planar discontinuity or the line of intersection of two planar discontinuities whichever is important from the point of view of instability			
α_j = Dip direction of joint; α_s = Direction of slope inclination;			
α_i = Direction of line of intersection of two discontinuities; β_j = Dip of joint;			
β_s = Inclination of slope; β_i = Plunge of line intersection of two discontinuities			
Category I = very favourable; II = favourable; III = fair; IV = unfavourable; V = very unfavourable			
C. Slope morphometry			
	Escarpment/cliff	$\geq 45^\circ$	2.0
	Steep slope	36° – 45°	1.7
	Moderately steep slope	26° – 35°	1.2
	Gentle slope	16° – 25°	0.8
	Very gentle slope	$\leq 15^\circ$	0.5
D. Relative relief			
	Low	<100 m	0.3
	Medium	101–300 m	0.6
	High	>300 m	1.0
Remarks —In regions of low seismic activity (1, 2 and 3 zones), the maximum rating for relative relief may be reduced to 0.5 and that of hydrogeological conditions be increased to 1.5 (Table 1). Accordingly the detailed ratings of these contributory factors (Table 2) may be multiplied by 0.5 and 1.5 respectively. For seismic zones 4 and 5, no corrections are required.			
E. Land use and land cover			
	Agricultural land/populated flat land		0.6
	Thickly vegetated forest area		0.8
	Moderately vegetated area		1.2
	Sparsely vegetated area with lesser ground cover		1.5
	Barren land		2.0
F. Hydrogeological conditions			
	Flowing		1.0
	Dripping		0.8
	Wet		0.5
	Damp		0.0
	Dry		0.2

amount and direction. In the present study, the Kuppanur–Yercaud ghat road section was divided into slope facets for assessment of individual LHEF. There were five facets with homogeneous terrain conditions was divided using topographical map based on slope inclination, relief (elevation difference), and slope direction.

The rock type and its resistance to the weathering and erosion process is one of the significant aspects in controlling slope stability [48]. The lithology map was prepared from the district resource map published by Geological Survey of India [24]. The charnockite is the main lithological unit in the study area. Hence, the ratings were evaluated by applying weathering condition of rocks in each facet. The geological structures such as bedding planes, joints, foliations, faults and thrusts are the discontinuities associated

with the in situ rocks over hill slopes, which play a major role in the occurrence of landslides. The relationship between the structural discontinuities and slope inclination has greater influence on slope instability. The relationships given in the LHEF scheme are (1) parallelism between the direction of slope and the discontinuity, (2) dip of discontinuity and inclination of slope, (3) dip of discontinuity [61]. The structural ratings for each facet were evaluated from the structural relationships of discontinuities with slope. In case of soil and debris slopes, the ratings were assigned based on the depth of soil and overburden. The structural point (SP) and soil slope point locations are shown in Fig. 1.

Slope morphometry map shows the different classes based on the frequency of occurrence of particular angles of slope [11]. The same number of contour lines per kilometre of horizontal distance exists within a facet was evaluated. In LHEF rating scheme, five different slope categories were used to represent the slopes; escarpment and cliff ($>45^\circ$), steep slope ($36^\circ\text{--}45^\circ$), moderately steep slope ($26^\circ\text{--}35^\circ$), gentle slope ($16^\circ\text{--}25^\circ$) and very gentle slope ($<15^\circ$). The temperature decline and rainfall affect the natural conditions at higher elevations, which support the occurrence of landslides [7]. Relative relief determines the maximum height of a facet from minimum value to maximum value measured along slope direction for each facet was evaluated using the topographical map. In LHEF rating scheme, three relative relief categories are described as low (<100 m), medium (101–300 m) and high relative relief (>300 m) zone.

Vegetation cover protects and controls the slope from the soil erosion and landslides [71]. Hence, it is necessary to consider the land use and land cover factor in landslide studies. The land use and land cover map were interpreted using ResourceSat2 LISS IV satellite image with the spatial resolution of 5.8 m and topographical map.

The hydrological properties of an area controlled by streams, rivers, underground water, saturation state of rocks/soils, and drainage pattern present in an area play a vital role in slope failure [35]. In hilly terrain, irregular flow of groundwater in rock slopes along structural discontinuities decreases shear strength of slope forming material and increases the possibility of slope failure. This irregular flow of groundwater seeps out and could be identified as surface indications along cut slope sections. The LHEF scheme suggests a direct method of field observation to identify the surface indication of hydrogeological conditions visually as flowing, dripping, wet, damp and dry and the ratings were assigned accordingly. It is desirable to take field data soon after the monsoon season [4].

The facet-wise LHEF ratings were evaluated for all the causative factors to calculate the total estimated hazard (TEHD). The ratings for seismicity and rainfall were added with TEHD to evaluate the final TEHD values for each facet. On the basis of final TEHD values, five classes of landslide hazard zones were classified as very low (TEHD < 3.5), low (3.51–5.0), moderate (5.01–6.5), high (6.51–8.0) and very high (TEHD > 8.01) hazard zones [4].

Rock mass rating (RMR_{basic}) system

The RMR_{basic} system [10] considered five parameters viz. Uniaxial Compressive Strength (UCS), Rock Quality Designation (RQD), spacing of discontinuities, condition of discontinuities, and groundwater conditions and its ratings (Table 3). A maximum RMR_{basic} value is 100, which can be obtained by adding the ratings of individual parameters. Based on the total RMR_{basic} , five classes are defined in the system as very poor rock (class V: 0–20), poor rock (class IV: 20–40), fair rock (class III: 40–60), good rock (class

Table 3 Rock mass rating (RMR) system and their ratings (after [10])

Parameters	Range of values				
Point-load Strength index (Mpa)	>10	4-10	2-4	1-2	For this low range uniaxial compressive test is preferred
Rating	15	12	7	4	0
Rock quality designation (RQD), %	90-100	75-90	50-75	25-50	<25
Rating	20	17	13	8	3
Spacing of discontinuities	>2 m	0.6-2.0 m	200-600 mm	60-200 mm	<60 mm
Rating	20	15	10	8	5
Condition of discontinuities	Very rough surfaces, not continuous, no separation, unweathered wall rock	Slightly rough surfaces, separation <1 mm, slightly weathered wall	Slightly rough surfaces, separation <1 mm, highly weathered wall	Slickensided surfaces, or Gough <5 mm thick, or separation 1-5 mm, continuous	Soft gouge >5 mm thick, or separation >5 mm, continuous
Ratings	30	25	20	10	0
Ground water	Completely dry	Damp	Wet	Dripping	Flowing
Rating	15	10	7	4	0

II: 60–80), and very good rock (80–100). The point load test was carried out using AIM-206-1 testing machine and the strength index was calculated using the Eq. (1)

$$I_{L(50)} = P/(DW)^{0.75} \sqrt{D} \text{ MN/m}^2 \tag{1}$$

where, $I_{L(50)}$ —point load lump strength index in kgf/cm^2 ; P—Peak load at failure in kgf ; DW—the minimum cross sectional area in cm^2 ; D—mean cross sectional thickness of specimen in cm ; W—mean width of specimen in cm ; D—standard size of lump (5 cm).

The RQD was evaluated through volumetric joint count method i.e. sum of the number of joints per metre cube (unit volume) for all joint sets [47] as given in Eq. (2)

$$\text{RQD} = 115 - 3.3 J_v \tag{2}$$

where, J_v is the sum of the number of joints per metre cube for all joint (discontinuity) sets.

The term discontinuity covers joints, beddings or foliations, shear zones, minor faults, or other surfaces of weakness, which are common features in rock masses [20]. Discontinuity spacing measures the distance between two adjacent discontinuities should be measured for all sets of discontinuities [79]. Discontinuity condition measures the discontinuity length, separation, roughness, infilling, and weathering condition of weak planes are measured in the field. The groundwater condition of a particular slope is completely dry, damp, wet, dripping and flowing, which can be measured based on nature of surface indications [3, 11].

Slope mass rating (SMR) system

The SMR system proposed by Romana [58], a modification to the $\text{RMR}_{\text{basic}}$ system, can be obtained from the $\text{RMR}_{\text{basic}}$ by adding resultant adjustment factors (Table 4) from

Table 4 Ratings for adjustment factors (after [58])

Case		Very favorable	Favorable	Fair	Unfavorable	Very unfavorable
P	$ \alpha_j - \alpha_s $	$>30^\circ$	$30^\circ-20^\circ$	$20^\circ-10^\circ$	$10^\circ-5^\circ$	$<5^\circ$
W	$ \alpha_i - \alpha_s $					
T	$ \alpha_i - \alpha_s - 180^\circ $					
P/T/W	F1	0.15	0.40	0.70	0.85	1.00
P/W	$ \beta_j $	$<20^\circ$	$20^\circ-30^\circ$	$30^\circ-35^\circ$	$35^\circ-45^\circ$	$>45^\circ$
	$ \beta_i $					
P/W	F2	0.15	0.40	0.70	0.85	1.00
T	F2	1.00	1.00	1.00	1.00	1.00
P	$\beta_j - \beta_s$	$>10^\circ$	$10^\circ-0^\circ$	0°	$0^\circ-(-10^\circ)$	$<-10^\circ$
W	$\beta_i - \beta_s$					
T	$\beta_j + \beta_s$	$<110^\circ$	$110^\circ-120^\circ$	$>120^\circ$	–	–
P/T/W	F3	0	–6	–25	–50	–60
Adjustment factors for method of excavation	F4	Natural slope	Presplitting	Smooth blasting	Mechanical excavation	Poor blasting
		+15	+10	+8	0	–8

P, planar failure; W, wedge failure; T, toppling failure, α_j , dip direction Joint; α_i , direction of line of intersection of two discontinuities, α_s , direction of slope inclination, β_s , inclination of slope, β_j , dip of joint, β_i plunge of line of intersection of two discontinuities

joint-slope relationship and method of excavation as given in Eq. (3). The SMR system describes five different stability classes based on total SMR values as completely stable (80–100), stable (60–80), partially stable (40–60), unstable (20–40) and completely unstable (<20).

$$SMR = RMR_{basic} + (F_1 * F_2 * F_3) + F_4 \quad (3)$$

where, RMR_{basic} is rock mass rating value; F_1 depends on parallelism between joints and slope face strikes; F_2 refers to joint dip angle in the planar mode of failure; F_3 states the relationship between the slope face and joint dips; F_4 the adjustment factor for the method of excavation

Factor of safety (FOS)

The kinematic analysis is an important task in stability analyses, which includes the determination of mode and direction of failure. The relationship of orientations of the discontinuity with the slope face gives the critical discontinuity set and the possible mode and direction of failure. The relationship can be evaluated through the analysis of stereographic projections, which is plotted using the geometry of discontinuity and slope measured in the field. The planar and wedge type of slope failures are most general types commonly occurred in rock mass influenced by discontinuities. The planar failure occurs, when a discontinuity strikes parallel or nearly parallel to the slope face and dips into the excavation at an angle greater than the angle of friction. The FOS for the planar failure case can be evaluated using Eq. (4) which is total force resisting sliding to the total force tending to induce sliding [31].

$$F = \frac{\left(\frac{2c}{\gamma H}\right) \cdot P + (Q \cdot \text{Cot}\Psi_p - R(P + S))\text{Tan}\Phi}{Q + R \cdot S\text{Cot}\Psi_p} \quad (4)$$

where,

$$P = \left(1 - \frac{z}{H}\right) \cdot \text{Cosec}\Psi_p \quad (5)$$

$$Q = \left(\left(1 - \left(\frac{z}{H}\right)^2 \text{Cot}\Psi_p - \text{Cot}\Psi_f\right) \text{Sin}\Psi_p\right) \quad (6)$$

$$R = \frac{\gamma_w}{\gamma} \cdot \frac{Z_w}{Z} \cdot \frac{Z}{H} \quad (7)$$

$$S = \frac{Z_w}{Z} \cdot \frac{Z}{H} \cdot \text{Sin}\Psi_p \quad (8)$$

The P, Q, R and S are all dimensionless ratios i.e. they depend upon the geometry but not upon the size of the slope; c—cohesion; z—height of tension crack; H—height of the slope; Φ —angle of friction

The wedge failure occurs along the line of intersection of two discontinuity planes [31]. The FOS of this slope can be derived from the Eq. (9) given by Hock et al. [30].

$$F = \frac{3}{\gamma H} (c_A \cdot X + c_B \cdot Y) + \left(A - \frac{\gamma_w}{2\gamma} \cdot X \right) \tan \Phi_A + \left(B - \frac{\gamma_w}{2\gamma} \cdot Y \right) \tan \Phi_B \quad (9)$$

where, c_A and c_B are the cohesive strengths of planes A and B; Φ_A and Φ_B are the angles of friction on planes A and B; γ is the unit weight of the rock; γ_w is the unit weight of water; H is the total height of the wedge.

$$X = \frac{\sin \theta_{24}}{\sin \theta_{45} \cdot \cos \theta_{2,na}} \quad (10)$$

$$Y = \frac{\sin \theta_{13}}{\sin \theta_{35} \cdot \cos \theta_{1,nb}} \quad (11)$$

$$A = \frac{\cos \Psi_a - \cos \Psi_b \cdot \cos \theta_{na,nb}}{\sin \Psi_5 \cdot \sin 2\theta_{na,nb}} \quad (12)$$

$$B = \frac{\cos \Psi_b - \cos \Psi_a \cdot \cos \theta_{na,nb}}{\sin \Psi_5 \cdot \sin 2\theta_{na,nb}} \quad (13)$$

where, The X, Y, A, and B are dimensionless factors which depend upon the geometry of the wedge; Ψ_a and Ψ_b are the dips of planes A and B respectively; na—pole of plane A; nb—pole of plane B; 1—intersection of plane A with the slope face; 2—intersection of plane B with the slope face; 3—intersection of plane A with upper slope surface; 4—intersection of plane B with upper slope surface; and Ψ_5 is the dip of the line of intersection of Planes A and B. The required angles can be measured on a stereonet of the data which plotted using the geometry of the wedge and the slope.

Results and discussion

Landslide hazard zonation (LHZ) mapping

The facet-wise ratings of all the causative factors were evaluated as per the LHEF rating scheme [11]. The facet 2 was assigned the highest rating of 1.00 for lithology, next the facet 4 and facet 3 was assigned the rating of 0.94 and 0.90 respectively. The evaluation of structural ratings involves the field measurements of structural discontinuities and slope orientation Table 5. These measurements were used to plot stereonet to evaluate facet-wise structural ratings through relationships of the discontinuity with the slope (Fig. 2). On the basis of the stereo-net plot, the structural rating values were calculated as per the BIS norms. Facet 3 has the highest structural rating of 1.05. The Facet 2 and 4 have the moderate structural rating of 0.67 and 0.68 respectively. The slope morphometry analyses in the study area reveal gentle slope (16° – 25°) and very gentle slope ($\leq 15^\circ$) categories are exists along the ghat road. The LHEF rating for gentle slope (facet 2, 3, 4, and facet 5) was awarded as 0.8, and for very gentle slope (facets 1) the rating of 0.5 was assigned. The relative relief of the individual facet reveals that the facet 2 having the high relief was assigned the rating of 0.5, while all other facets possess the moderate relief was assigned the ratings of 0.3. The fairly dense scrub and forest plantation are the land use and land cover features

Table 5 Facet wise geometry of structural discontinuities

Facet no.	Location details		Orientation of slope direction and inclination	Orientation of discontinuities (direction and dip amount)		
	Latitude	Longitude		Joint set—1	Joint set—2	Joint set—3
Facet-1	There is no rock slope sections found					
Facet-2	11°45'16" N	78°15'33" E	N 120°/28°	N 320°/65°	N 173°/75°	N 240°/70°
	11°45'22" N	78°15'37" E	N 180°/30°	N 355°/49°	N 224°/85°	–
	11°45'24" N	78°15'40" E	N 124°/29°	N 340°/39°	N 150°/64°	–
	11°45'34" N	78°15'46" E	N 148°/28°	N 240°/65°	–	–
Facet-3	11°45'52" N	78°15'55" E	N 185°/26°	N 85°/30°	N 250°/62°	–
	11°46'04" N	78°16'04" E	N 115°/25°	N 25°/78°	N 350°/74°	N 135°/65°
	11°46'09" N	78°16'04" E	N 95°/27°	N 345°/80°	N 295°/25°	N 115°/15°
Facet-4	11°46'19" N	78°16'06" E	N 120°/30°	N 225°/58°	N 85°/75°	–
	11°46'26" N	78°16'26" E	N 75°/25°	N 125°/80°	–	–
	11°46'31" N	78°16'11" E	N 165°/19°	N 215°/80°	N 155°/58°	–
Facet-5	There is no rock slope sections found					

present in the study area. The LHEF rating of 0.80 has given to the facets 1, 2, 3 and 4 with fairly dense scrub, whereas the facet 5 mixed with fairly dense scrub and forest plantation area of has assigned 0.7. Facet wise evaluations of the ratings for hydrogeological conditions over rock and soil slope locations are visually observed and estimated ratings reveals the facets 3 have the maximum ratings of 1.50. The facets 4 and 2 possess the moderate rating for hydrogeological conditions as 1.28 and 1.13 respectively, while facet 5 was assigned the rating of 0.75. The LHZ map was prepared by calculating the TEHD by adding the ratings of all the causative factors (Fig. 3) and corrections due to triggering factors within a facet. Based on the LHEF rating scheme, the TEHD values were evaluated for all the five facets. The ratings for individual causative factors in each facet, TEHD, corrected TEHD, and hazard zones are given in Table 6. The landslide hazard zonation mapping for the Yercaud (alternate) ghat road section indicates that, out of five facets, facet 3 falls in high hazard zone (HHZ) category, facet 2 and 4 falls in moderate hazard zone (MHZ) category and the facet 1 and 5 falls in very low hazard zone (VLHZ) category (Fig. 4).

Slope stability analyses of rock sections

The detailed slope stability analyses were carried out on selected rock slope sections along Kuppanur–Kotanchedu ghat road section. For this detailed study, three facet sections were selected respectively from moderate hazard zones (facet 2 and 4) and high hazard zone (facet 3) along Yercaud (alternate) ghat road. The slope stability analyses of rock slope sections were carried out over this moderate and high hazard zones. These RS sections were identified based on appropriate slope amount, height, presence of discontinuities and its conditions. In these three facets, six potential rock slope (RS) sections were identified from facet 2 and facet 3 for RMR, SMR and FOS analyses are shown in Fig. 1.

The RMR parameters are measured for each structural unit in the field and recorded in field data sheet. The samples were collected from the field for compressive strength

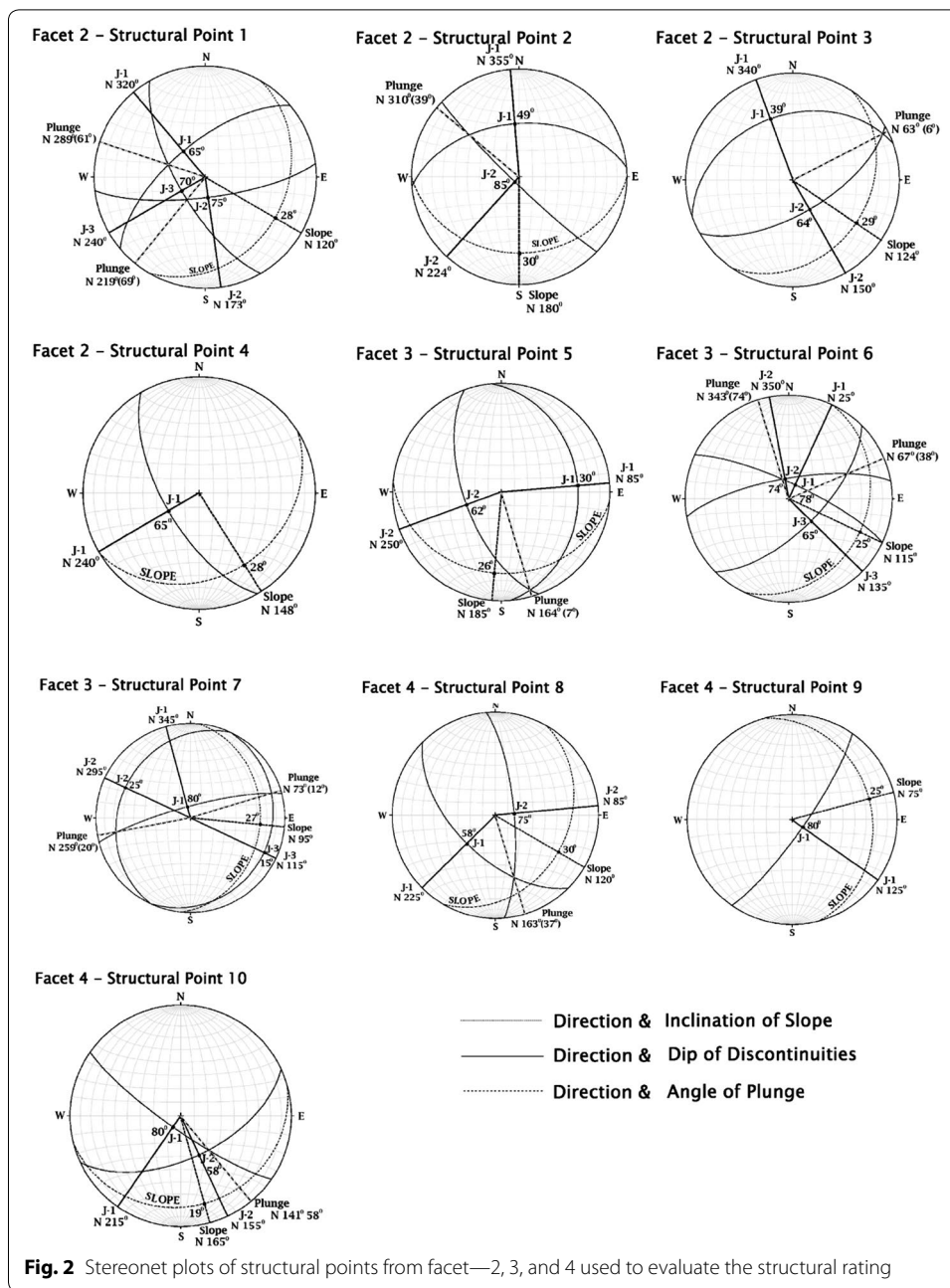
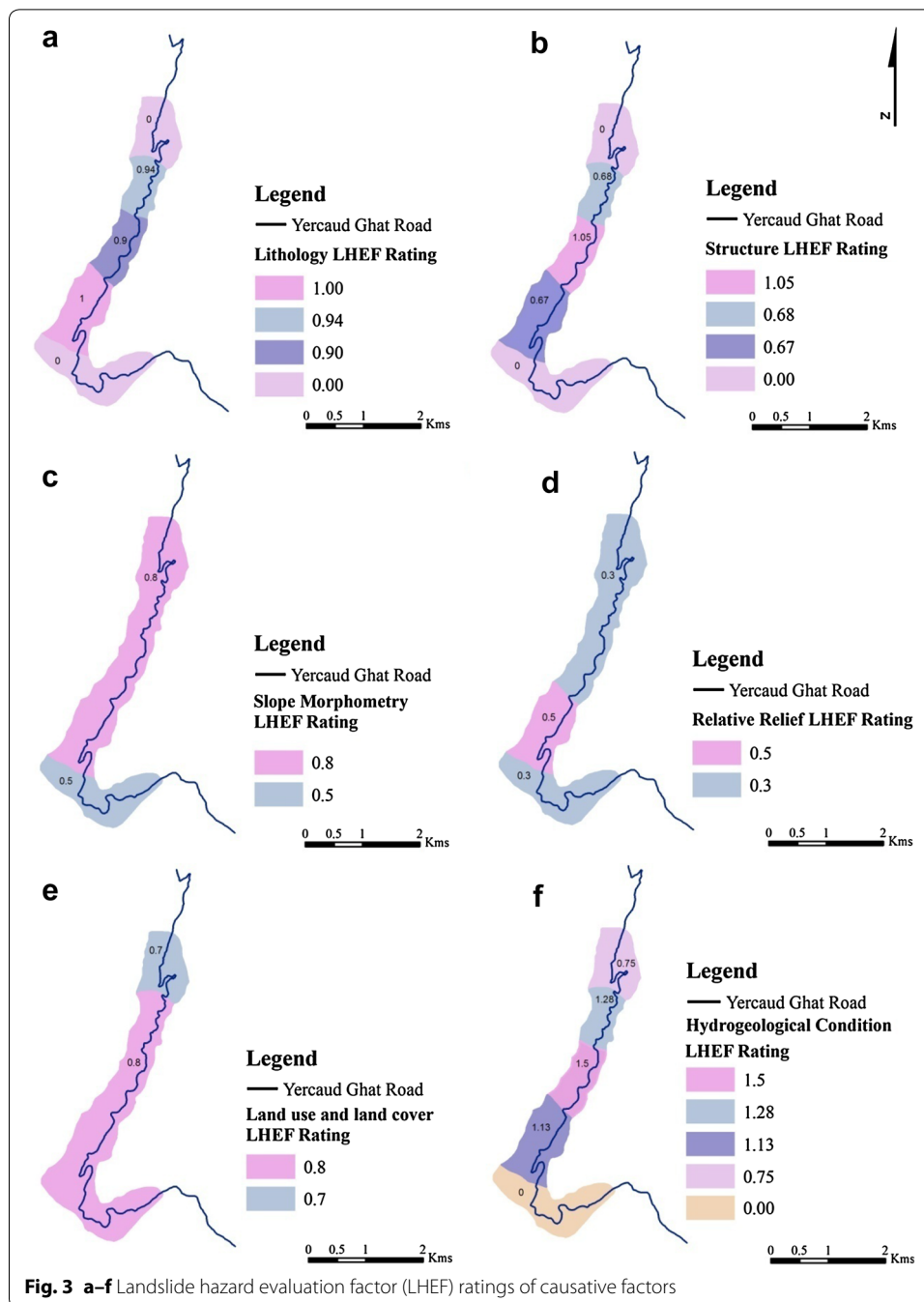


Fig. 2 Stereonet plots of structural points from facet—2, 3, and 4 used to evaluate the structural rating

(Point Load Test) analysis. The RS-4 has minimum compressive strength of 4.7755 Mpa while the RS-3 has maximum compressive strength of 10.088 Mpa. Based on the parameters observed in the field and point load test, the ratings were assigned according to the rock mass rating [10]. The total RMR value is calculated by means of algebraic sum of RMR parameters. The area depicts class III (RS-1, 2, 4, 5, 6) and class IV (RS-3) of RMR classes. The result of RMR indicated that the rock sections 1, 2, 4, 5 and 6 fall in fair rock class and rock section 3 classified as poor rock type. The RMR values, ratings of observed parameters and their class description, cohesion of rock mass, and angle of internal friction of rock mass of selected rock sections are given in Table 7.



In the field, the orientation of discontinuities (strike, dip amount and dip direction) are measured for all the selected RS sections. The structural values of all the RS sections and their discontinuities are plotted on the stereonet plot, to find the type of failure and plunge of discontinuity. The relationship between the slope and discontinuities was made to determine the adjustment ratings for F1, F2, and F3. In the study area, the cut slopes are formed by mechanical excavation of slopes, and is often combined with some preliminary blasting. This method of excavation neither increases nor decreases the slope stability, so the adjustment factor for F4 is given as 0. These F1, F2, F3, and F4

Table 6 Facet wise landslide hazard evaluation factor (LHEF) ratings and hazard zones

Facet no.	Causative factors					TEHD of causative factors	Correction due to triggering factors		TEHD of causative factors + rating of triggering factors	Hazard class
	Lithology	Structure	Slope morphology	Relative relief	Land use and land cover		Hydrogeological condition	Seismicity		
Facet-1	0.00	0.00	0.50	0.30	0.80	0.00	0.20	0.40	2.20	VLHZ
Facet-2	1.00	0.67	0.80	0.50	0.80	1.13	0.20	0.40	5.50	MHZ
Facet-3	0.90	1.05	0.80	0.30	0.80	1.50	0.20	0.40	6.25	HHZ
Facet-4	0.94	0.68	0.80	0.30	0.80	1.28	0.20	0.40	5.40	MHZ
Facet-5	0.00	0.00	0.80	0.30	0.70	0.75	0.20	0.40	3.15	VLHZ

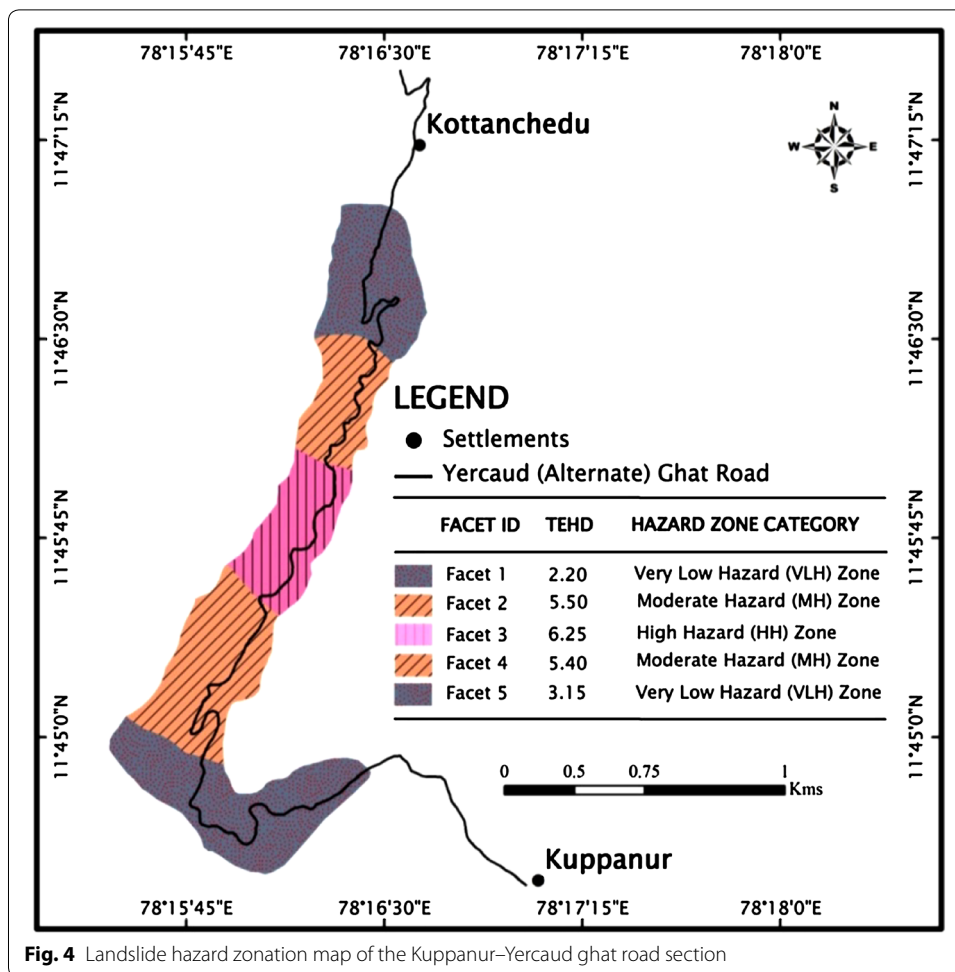


Fig. 4 Landslide hazard zonation map of the Kuppanur–Yercaud ghat road section

values were added with the RMR basic value to find the SMR values. The results of SMR values, class, description, stability, probable type of failure and supportive measures are shown in the Table 8.

The stability analyses of critical discontinuity sets from RS section were identified for planar as well as wedge mode of failure conditions. The FOS for planar and wedge type of failure modes was evaluated using Hoek and Bray Eqs. 4 and 9 respectively. The structural readings (slope and joint set), friction angle values were plotted in the Stereonet and made analysis to find out the possible failure modes i.e. type of failure. The possible critical failure modes and critical discontinuity sets from all the sections were identified and given in the Table 9. The input parameters required for the evaluation of FOS of planar and wedge types of failures were derived from the stereoplots shown in Fig. 5. The calculation of FOS of RS-3 (planar failure) and RS-6 (wedge failure) is given in Tables 10 and 11 respectively. The planar analysis of RS-1, RS-2, RS-3, RS-5 and RS-6 gives the FOS values of 4.65, -1.58, 0.53, 2.28 and 4.82 respectively. The FOS of wedge analysis for sections RS-4 and RS-6 are 11.54 and 26.31 respectively. The results based on planar failure analysis the RS-2 and RS-3 having FOS < 1 under the tension crack is completely filled with water condition. Hence, the sections are more unstable for slope failure. The wedge failure analysis shows that all the rock sections having FOS > 1 fall in safe conditions.

Table 7 Results of rock mass rating (RMR) for rock sections

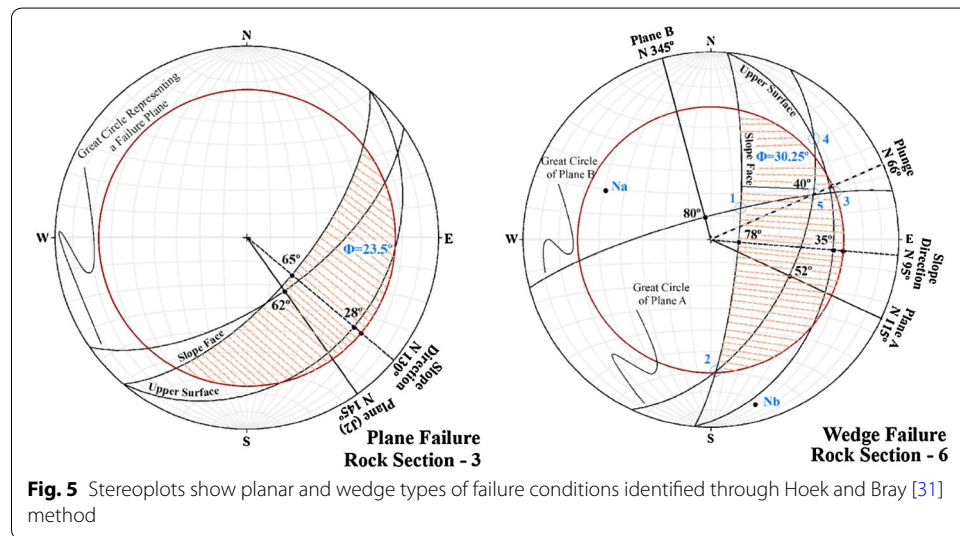
Location no.	Rock type	Rating			RMR value	Description	Class	C (in kPa)	φ (in degree)
		Strength of intact rock	RQD	Spacing of discontinuity					
Rock mass rating (RMR)									
RS-1	Charnockite	1	17	10	44.00	Fair rock	III	220.00	27.00
RS-2	Charnockite	1	20	15	44.60	Fair rock	III	222.50	27.25
RS-3	Charnockite	2	8	15	37.00	Poor rock	IV	185.00	23.50
RS-4	Charnockite	1	20	15	53.50	Fair rock	III	267.50	31.75
RS-5	Charnockite	2	17	15	42.00	Fair rock	III	210.00	26.00
RS-6	Charnockite	2	20	15	50.66	Fair rock	III	252.50	30.25

Table 8 Results of slope mass rating (SMR) for rock sections

Rock section	RS-1	RS-2	RS-3	RS-4	RS-5	RS-6
Class no	III	III	IV	III	III	III
SMR	44.00	44.60	37.00	49.90	42.00	48.62
Description	Normal	Normal	Bad	Normal	Normal	Normal
Stability	Partially stable	Partially stable	Unstable	Partially stable	Partially stable	Partially stable
Probable type of failure	Planar or many wedges	Planar or many wedges	Planar or big wedge	Planar or many wedges	Planar or many wedges	Planar or many wedges
Support	Systematic supports	Systematic supports	Important corrective measures	Systematic supports	Systematic support	Systematic support

Table 9 Identified critical sections for factor of safety analyses

Mode of failure	Section ID	Joint sets
Planar failure	Rock section-1	Joint set 2
	Rock section-2	Joint set 2
	Rock section-3	Joint set 2
	Rock section-5	Joint set 1
	Rock section-6	Joint set 3
Wedge failure	Rock section-4	Joint set 1 and 2
	Rock section-6	Joint set 1 and 3



Conclusion and recommendations

The landslide hazard zonation mapping carried-out by considering lithology, structure, slope morphometry, relative relief, land use and land cover, and hydrological conditions has indicated that facet 1 and 5 are categorized under very low hazard zone (VLHZ). The facet 2 and 4 are categorized under moderate hazard zone (MHZ). The facet 3 classified under high hazard zone (HHZ). Based on the analyses of LHEF rating values of each facet

Table 10 Calculation of factor of safety—rock section-3 (planar failure)

RMR _{basic} = 37 (class IV, poor rock), SMR value = 37 (class IV, bad, unstable)	
Input data	$\Psi_p = 28^\circ; \Psi_f = 65^\circ; \gamma = 2.65 \text{ gm/cc}; \gamma_w = 1.001;$ $c = 1850 \text{ gm/cc}; H = 1000 \text{ cm}; \phi = 23.5^\circ$ $\gamma_w/\gamma = 0.3777; Z_w/z = 1; z/H = 1; 2c/\gamma H = 1.019$
Calculated P = 0.5283; Q = -0.1100; R = 0.2840; S = 0.3531	
When, $Z_w/z = 1$ (i.e.) The tension crack is completely filled with water ($z = Z_w$),	
The factor of safety (FOS) = $(2c/\gamma H) \cdot P + (Q \cdot \cot \Psi_p - R(P + S)) \tan \Phi / Q + R \cdot S \cot \Psi_p = 0.53$	

Table 11 Calculation of factor of safety—rock section-6 (wedge failure)

RMR _{basic} = 41.33 (class III, fair rock), SMR value = 17.33 (class I, very bad, completely unstable)	
Input data	Intersections 1 = 71°; 2 = 31°; 3 = 32°; 4 = 25°; 5 = 40°; Pole of plane A(N _a) = 10°; Pole of plane B(N _b) = 38°; $\theta_{na-nb} = 114^\circ; \theta_{24} = 110^\circ; \theta_{45} = 24^\circ; \theta_{13} = 42^\circ; \theta_{35} = 10^\circ; \theta_{1nb} = 61^\circ;$ $\theta_{2na} = 24^\circ; \phi_A = 30.25^\circ; \phi_B = 30.25^\circ; \gamma = 2.65 \text{ gm/cc}; \gamma_w/2\gamma = 0.1910; \gamma_w = 1.001;$ $c_A = 2525 \text{ g/cc}; c_B = 2525 \text{ g/cc}$ and H = 1200 cm
Calculated	A = 1.4368; B = -0.0601; X = 2.5293; Y = 7.9502
FOS = $((3c_A/\gamma H) \cdot X + (3c_B/\gamma H) \cdot Y) + (A - (\gamma_w/2\gamma) \cdot X) \cdot \tan \Phi_A + (B - (\gamma_w/2\gamma) \cdot Y) \cdot \tan \Phi_B = 26.31$	

indicates that the weathering, structural discontinuities, slope morphometry, relief and hydrogeological conditions are the major causative factors for occurrence of landslides. The output is useful to carry out proper preventative and restoration process to avoid occurrence of landslide in future. This has indicated that the necessity of conducting a detailed geotechnical studies to prevent or minimize the slope failures. The result of RMR indicated that the rock sections 1, 2, 4, 5 and 6 fall in fair rock class and rock section 3 classified as poor rock type. The result of SMR has indicated that the rock sections 1, 2, 4, 5, and 6 classified as partially stable, rock sections 3 categorized as unstable. The F calculated for critical sections, which is identified through slope-joint relationship from stereonet plot. The FOS was calculated based on Hoek and Bray [31] method. In planar failure case, the FOS for RS-2 and RS-3 show values <1 FOS indicating that more critical condition for slope failures. While in the case of wedge failure, the FOS is >1 indicating that the slopes RS-4 and RS-6 are safe for wedge mode of failure. Based on this study, the rock section falling under partially stable category requires systematic supports. The unstable section RS-3 requires important corrective measures. Overall, the study has provided detail rock mass classification information on the section and location of slope failures along ghat road of Yercaud hills. The output is useful to carryout proper preventative and restoration process to avoid occurrence of landslides in future.

Authors' contributions

SA supervised the research work and participated in amending the manuscript. VR, SM, MB, and GK carried out the field work, data and sample collection, laboratory analyses, GIS work, and preparation of manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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