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Geotechnical Assessment and Slope Stability Analysis in Elk Hill, Ooty Municipality, The Nilgiris, Tamil Nadu, India

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Abstract. This paper assists in comparing geotechnical properties and slope stability of the area at Elk Hill, the Nilgiris District, Tamil Nadu with the landslide prone areas that have grown as a result of rising urbanization and tourist induced environmental pressures. Instability of the slopes in this region has been evident causing frequent landslides. To determine slope profile, soil properties and stability conditions, field as well as laboratory research was done. CFC method was used in establishing the factor of safety (FoS) of all profiles at a given level of saturation. The findings reveal that Profiles 1 and 2 are stable when there is a normal climatic condition but become unstable during moderate and heavy rainfalls. Their factor of safety is greater than one when dry but decreases to less than one when completely wet hence the possibility of failure. The profiles 3 and 4 only have a stability under dry conditions, when in the partially and fully saturated condition, their factor of safety is less than one, and they become prone to failure. In Profile 4 though, the slope is steady, and its factor of safety is greater than one even in saturation.

1 Introduction

Landslides are among the most destructive natural hazards in mountainous regions, often causing significant damage to life and infrastructure. In India, approximately 12.6% of the total area is prone to landslides, with around 21% of this vulnerable zone located in the Western Ghats of Tamil Nadu, where incidents are particularly frequent during the monsoon season [1][2][3]. Hill areas in Southern India are experiencing rapid population growth and urbanization, especially in tourist hotspots like Ooty in the Nilgiris District [4]. Slope failures pose serious geo-environmental risks to human life, transport networks, and critical infrastructure such as buildings and dams [6]. Evaluating and forecasting slope stability remains a key challenge for geotechnical engineers [8], as infrastructure projects including roads, tunnels, dams, and hotels require careful planning [10]. Unplanned development often triggers soil slips, infrastructure destruction, community disruption, and loss of life [9][13]. The Elk Hill area (Figure 1), central to Ooty municipality (ward no. 32), is densely settled on steep slopes and experiences frequent landslides due to increased construction, conversion of kutcha buildings to framed structures, and deforestation at hilltops [14][15]. This study assesses slope stability by integrating field data collection, soil sampling, geotechnical analysis, and stability condition modeling to propose strategies for sustainable development and disaster prevention in hill regions [5][11][12].

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2 Study Area

2.1 Geology and Geomorphological Context

The Nilgiris, part of the Southern Granulite Terrain of the Archean Craton in the Western Ghats, contains Neoarchean tectonic evidence, including subduction-accretion and ocean plate stratigraphy. Biotite gneissic rock is found throughout the area [7]. The primary soil classes are red sandy, colluvial and red loam. Elk Hill (Figure 1), located within the Ooty municipality at a longitude of (76°42'20" E) and latitude of (11°23'56" N) and a peak elevation of around 2400m, has a complex topography with a mixture of dense vegetation, cultivated land, and settlements [3]. Figure 1 shows the location of Elk Hill.

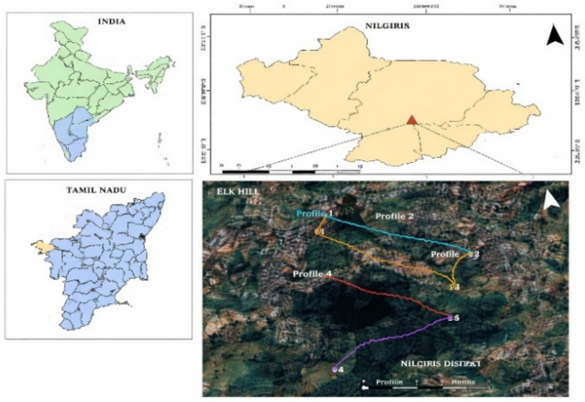

Figure. 1. Location map of Elk hill, Ooty Municipality

3 Methodology

3.1 Profile and Slope Analysis

Four slope profiles were selected within the Elk Hill sector, spanning from the upper ridge to the lower inhabited terrain, based on observable geomorphic variability, anthropogenic disturbance, field measurability, and settlement and cut-slope locations. Field surveys measured profile length, elevation difference, mean slope angle, and local land-use features. Figure 2 illustrates the spatial distribution of these profiles, ensuring that the most critical settled slopes in Elk Hill were represented in the analysis.

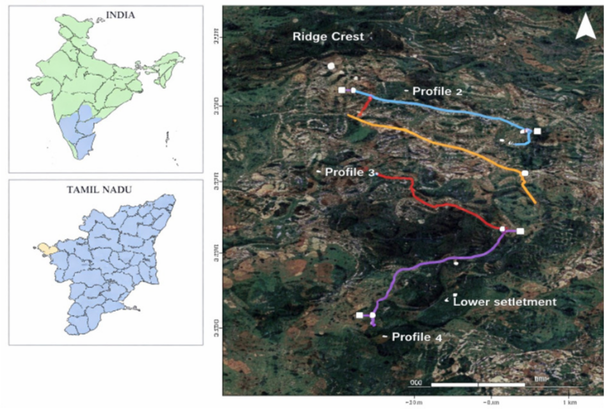

Figure. 2. Surveyed slope profile locations in Elk Hill

3.2 Soil Sampling and Testing

The samples were collected in different location (upper, middle, and lower). They were collected by removing the weathered portion up to feet and collected and preserved in plastic cover. The core samples were collected using a cylindrical core cutter of dimensions (13cm long and 10cm diameter), with a steel dolly (2.5cm long, 10cm diameter), by removing the weathered portion of the soil. Soil samples were collected for laboratory testing, including:

Core cutter test (BIS 2720-29 1975) is used to find out soil water content and dry density of the of the soil for stability calculation. Standard Proctor Compaction Test (BIS 2720-8 1983) was conducted to determine the relationship between the moisture content and the dry density of the soil It is expressed as (Equation 1):

$$\tau = c + \sigma \cdot tan\phi \quad (1)$$

where, τ is shear strength, c is cohesion, σ is normal stress, and ϕ is the internal friction angle.

3.3 Circular Failure Chart (CFC) Method

Slope profiles were analyzed for stability under varying saturation conditions using the Circular Failure Chart (CFC) method. Field and lab parameters slope height (H), slope angle (β), soil unit weight (γ), cohesion (c), and internal friction angle (ϕ) were converted into dimensionless stability ratios. Cohesion effects were expressed as $c/\gamma H$, frictional effects as $tan\phi$, and slope geometry by β.

4 Result and Discussion

The study focuses on the heavily settled slopes of Elk Hill, where four profiles were surveyed from the hilltop to the Racecourse (bottom). Levelling points were collected, and profiles were generated to analyze slope stability. For geotechnical analysis, three soil samples were collected from each profile (Table 1 &2).

Table 1. Tri-axial Shear Strength Test Results

Profile No	Sample ID	Cell pressure (σ_3) (Kn/m^2)	Deviator stress (σ_d) (Kn/m^2))	Normal stress ($\sigma_1 = \sigma_d + \sigma_3$) (Kn/m^2)	Cohesion of soil (kPa)	Angle of shearing resistance
1	I LS	100	923.9462215	1023.94622	**132**	40.71118
		150	1176.937735	1326.93773		
		200	1302.59188	1502.59188		
	I MS	100	697.5527992	797.552799	83	39.8207
		150	999.8341479	1149.83415		
		200	1066.908975	1266.90898		
	I US	100	508.5554987	608.555499	89	31.0406
		150	679.1643877	829.164388		
		200	734.2343455	934.234346		
2	II LS	100	610.9621187	710.962119	150	24.4393
		150	679.1326288	829.132629		
		200	744.1590063	944.159006		
	II MS	100	519.5440831	619.544083	28	42.16603
		150	764.0718457	914.071846		
		200	956.9596132	1156.95961		
	II US	100	508.5554987	608.555499	89	31.0406
		150	679.1643877	829.164388		
		200	734.2343455	934.234346		
		200	678.0369462	878.036946		
		300	996.1183549	1296.11835		

Table 2 shows that slope stability in Elk Hill is strongly influenced by soil strength, slope geometry, and moisture content. The factor of safety decreases markedly from dry to fully saturated conditions, confirming that rainfall infiltration is the primary triggering factor. This reduction is mainly due to loss of effective stress, soil softening, and decreased apparent cohesion under saturation. In addition to geotechnical properties, instability is further affected by slope steepness, human modifications, and concentrated settlement loads on the upper and middle slope sections.

Table 2. CFC Test Results

P No	Soil section	Soil		Chart no	Degree of saturation %	Intercept		Factor of safety (F1+F2)/2
		Cohesion (kPa)	Angle of internal friction (°)			X (F2)	Y (F1)	
1	U	132	40.71118	1	25	1.508	1.535	1.522
				3	50	1.205	1.191	1.198
				5	100	1.217	0.778	0.998
	M	83	39.8207	1	25	1.576	1.566	1.573
				3	50	1.233	1.265	1.249
				5	100	0.991	0.997	0.974
	L	89	31.0406	1	25	1.950	1.946	1.951
				3	50	1.427	1.438	1.435
				5	100	1.226	1.225	1.225
2	U	150	24.4393	1	25	1.467	1.453	1.460
				3	50	1.055	1.046	1.051
				5	100	0.93	0.902	0.916
	M	28	42.16603	1	25	1.578	1.491	1.534
				3	50	1.100	1.084	1.092
				5	100	0.919	0.918	0.919
	L	89	31.0406	1	25	1.840	1.832	1.836
				3	50	1.310	1.230	1.270
				5	100	1.177	1.145	1.161

Table 3 shows the variation of the factor of safety (FoS) for all slope segments under 25%, 50%, and 100% saturation. The FoS decreases progressively with increasing saturation, confirming that moisture ingress is the primary driver of slope instability. Profiles I and II are unstable even at low saturation, while their upper and middle segments stabilize at full saturation. The reduction in FoS between 25% and 100% saturation highlights the most vulnerable slope segments.

Table 3. Numerical interpretation of slope stability trends across profiles

Profile	Segment	FoS at 25% Saturation	FoS at 50% Saturation	FoS at 100% Saturation	FoS Reduction (25% to 100%)
I	U	1.522	1.198	0.998	0.524
I	M	1.573	1.249	0.974	0.599
I	L	1.951	1.435	1.225	0.726
II	U	1.460	1.051	0.916	0.544
II	M	1.534	1.092	0.919	0.615
II	L	1.836	1.270	1.161	0.675
III	U	1.038	0.753	0.595	0.443
III	M	1.205	0.890	0.698	0.507
III	L	1.409	0.984	0.832	0.577
IV	U	1.089	0.839	0.656	0.433
IV	M	1.393	0.965	0.832	0.561
IV	L	1.971	1.381	1.236	0.735

Slope Stability Analysis Across Different Profiles

Profile I: Stability is generally maintained under dry and moderately moist conditions due to available cohesion and frictional resistance. However, at full saturation, the upper and middle slopes become unstable, indicating that rainfall infiltration significantly reduces effective stress, making these segments prone to shallow failures.

Profile II: The upper and middle segments remain stable under dry and partial saturation, but fail under full saturation. The lower slope remains stable due to gentler geometry and higher shear resistance. Debris from upper slopes, however, could increase local hazards in the lower region.

Profile III: This is the most critical profile, with the factor of safety declining sharply even under intermediate moisture levels. Low geotechnical resistance, reduced cohesion, and frictional loss under rainfall make it highly susceptible to progressive failure during extended wet periods.

Profile IV: Stability varies along the slope. The upper and middle sections become progressively unsafe with increasing saturation, whereas the lower slope remains stable even under full saturation due to favorable geometry and shear strength. This highlights the need for segment-specific evaluation in slope stability assessments. Saturation is the primary driver of instability at Elk Hill. The reduction in shear strength due to rainfall, combined with slope geometry, cohesion, friction, and anthropogenic modifications, dictates slope response. These findings emphasize the importance of drainage, controlled construction activities, and targeted slope protection, especially in the vulnerable upper and middle slope sections.

5 Summary and Conclusion

Elk Hill within Ooty Municipality is one of the areas that are prone to landslides and this has been because of heavy rainfall, deforestation and human activities. The paper will discuss slope stability using field survey, soil sample and laboratory test referencing to the geotechnical properties that influence the stability. In the case of slope profiles, four profiles were measured all with three sampling points (Upper, Middle, and Lower). Core cutter test, triaxial shear test, density and moisture content of the soil was measured in accordance with the requirements of IS: 2720.

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