Prediction of Stability of an Infinite Slope Using Geospatial Techniques

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1 Introduction

Geospatial techniques comprise Remote Sensing, Photogrammetric, Geographical Information Systems (GIS), and Global Positioning Systems (GPS). They deal with acquisition, processing, storing, manipulating, storing, and disseminating spatial data. Remote sensing of the earth is a science and art of obtaining information about natural and artificial features. GIS refers to the analysis, capturing manipulating spatially related data. Photogrammetry refers to the acquisition processing of data using photographs. GPS refers to satellites positioned in space, which provides accurate and precise location information of the earth's features. Information collected from conventional and geospatial techniques can perform various spatial and temporal analyses of various land resources. Soil, one of the natural materials, has different properties and varies both spatially and temporally. Soil properties, index, and engineering properties help predict the soil's suitability as foundation and construction material. Engineering property, shear strength, is used to determine the slope's stability, bearing capacity, and the earth's pressure on one of the significant parameters, soil moisture.

Slope stability assumes a significant job in structural building, particularly in the design of expressways, railways, channels, surface mining, decline removal earth banks, and dams, just like numerous other human exercises, including construction

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and unearthing. Changes in external loads and pore water may cause slope failure and mass movement of the well-stabilized slopes [1]. Highway alignments, established along the hilly or mountainous terrain, taking or without considering hazard maps, are subjected to slope failures. The mass movement of soil succeeded by slope failure poses a high risk of damage to both lives and infrastructure. Quantitative and qualitative assessment of such mass movement of soil, its exact configuration, and spatial location is complicated to predict. However, depending on the in situ data and a few analytical postulates, quantitative assessments can be made. This quantitative examination decides the safety characteristics considering taking into account the causes that constitute the condition of strength and potential outcomes of the slopes to fail, regularly turned in a lead indicator called Factor of Safety (FOS). However, these assessments have a few limitations due to the difficulties in obtaining, checking, and processing large spatial and temporal data sets and varying soil moisture. With limited site investigation data and a lack of temporally varied data, useful slope failure analysis in mountainous areas, especially in mountainous urban areas, has become a paramount concern. With its potential and versatility for processing spatial data and temporal data, geospatial technologies have attracted significant attention to assessing soil and its properties. By establishing a statistical relationship between the slope stability and the factors influencing it and utilizing geospatial technologies in both acquisitions of spatial and temporal data and utilizing GIS, the FOS data can be created, assessed, and a map can be disseminated. The maps thus prepared help ease the planning of infrastructure before construction and indicate the possible failure zones or the risk-prone areas near the existing infrastructure.

In India, 15% of the area is prone to landslides [2]. Numerous landslides triggered by unusually high rainfall in India's Western Ghats regions caused widespread damage to property and life and resulted in 14.9% of landslides in the moderate slopes area in Karnataka state [3]. Considering the necessities and possibilities of geospatial techniques, the stability of an infinite slope was carried out near the Ballari area, which covers a part of National Highway 150A (NH 150A); a motorway in Karnataka state that connects Jewargi and Chamarajanagar employing the limit equilibrium method for the stability of an infinite slope is predicted. The infinite slope model used to calculate an FOS based on limit equilibrium analysis determines the balance between shear stress and shear strength. The necessary input parameters in developing the infinite slope model are (i) Cohesion, (ii) Angle of Shearing Resistance, (iii) Unit Weight of Soil, and (iv) Soil moisture. Soil water content is assessed from field observations; the estimations of these variables (c, φ, γ) are evaluated through the correlations. Digital Elevation Model (DEM) obtained from Cartosat-1 from Bhuvan is utilized in this study (Fig. 1).

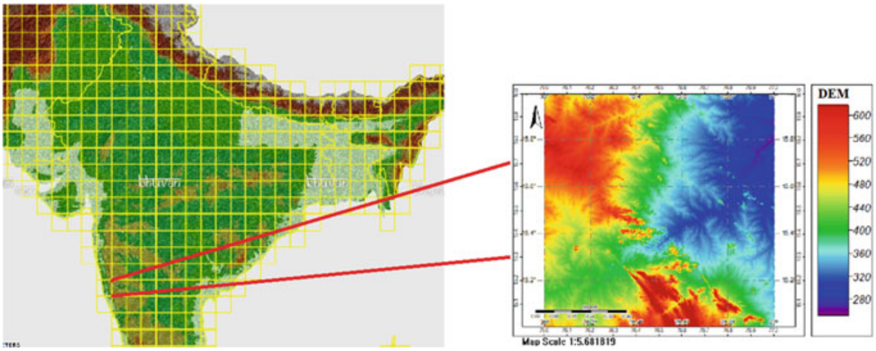

Fig.1 Cartosat Dem data from Bhuvan website

2 Objectives

The primary advance in this paper is by utilizing geospatial technologies to assess the sensitivity of the infinite slope over a spatial extent. To make the study achieve effectively, the explicit goals of this exploration are as follows:

1. Soil moisture maps to be prepared.
2. To determine the slope angle from Cartosat-1 DEM data.
3. Slope stability modeling using (i) Cohesion, (ii) Angle of Shearing Resistance, and (iii) Unit Weight of Soil.
4. To predict the Factor of Safety (FOS) of infinite slope from SAGA GIS.

3 Materials and Methods

3.1 Materials

Primary Data collected during field investigation, including satellite data and ancillary data, is used in this research. For satellite data, Cartosat-1 DEM was used. The Cartosat-1 Digital Elevation Model (CartoDEM) is a National DEM developed by the Indian Space Research Organization (ISRO), having a resolution of 2.5 m. The data extent was from 76–77°E and 15–16°N. However, the data was clipped further specific to the study area extent, i.e., 76.60–77°E and 15–15.32°N. The extent of NH150A obtained from urban land use and land cover map acquired from the Bhuvan website used in preparing a road network map for the study area is shown in Fig. 2. The extent of the NH150A, along with its terrain characteristics, is shown in Fig. 3.

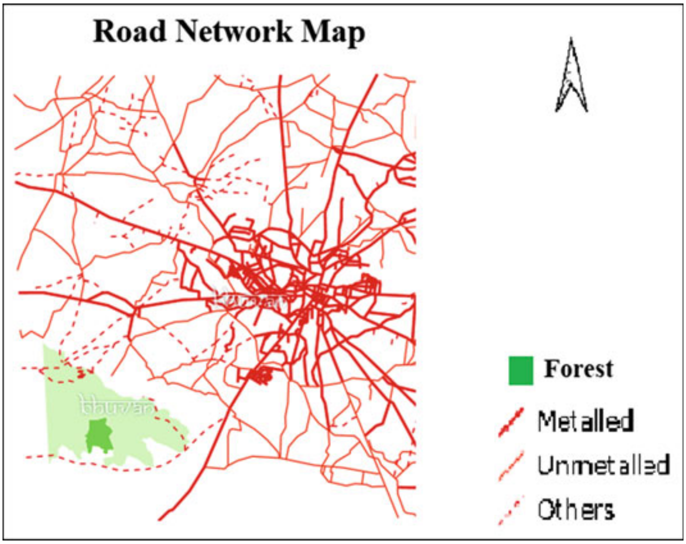

Fig.2 Overlaid map of the study area

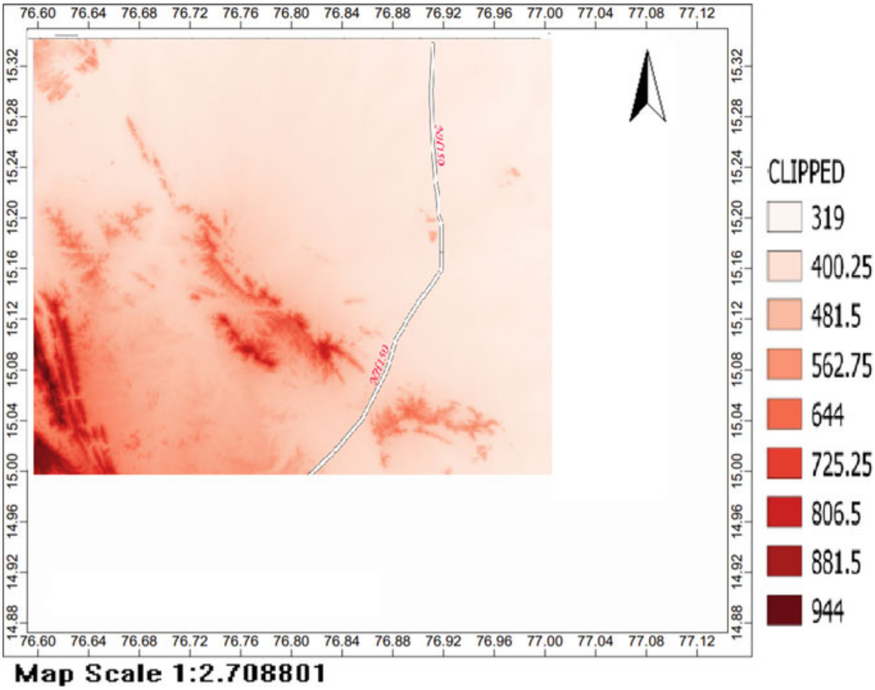

Fig.3 Topographic feature of the study area

3.2 Methods

3.2.1 Field Observation

Variables such as soil water content and soil samples of 20 selected points from the study region were obtained during the field investigation that was performed on Wednesday, January 2, 2019. Open-source software such as QGIS is used for mapping. SAGA GIS software is used for image processing.

3.2.2 Infinite Slope Stability Modeling

The slope's stability is a function of various parameters and depends on the soil geotechnical properties, land use land cover, and geological features. Frictional resistance of the soil is affected by the presence of water and pore water pressure. As the quantity of interstitial fluid rises, the soil weight increases, further destabilizing the slope. Evaluating the slope's stability using the infinite slope model provides simple equations for determining the Factor of Safety (FOS) with a surface of plane failure parallel to the slope surface. By adapting Factor of Safety (FOS) [4] for the hydrostatic condition used in this research for the infinite model, we get

$$\begin{aligned}\mathrm{FS} = &(\tan\phi/\tan\alpha) + (\mathrm{c}/(\gamma(\mathrm{D}-\mathrm{y}))\,(1/(\sin\alpha\cos\alpha)) \\ &+ (\mathrm{y}/(\mathrm{D}-\mathrm{y}))(\gamma\omega/\gamma)\,(\tan\phi/\tan\alpha)\end{aligned} \tag{1}$$

where D assumed as 10 m is the height of soil from the water table, and y estimated to be a constant 2.5 m is the thickness of the slab, reflecting the average debris-flow thickness in the region of the study area [4] and recommended for a shallow landslide [5].

Considering the influence of geotechnical parameters alone on the stability of an infinite slope using limit state equilibrium condition and modeling in the QGIS software, an FOS map can be developed. The necessary input parameters in developing the infinite slope model are (i) Cohesion, (ii) Angle of Shearing Resistance, (iii) Unit Weight of Soil, and (iv) Slope Angle. Utilizing the relationship between the soil moisture (ω) and geotechnical parameters, adapted in [6, 7], the cohesion of the soil (c), angle of shearing resistance (ø), and unit weight of the soil (γ) for an infinite slope are determined from the QGIS model maker from the equations below.

(i) The cohesion of the soil (c in kPa):

$$c = -1.2009\omega^2 + 56.412\omega - 587.87 \tag{2}$$

(ii) Angle of shearing resistance:

$$\phi = 11212\omega^{-1.1929} \tag{3}$$

(iii) The unit weight of the soil (γ in kN/m^3):

$$Y = -0.1337\omega + 17.457 \tag{4}$$

The values thus obtained served as input parameters for determining the Factor of Safety.

4 Results

As shown in Fig. 4, the soil moisture map prepared from soil moisture measurements made at 11 points in the field serves as an essential input parameter to determine the (i) Cohesion, (ii) Angle of Shearing Resistance, and (iii) Unit Weight of Soil. Measurement of slope angle is made from Carosat-1 DEM data. Figure 5 presents the Factor of Safety Map for the entire study area. Each pixel in the image represents the value of FOS. It provides a quantitative sign of slope stability. A value of FOS = 1.0 indicates that the slope is at the verge of failure; under the current condition value of FOS, less than 1.0 points out that the slope is unstable, and a value of FOS greater than 1.0 points toward a stable slope [8]. Figure 5 explains the dependence of conditionally stable elements on the soil moisture within the elevation. The least

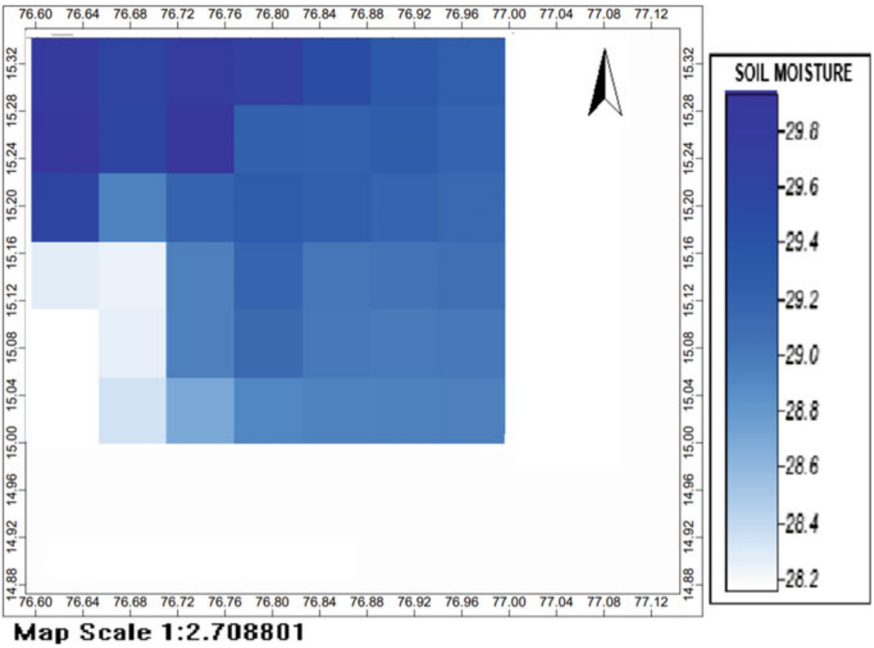

Fig. 4 Soil moisture mapped interpolated from field observations

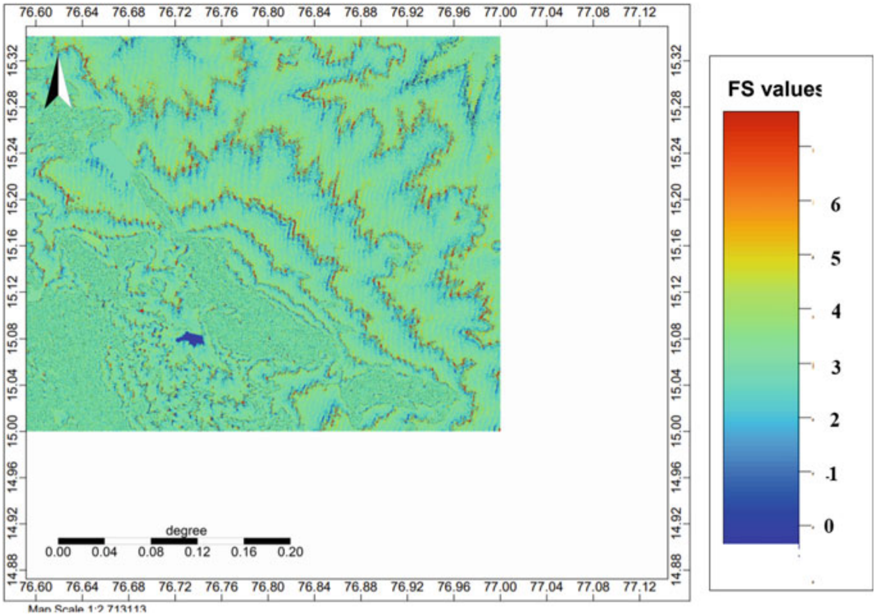

Fig. 5 Slope stability map depicting location of unstable slopes

factor of safety in the southwest part of the study area is attributed to forest cover having more soil moisture. Frictional resistance dependant on the soil moisture is least in the southwest region with high elevations. Further, the factor of safety values more significant than the one with the least slope failure is concentrated in regions with low soil moisture.

For validating the model, laboratory experiments were carried out. Table 1 shows the comparative analysis of soil parameters of 11 observation samples.

5 Conclusions

This paper presents the prediction of the infinite slope stability of NH150A across the Ballari region using geospatial techniques. The model created in QGIS estimates where a failure phenomenon could occur by simulating most geotechnical parameters and assessing its stability based on the infinite slope model. The application of geospatial techniques in predicting the stability of an infinite slope demonstrates the model's ability to perform according to input parameters and terrain topography; moreover, it highlights the strengths of the model that can be disseminated at the spatial extent. Soil moisture, one of the critical parameters, varies both spatially and temporally. Further enhancement of the model in predicting the stability of an infinite

Table 1 Comparative analysis of soil parameters

Borehole	Geospatial				Experimental		
	Soil moisture (%)	Cohesion (kPa)	Friction angle (°)	Unit weight (kN/m^3)	Cohesion (kPa)	Friction angle (°)	Unit weight (kN/m^3)
1	30	23.7	19.39	13.45	15.31	16.34	19.42
2	25	71.9	24.10	14.11	65.4	22.19	20.06
3	24.98	71.9	24.12	14.12	68.09	24.27	18.33
4	28	50.2	21.05	13.71	41.11	17.02	19.25
5	28.1	49.1	20.96	13.70	40.21	17.12	19.41
6	25.1	71.5	23.98	14.10	67.85	24.25	19.87
7	26.1	66.4	22.89	13.97	61.28	22.61	19.92
8	28.3	46.8	20.79	13.67	39.66	17.37	18.45
9	30.1	22.1	19.31	13.43	15.45	18.43	18.03
10	28.01	50.1	21.04	13.71	41.06	21.55	19.63
11	27.3	57.2	21.70	13.81	53.55	23.61	20.71

slope at the temporal scale from satellite-derived soil moisture data is possible using geospatial techniques. However, the accuracy and reliability of the model should be validated with the ground truth measurements. Natural soil moisture varies seasonally, and which in turn influences the stability of slopes, which need to be considered. The R^2 values of 0.991, 0.657, and 0.523 for c, φ, and γ, respectively, are found to be statistically significant. The proposed model has the ability to represent a visual and virtual geotechnical laboratory as correlations are arrived at using soil moisture with slope and geotechnical parameters.

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