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PROBABILISTIC ANALYSIS IN TERRACED SLOPES USING PHYSICS-BASED LANDSLIDE SUSCEPTIBILITY MODELS

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Abstract: The increased frequency of rainfall-triggered landslides in anthropogenically modified terrains highlights the critical need for accurate geohazard assessment methodologies. However,the limited availability of fine-resolution geomorphological and geotechnical data, particularly in developing countries often restricts regional scale landslide susceptibility models from capturing the detrimental effects of fine-scale terrain modifications. These includes terracing practices on natural slopes which are modified without adequate drainage systems, leading to elevated pore pressures that significantly reduce slope stability. Addressing this challenge, the current study focuses on probabilistic analysis combined with high-resolution digital elevation models (DEMs) to assess landslide susceptibility in such terrains. The methodology redefines an available 10-meter resolution Cartosat DEM into a high-resolution DEM, accurately capturing small-scale terrain modifications, particularly terraced slopes, by incorporating terracing patterns extracted from high-resolution satellite imagery using edge detection algorithms and field observation data. This high-resolution DEM captures the intricate topography of terraced slopes, providing the necessary input for probabilistic, physically-based landslide susceptibility modelling. The Transient Rainfall Infiltration and Grid-based Regional Slope Stability – Probabilistic (TRIGRS-P) model is employed, incorporating uncertainties in soil properties such as cohesion, friction angle, and hydraulic parameters. Input parameters are treated as random variables following Gaussian or uniform distributions and analysed through Monte Carlo simulations. The iterative approach probabilistically evaluates slope stability under transient rainfall infiltration, accounting for variations in pore pressure and shear strength. A case study of the 2019 Kavalappara landslide demonstrates the effectiveness of this approach in the Western Ghats of India. The probabilistic model with the redefined DEM estimated a 41% failure probability before the event, whereas the deterministic model with the resampled DEM identified instability only post-failure. The framework predicted a mean FoS of 1.12, compared to 1.9 with the resampled DEM, highlighting its improved sensitivity to terrain modifications. These results underscore the value of high-resolution DEMs and probabilistic modelling for landslide hazard assessment.

Keywords: Anthropogenic slope modification, Landslide Susceptibility, Monte Carlo Simulation, Probabilistic slope stability, TRIGRS, Rainfall induced landslides.

1. Introduction

Landslides are among the most catastrophic natural disasters globally, often influenced by natural factors such as rainfall and earthquakes, as well as anthropogenic activities like terraced farming, road construction, and deforestation (Ajith et al., 2024). Physically-based models, such as TRIGRS, can be used forlandslide susceptibility assessments under transient hydrological conditions by incorporating slope stability and infiltration analyses (Baum et al., 2008). However, the reliance of these models on freely available low-resolution Digital Elevation Models (DEMs), limits their ability to accurately capture fine-scale topographic modifications like terraced slopes, which are critical in slope stability analyses (Ajith et al., 2024). Globally, high-resolution DEMs (e.g., <2.5 m), derived from LiDAR or advanced satellite imagery, have demonstrated improved accuracy in hydrological and geotechnical modelling, but their limited availability in developing regions remains a challenge.In parallel, probabilistic approaches have gained attention for their ability to address uncertainties in geotechnical parameters such as cohesion, friction angle, and permeability, which deterministic models often overlook. Probabilistic techniques like FOSM and Monte Carlo simulations have been integrated into infinite slope models to address variability in soil properties, slope angle, and failure depths. While models like TRIGRS-P (Raia et al., 2014) and TRIGRS_FOSM (Ajith & Pillai, 2024) show promise in incorporating uncertainties, their application to rainfall-induced landslides remains limited, especially in areas with anthropogenic slope modifications.This study combines these two aspects by focusing on the Western Ghats of India, a region characterized by steep, terraced terrains prone to rainfall-triggered landslides. Using a refined Cartosat DEM of 10 m resolution, integrated with high-resolution terracing patterns extracted from satellite imagery, this work develops a high-resolution DEM capable of capturing intricate topographic features. A probabilistic adaptation of the TRIGRS model (TRIGRS-P) is employed, treating geotechnical and hydrological parameters as random variables within a Monte Carlo simulation framework. The approach is applied to the 2019 Kavalappara landslide, demonstrating the critical role of high-resolution DEMs and probabilistic methods in improving landslide hazard assessments. This study provides a robust, scalable methodology for addressing data scarcity and uncertainty, offering global relevance for similar anthropogenically modified terrains.

2. Methodology

2.1. *DEM Enhancement Process*

Accurate representation of terraced landscapes in DEMs is crucial for effective landslide susceptibility analysis. To overcome the shortcomings of resampled DEMs (R-DEMs) in depicting detailed terrain features, this study utilized high-resolution satellite imagery with a spatial resolution of 0.3 m from the Google Earth database. The overall methodology of the study is illustrated in Fig. 1. Terrace features were identified through Python-based image processing techniques, leveraging multispectral data to detect terrain patterns. The Canny edge detection algorithm, combined with grayscale preprocessing, was applied to highlight terrace boundaries, which were further refined using skeletonization to create preciseterrace lines. These terrace patterns were validated and updated with elevation details using field measurements of terrace dimensions such as depth and spacing, and further integrated with the R-DEM by interpolating the revised data using the Kriging method. To account for the uncertainty in Kriging interpolation, a cross-validation approach was implemented. The accuracy of the interpolation was assessed using the coefficient of determination (R^2), comparing interpolated elevation values with field-measured elevations to evaluate the model's predictive performance.This process ensured the generation of a high-resolution DEM, denoted as M-DEM (Modified DEM) that precisely represents terrace-induced elevation changes, avoiding the overly smoothening due to interpolation which makes it suitable for hydrological modelling and landslide assessments in terraced agricultural landscapes.

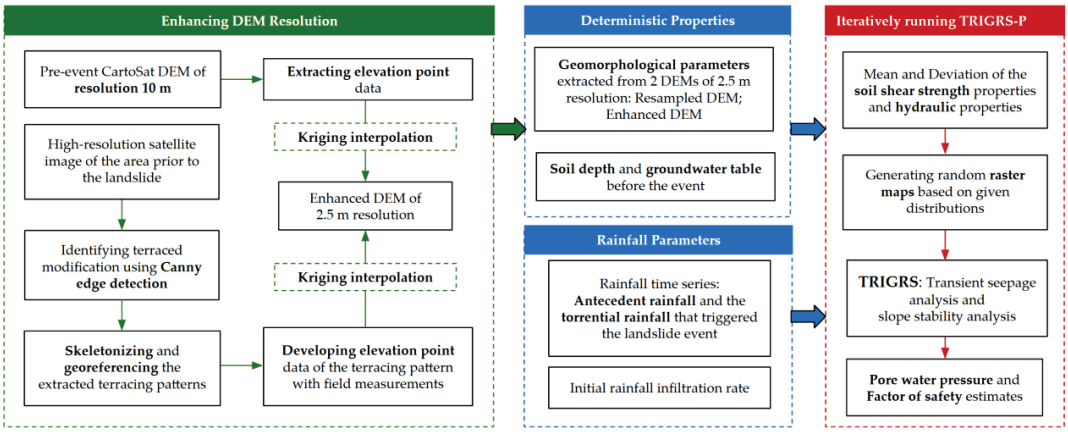


Fig. 1. Layout of the overall methodology of the study

2.2. *Probabilistic Landslide Susceptibility Modelling*

The Transient Rainfall Infiltration and Grid-Based Regional Slope Stability (TRIGRS) model, developed by the United States Geological Survey, is a physics-based tool for assessing rainfall-induced landslide susceptibility. It integrates transient seepage and slope stability analysis by estimating variations in pore water pressure and calculating the factor of safety (FoS) at the pixel level using an infinite slope stability model (Baum et al., 2008). TRIGRS incorporates transient changes in groundwater levels through the one-dimensional Richards equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial Z}\left[K(\psi)\left(\frac{1}{cos^2\delta}\frac{\partial \psi}{\partial Z} - 1\right)\right] \quad (1)$$

where ¸ is soil water content; *t* is time, *Z* isvertical depth, K(È) is hydraulic conductivity, È is pore pressure and ´ is the ground slope surface.TRIGRS model evaluates the slope stability through the Factor of Safety (FoS) equation given:

$$FoS(Z,t) = \frac{tan\phi}{tan\delta} + \frac{c - \varphi(Z,t)\,\gamma_w\, tan\phi}{\gamma_s\, Z\, sin\delta\, cos\delta} \quad (2)$$

where, *c*and Õare cohesion and soil friction angle for effective stress, ³ $_s$is unit weight of the soil and³ $_w$is unit weight of groundwater. The TRIGRS model was extended to TRIGRS-P by Raia et al. (2014) to incorporate probabilistic analysis, enabling the representation of uncertainties in slope material and hydrological properties. In TRIGRS-P, input material parameters used in equation 1 and 2, along with hydraulic diffusivity (D_0), residual water content (θ_r), saturated water content (θ_s), and the inverse capillary fringe height (α) are modelled as random variables, governed by either normal or uniform probability distributions. These distributions enable the generation of a range of plausible parameter sets, providing a systematic framework for uncertainty quantification. This study enhances the probabilistic capability of TRIGRS-P by incorporating Monte Carlo

quantification. This study enhances the probabilistic capability of TRIGRS-P by incorporating Monte Carlo Simulation through an external shell scripting interface. The script automates the execution of multiple TRIGRS-P model runs, each with a unique set of randomized input parameters, based on the number of simulations specified by the user. This integration enables extensive sampling of the parameter space, providing a comprehensive evaluation of parameter uncertainties and their influence on landslide susceptibility predictions.By adopting a stochastic framework using Monte Carlo, this approach ensures a more robust and reliable assessment of slope stability under variable conditions.

3. Case Study: Kavalappara Landslide

The Kavalappara landslide, a catastrophic event in Malappuram district, Kerala, during August 8–10, 2019, was triggered by extreme rainfall, with cumulative precipitation exceeding to almost 4 times the normal. To analyze this event, a high-resolution Modified DEM (M-DEM) with a spatial resolution of 2.5 m (Fig. 2a) was constructed using the proposed methodology to incorporate anthropogenic modifications, such as terraced rubber plantations with an average depth of 1.5 m. The M-DEM-derived slope angle at the crown region (43.12°) closely aligned with field observations (44°), reflecting the model's accuracy. Soil material properties with their variability were taken from field studies by KSCSTE (2019) and Das et al. (2022), as listed in Table 1, while the hydraulic properties and its variation were estimated using the ROSETTA model based on the grain size distribution (Table 1). Rainfall data from August 1–14, 2019 (Fig. 2c), were used for transient seepage analysis, with initial infiltration estimated based on normal rainfall data to represent long-term averages. Soil depth, initially modelled using a cosine function, was adjusted based on field data to reflect terracing-induced modifications. These enhancements to the DEM and the incorporation material uncertainties provide a robust basis for analysing the landslide's hydrological and mechanical behaviour.

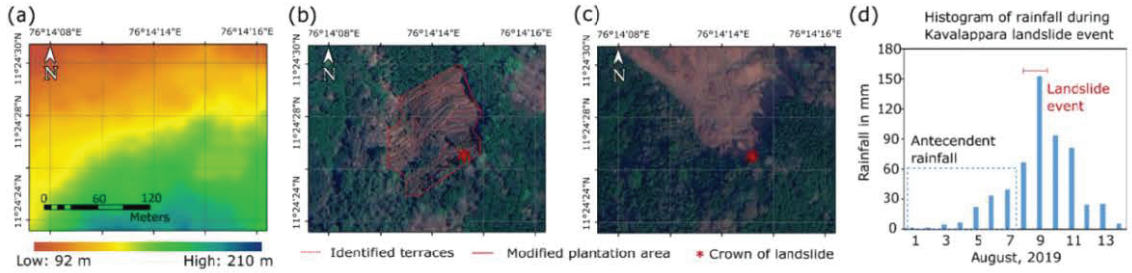


Fig. 2.Developed M-DEM of Kavalappara, Satellite images of Pre and Post Kavalapparaevent and rainfall histogram data

Table 1. Input parameters used for Kavalappara case study area(KSCSTE, 2019; Das et al. 2022)

Parameter	Mean Values	Minimum value	Maximum value	Standard deviation	Unit
Angle of internal friction	25	22.29	36.69	2	degrees
Cohesion	20.5	2	74	6	kPa
Unit weight of soil	15.5	1.34	1.76	0.07	kN/m^3
Percentage clay + silt	48	20	76	-	%
Percentage sand	45	21	54	-	%
Percentage gravel	7	1	40	-	%

4. Results and Discussion

The probabilistic and deterministic model comparison highlights the advantage of probabilistic modelling in predicting slope instability at the Kavalappara landslide site. As shown in Fig. 3, the probabilistic model utilizing the M-DEM detected an increasing failure probability in the crown area, reaching 30% by August 7th, 41% by August 8th (the day of failure), and rising by 10% on August 9th. Conversely, the deterministic model with the R-DEM failed to map instability until August 9th, a full day after the event, demonstrating the advantage of the probabilistic approach in early warning.This superior performance is primarily due to the consideration of variability in residual soil properties. Residual soils in the study area exhibit high porosity, moderate permeability (10^{-5}–10^{-7} m/s), and variability in cohesion (2–74 kPa, mean = 20.5 kPa, SD = 6 kPa) and friction angle (22.29°–36.69°, mean = 25°, SD = 2°) (Table 1). The deterministic model, using fixed mean values, fails to capture localized weaknesses, leading to delayed failure predictions. The probabilistic model, in contrast, treats these parameters as random variables, incorporating inherent soil heterogeneity through Gaussian distributions.Additionally, MCS enabled the probabilistic model to assess numerous of slope conditions under transient rainfall infiltration, capturing a wider range of failure scenarios compared to the single-condition deterministic model.

A detailed analysis of the crown area further underscores the role of high-resolution terrain data. The M-DEM predicted a mean Factor of Safety (FoS) of 1.12 (SD = 0.26) on August 7th, compared to 1.9 (SD = 0.534) from the R-DEM, highlighting its improved sensitivity to terraced slope modifications. These findings emphasize the importance of integrating probabilistic modelling with high-resolution DEMs for landslide hazard assessments in residual soil terrains.

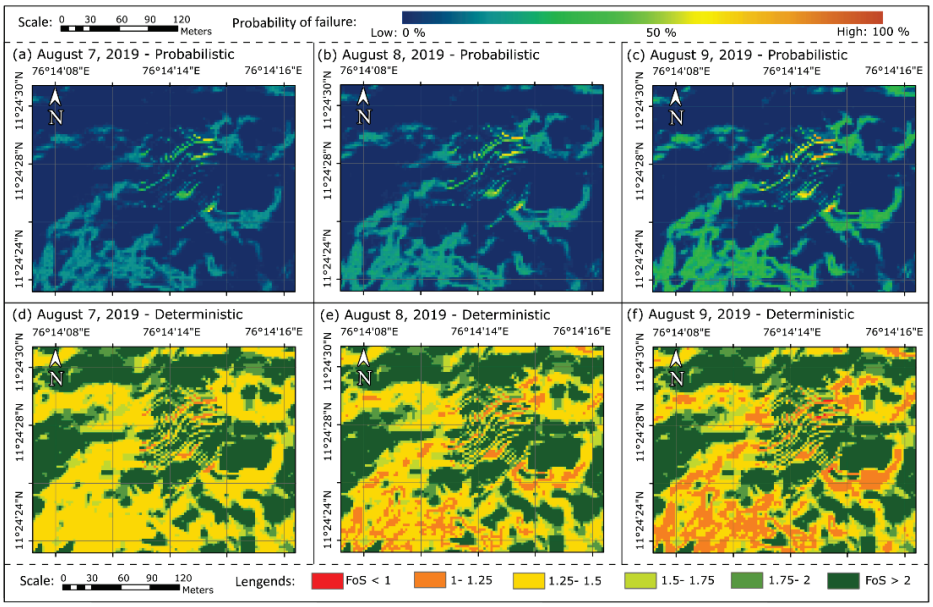


Fig. 3. Comparison of probability of failure map and FoS map from probabilistic and deterministic analysis using M-DEM

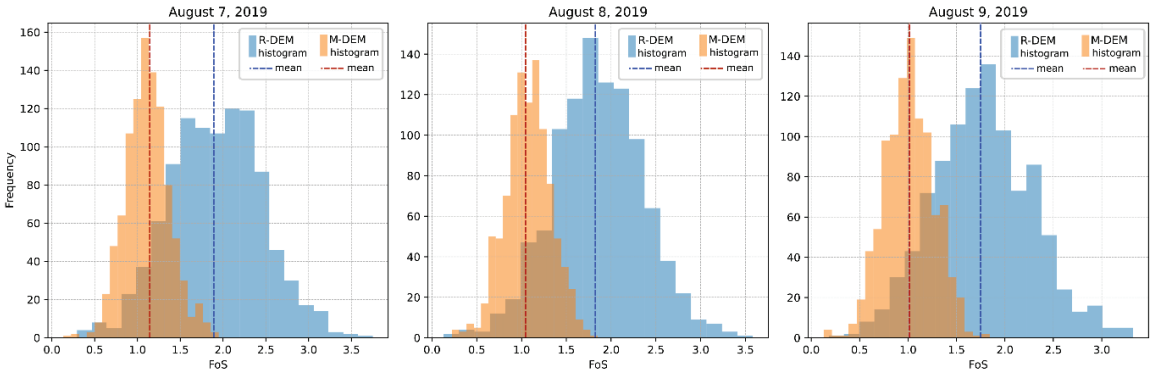


Fig. 4. Comparison of FoS histogram of plantation area from 1000 MCS runs using M-DEM and R-DEM

5. Conclusion

The probabilistic model, combined with the proposed modified DEMmethod, was able to delineate affected areas more effectively than the deterministic approach, capturing the impact of slope modifications well in advance. While the deterministic model using the resampled DEM performed better than the deterministic model with the proposed DEM enhancement framework, it still lagged in identifying critical failing areas in time. This comparison highlights the importance of high-resolution DEMs in improving the accuracy and reliability of landslide susceptibility predictions, particularly when combined with probabilistic modelling techniques.

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