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Failure probability of shallow landslides at a regional scale: the effect of root cohesion on distributed modelling

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ABSTRACT: This study presents a regionally distributed modelling of shallow landslides at a regional scale that incorporates the vegetation effect of the mechanical reinforcement provided by the roots. The long-term effects of evapotranspiration and canopy rainfall interception on water infiltration were also investigated. The analyses were conducted using HIRESSS (HIgh REsolution Slope Stability Simulator), a physically-based distributed slope stability model that enables efficient large-scale assessments across extensive spatial and temporal domains due to its parallel computing architecture. The stabilizing contribution of vegetation was accounted for by incorporating spatially variable root reinforcement based on the distribution and characteristics of local plant species. To model the inherent variability of spatial geotechnical parameters and manage their uncertainty, Monte Carlo simulations were employed. The model was applied to two case studies in Italy, and the simulation outcomes were evaluated focusing on the effect of the root reinforcement. Results indicate that the influence of the root reinforcement on slope stability is sensitive to rainfall intensity and duration. Under near-saturated soil conditions, however, the contribution of plant roots appears to be marginal.

Keywords: Root Reinforcement; Evapotranspiration; Distributed Modelling; Shallow Landslides; Landslide Hazard

1 INTRODUCTION

The study, modelling and forecasting of shallow landslides remain a research priority because such events usually have not premonitory signs, act as precursors of large debris flows and generate multiple simultaneous failures across a region. Their occurrence depends on the processes determining soil-vegetation-atmosphere interaction; indeed, they are commonly triggered by intense rainfall and the main factors of land surface susceptibility to failure are the hydraulic and geotechnical soil properties, topography, vegetation (mainly root reinforcement, evapotranspiration and rainfall interception effects), and land use. To support risk mitigation and early warning systems, two main strategies are adopted: (i) hazard assessment for land-use planning and (ii) forecasting of temporal and spatial landslide occurrence. Forecasting approaches are either empirical—based on statistical rainfall thresholds—or physically based, combining hydrological and slope-stability models. The latter often rely on the infinite-slope formulation coupled with simplified soil-moisture dynamics derived from wetness indices or approximate solutions of the Richards equation to compute the Factor of Safety. Recent advances incorporate the effects of vegetation, which is known to enhance slope stability mechanically, by root reinforcement, and hydrologically, through evapotranspiration control.

Representing the spatial variability of root cohesion, however, remains challenging, particularly at regional scale. Proposed methods include extrapolating field measurements, estimating root strength from vegetation structure or remote-sensing data, and applying eco-hydrological or stochastic Monte Carlo frameworks to capture natural variability.

In this study we modified, calibrated and applied the physically based model HIRESSS (Rossi et al. 2013) to investigate shallow landslides susceptibility of two extremely different case studies: pyroclastic slopes of Cervinara (Campania) and alpine terrains of Valle d'Aosta, simulating and studying the influence of evapotranspiration, rainfall infiltration, and root reinforcement on slope failure probabilities under different hydrological and seasonal conditions.

2 METHODS

HIRESSS model is a physically-based distributed simulator that computes transient infiltration, matric suction, and factor of safety (FS) over large areas. The model combines a hydrological module based on a simplified Richards equation with an infinite slope stability approach. Monte Carlo simulations are used to manage uncertainties (particularly unavoidable in such large areas) in the geotechnical and hydrological static

input parameters of the study areas. Root cohesion (c_r) was introduced as an additive term to effective cohesion (c') (e.g., Waldron and Dakessian, 1981; Gray and Ohashi, 1983; Operstein and Frydaman, 2000; Giadrossich et al., 2010), so that total cohesion is expressed as $c_{tot} = c' + c_r$ (Masi et al. 2023). The modified FS equations for unsaturated and saturated conditions account for both suction and root reinforcement effects.

Two representative study areas were analysed: (i) the Cervinara hillslope (Campania, southern Italy), characterized by unsaturated pyroclastic soils and covered by beech and oak forests, grading downslope into mixed chestnut and holm oak woodlands, while small agricultural plots prevail near urban areas; and (ii) the eastern Valle d'Aosta region (northwestern Italy), dominated by alpine glacial deposits and covered by forests, natural grasslands, and rocky outcrops with sparse vegetation (coniferous species dominate the forests—over 90%—with larch, Norway spruce, Scots pine, cembra pine, and silver fir as the most common, alongside patches of mixed coniferous and broad-leaved stands) (Masi et al. 2023, Cuomo et al. 2021).

For both sites, input data included slope morphometry, soil properties, rainfall intensity and root reinforcement (Figure 1).

In the Cervinara case study, also rainfall interception by the canopies and evapotranspiration were estimated, using the FAO-Penman–Monteith method for the latter (Cuomo et al. 2021).

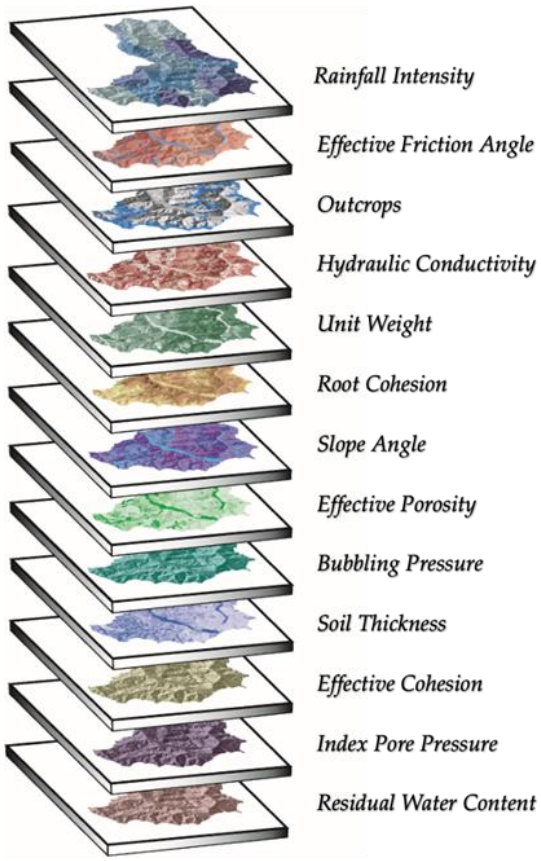


Figure 1. HIRESSS input data (Masi et al. 2023)

These estimations were carried out for a four-year period, the results suggested that their impact is negligible when simulating a short event of rainfall, particularly in December and when the objective is determining failure probability of shallow landslides. Details of estimated rates of evapotranspiration and interception for the Cervinara case study were presented in Cuomo et al. 2021.

Simulations were performed with 10 meters spatial (Valle d'Aosta) and 5 meters (Cervinara) resolutions, 1 hour time steps for the rainfall intensity, 1000 Monte Carlo iterations and one depth was set for the FS analyses, placed at the contact soil-bedrock. In case study Valle d'Aosta, multiple past rainfall events that triggered shallow landslides were simulated to calibrate the model to the area, validating in time and space the results based on the occurred landslides (Figure 2), this in the later perspective of a set-up of a regional early warning system. In case study Cervinara, the model was first calibrated based on hourly rainfall data recorded over a 4-day event (December 14–17, 1999) causing destructive landslides (Figure 3) also here comparing the results of model simulations to the occurred landslides; then, the calibrated model was applied for a long-term simulation where daily rainfall data recorded over a 4-year period (January 1, 2005–December 31, 2008) were considered to study the behaviour of the area in response to a long period of rainfall.

Calibration of the modelling process is needed essentially to determine pixels resulting unstable even in absence of rainfall and to define thresholds of failure probability and number of pixels to classify a spatial unit as unstable, when transformation from the output with trigger probability for each pixel to an aggregate map of basins identified as potentially unstable is desired.

In order to study the influence of the root reinforcement, multiple simulations were performed for both study areas, with and without the inclusion of root cohesion, to compare results and evaluate the influence on the failure probabilities computed by the model. With



Figure 2. Debris flow triggered during a rainfall event in 2019 in Fontainemore municipality, Valle d'Aosta (photo courtesy of Centro Funzionale Regione Autonoma Valle d'Aosta)

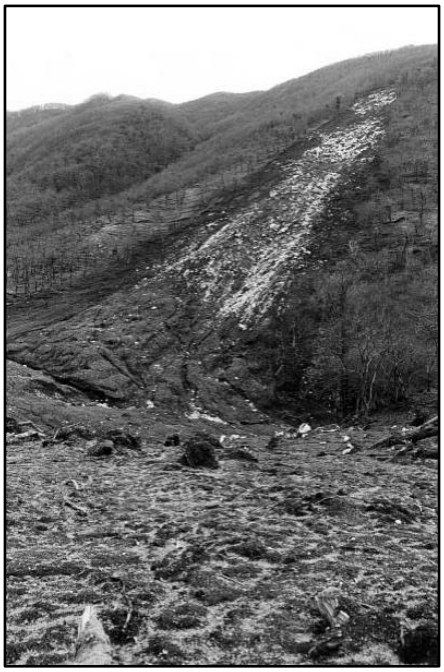


Figure 3. One of the landslides triggered during the December 1999 event in Cervinara municipality (Campania)

this specific purpose, in total, eleven simulations were carried out — nine for the Valle d'Aosta region and two for the Cervinara site.

The simulation results were compared through three complementary analyses:

(i) assessing pixel-by-pixel differences in failure probability between runs with and without root cohesion during both rainy and dry days;

(ii) evaluating the temporal evolution of unstable pixel differences—calculated as the number of unstable pixels in the simulation without root cohesion minus those in the simulation including it—across the entire study period and within selected subareas; and

(iii) analysing the variation of failure probabilities by comparing the number of unstable pixels in each probability class for simulations with and without root cohesion, under both wet and dry conditions in the different subareas.

3 RESULTS AND DISCUSSION

The calibration phase of the Cervinara case study confirmed that the model effectively captured the periods of higher failure probability corresponding to the timing and spatial distribution of observed landslides. The long-term simulation identified nine days during the four years during which the Factor of Safety fell below 1.2 (this value was used in the study as threshold for instability) across a substantial number of cells. In these instances, potential instability was concentrated within specific sectors and catchments of the study area, with certain sub-basins repeatedly exhibiting susceptibility to slope failure. Moreover, the analysis revealed distinct weekly and seasonal oscillations in overall slope

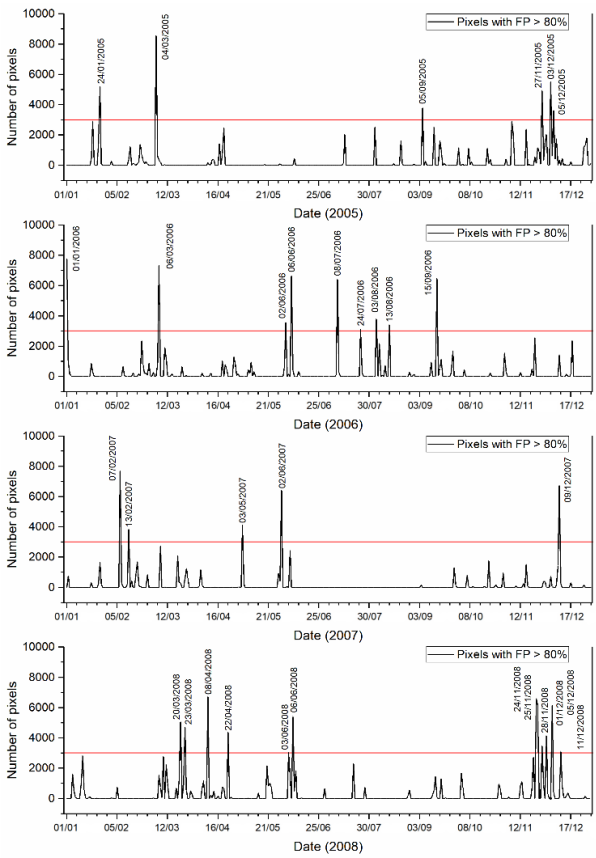


Figure 4. Cervinara case study: daily count of cells with a probability (P) of > 80% and factor of safety (FS) of < 1.2 from 2005 to 2008 (Cuomo et al. 2021)

stability, highlighting the temporal variability of the behaviour of the slope-vegetation-atmosphere domain.

The comparative analyses conducted on the simulation results, with and without the inclusion of root reinforcement in the selected model, revealed that the effect of this parameter was more evident during non-rainy periods, particularly in terms of the failure probabilities computed over extensive areas. This behaviour is mainly attributed to the way the root cohesion contribution was implemented within the model and to the nature of the comparison, which was based on probabilistic outputs rather than on deterministic Factor of Safety values.

As expected, the additional cohesion provided by root systems increased the Factor of Safety, according to the governing equations of the stability model and the adopted increment in rooted soil cohesion induced by roots in the investigated case studies. However, when considering the failure probabilities obtained through Monte Carlo iterations, the influence of root cohesion appeared marginal. This trend was especially clear under saturated soil conditions, where the stabilizing effect of roots becomes less significant since the reinforcement was modeled as standard cohesion and its effect is attenuated.

4 CONCLUSIONS

This work integrates physically based, probabilistic slope-stability modelling with a representation of the vegetation effects (root reinforcement, rainfall interception and evapotranspiration) to explore how soil–vegetation–atmosphere interactions influence the temporal and spatial patterns of shallow-landslide susceptibility. By applying an extended version of the HIRESSS model to two contrasting Italian environments—the pyroclastic slopes of Cervinara (southern Apennines) and the alpine catchments of Valle d'Aosta—the study evaluates the combined effects of rainfall, evapotranspiration, and vegetation-induced cohesion on slope behaviour over multi-seasonal time scales.

Two clear messages emerge. First, vegetation confers a measurable mechanical benefit: inclusion of root cohesion raises computed factors of safety and tends to reduce the spatial extent of unstable zones under moderate moisture conditions. However, this stabilizing effect (modelling the root reinforcement as an additional effective cohesion) is strongly state-dependent — it declines markedly as soils approach saturation during prolonged or intense rainfall. Second, seasonal hydrology dominates the temporal pattern of instability: evapotranspiration and matric suction recovery during dry periods increase safety, while rainy seasons produce recurrent days of elevated failure probability concentrated in specific catchments and sub-basins. The high-resolution probabilistic approach applied, proved effective at identifying those recurrently susceptible sectors and brief windows of heightened risk across multiyear simulations.

The research enabled the evaluation of a commonly adopted root cohesion model through the application of a distributed slope stability simulator over regional areas. The findings suggest that an alternative root cohesion model may be more suitable in the context of shallow landslides in similar environments, particularly when working with failure probabilities. Modelled as a standard cohesion, when saturation is reached, the root reinforcement effect has a weak impact on the stability. Even if a certain decrement of the effect is reasonable, an alternative model should represent the fact that the cohesion effect due to the presence of roots is attenuated less than the standard soil cohesion. In this context, further investigations—building upon those already conducted—into the relationship between root cohesion and soil moisture would be highly valuable.

Results of the study support this further following conclusions for research and practice:

- adopt probabilistic, high-resolution forecasting to locate recurrently vulnerable sub-basins and to prioritise monitoring and mitigation measures; such probabilistic outputs are more useful to stakeholders than single FS snapshots;
- improve representation of vegetation by combining species-aware parametrizations (root tensile strength, root area ratio) with stochastic approaches to capture natural variability; yet be cautious: different methods to estimate root cohesion (Wu model, fiber-bundle approaches, biome-level values) lead to varied outcomes and must be chosen transparently.
- the role of evapotranspiration and canopy interception is undoubtedly significant over the long term, particularly when estimating the actual amount of rainfall that effectively reaches the soil surface; in the context of shallow landslide forecasting triggered by intense rainfall events, accounting for these processes can be especially useful in reconstructing the initial saturation conditions from which the simulation starts; however, during the rainfall event itself, their influence becomes negligible if necessary, given the high rainfall intensities typically involved in landslide-triggering events, the short-term effects of evapotranspiration and interception on the hydrological response of the slope are minimal and can reasonably be neglected in dynamic slope stability simulations focused on the triggering phase.

Once the most efficient method for modelling root reinforcement has been identified, further developments for the use of the slope stability model HIRESSS in the context of early warning systems and landslides hazard assessment could focus on improving the assessment of vegetation distribution and density through remote sensing techniques, and on integrating additional vegetation-driven effects (both hydrological and mechanical).

5 ACKNOWLEDGEMENTS

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