

A three-dimensional numerical study of the effect of vegetation removal on the stability of riverbanks: insights into best practice vegetation management

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ABSTRACT: It is well established that vegetation plays a crucial role in controlling the stability of slopes. Its removal or degradation, caused by wildfires, droughts, or anthropogenic action, often acts as a contributing factor for landslide initiation, particularly on slopes already close to failure. This study proposes a comprehensive methodology that integrates field data, phenomenological interpretation, and numerical modelling to quantitatively assess root-induced mechanical reinforcement and provide general insights into best practices for vegetation in high landslide susceptibility areas.

A three-dimensional finite element model was developed for a riverbank where a rainfall-induced shallow landslide occurred (Øysand, Norway), confined to an area previously cleared of natural vegetation. A back-analysis of the event was performed by applying monitored precipitation as boundary condition, enabling validation of the phenomenological diagnosis and providing a reliable numerical analysis. The model was then tested under a vegetated scenario by incorporating a reinforced superficial layer, allowing the determination of the minimum root-induced mechanical increase in soil shear strength parameters required to prevent failure, consistent with the absence of landslide occurrence in nearby uncleared areas. Finally, the validated model was used for a scenario analysis to investigate the effects of different extents and geometrical patterns of vegetation clearance on slope stability.

Keywords: Stability analysis; Vegetation Management; Sustainable Landslide Risk Mitigation; Soil-Vegetation-Atmosphere Interaction; Nature-Based Solutions

1 INTRODUCTION

Vegetation cover often plays a fundamental role in protecting soil from erosion and enhancing slope stability. The soil–vegetation–atmosphere interaction involves numerous and complex mechanisms, primarily hydrological and mechanical, that generally exert a globally beneficial influence on slope behaviour. From a hydrological perspective, vegetation can increase matric suction via root water uptake and modifies the soil water balance through canopy interception and evapotranspiration. Mechanically, plant roots reinforce the soil-root matrix: fine roots enhance cohesion by binding soil particles, while larger woody roots can penetrate deep into the ground and anchor surface soil layers to more stable subsurface strata, often intersecting potential slip planes.

The importance of preserving natural vegetation on slopes has been recognized for centuries. Numerous documented cases show that vegetation removal, whether from deforestation, land-use change, or construction, can decisively alter the top-slope boundary condition, contributing to landslide triggering or, at the

very least, increasing the slope susceptibility to shallow landslides (Lehmann et al., 2019). Vegetation removal has also been associated with larger variations in soil water content, which can amplify seasonal deformations and compromise the serviceability of road and railway embankments (Smethurst et al., 2023). Studies investigating the spatial distribution of vegetation removal have also highlighted areas where its preservation is particularly important for slope stability and infrastructure performance (Tsiamposi, 2024; Mao et al., 2014).

Vegetation reinforcement is governed by many interdependent variables, including plant species, root depth, root density and external environmental conditions (Tagarelli & Cotecchia, 2022; Cecconi et al., 2025). Few modelling approaches have been proposed in the past to quantify the vegetation effects on slope stability. As for the mechanical contribution, the most adopted approach to model vegetation reinforcement treats the root–soil system as a homogeneous composite material and model root reinforcement as an additional cohesion, typically estimated based on average root tensile strength (e.g., Wu, 1976; Waldon, 1977).

The work presented aims to propose a simple yet effective framework to deliver valuable insights to support informed decision-making for vegetation management on natural slopes and embankments by employing accessible numerical modelling tools. This approach is developed with reference to the case study of the Øysand slope (Trondheim, Norway), where a shallow landslide occurred on a slope section where the natural vegetation cover had been artificially removed. Adjacent vegetated areas remained stable under the same conditions, suggesting a significant protective role played by the pre-existing vegetation. A finite element, FE, numerical back-analysis was carried out to simulate the occurrence of the failure event (model validation), followed by a sensitivity analysis to estimate the stabilizing contribution of the vegetation before its removal.

Based on these results, a series of hypothetical scenarios were developed to assess the effects of partial vegetation loss on slope stability. The aim of this analysis was to propose a simple, scenario-based framework to assess the implications of vegetation loss in localized areas and support both post-disturbance evaluations (e.g., after windthrow or wildfires) and optimal planning of vegetation management interventions, for instance along road cuts and embankments where vegetation clearance is often required for visibility or safety reasons.

2 THE ØYSAND CASE STUDY

The slope investigated is located at Øysand, approximately 15 km southwest from Trondheim, Norway. It probably developed as a riverbank, originated by erosion during the Gaula River meandering process, but ongoing fluvial morphodynamic processes have nowadays shifted the river channel away from the slope base. The slope bounds the south edge of a wide site included in the Norwegian Geotechnical Test Sites project (NGTS), deeply investigated and characterized in 2019 (Quinteros et al., 2019). A detailed stratigraphic description of the slope is provided by Shin et al. (2020). A superficial silty sandy layer was found in the very first meter of the slope, while clayey silty soil was found from 2 m to about 5.5 m depth. Below 5.5 m and down to about 10 m depth interlayered gravelly sand and gravels were found while below that depth and down to 20 m sandy silty and gravelly sands were found. The natural slope was originally covered by dense vegetation, mainly composed of willows (*salix caprea*) and rowanberries (*sorbus acuparia*) and the natural slope angle varied between 28° at the top and 34° on the bottom (Shin et al., 2020). Within the NGTS project, the slope was initially selected and monitored with the aim of observing the effects of freezing thawing cycles on slope stability. For this purpose, a test slope was

realized removing with an excavator the vegetation cover on a 15 m wide slope portion (Figure 1).

Over a monitoring period of several months, pore water pressure (PWP), soil temperature and soil moisture were recorded at various depth along the slope. Between late March and April 2020, a shallow failure occurred (Figure 1), although the exact timing is unknown. Several tension cracks were observed on the top of the slope and a large crown crack propagated from the top of the slope. Rainfall was recognized as the primary trigger for the failure. Nevertheless, even if minor, also the effect of freezing thawing cycles was reasonably not negligible: the cracks developed during the thawing season could have increased the permeability of the topsoil and consequently infiltrated water fluxes in April, raising PWP and reducing matric suctions (Shin et al., 2020). It is worth mentioning that the slope failure only developed in the bare portion of the site while the rest of the slope, where the natural vegetation was preserved, did not experience failure or soil displacements. Although rainfall appeared to trigger the slope failure, vegetation removal likely acted as a predisposing factor, making that portion of the slope more prone to failure.



Figure 1. Picture of the slope after the failure

3 MATERIALS AND METHODS

In order to perform the analysis of the different vegetated scenarios, it was essential to develop a reliable numerical model capable of reproducing the slope behaviour when interacting with the atmospheric forcing action. A preliminary two-dimensional (2D) model was implemented using the FE software PLAXIS, representing a cross-section of the failed bare portion of the slope. Field investigations and monitoring data were employed for the model calibration and validation, while measured precipitation (including rainfall and snowmelt) was applied as top boundary condition to simulate the slope-atmosphere interaction. Consistently with the results of the in-situ investigation (Shin et al, 2020), three soil layers were implemented in the model, whose mechanical and hydraulic parameters are listed in table 1. The Mohr-Coulomb elastoplastic model was adopted.

Table 1. Geotechnical parameters adopted in the models: γ , unit weight of the soil; e_0 , initial void ratio; E' , Young's modulus; ν' , Poisson's ratio; K_0 , coefficient of earth pressure at rest; k_x and k_y , horizontal and vertical saturated permeability; c' , cohesion; ϕ' , friction angle

	γ [kN/m ³]	e_0	E' (kPa)	ν'	K_0	k_x [m/day]	k_y [m/day]	c' [kPa]	ϕ' [°]
Unit 1.1-clayey sand	19	1	10 ⁴	0.3	0.65	9×10 ⁻³	4.5×10 ⁻³	7.5	24
Unit 1.2-clayey sand	19	1	10 ⁴	0.3	0.65	0.1×10 ⁻³	0.5×10 ⁻⁴	7.5	24
Unit 2-sand with gravel	19	0.4	10 ⁵	0.3	0.65	4	4	2	35.5

Although not discussed in detail in this contribution, the simulation successfully reproduced the temporal evolution of PWP at different depths in response to precipitations and both the timing and location of slope failure, along a slip surface consistent with observations in the field (Donvito, 2024). Since the real 3D slope geometry was regular, and failure was observed only where vegetation had been removed, vegetation cover emerges as the sole source of heterogeneity influencing slope behaviour. The original 2D model was then extruded into a 3D setting with the aim of carry out simulations to investigate multiple vegetation cover scenarios. Starting from a fully vegetated slope, different cases involving selective vegetation removal were tested. Variations included different strip widths and removal at various slope heights. Soil parameters derived from the field investigation and from previous analyses (Table 1) were adopted. Regarding root reinforcement, since the observed failure was relatively shallow, only the mechanical effects of root systems were considered, while hydrological effects were excluded. Root reinforcement was represented by assigning an additional cohesion to a cluster representing the superficial layer permeated by roots. In general, the magnitude of vegetation reinforcement can be assessed through site-specific surveys and tests investigating vegetation characteristics at both the stand and root scale. In this case, however, no samples were collected, and thus no experimental data could be obtained. The root cohesion, c'_{root} , and depth of the root system, d_{root} , were both evaluated through a preliminary 2D sensitivity analysis aimed at identifying the minimum values required to avoid the failure occurrence in the 2020 event. A steady-state drained plastic calculation was firstly simulated by applying a surface inflow to recreate a groundwater condition consistent with that observed in the field. Subsequently, a factor of safety, FoS, calculation was conducted for all the vegetation removal scenarios (Figure 2) by means of c' - ϕ' reduction in which the strength parameters of all soil layers, including rooted ones, were progressively reduced until failure.

4 RESULTS

Through the preliminary sensitivity analysis, a root cohesion of 1.5kPa and a rooting depth of 1.5m were identified as the minimum conditions required for the vegetated portion to prevent slope failure in areas where

vegetation was kept. Capobianco et al. (2021) reported for goat willows, the most abundant species on the slope, c'_{root} of about 1.37kPa and d_{root} of about 1m, which well align with those resulting from the sensitivity analysis. Furthermore, these vegetation parameters also appear realistic and consistent with values reported for other common tree species in the literature (Schwarz et al., 2009; Pollen & Simon, 2005). These results demonstrate that for shallow landslides, even modest increases in soil strength from root systems can be sufficient to prevent failure. Consequently, preserving vegetation cover on natural slopes and embankments is crucial not only for slope stability but also for ensuring the safety and serviceability of infrastructures interacting with the slope.

The scenario analysis results are summarized in Figure 2b. The fully vegetated slope was used as the reference case, and other scenarios were evaluated in terms of percentage variations in FoS. Vegetation removal clearly had a destabilizing effect, although the reduction was modest. Even in the worst-case scenario, with complete removal of vegetation, the FoS decreased by only about 5%. However, this reduction could be critical on marginally stable slopes. Moreover, these findings are likely conservative: incorporating hydraulic effects would likely amplify the destabilizing influence of vegetation removal.

The location of the failure slip surface exhibited minimal variation across the scenarios. Further analysis highlights these key trends: *i*) strip width: vegetation removal over a narrow strip has little effect on slope stability unless the strip is at least 15 m wide (e.g., Cases 2 and 3); *ii*) slope position: vegetation near the toe and crest contributes more to reinforcement than vegetation at mid-slope (Cases 6 and 7); this is consistent with previous findings that potential failure surfaces often span the full slope height but remain shallower near the toe and crest, where root reinforcement is most effective; *iii*) top/bottom vegetation removal: in Cases 4 and 5, comparing vegetation removal from the upper and lower halves of the slope, results show that vegetation in the lower half has a greater influence on overall stability than vegetation at the top; *iv*) partial strip removal: in scenarios where vegetation was removed from a 15 m-wide strip covering only half of the slope height, the reduction in FoS was minimal, indicating that partial vertical removal over limited widths is less impactful.

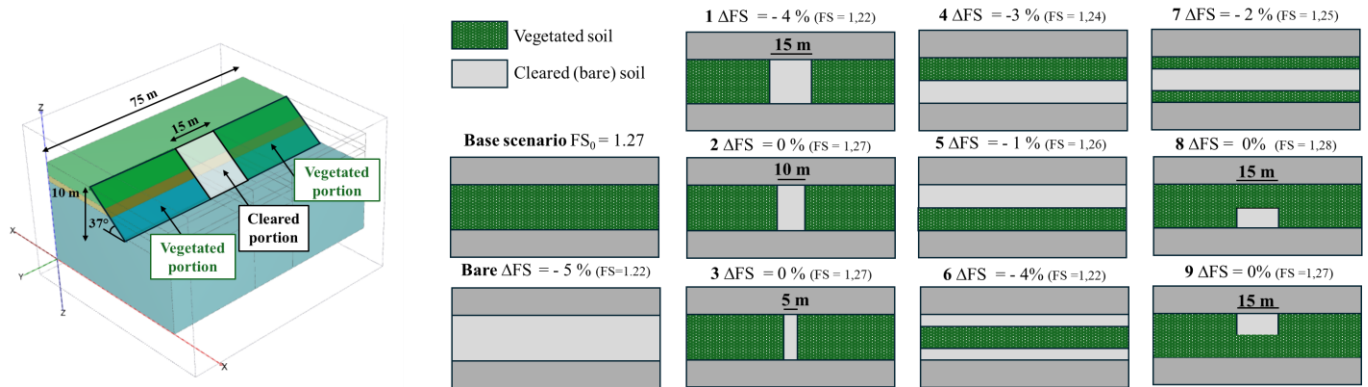


Figure 2. a) 3D geometry of the case study; b) results of the scenarios analysis in terms of percentage of reduction of the FoS

5 CONCLUSIONS

This study presents a simple yet effective framework to evaluate the impact of vegetation removal on slope stability, demonstrated through the case of the Øysand slope. The FEM model and the sensitivity analysis revealed that even modest increases in soil cohesion due to root presence can be sufficient to prevent shallow slope failures.

The Øysand slope can be considered as a representative case study for a broad class of riverbank slopes. The findings of this work offer preliminary insights that may help establish best practices for vegetation management in similar contexts. Given the goal to deliver broadly applicable recommendations, the root reinforcement was modelled using a simplified approach. Though, this methodological framework can be adapted to obtain site-specific insights. By incorporating detailed vegetation features, more targeted predictions can be achieved. Future work will incorporate the effects of vegetation on soil moisture evolution over time and evapotranspiration fluxes, which could yield more accurate and comprehensive results.

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