

Contribution of tree felling to a landslide: a case study from Spain

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ABSTRACT: This study investigates the role of tree removal in a landslide that occurred in Spain, where a historical fill supported by a retaining wall collapsed, damaging multiple buildings. An earlier ground movement, attributed to an overturning effect from tree loading at the crest, prompted the removal of vegetation. However, this intervention did not prevent the subsequent and more severe failure. The research aims to quantify the impact of this tree removal on slope stability. To understand the failure mechanism, a detailed timeline of events was reconstructed, and a comprehensive post-failure site characterization was conducted. These data were incorporated into a finite element method (FEM) numerical model that considers both the mechanical reinforcement provided by roots and the hydrological influence of partial soil saturation. The modelling approach reflects current advances in simulating vegetation effects on slope stability, particularly in unsaturated conditions. The results reveal that both root cohesion and partial saturation played significant roles in maintaining slope stability prior to failure. Their removal, through vegetation clearance and increased moisture due to an irrigation leak, contributed to the eventual collapse. This case study emphasizes the need to integrate biological and hydro-mechanical factors into slope stability analyses, which are often overlooked in conventional engineering practice. Overall, the findings demonstrate that vegetation management, if not carefully evaluated, can inadvertently reduce slope stability. Incorporating root reinforcement and unsaturated soil behaviour into numerical models offers a more realistic and robust framework for assessing landslide risk.

Keywords: Slope Stability; Root reinforcement; Partial saturation; FEM

1 INTRODUCTION

The use of vegetation for slope stabilization is an exemplary application of bioengineering (Coppin & Richards, 2007). The mechanisms through which roots influence slope stability can be grouped into hydrological and mechanical (Reubens et al., 2007). From a hydrological perspective, the presence of roots in the soil mass leads to an increase of suction through the process of evapotranspiration, and the generation of macropores during root growth increasing infiltration capacity (Ni *et al.* 2018). In terms of mechanical reinforcement, root-mediated stabilization mechanisms include basal and lateral reinforcement (by roots that cross a potential failure surfaces) and soil stiffening due to the presence of roots in the sliding mass, particularly when there is interaction between neighbouring root systems (Schwarz et al., 2015, Giadrossich *et al.* 2017, Andreozzi *et al.* 2025).

Although most root systems can penetrate up to 3 m into the soil, between 80% and 90% of tree roots are concentrated within the top 0.9 m of soil (Norris et al., 2008). Consequently, most soil–root interaction phenomena occur under low confinement stress conditions.

The root soil interaction features described above, combined to low confinement stresses, make the geotechnical modelling of vegetated slopes complex.

One of the most challenging aspects to incorporate root reinforcement into slope stabilization models is the interplay between hydraulic effects, and mechanical reinforcement (Stubbs et al., 2019). Finite Element Method (FEM) based numerical models usually incorporate the mechanistic reinforcement by means cohesive regions within the numerical domain (Liang et al. 2020) often neglecting the hydromechanical coupling. Only recently this aspect has been addressed in research (Zhang et al 2022).

This paper presents the analysis of a landslide that occurred in April 2017 on Pui Pinós hill, located in the city of Alcañiz (Spain), as part of a forensic engineering study aimed at clarifying the causes of this landslide, with special emphasis on the effects of the presence of trees on the stability of the failed slope. A FEM numerical model considering both the mechanical reinforcement and the hydrological influence of partial soil saturation is used to show that both effects played a significant role in maintaining slope stable prior to failure.

2 PROBLEM SETTING

In December 2016, initial evidence of instability was documented at the Pui Pinós hill in Alcañiz, where semicircular cracks developed about 10 m from the crest, within an area containing two cypresses and a pine with a quasi-horizontal trunk (Figure 1).



Figure 1. Cracks on the crest and landslide affected zones

Preventive removal of these trees was undertaken by local authorities on the assumption that their presence induced tensile stresses at the slope crest. Downslope, the affected sector intersected the remains of a medieval retaining structure, approximately 5 m in height and 30 m in length, which, despite its deteriorated condition, had historically functioned as a debris-retaining wall. On the night of the 17 April 2017, a large landslide took place on the previously cracked section. Several buildings were destroyed, but, as rockfalls started 4 hours before the final collapse, there was time for evacuation and no casualties were to be lamented. From a climatic standpoint, Alcañiz is classified within the semi-arid domain of Spain (<600 l/m² annual precipitation). The period preceding the failure was not unusually rainy. However, an irrigation main conduit was present at the crest (see Figure 1). Post-failure analysis indicates that it released approximately 1,000 m³ of water during the night. This water release likely contributed to fill saturation at the slope, thereby triggering the final collapse mechanism.

3 CHARACTERIZATION OF MATERIALS

Following the landslide event, a geotechnical investigation was carried out. The program included twelve dynamic penetration tests (DPSH), two drone-based topographic surveys, and the collection of surface samples for laboratory testing. Results indicated that the slope is composed of two distinct geotechnical units: (i) the natural Tertiary bedrock, consisting of alternating harder sandstones and softer argillites and marls in a sub-horizontal arrangement, and (ii) anthropogenic fill materials of Quaternary age, overlying the rock mass. Based on comparisons between the original and post-cleaning topography, the fill thickness within the landslide zone was estimated to range between 4 m and 9 m. Laboratory analyses were performed on selected samples of the fill material. The results showed that the fill consists of a

heterogeneous mixture of cobbles, blocks, and anthropogenic debris embedded in a predominantly silty matrix. Moisture contents were generally higher in samples collected along the landslide axis compared to those from the margins. The void ratio was estimated at approximately 0.7, indicative of a loose, uncontrolled fill. Correspondingly, degrees of saturation ranged between 32% at the margins and up to 70% along the axis of the slide, consistent with the low penetration resistance measured in the DPSH tests. Given the partial saturation of the fill, a soil–water retention curve was estimated using the method of Aubertin et al. (2003), and the contribution of suction to shear strength was evaluated following the approach of Fredlund et al. (1993) (Figure 2)

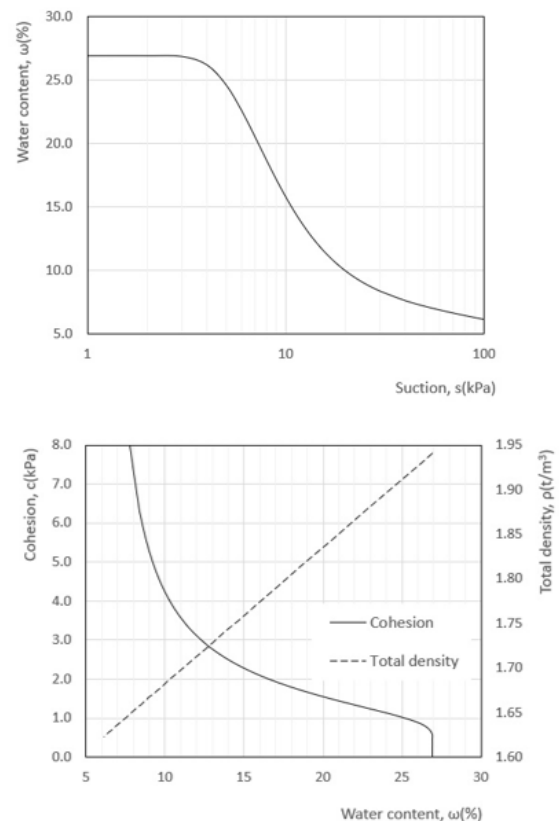


Figure 2. Estimated retention curve (up) and variation in extra cohesion and total density with respect to moisture content (down) for the fill materia

Direct shear tests were conducted on two samples, though limited to the soil fraction smaller than 2 mm, and therefore unrepresentative. After the landslide, the average slope angle was approximately 36°, while the angle of repose observed in the fill material deposited at the slope base during cleanup ranged between 33° and 35°.

4 LANDSLIDE ANALYSIS

To investigate the potential failure mechanisms, slope stability analyses were performed using FEM. The analyses were carried out on a representative cross-section of the slope long with the FEM mesh (Figure 3).

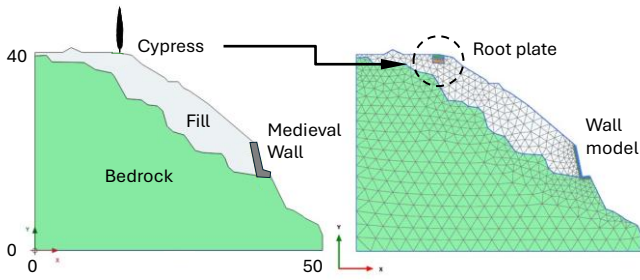


Figure 3. Representative cross-section of the slope and FEM model mesh

Two scenarios were considered: (A) without the presence of the medieval wall remains, and (B) with the wall included. In the latter case, given the limited information available, the wall was idealized as two rigid L-shaped plates, approximately 5 m high and 2 m deep, assumed to rest directly on the bedrock. At the wall–rock contact, a cohesion of 5 kPa and a friction angle of 45° were assigned, based on published values for masonry structures (Alejano et al., 2012). Within scenario B, two subcases were analysed: (1) progressive reduction of the shear strength of the fill material, while maintaining the wall–rock contact strength, and (2) progressive reduction of the wall–rock contact strength until failure occurred.

The geomechanical properties of the fill were estimated assuming a moisture content of 8%, representative of the pre-failure state, in accordance with performed lab tests on samples recovered from the landslide margins. The underlying rock mass was modelled as elastic and very stiff to provide a strong mechanical contrast with the overlying fill. Table 1 summarizes the adopted parameters.

Table 1. Model parameters

Material	ρ (t/m^3)	ϕ ($^\circ$)	c (kPa)	E (MPa)	ν
Fill	1.65	36	6.4	30	0.2
Bedrock	1.67	---	---	1000	0.2

The results of the analyses are illustrated in Figure 4. In case A (no wall), failure occurred along a continuous slip surface, leading to a global loss of stability. In case B, two distinct failure morphologies were observed: in the subcase where strength reduction occurred within the fill, the failure was relatively shallow.

In the subcase involving reduction at the wall–rock interface, the failure surface was deeper and more extensive. This latter morphology corresponds closely with field evidence. These results suggest that the immediate cause of the Pui Pinós landslide was the motion of the medieval retaining wall that ruptured an irrigation pipe located at the slope crest (see Figure 1), releasing large volumes of water onto the slope head. The water inflow reduced the shear strength of the fill and increased the load acting on the wall, ultimately triggering the catastrophic failure observed in the field.

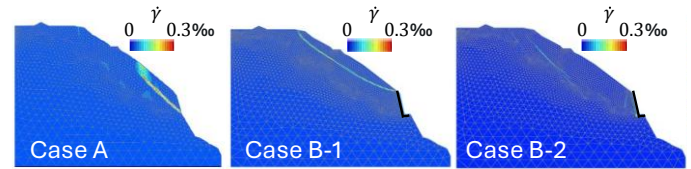


Figure 4. From left to right failure mechanisms, without wall, with wall considering fill strength reduction and with wall considering interface strength reduction ($\dot{\gamma}$ =incremental deviatoric strain)

4.1 Effect of Trees on the Slope Crest

The influence of trees at the crest of the slope—removed by authorities as noted in Section 2—was analysed by extending the slope stability model described above to include root reinforcement. The contribution of root cohesion was incorporated following the approach of Wu (1979) and Bischetti et al. (2009), which considers roots as cylindrical, elastic elements mobilizing tensile resistance through soil–root friction when intersecting a potential failure plane (see the root plate in Figure 3). Root cohesion was estimated as a function of soil friction angle, root inclination, and mobilized tensile resistance per unit soil area, with adjustments for angular variability and differential root breakage.

For this study, parameters were adopted from published ranges, consistent with values reported by Bischetti et al. (2009). Root Area Ratio (RAR) distributions were taken from Stokes et al. (2008), assuming conditions similar to *Cupressus sempervirens*, the cypress species identified at the site. The tensile strength of roots was estimated at $T_r = 10$ MPa, based on average published values for roots with diameters greater than 10 mm. Root depth was assumed to reach a maximum of 1.5 m, with a distribution of RAR and root cohesion varying with depth. Equivalent geomechanical properties of the root–soil composite are in Table 2. For more details on the model parameter derivations refer to Arroyo et al. (2025).

Table 2. Equivalent geomechanical parameters for soil–root composite

Material	ρ (t/m^3)	ϕ ($^\circ$)	c (kPa)	E (MPa)	ν
Fill + roots	1,65	36	26.4 ^(*)	30	0.20
			15.4 ^(**)		
			7.2 ^(***)		

(*) $z=0-0.5\text{m}$; (**) $z=0.5-0.75\text{m}$; (***) $z>0.75\text{m}$

The influence of roots was analysed for Scenario B (slope with wall), under both subcases: (1) failure developing through the fill and (2) failure driven by wall–rock detachment. The results (Figure 5) indicate that for shallow slides, root reinforcement shifts the failure surface downward, showing that roots provide an effective stabilizing contribution up to depths of approximately 1.5–2 m. However, for deep-seated failures governed by wall

instability, the influence of roots is negligible, as the failure morphology remains essentially unchanged with or without trees included in the model.

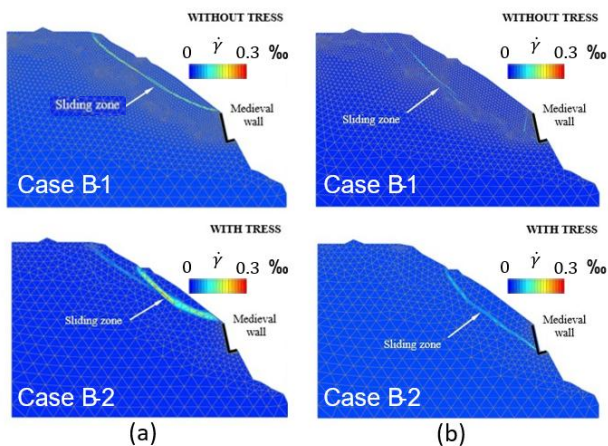


Figure 5. a) Effect of vegetation for fill failure scenarios; (b) effect of vegetation for wall sliding failure scenarios reduction ($\dot{\gamma}$ =incremental deviatoric strain)

These findings suggest that the presence of trees at the crest of the slope can play a beneficial role in preventing shallow failures, though their stabilizing effect diminishes markedly in the case of deeper-seated landslides such as the one observed at Pui Pinós.

5 CONCLUSIONS

The case study demonstrates the positive role of trees in enhancing slope stability against shallow failures, particularly for failure surfaces located within the upper 1.5–2 m. However, their contribution becomes negligible in the case of deep-seated instabilities. The results further highlight the importance of accounting for partial saturation, since matric suction can provide additional resistance against sliding. Accurate estimation of the soil–water retention curve is therefore essential. Nevertheless, as full saturation eliminates the stabilizing effect of suction, it is imperative to minimize risks associated with pipe ruptures, excessive irrigation, and hydraulic works (e.g., canals and drains) through appropriate inspection and maintenance programs.

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