Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X

doi: doi.org/10.53243/RootS2025-23

Hydro-mechanical response of slopes intensively cultivated with apple orchards: a preliminary investigation

D. Bianchi[1], G. Pedone[1], L. Simeoni[1]

[1]*Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy*

ABSTRACT: The rising demand for food is significantly driving intensive farming with high yield production and large water consumption. In this scenario, soil shear strength reductions may be observed as a consequence of soil suction reductions, depending on soil hydro-mechanical properties, seasonal weather variations and irrigation methodologies. Consequently, when sloping areas are cultivated and irrigation practices are not appropriately managed, landslide phenomena may be triggered, potentially causing human and financial losses. Within this context, the paper investigates the effects of replacing grassland with apple orchards on slope stability, focusing on the Val di Non area (Trentino, Italy), where intensive apple cultivation is widespread. The impact of replacing grassland with apple orchards on slope stability is assessed by performing soil-vegetation-atmosphere interaction finite element seepage analyses. The analyses consider infiltration due to precipitation and irrigation, runoff losses, as well as soil evaporation and plant transpiration. The pore-water pressure distributions obtained through the seepage analyses are finally used for limit equilibrium analyses aimed at assessing the impact of apple orchard intense cultivation on slope stability.

Keywords: roots; apple orchards; soil-vegetation-atmosphere interaction; slope stability

1 INTRODUCTION

In Trentino (Northern Italy), permanent crops, such as vines and apple trees, modify the hydro-mechanical behaviour of hilly landscapes. Specific studies of the soil-apple trees-atmosphere interaction are required with the aim of planning proper soil monitoring for improving water management and studying the stability of cultivated slopes.

In order to effectively study those aspects with site specific numerical models, it is necessary to characterise the hydro-mechanical behaviour of the soil-root system (Fraccica et al, 2025; Dias et al., 2022; Tarantino et al., 2002). Although the hydro-mechanical characterisation of vegetated slopes has been recently discussed in the literature (Capobianco et al., 2023; Bischetti et al., 2009; Elia et al., 2017), there is still a lack of data specifically referred to apple-tree orchards.

This paper aims at presenting a first glimpse of the effects of replacing grassland with apple orchards on slope stability, taking the Val di Non area as a reference. For this purpose, simple 2D Finite Element (FE) seepage analyses have been conducted, modelling slope-vegetation-atmosphere interaction processes under two different scenarios: (i) lawn and (ii) apple orchard cultivation (with continuous irrigation from March to September). Based on these seepage simulations, limit equilibrium analyses have been carried out for a preliminary assessment of the impact that apple orchard intense cultivation might have on slope stability.

2 FE SEEPAGE ANALYSES

2.1 *Geometry discretisation*

Finite Element (FE) seepage analyses have been carried out by means of Seep/W (Geostudio 2024.2.1). The mesh generated for the 2D FE seepage analyses is presented in Figure 1(a) and it is representative of apple orchard rows aligned in the longitudinal direction.

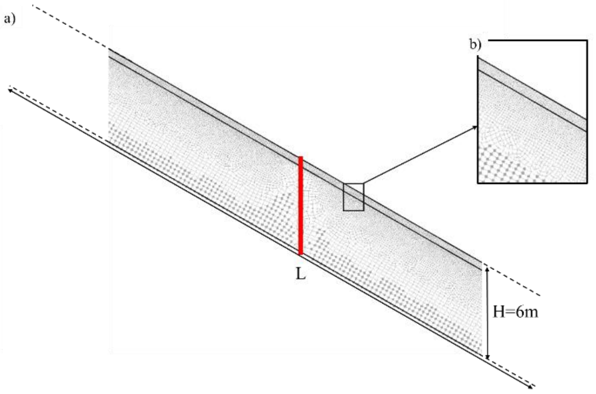

Figure 1. Mesh generated for seepage analyses

Slope angle and model length have been varied in order to study their impact on the slope response. For sake of brevity, this work only presents analyses referred to an inclination of 30°, a length L=90 m and a height H=6 m. The top 50 cm of the slope have been divided in 10 cm thick sub-layers, to assign representative rooted soil properties. Next to ground level, elements with an average length of 5 cm were used (Figure 1(b)), whose size is gradually increasing at larger depths. The mesh is formed of 41728 elements and the analyses adopted a time step of 0.25 days.

2.2 *Soil hydraulic properties*

The soil properties are related to a sandy silt unit cultivated with apple orchards already analysed by Bosco et al. (2018) and discussed more extensively by Dalpiaz (2015). For simplicity, the baseline analyses, conducted with reference to grass conditions, assumed the soil properties derived for bare soil, simply accounting for the presence of grass in terms of evapo-transpiration effects. On the other hand, the hydraulic properties of the apple rooted-soil have been defined following indications reported in the literature (e.g. Dias et al., 2022). The water retention curve (in terms of volumetric watrer content, θ) and the hydraulic conductivity (K) function for bare and apple rooted-soils are represented in Figure 2.

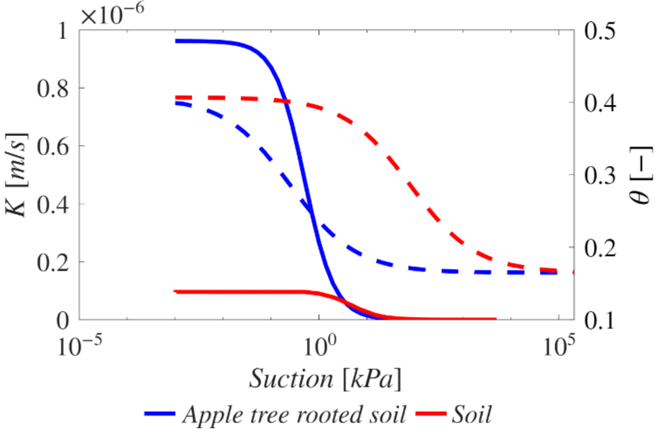

Figure 2. Soil water retention curves (dashed lines) and hydraulic conductivity functions (continuous lines)

2.3 *Boundary conditions*

The top boundary condition has been defined based on daily weather data recorded at the meteorological station located in Cles (Trentino, Italy). A net infiltration has been applied, corresponding to the difference between daily influxes (i.e. rainfall and irrigation) and evapo-transpiration. A uniform sprinkler irrigation has been assumed for apple orchards from March to the end of September, taking as a reference an irrigation of 1.97mm/d following Bosco et al. (2018). The evapo-transpiration has been estimated with the FAO Penman-Monteith method (Allen et al., 1998).

As part of this method, a reference crop evapo-transpiration, ET_0, is first evaluated (referred to ideal grass conditions) and then multiplied by a (single) crop coefficient, K_c, and a water stress coefficient, K_s. The crop coefficient (K_c) is a function of time, since it considers different growing stages. During summer, the growing phase of the apple trees reaches its peak and the maximum transpiration is attained, also due to higher temperature and longer days. On the contrary, during winter, apple trees are in the dormient phase, and transpiration tends to be lower. A crop coefficient $K_c = 0.45$ was therefore assumed for winter, while $K_c = 0.95$ was considered during summer, decreasing to $K_c = 0.7$ in autumn (de la Fuente et al., 2024; Mobe et al., 2020; Pereira et al., 2021; Zanotelli et al., 2019).

The water stress coefficient (K_s) depends on the soil characteristics. When the topsoil dries out, a reduction in evaporation rate begins to occur in proportion to the amount of water remaining in the top soil layer (Dainese and Tarantino, 2021). More specficially, K_s has been assumed constant and equal to 1 up to a suction s=40 kPa, with a subsequent linear reduction to 0 at a suction s=500 kPa.

The initial conditions have been defined through a steady state seepage analyses giving rise to a near hydrostatic pore pressure distribution having 0 kPa at the bottom of the slope and a s=60 kPa at ground level (Bosco et al., 2018). Subsequently, a transient seepage analysis simulating 10 years of weather conditions (i.e. 1994-2004) has been conducted (see Figure 3 for the corresponding boundary conditions). However, results referred to the initial 5 years are not herein reported, given that the first 5 years have been carried out only to approach representative initial conditions.

Three different analyses have been conducted: (1) top boundary condition accounting for grass evapo-transpiration (considering the reference crop evapo-transpiration, ET_0); (2) top boundary condition accounting for apple orchard evapo-transpiration (including apple orchard irrigation); (3) top 50 cm presenting hydraulic properties of apple tree rooted-soil also accounting for apple orchard evapo-transpiration (including apple orchard irrigation). Figure 3 shows the two top boundary conditions used in the analyses.

A null unit flux has been assigned to the bottom boundary (i.e. simulating an ideally impermable bedrock below the soil layer analysed; Bosco et al., 2018). A zero unit flux has also been considered on the lateral boundaries, but in combination with a 0 kPa pore pressure cut-off.

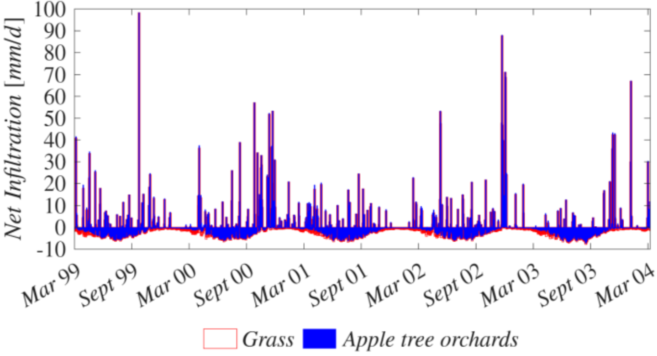

Figure 3. Boundary conditions for grass (red) and apple trees (blue). Months and years are shown on the horizontal axis (e.g. Mar 99 refers to March 1999)

2.4 Hydraulic slope response

The pore water pressure evolution with time at 2m depth at the centre of the slope is reported in Figure 4. The change in evapo-transpiration, from “Grass” to “Apple orchards” (from thin continuous line to thin dahsed line in Figure 4), has a clear impact on the hydraulic response of the slope. The results are also showing the influence of employing hydraulic properties specifically referred to an apple orchard-rooted soil, yielding higher pore pressures (compare thin dashed line and bold continuous line in Figure 4). During wet periods, the apple orchard rooted soil reaches saturation at ground level, due to the high amount of water entering the slope. This includes irrigation, whose accurate management is therefore necessary to avoid unexpected slope instabilities (Bosco et al., 2018). On the other hand, grassland allows for higher suctions to develop, due to the higher evapo-transpiration accounted for in the analysis.

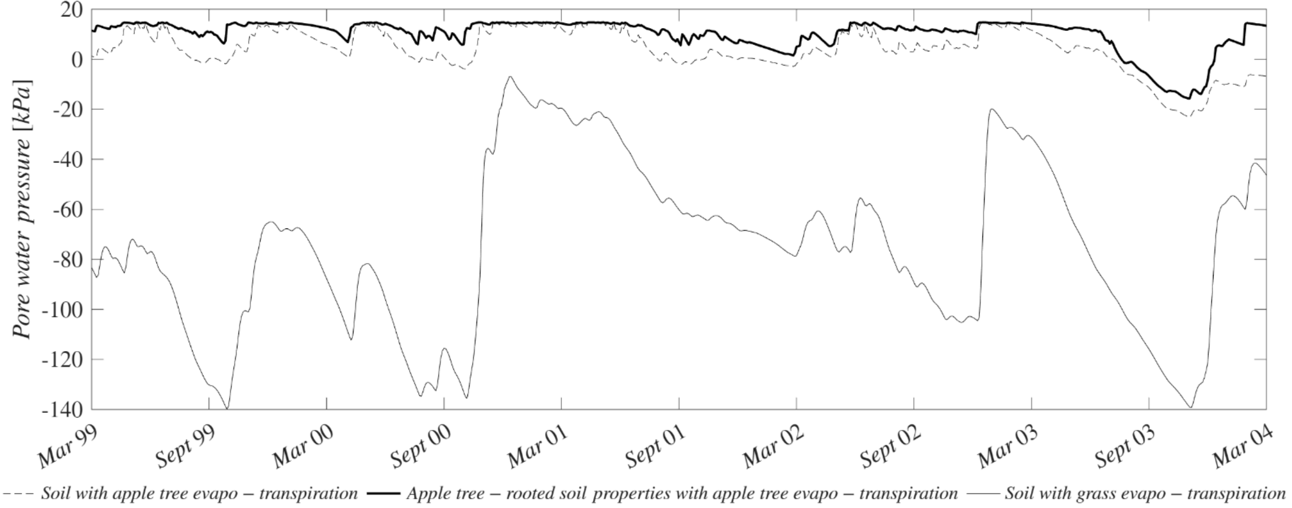

Figure 4. Pore water pressure evolution with time at 2m depth at the centre of the slope

3 SLOPE STABILITY ANALYSES

3.1 Soil mechanical properties

Slope stability analyses have been carried out by means of Slope/W using the Morgenstern and Price method (1965). The mechanical properties of both sandy silt and grass-rooted soil are $c' = 0kPa$ and $\varphi' = 35°$ (Dalpiaz, 2015), hence neglecting, for simplicity, any additional contribution induced by the presence of grass roots. As mentioned before, grass is only accounted for in terms of evapo-transpiration effects. By considering already existing datasets for trees (Bischetti et al., 2009; Cazzuffi et al., 2014), the rooted soil with apple trees has been assigned a nominal cohesion $c' = 10kPa$ associated with $\varphi' = 35°$.

3.2 Slope stability variations

A 2m-deep landslide body has been taken as reference and the evolution of the corresponding safety factor with time is reported in Figure 5. The grassland conditon generate the highest safety factors, showing generally stable conditions. When considering the effects of apple roots uniquely on the boundary condition, i.e. case (2), the landslide body analysed becomes unstable. This is mainly due to the irrigation continuously applied from March to September.

In case (3), where the influence of apple tree roots is considered also in terms of soil hydro-mechanical properties, further factor of safety reductions are observed, suggesting that the mechanical reinforcement due to the roots ($c' = 10kPa$) cannot completely balance the unfavourable effect of the pore-water pressure increments due to the increase in hydraulic conductivity (see Figure 2).

It should be acknowledged that the assumption of an ideally unfractured and impermeable bedrock is likely to represent the worst case scenario for slope stability. On the other hand, a fractured and more permeable bedrock would have been associated with lower pore pressures, resulting in higher factors of safety.

4 CONCLUSIONS

This is an exploratory work aimed at providing preliminary results regarding the interaction between slope, vegetation and the atmosphere, either considering a lawn cover or apple tree orchard covers. A simple 2D slope model has been analysed, in order to study the impact of apple orchard intense cultivation under continuous sprinkler irrigation conditions.

The presence of apple tree roots in the shallower layers has been modelled by considering a representative atmospheric boundary condition and by modifying the soil hydro-mechanical properties based on literature data. However, these data refer to different vegetation types, so a more specific hydro-mechanical characterisation of apple tree-rooted soils is necessary to simulate more representative scenarios. Site-specific ground conditions should be also investigated to assume more realistic boundary conditions at the slope bottom.

Despite their preliminary nature, the results obtained from the analyses suggest that the impact of apple trees on slope stability should be carefully assessed, especially if plants' irrigation is not accurately planned.

More realistic scenarios would also require three-dimensional (3D) numerical models to be developed, possibly involving fully coupled hydro-mechanical approaches. 3D models would allow to simulate different plant alignments and more realistic irrigation plans, moving from sprinkler to drip irrigation, whose impact should be account for also in terms of root architecture development.

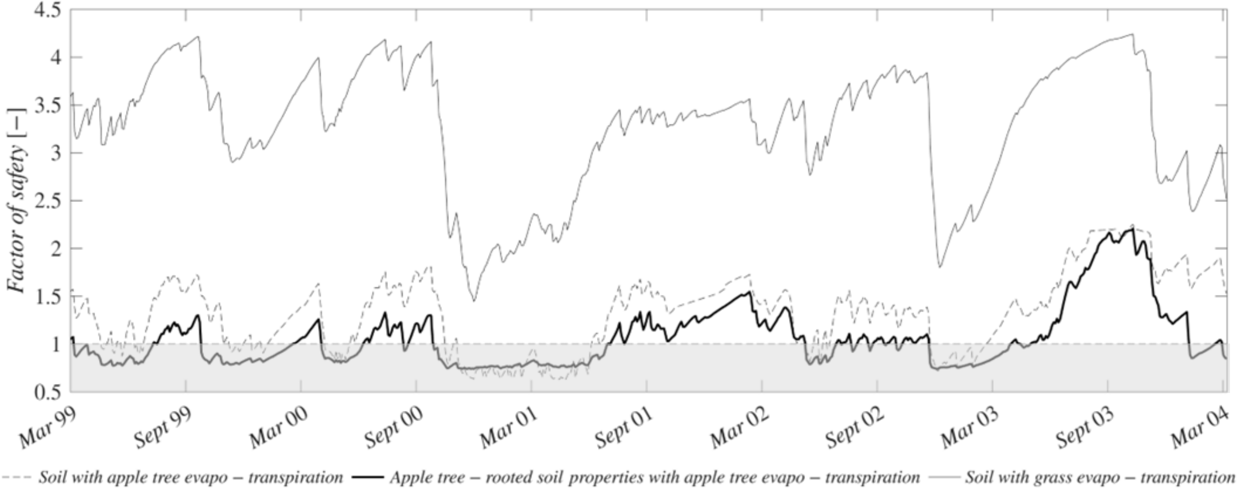

Figure 5. Factor of safety evolution with time for the selected 2m-deep landslide body (factor of safeties <1 do not have any specific physical meaning, but they have been reported simply to show how the level of instability varies with time)

5 REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., Smith, M. 1998. *FAO Irrigation and drainage paper No. 56.* Food and Agriculture Organization of the United Nations, Rome.

Bischetti, G. B., Chiaradia, E. A., Epis, T., Morlotti, E. 2009. Root cohesion of forest species in the Italian Alps, *Plant and Soil* **324**.

Bosco, G., Simeoni, L., Dalpiaz, M. 2018. Agricultural effects on air–soil exchange and slope instability, *Environmental Geotechnics* **5**, 285–299.

Capobianco, V., Cascini, L., Cuomo, S., Foresta, V. 2023. Wetting–drying response of an unsaturated pyroclastic soil vegetated with long-root grass, *Environmental Geotechnics* **10**, 332–350.

Cazzuffi, D., Cardile, G., Gioffrè, D. 2014. Geosynthetic Engineering and Vegetation Growth in Soil Reinforcement Applications, *Transportation Infrastructure Geotechnology* **1**, 262-300.

Dainese, R., Tarantino, A. 2021. Measurement of plant xylem water pressure using the high-capacity tensiometer and implications for the modelling of soil-atmosphere interaction, *Geotechnique* **71**, 441–454.

Dalpiaz, M. 2015. *Effects of fruit orchard management on slope stability in the Val di Non region (Northern Italy).* MSc thesis - University of Trento (in Italian).

de la Fuente-Saiz, D., Ortega-Farias, S., Carrasco-Benavides, M., Ortega-Salazar, S., Tian, F., Wang, S., Liu, Y. 2024. Assessment of satellite-based water requirements for a drip-irrigated apple orchard in Mediterranean agroclimatic conditions, *Heliyon* **10**.

Dias, A.S., Pirone, M., Nicotera, M.V., Urciuoli, G. 2022. Hydraulic characterization of an unsaturated vegetated soil: The role of plant roots and hydraulic hysteresis, *Geomechanics for Energy and the Environment* **30**.

Elia, G., Cotecchia, F., Pedone, G., Vaunat, J., Vardon, P. J., Pereira, C., Springman, S. M., Rouainia, M., van Esch, J., Koda, E., Josifovski, J., Nocilla, A., Askarinejad, A., Stirling, R., Helm, P., Lollino, P., Osinski, P. 2017. Numerical modelling of slope–vegetation–atmosphere interaction: an overview, *Quarterly Journal of Engineering Geology and Hydrogeology* **50**, 249–270.

Fraccica, A., Romero, E., Fourcaud, T. 2025. Effects of vegetation growth on soil microstructure and hydro-mechanical behaviour, *Geotechnique* **75**, 293-307.

Mobe, N. T., Dzikiti, S., Zirebwa, S. F., Midgley, S. J. E., von Loeper, W., Mazvimavi, D., Ntshidi, Z., Jovanovic, N. Z. 2020. Estimating crop coefficients for apple orchards with varying canopy cover using measured data from twelve orchards in the Western Cape Province, South Africa, *Agricultural Water Management* **233**.

Morgenstern, N.R., Price, V.E. 1965 The Analysis of the Stability of General Slip Surfaces, *Géotechnique* **15**.

Pereira, L. S., Paredes, P., Melton, F., Johnson, L., Mota, M., Wang, T. 2021. Prediction of crop coefficients from fraction of ground cover and height: Practical application to vegetable, field and fruit crops with focus on parameterization, *Agricultural Water Management* **252.**

Tarantino, A. Mongiovì, L. Mc Dougall, L.R. 2002. Analysis of hydrological effects of vegetation on slope stability. *Proc. 3rd Int. Conf. on Unsat. Soils* (Eds: Jucá, J.F.T:, de Campo, T.M.P. & Marinho, F.A.M.), 749-754. A.A: Balkema Publishers, Lisse/Abingdon/Exton/Tokyo.

Zanotelli, D., Montagnani, L., Andreotti, C., Tagliavini, M. 2019. Evapotranspiration and crop coefficient patterns of an apple orchard in a sub-humid environment, *Agricultural Water Management* **226**.