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Wildfires and shallow landslides in urban areas: preliminary insights from the Mt. Mario case study (Rome, Italy)

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ABSTRACT: The study of Mt. Mario landslide case lies within a collaboration agreement between ISPRA and the Civil Protection Department of the Municipality of Rome. For this site, the study is aimed at identifying the potential failure kinematics and predisposing/triggering factors as well as setting up an early warning monitoring system of the potential shallow landslides that could develop in the soil covers of the slope, following rainfall events. Indeed, evidence of shallow landslides was observed after intense rainfalls and severe wildfires that affected many trees on the studied slope. In-situ geognostic and freatimetric monitoring campaign as well as geophysical surveys and hydro-mechanical laboratory tests are in progress in order to predispose the geological and geotechnical model of the area. For this paper, some preliminary numerical modelling has been carried out to infer the potential effect of the vegetation roots decay and of the presence of ash on the ground surface on the hydro-mechanical behaviour of the slope during the rainfall events which were deemed to be the main triggering factor of the landslide phenomena. Modelling results show that a low hydraulic conductivity in the hypothetically bare slope limited rainfall infiltration and avoided instability. The higher hydraulic conductivity generated by roots growth and decay was compensated by the additional soil cohesion in the slope with hypothetically living vegetation: this combination ensured stability. Instability was instead observed when reducing the cohesion, assuming vegetation's death.

Keywords: wildfire-related landslides; geotechnical testing; soil-root numerical modelling; slope stability

1 INTRODUCTION

Landslides in densely populated areas could represent threats or interruptions to the functionality or operation of facilities, infrastructure, cultural heritage, and public safety. For this reason, an agreement between ISPRA and the Civil Protection Department of Rome Municipality has been set to characterize and monitor three study sites that were affected by rainfall-induced shallow landslides, for early warning purposes, in the city of Rome. Among these sites, Mt. Mario site was affected by severe wildfires (on 31 July 2024 and on 5 June 2025), covering an area of about 12.5 hectares. The most severe wildfire was a combination of crown and surface typologies, lasted more than 10 hours (Italian Fire Corps) and was associated with a very high severity, according to the classification provided by the Italian Civil Protection. Indeed, complete damage was observed on trees and shrubs present on the slope. Following the first and more extended fire event and an intense rainfall event, on 3 September 2024, landslide trenches and scarps were observed on the slope. It is well known from the literature that wildfires dramatically affect the hydro-mechanical behaviour of soils and slopes in different ways: 1) root reinforcement may be lost and hydraulic conductivity locally increases where the decayed roots are present, 2) rainfall canopy interception and vegetation-induced evapotranspiration are lost, with indirect effects on the hydraulic state evolution in the slope, 3) the ashes produced by the fire and deposited on the slope reduce soil permeability and generate hydrophobic layers on the shallower soil portions, increasing surface runoff and affecting seepage (Abdollahi et al., 2024; Rengers et al., 2020). While fast and surface wildfires can cause slight effects on soil properties (Stasi et al., 2025), more persistent wildfires can damage (even char) the roots and affect significantly their reinforcing action on soil (Peduto et al., 2022). It is therefore important to consider these coupled hydro-mechanical effects of vegetation decay within the site geotechnical modelling, when assessing post-fire slope stability. This paper provides some preliminary numerical modelling results and insights into the effects of the wildfire on the analysed case.

2 STUDY SITE

Concerning the geology of the study site, landslide trenches and scarps were observed in the alteration soil of the MTM1 formation (*Monte Mario formation – Farneto member*), consisting of lightly cemented

sandy silts. For further details, see Funiciello and Giordano (2008).
Concerning the rainfalls, after the wildfire of 31 July 2024 and a dry period, on 3 September 2024, a peak rainfall intensity of 21.6 mm/h was recorded, preceded and followed by minor rainfall intensities from 0.4 to 4.4 mm/h. (“Roma Monte Mario” meteorological station, Regione Lazio). Landslide trenches and scarps were observed during a survey carried out three days after the intense rainfall event.

Regarding the vegetation and reporting official information from the Mt. Mario Natural Park website, the different vegetation species are: *Holm Oak* (tree), *Cork Oak* (tree) and *Cistus* (shrub).

Table 1. Cohesion, friction angle, dry unit weight and hydraulic conductivity of the soil layers used in this study. MTM1-s = MTM1-shallow

ID	**c' kPa**	**φ' °**	**γ_d kN/m^3**	**k_w m/s**
MTM1	10[a]	23[a]	17	3.4x10^{-7} [b]
MTM1-s	0	23[a]	17	3.4x10^{-7} [b]
MTM1-s+shrubs	15[d]	23	17	3.4x10^{-6}
MTM1-s+trees	19[c]	23	17	3.4x10^{-6}
MTM1-s+burnt vegetation	0	23	17	3.4x10^{-6}

[a] Bozzano et al. (2006); [b] Schillirò et al. (2019); [c] Masi et al. (2023); [d] average value for shrubs from De Baets et al. (2008)

3 NUMERICAL MODELLING

The topographic profile of the slope was built on a Digital Surface Model (DSM), with 5 cm resolution, produced in 2022. A 3D visual observation of the orthophoto and the DSM and comparison with close sections allowed to identify and remove the trees and shrubs present on the topographic profile. For numerical modelling purposes (to avoid geometrical singularities and to reduce the number of Finite Element nodes), the profile geometry was simplified by taking one elevation point on the surface every 1 m. Numerical modelling was carried out in Slide2 (RocScience) with a de-coupled hydro-mechanical analysis. Steady state and transient hydraulic analyses (rainfalls) were carried out through a Finite Element solver while the safety factors were evaluated by Limit Equilibrium with the Morgenstern and Price (1965) approach. *Cistus* shrub roots partitions were traced according to the maximum depth (0.5 m) indicated by Silva and Rego (2004). *Holm Oak* and *Cork Oak* tree roots partitions were traced with a maximum depth of 2 m because the trees were still young and the highest root density, which affects soil cohesion, lies within this depth range (Moreno et al., 2005; Masi et al., 2023). The analysed profile geometry is indicated in Figure 1. The soil layer “MTM1-shallow” was implemented to reproduce the alteration soil of the MTM1 formation. Only cohesion and the hydraulic conductivity changed within the vegetated layers (Table 1), as roots have been commonly found to have minor effects on friction angle. All the layers share the same soil water retention curve (SWRC) for ease of comparison and due to the preliminary analyses presented here. The SWRC used is typical of a sandy silt and is represented by the following parameters of the van Genuchten (1980) model (in terms of volumetric water content): α = 0.32 m^{-1} (suction was formulated in terms of pressure head), n = 2, m = 1.

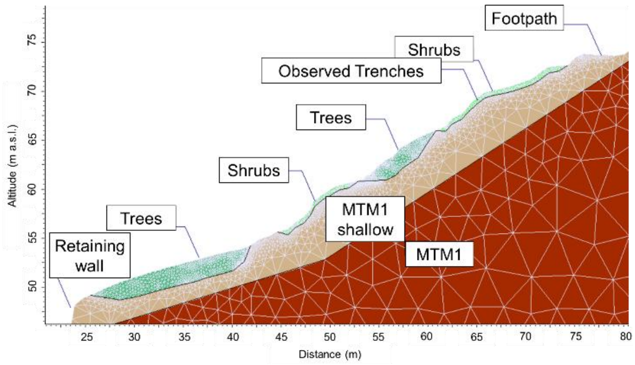

Figure 1. Vegetated section in RS2 software. The vegetated partitions are in green

The material has an air-entry value of 10 kPa and tends to the residual water content at a matric suction of 400 kPa. Soil permeability under unsaturated conditions is accounted in the model through the law given by Gardner and Hsieh (1956), with model parameters: a = 0.1 m^{-1} (suction as pressure head) and n = 2. Finally, additional soil shear strength at unsaturated states was provided by the model proposed by Fredlund et al. (1978), based on the Mohr-Coulomb failure criterion. The angle of friction accounting for matric suction contribution to shear strength, φ'_b was chosen equal to 8° according to measurements done by Fraccica (2019) on a silty-clayey sand with properties similar to those of MTM1.

The initial hydraulic state was set by a steady state hydraulic simulation. The initial piezometric level (total head of 57 m above sea level, at about 140 m from the slope toe, see Figure 2) was attributed according to the measurement of piezometer P1401 in the piezometric monitoring system of the city of Rome (ISPRA). The piezometer is located at around 900 m from the toe of the slope and is located within the same hydrogeological formation (MTM1). Then, rainfall occurred on 3 September 2024 was simulated on four different cases: a) with “living vegetation” (i.e. with layers implementing effects of roots on cohesion and permeability), b) with “burnt vegetation” (i.e. with effects on permeability only), c) with “burnt vegetation"+shallow ash on the ground surface d) bare soil (i.e. without layers implementing vegetation). Ash generated by the wildfire and deposited on the ground is deemed to decrease the water permeability of the soil (Abdollahi et al., 2024). Its presence was simulated by alternating (1 m : 1 m ratio), on the whole slope's ground surface, a boundary condition (*vertical infiltration* in Slide2) simulating the rainfall (flow rate per unit area) and a boundary condition (*nodal flow rate* in Slide2) imposing a null flow rate without allowing the *seepage face condition.* The final hydraulic states of the slope for the abovementioned cases are presented in Figure 2. The increase of permeability in the vegetated layers (Figure 2a) favoured a quicker saturation of the first 0.5 m, compared to the bare case (Figure 2c). An intermediate result was obtained when ash on ground surface was simulated (Figure 2b).

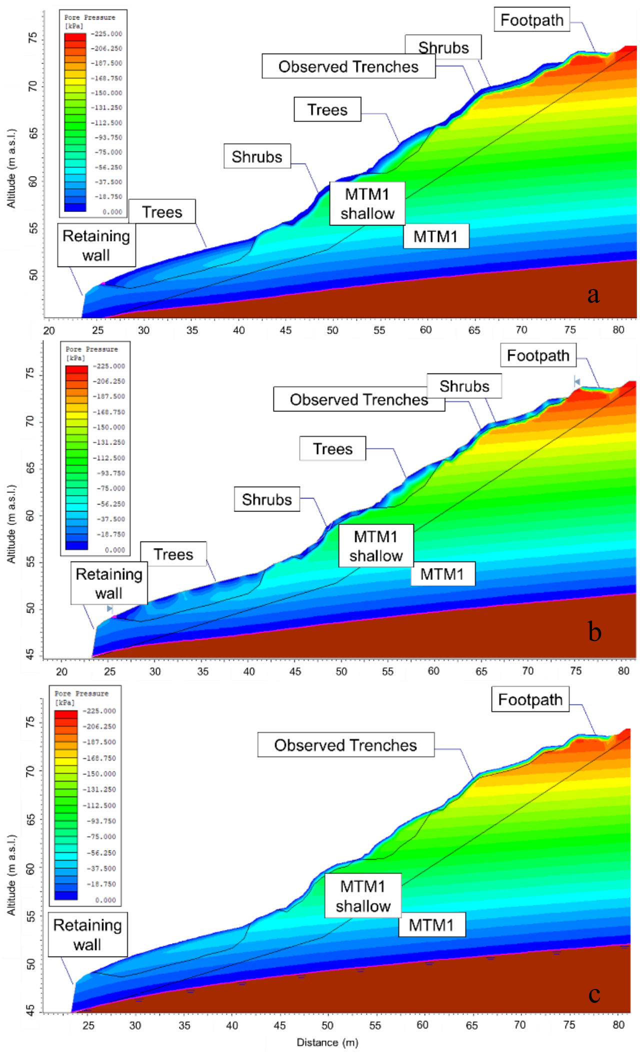

Figure 2. Hydraulic state after the rainfall of 3 September 2024 in: a) vegetated (living/burnt) slope, b) vegetated (burnt)+shallow ash on slope surface, c) without vegetation

Therefore, safety factor's distribution dramatically varied, within the analysed cases, at the end of the rainfall (Figure 3).

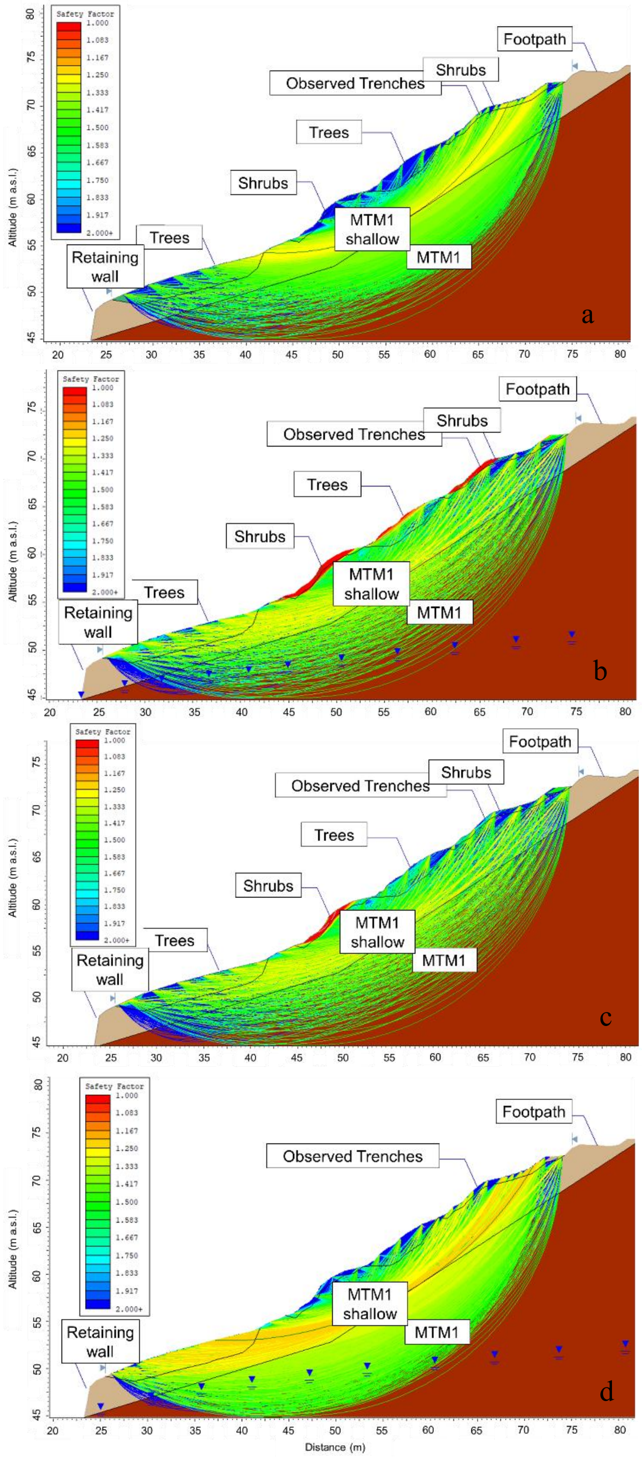

Figure 3. Slope safety factor after the rainfall of 3 September 2024 in a) case with living vegetation, b) burnt vegetation, c) burnt vegetation and surface ashes, d) no vegetation

In particular, the cases: a) with living vegetation and d) bare soil don't show instability (Figure 3a and d). In the first simulation, safety is provided by the higher cohesion in the root's zone, while in the last one by the lower permeability, which maintained the slope unsaturated below the first 0.3 m from the ground surface (Figure 3d). The other two cases showed shallow instabilities (i.e. between 0.5 m and 1.0 m) which are predicted close to the area where trenches and scarps were observed on the slope and, hence, are compatible with the phenomena observed on the site (Figure 3b-c). The minimum Factor of Safety before rainfall (in all the cases) was of 1.3. Minimum values of Factor of Safety after the rainfall ranged between 0.93 (burnt vegetation case) and 1.27 (living vegetation case).

4 CONCLUSIONS

This paper has provided some preliminary and parametric numerical analyses on the post-wildfire slope stability, for a real case. Although some soil and vegetation parameters were retrieved from the literature, the results seem realistic and reflect in-situ observations. Numerical results suggest that considering parameters such as cohesion and permeability as well as unsaturated soil states is fundamental in rainfall-induced shallow landslides affecting vegetation. The instabilities predicted by the modelling well agree with the kinematics and depths of the soil slips observed in-situ. These results will be useful in the decision of the depths of the sensors of water content, suction and 3D displacements (clinometers) for early warning. Future laboratory results and in-situ monitoring (soil suction/water content, rainfall intensity, solar radiation, air relative humidity and wind speed and direction) will provide deeper understanding of the behaviour of the slope under saturated and unsaturated conditions and will improve the numerical predictions under evapotranspiration and rainfall regimes too.

5 ACKNOWLEDGEMENTS

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