Rainfall-induced shallow landslides triggered after vegetation removed because of fires: G-XSLIP application to Gioiosa Marea (Sicily, Italy)

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Abstract. The paper analyses how vegetation prevents the triggering of rainfall-induced shallow landslides by using the G-XSLIP platform, which is based on G-SLIP model, i.e., the SLIP model updated with vegetation parameters for root reinforcement and rain interception due to canopy. G-XSLIP is applied to an area in Gioiosa Marea (Sicily, Italy), where on 9th September 2016 shallow landslides occurred, depositing on the state road SS 113. The analyses demonstrate that the triggering of these phenomena is related to the removal of vegetation after summer fires some months before, which decreases computed safety factors by about half.

1 Introduction

Rainfall-induced shallow landslides are natural phenomena involving layers of shallow soil (topsoil); they are triggered by intense and/or prolongated rain which, infiltrating through macropores, causes an increase in the degree of saturation and a reduction in shear strength [1,2]. One of the mathematical models used to study the triggering of rainfall-induced shallow landslides is SLIP (Shallow Landslide Instability Prediction), i.e., a physically-based model which analyses the topsoil's stability through an infinite slope scheme, including in a simplified way the effect of rain on soil apparent cohesion [3,4].

Due to its simplicity and reliability, SLIP was adopted in analyses at different scales: from slope scale to large areas [5-9]. In the latter case, the application was possible thanks to its implementation in DEWETRA, i.e., the multi-risk platform owned by the Italian Department of Civil Protection (DCP), where SLIP was implemented for real-time large-scale analyses [10]. Recently, Gatto and Montrasio [11] developed an algorithm to perform large-scale stability analyses independently of the DCP, suitable for insights with research purposes: this is the X-SLIP platform.

One of the aspects focused on by X-SLIP is the vegetation's contribution to slope stability. The scientific interest in this topic started in the 60s, from the experimental observation of an increased number of phenomena related to deforestation [12]. Over the years, two aspects have been studied: the soil reinforcement provided by roots and the rainfall interception due to vegetation canopy. In the first case, literature generally quantifies a root cohesion c_r through experimental tests, numerical and theoretical modelling; it is a cohesion to be added in the well-known Mohr-Coulomb criterion for soil strength. As regards rainfall interception, empirical observations on the water rate β^* intercepted by plants, which depends on species and foliage type, are the most common. A useful state-of-art review is provided by Montrasio and Gatto [13].

Both vegetation effects have been recently introduced in the SLIP formulation and the X-SLIP platform, which have been updated accordingly in G-SLIP and G-XSLIP [14]. The presence of vegetation has been shown to improve the territorial stability and the prediction quality of the G-SLIP model in analyses with vegetation effects is even better, due to more realistic modelling. It follows that the vegetation removal from anthropic or natural decreases stability.

This paper shows the G-XSLIP application to an area of Gioiosa Marea (Sicily, Italy), where rainfall-induced shallow landslides occur with high frequency. In September 2016, some of these phenomena were triggered and debris were deposited on the state road SS113; local newspapers ascribed their occurrence to summer fires which have determined the vegetation removal exactly in the triggered points. G-XSLIP analyses are therefore performed with or without the effect of vegetation coverage to quantify the contribution of vegetation on stability.

2 Brief overview of the G-SLIP model

The G-SLIP model analyses the stability of the topsoil (thickness H) by evaluating the safety factor FS through a relationship derived from the infinite slope scheme, together with simplified assumptions considering the effects of rainfall on soil shear strength:

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$$FS=\frac{\tan\varphi'}{\tan\beta}+\frac{c'+c_r+AS_r(1-S_r)^{\lambda}\left[1-\frac{1-\beta^*}{nH(1-S_r)}\sum_{j=1}^{\omega}h_j e^{-k_t\Delta t_j}\right]^{\alpha}}{\gamma H\cos\beta\sin\beta} \quad (1)$$

FS depends therefore on morphological parameters (slope angle β), physical and mechanical soil parameters (unit weight γ, porosity n, effective cohesion c' and friction angle φ'), vegetation parameters (root reinforcement c_r and rainfall interception β^*). The summation of Eq. (1) allows us to evaluate the effects of ω rainfall events on the actual stability (and soil apparent cohesion), through the slope drainage coefficient k_t and according to the time gap Δt_j between the generic rainfall event h_j and the instant of stability analysis. S_r is the initial degree of saturation and A, α and λ are modelling parameters. A detailed description of the model can be found in [3,4,9].

To evaluate the stability over large areas, the G-XSLIP multi-approach algorithm has been recently presented, for the application of G-SLIP formulation to pixels of a reference grid. A complete description of the algorithm can be found in [11,14]. All the parameters of Eq. (1) need to be evaluated spatially and this is possible by knowing some basic geographic data, easily available in the territorial databases (e.g., Digital Terrain Model, Geology Map, Land Uses, etc.). Specifically, mean soil strength parameters, experimentally derived, are associated with each geologic unit.

3 The case study of Gioiosa Marea – September 2016

Gioiosa Marea is a small Italian municipality (26 km^2) in the province of Messina (Sicily). This territory has high hydrogeological risk and many landslides (including rainfall-induced shallow landslides) occur causing inconvenience for years, especially when interacting with infrastructure.

Several rainfall-induced shallow landslides occurred on 9th September 2016, depositing debris on a segment of the state road SS113, as evidenced by Figure 1.

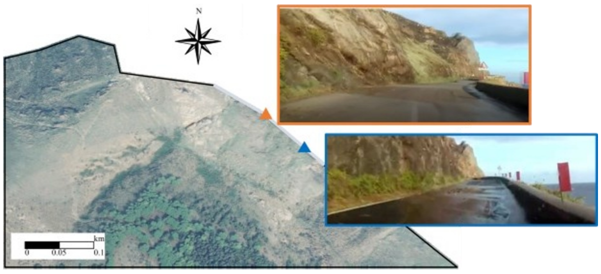

Fig. 1. Orthophoto of the study area and rainfall-induced shallow landslides detected from the 9th September 2016 event.

According to local newspapers, different fires had affected this area the previous summer, causing the removal of vegetation coverage. This could have been responsible for the landslide triggering. We have applied the G-XSLIP to investigate any change in stability (and safety factor evaluated through the G-SLIP model) when vegetation is removed.

3.1 Morphology, soil and vegetation parameters

We have derived slope angles by applying a finite-difference algorithm to the Digital Terrain Model (DTM); due to the small dimension of the study area, a high-resolution DTM (0.5x0.5 meter) can be adopted with good computational efficiency. Figure 2 shows the map of the calculated slope angles.

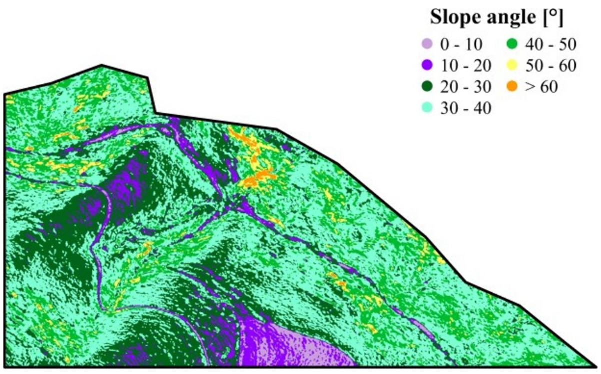

Fig. 2. Map of slope angles derived from the 0.5m-resolution DTM (From Sicilian Region Database [15])

Spatially distributed soil parameters are assigned through a geology-based approach, depending on the geologic map. Figure 3 shows that the area under examination is underlain by two geologic materials: debris and metamorphic rock. A specific parameter set is adopted for each geologic type and reported in Table 1. Effective cohesion is initially assumed null for both materials.

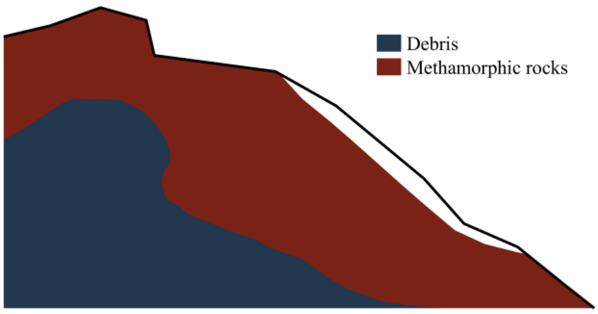

Fig. 3. Simplified geologic map (Gagliano et al. [16])

Table 1. Set of soil parameters adopted for each geology classes.

Description	n (-)	φ' (°)	A (kPa)	k_t (h^{-1})
Metamorphic Rocks	0.3	36.5	80	0.0025
Debris	0.4	25.0	40	0.0065

For vegetation, a map-based approach is used also to differentiate the parameters. Information on vegetation types and their spatial distribution is derived from the Land Use Map, shown in Figure 4. Four vegetation types are recognized in the study area. Since our main interest is in the area near SS113, we have considered two main vegetation types: Mediterranean shrub (including lenses of shrub and Cistus and rosemary) and Conifers. Vegetation parameters are derived from previous literature studies [17-20]; values adopted in the analyses "with vegetation" are shown in Table 2.

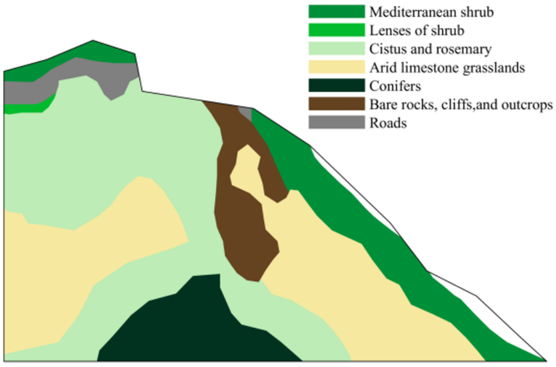

Fig. 4. Land Use Map (From Sicilian Region Database [15])

Table 2. Vegetation parameters adopted in X-SLIP analysis "with vegetation".

	c_r (kPa)	β^* (%)
Mediterranean shrub	10	21
Conifers	10	30

3.2 Rainfall data

To analyse the stability on 9th September 2016, rains recorded from 8th August to 9th September 2016 are considered. Data are provided by the Agro-Meteorological Information Service of Sicily ([21]): hourly recordings at the gauging stations of Patti, Militello Rosmarino, Mistretta, San Fratello, Torregrotta, Antillo and Leni are considered. After their interpolation, these data are used to evaluate stability through the sum in Eq. (1) [11]. Figure 5 shows the time history of rainfall recorded in Patti (the closest station to the study area).

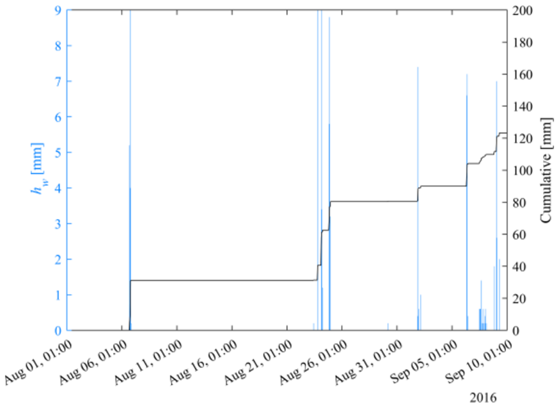

Fig. 5. Rain recorded at Patti Station ([21])

4 Results and Discussion

The safety factor is evaluated on 9th September at 2 AM (time occurrence of the maximum rainfall recorded at Patti station) for the pixels covering the study area. We consider two cases 1) with the original vegetation (Figure 6) and 2) with the removal of the Mediterranean shrub (vegetation type near SS113) because of fires (Figure 7).

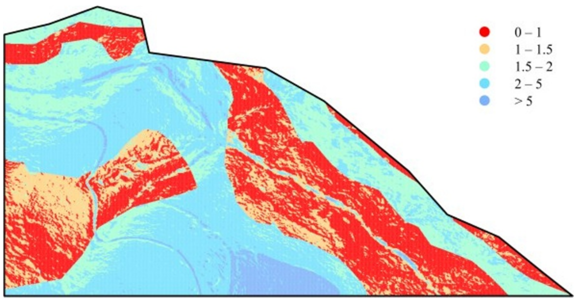

Fig. 6. Map of safety factors with vegetation (case 1) – Event of 9th September 2016

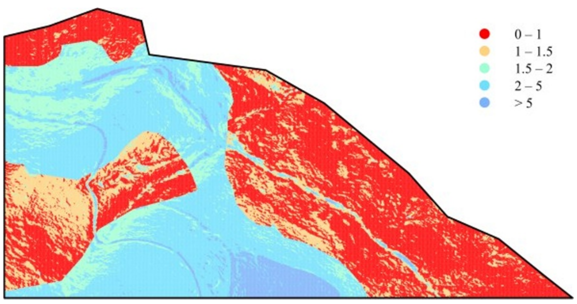

Fig. 7. Map of safety factors after removal of vegetation close to SS113 (case 2) - Event of 9th September 2016

Our analyses show the lack of vegetation causes an increase of unstable areas. This result is aligned with previous empirical observation [12]. Since the summer fires did not completely remove the Mediterranean shrub shown in Figure 4, we focus on the observed soil slips. The FS varying with time is represented for the two points indicated in Figure 1: Figure 8 is related to the orange point P1, while Figure 9 represents the blue point P2.

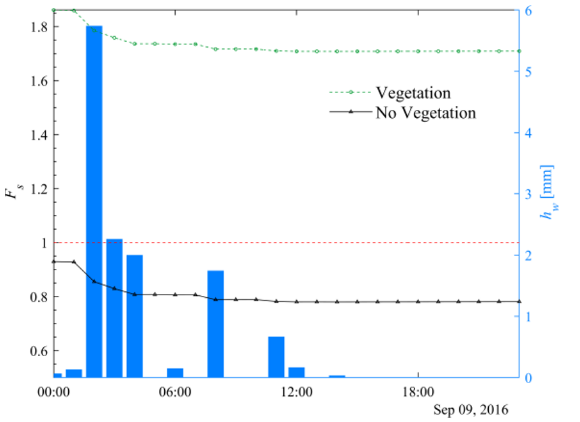

Fig. 8. Trend of the safety factor *FS* obtained for observed soil slip P1 (orange point in Figure 1)

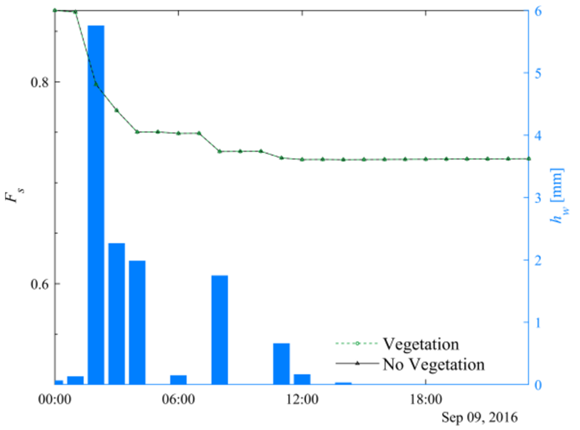

Fig. 9. Trend of the safety factor *FS* obtained for observed soil slip P2 (blue point in Figure 1)

Figure 8 indicates that the safety factor is significantly reduced by vegetation removal. Its value is 1.71 with vegetation, and 0.78 without vegetation; it is not only reduced by about half, but its reduction determines a change from stability (FS>1) to instability (FS<1). For P2 (Figure 9) instability is predicted by the SLIP model but no variation occurs between the two analyses. This is because it is a point with no vegetation according to the land use map (Figure 4).

Generally, if there had been vegetation, it would have reduced the instability during the analysed rainfall event. Further analyses will define which contribution (root reinforcement or rainfall interception) is more relevant in terms of stability. Stabilisation through the planting of proper vegetation will be also assessed.

5 Conclusion

We analysed the stability of an area in Gioiosa Marea (Italy) frequently affected by rainfall-induced shallow landslides, with a focus on past events which were attributed to vegetation removal due to fires. Vegetation has a beneficial effect on slope stability, due to roots and foliage. Its removal is responsible for a strength loss and an increase in triggering of landslides. These changes can halve the safety factor, sometimes inducing instability. This means that when planning removal of vegetation in slopes (e.g., deforestation) an analysis of the effects on slope stability should be performed. Furthermore, when vegetation is removed due to fires, its restoration may be essential to prevent future landslides.

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