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Soil reinforcement provided by the root system of grapevines: Quantification and spatial variability

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ABSTRACT

Rainfall-induced shallow landslides represent a major threat for cultivated steep terrain, including vineyards that are typically established on hillslopes. Vineyards represent high-value cultivation in many countries; there is a tendency to adopt new and more intensive cultivation practices and/or to extend plantations to inappropriate sites, which influences the natural environment. Considerable damage thus increasingly affects vineyards in terms of partial or total destruction of cultivation, structures and infrastructures, as well as the surrounding landscape. However, little research has been conducted to date to investigate the role of grapevine plants on slope stability and to reduce the related impacts on the environment.

Aiming to help fill the gap, we carried out a study to quantify the role of vineyards on slope stability by modelling the additional reinforcement to the soil provided by grapevine roots and their spatial distribution (i.e. considering the distance from the trunk) using the Root Bundle Model. A back analysis on a number of shallow landslides that occurred in vineyards was also conducted to validate the results. The area of our investigation was in the northeastern part of Oltrepò Pavese, Northern Italy, which is a hilly terrain cultivated for many decades with vineyards and prone to landslide phenomena that in recent years have caused great economic losses to the agricultural sector and damage to buildings and roads. Moreover, abandoned vineyards represent an issue in terms of their "return" to a natural state

Values simulated by modelling and back-calculated from the landslide inventory completely agree and are in the range of reinforcements commonly obtained for many other species. However, in contrast to native species, the spatial variability of the reinforcement in the case of vineyards is lower because of the regularity of planting and the lack of differences in plant age. Additionally, the variability of the rooting depth is negligible because it is controlled by the rootstock.

Finally, the results obtained in this work show that the models developed for native species can also be adopted for grapevines and, if coupled with a slope stability model, represent a basis for providing guidelines to design vineyard plantations in those areas susceptible to instability, to support decisions concerning land management and land use change and more generally to reduce environmental impacts.

1. Introduction

Rainfall-induced shallow landslides are the most frequent gravitational processes affecting both cultivated steep terrains and natural slopes around the world (e.g. Beguería, 2006; Crosta et al., 2003; Glade, 2003; Lee and Pradhan, 2006; Mugagga et al., 2012; Reichenbach et al., 2014; Roering et al., 2003; Schmidt et al., 2001). These phenomena are typically translational slope failures of soil mantle or regolith a few metres thick (Hovius et al., 1997; Godt et al., 2009; Caine and Swanson, 2013). They are generally triggered by high-intensity and concentrated rainfall, which causes a sudden increase in soil water content, a decrease in soil suction and consequently a reduction of soil shear strength (Gasmo et al., 2000; Iverson, 2000; Van Asch et al., 1999).

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Nomenclature

ϕ	Root diameter, (mm)
Θ	Stem diameter of plant (m)
d	Distance from plant stem (m)
ρ_{FR}	Density of the roots with diameter less than 1 mm (roots)
ρ_{CR}	Density of the roots with diameter greater than 1 mm (roots)
N_{FR}	Total number of the roots with diameter less than 1 mm (roots)
d_{max}	Maximum distance from the plant stem that the roots could reach (m)
μ	Pipe coefficient (roots m^{-2})
ψ	Empirical proportionality constant (–)
γ	Decay constant (–)
ϕ_0	Reference diameter of 1 mm
ϕ_{max}	Maximum root diameter (mm)
η	Self-similarity coefficient (–)
MPE	Mean percentage error (–)
RMSE	Root mean square error (roots)
n	Number of observations (roots)
x_i	Observed root density (roots)
y_i	Simulated root density (roots)
F_{max}	Maximum tensile force (N)
E	Young's modulus (MPa)
L	Root length (mm)
F_0	Multiplicative coefficient for maximum tensile force (N)
E_0	Multiplicative coefficient for young's modulus (MPa)
L_0	Multiplicative coefficient for root length (mm)
ξ	Exponential coefficient for maximum tensile force (–)
β	Exponential coefficient for young's modulus (–)
α	Exponential coefficient for root length (–)
F_{tot}	Total force of a bundle of roots (N)
F	Force contribution of each root (N)
S	Weibull survival function (–)
Δx	Displacement (mm)
Δx^*	Normalized displacement (mm)
λ	Scale Weibull parameter (–)
ω	Shape Weibull parameter (–)
FoS	Factor of safety (–)
C_s	Soil effective cohesion (Pa)
C_{rb}	Basal root reinforcement (Pa)
C_{rl}	Lateral root reinforcement (Pa)
D	Soil depth (m)
D_w	Groundwater level (m)
A_l	Latera area (m^2)
A_b	Basal area (m^2)
γ_s	Unit weight of dry soil (N m^{-3})
γ_w	Unit weight of water (N m^{-3})
q_0	Tree surcharge per unit area (Pa)
ϕ'	Effective internal friction angle (rad)
θ	Slope steepness (rad)
R	Steady state recharge (m h^{-1})
a	Contributing area (m^2)
b	Contour length of lower bound of each contributing area (m)
K_s	Saturated hydraulic conductivity (m h^{-1})

These phenomena frequently affect vineyards, typically located on sloping terrains, and involve anthropogenic soils. The consequences are a partial or complete destruction of grapevine fields, local structures and infrastructure and thus huge economic damages and more general impacts on the environment. Landslides are a serious threat in the context of European vineyards, in particular where grapevines have been cultivated for a long time, as in Germany, (Grunert, 2009), Slovenia (Komac and Zorn, 2009), Romania (Margarint et al., 2013), Spain (Ramos et al., 2007), Portugal (Pereira et al., 2012), France (Marre et al., 1997; Van Den Eeckhaut et al., 2010) and especially in Italy (Blahut et al., 2014; Bordoni et al., 2016; Camera et al., 2015; Cevasco et al., 2014; Fonte and Masciocco, 2009; Meisina and Scarabelli, 2007; Zizioli et al., 2013). Moreover, landslide risk is increasing in those areas where vineyards have been introduced more recently and have replaced natural vegetation (Guthey and Whiteman, 2009; Opperman et al., 2005). Indeed, the modifications of land use and agricultural practices have important effects on hydrological processes and on the mechanical structure of the soil (Greenway, 1987; Reichenbach et al., 2014; Schmidt et al., 2001).

Despite the risk for human safety, the direct and indirect economic loss, the impact on natural landscapes, and the social impact on local communities in terms of land and settlement abandonment, few studies have been carried out to date to highlight the role of grapevines on slope stability.

The beneficial effects of vegetation in preventing slope instabilities have been demonstrated by several studies (Hubble et al., 2013; Rickli and Graf, 2009; Roering et al., 2003; Schmidt et al., 2001; Sidle et al., 1985), and it is now clear that plants positively influence the triggering mechanisms via root strength, root anchorage, and evapotranspiration (e.g. Sidle and Bogaard, 2016). In particular, since the pioneering work of Endo and Tsuruta (1969), considerable attention has been focused on the quantification of the mechanical contribution of root reinforcement to soil shear strength (Bischetti et al., 2009; Fan and Su, 2008; Schwarz et al., 2010c; Wu et al., 1979) and the value of such reinforcement for different vegetation species growing in different environments. However, most such studies have considered natural and/or forest species and sometimes pastures.

The aim of this study was to increase our knowledge of the role and limits of grapevine plants in stabilizing slopes in comparison with natural vegetation. In particular, drawing from the results obtained by Bordoni et al. (2016), we evaluated the mechanical root reinforcement of grapevine plants as a function of their size and spatial distribution along a cultivated hillslope in a typical vineyard context in Northern Italy (Oltrepo' Pavese, Lombardy). The results obtained by modelling the root reinforcement contribution according to the current state of knowledge were compared with those obtained by carrying out a back analysis on landslides that had occurred in steep-slope vineyards.

Indeed, back analysis provides reliable estimates of the additional rooted-soil reinforcement necessary to stabilize the selected landslide area; however, it is not able to explain the spatial variability or the driving mechanisms occurring between plants and soil. On the other hand, modelling the root reinforcement at specific experimental sites by carrying out detailed field and laboratory measurements provides results liable to a certain degree of generalization. In particular, modelling allows consideration of the wide variability and uncertainty linked to the mechanical properties and the spatial distribution of the roots, which remain a great challenge (Giadrossich et al., 2016; Loades et al., 2010). Moreover, such variability could be exaggerated in the case of vineyards by a great number of factors connected with their agricultural practices. In fact, the literature in the field of viticulture shows that a balance exists between the top growth and root growth in grapevines and that it is affected by cultivation practices (de Herralde et al., 2010; Saayman and Van Huyssteen, 1980; Southey, 1992; Van Zyl and Van Huyssteen, 1980). Additionally, some studies have demonstrated