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An investigation of plant-induced suction and its implications for slope stability

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Both above- and below-ground biomass of plants provide additional strength to soil through different mechanisms, which help to increase the stability of a vegetated slope. Nonetheless, shallow landslides on steep slopes covered with vegetation still occur, often being triggered above the groundwater table, due to loss of suction subsequent to rainfall. Therefore, it is essential to know to what extent vegetation enhances slope stability, and to quantify the contribution of vegetation to the shear strength of soil to determine factors of safety. Results of large-scale direct shear experiments on root-permeated soils and slope geometry from a landslide database were synthesised through an infinite slope analysis under partially saturated conditions to find critical combinations of slope angle and suction stress. Monte Carlo simulations yielded a clear separation of stable and unstable zones, which can be used to define the susceptibility of a slope to near surface failure. This method, based on the simulations, has the potential to be used as a regional early warning system.

Notation

c'	drained cohesion intercept
L	length of landslide
N	number of Monte Carlo simulations
$(u_a - u_w)$	matric suction
z	depth of landslide
α, n	parameters of Van Genuchten (1980) equation
β	slope angle
γ	bulk unit weight
κ	scale factor of Weibull distribution
λ	shape factor of Weibull distribution
μ	mean value
σ^S	suction stress
ϕ'	internal friction angle

1. Introduction

A slope would be marginally stable when the slope angle is equal to the internal friction angle of dry soil. Any additional shear strength can be mobilised due to suction, vegetation, or any other stabilising agents for a slope with an angle steeper than the internal friction angle of the soil. This additional strength due to suction can be lost either after a heavy rainfall event over a short duration (Brand *et al.*, 1984; D'Amato Avanzi *et al.*, 2004; Guzzetti *et al.*, 2004) or more moderate rainfall over a long duration (Lumb, 1975). This loss, or even a decrease in suction, can trigger rainfall-induced landslides (Greco *et al.*, 2010; Picarelli *et al.*, 2016; Urciuoli *et al.*, 2016).

Conventional civil engineering techniques – for example, soil nailing or shotcrete, were common slope stabilisation measures

in the past (Leung *et al.*, 2015), whereas plants have been recognised widely as sustainable and eco-friendly alternatives owing to

- provision of mechanical resistance from root tensile strength (Graf *et al.*, 2009; Gray and Barker, 2004; Wu *et al.*, 1979)
- reduction in water content of soil through canopy interception and root water uptake results in partial saturation of shallow soil layers, causing an increase in matric suction (Simon and Collison, 2002).

Hydrological reinforcement function of plants can even lead to greater increase in strength than their mechanical function (Boldrin *et al.*, 2018; Pollen-Bankhead and Simon, 2010). However, the increase in factor of safety (FoS) of a vegetated slope due to plant-induced suction fluctuates throughout a year due to the seasonal variation effects of vegetation on the hydrological regime of a slope, which has been shown to be most significant during dry periods (Kim *et al.*, 2017; Leung and Ng, 2013)

An extreme rainfall event in late August 2005 caused considerable damage, and even loss of lives, by landslides, floods and debris flows in large parts of Switzerland (Hilker *et al.*, 2009). Three landslide inventories were collected after the rainfall in August 2005 from three regions in Switzerland, namely, Entlebuch, Napf and Praetigau, by Rickli and Graf (2009). In their study, 133 shallow landslides were documented from these regions, 50 of which happened on forested slopes. In order to understand better how vegetation influences slope

stability, it is essential to know how changes in the plant-induced suction affect the shear strength of soil and how these changes are reflected in terms of increased stability.

Rickli and Graf (2009) recorded information on 522 shallow landslides, of which 240 took place on forested slopes, from six different locations in Switzerland. Table 1 shows the number of landslides and the slope angles for each study site. The increase in the stability of the slope due to vegetation can be seen virtually in the differences between angles of the slopes on which the landslides took place, in the forest area and open land. Higher angles were observed for landslides on the forested slopes for all locations. The effects of vegetation on the slope stability, either due to mechanical root reinforcement or plant-induced suction, have been demonstrated in the past with varying methods, such as infinite slope stability analysis (Chirico *et al.*, 2013), the finite-element method (Mao *et al.*, 2014), probabilistic analyses (Hazra *et al.*, 2017), fibre bundle models (Schwarz *et al.*, 2013) or physical modelling (Leung *et al.*, 2017; Liang and Knappett, 2015). Measured or simulated plant-induced suctions were used in models of slope stability to evaluate the increase in the stability due to vegetation (Rahardjo *et al.*, 2014).

The results of the direct shear experiments presented in Yildiz *et al.* (2019) and the information on 50 documented landslides from the Praetigau region from a landslide database (Rickli and Graf, 2009) were analysed to reveal how they can be upscaled to improve the understanding of slope stability, since the soil used in the experiments was obtained from one of the locations presented in the landslide database. Combining large-scale direct shear tests on planted specimens, measurement of plant-induced suction in the laboratory, and historical landslide data has decreased the number of assumptions. Therefore, it provided a chance to develop a simple tool based on realistic data from different scales. A physically based landslide susceptibility model was developed, referring to the outcomes of Monte Carlo simulations, which were then used to provide insight on which combinations of slope angle and suction stress could trigger a shallow landslide in the Praetigau region.

Table 1. Information about the shallow landslides presented in Rickli and Graf (2009)

Study area	No. of landslides	Slope angles: degrees		
		Minimum	>90%	Median
Entlebuch	F: 10 O: 37	F: 26 O: 19	F: 27 O: 25	F: 36 O: 29
Praetigau	F: 26 O: 24	F: 25 O: 23	F: 28 O: 25	F: 33 O: 30
Napf '05	F: 14 O: 22	F: 25 O: 21	F: 26 O: 23	F: 39 O: 27
Napf '02	F: 30 O: 21	F: 28 O: 27	F: 35 O: 30	F: 39 O: 35
Appenzell	F: 34 O: 48	F: 26 O: 23	F: 30 O: 26	F: 35 O: 31
Sachseln	F: 126 O: 130	F: 30 O: 28	F: 35 O: 32	F: 39 O: 36

F stands for landslides on the forested slopes, while O represents landslides on open land

2. Materials and methods

2.1 Study site and soil

The St Antoenien study site is located near Praetigau in the canton of Grison, Switzerland. Figures 1(a), 1(b) and 1(c) show a photograph of the landslide under investigation, the location of the study site and information on the documented shallow landslides around the study site, respectively. The area has been affected by many landslides during the Holocene epoch, dating back as far as 10 000 calendar years before the present, owing to climatic changes, vegetation changes and anthropogenic influences (Dapples *et al.*, 2003).

During the 2005 heavy rainfall event, 26 shallow landslides out of 50 were triggered on forested slopes after a total rainfall of 145 mm within three consecutive days. The underlying bedrock is Praetigau-Flysch that contributes clayey, sandy debris to mantle the steep slopes, with median slope angles of 33° and 30° for forested and open land slopes, respectively (Bezzola and Hegg, 2007; Rickli and Graf, 2009). Soil was obtained from one of the landslide locations, and classified as clayey sand (SC) according to the Unified Soil Classification System (USCS). The index properties of Praetigau soil are given in Table 2.

Yildiz *et al.* (2019) performed large-scale direct shear tests on planted specimens prepared with Praetigau soil. The biodiversity on a vegetated slope was represented by planting shear boxes with *Poa pratensis* (L.), *Trifolium pratense* (L.), *Alnus incana* (L.) Moench, *Achillea millefolium* (L.), *Anthyllis vulneraria* (L.) and *Salix appendiculata* Vill. Species of genera *Salix* and *Alnus* have been used in soil bioengineering applications (Böll *et al.*, 2009), while the other species are found in subalpine grasslands and pastures (Jeangros and Thomet, 2004; Pohl *et al.*, 2009; Stampfli and Zeiter, 2004). Seedlings of the aforementioned species were grown in two different combinations in shear boxes in a climate-controlled chamber for 6 and 12 months. The details of the plant growth and sample preparation can be found in Yildiz *et al.* (2019).

2.2 Stability of a partially saturated slope

Infinite slope analysis is still used as a guide to quantifying slope stability, especially for slopes susceptible to shallow landslides with certain slope length to soil thickness ratios (Wu and Sidle, 1995), although it is rather a simplistic method. Results of finite-element method analyses performed by Griffiths *et al.* (2011) yielded higher FoS values than infinite slope analysis up to a length to depth ratio (L/z) of 16. Higher values of L/z resulted in identical FoS values for both types of analysis. Furthermore, Milledge *et al.* (2012) showed that FoS values calculated from the finite-element method and infinite slope analysis converge within 5% when L/z is higher than 25. Convergence occurred at much lower L/z values, as low as 4, depending on the material properties of the soil.

Figure 1. (a) Study site in Praetigau after the heavy rainstorm in August 2005 (photograph: Christian Rickli); (b) location of the study site in Switzerland; and (c) information on the landslides in the region (modified from Rickli and Graf (2009)). Landslide statistics are given as the median values

Table 2. Index properties of Praetigau soil

Gravel (>4.75 mm): %	14.1
Sand (<4.75 mm and >0.074 mm): %	45.6
Fines (<0.074 mm): %	40.3
Liquid limit: %	23.5
Plastic limit: %	13.7
Plasticity index	9.8
Specific gravity	2.69
USCS classification	SC

Figure 2. (a) Boxplot of length to depth ratios (L/z) of Praetigau landslides on forested ($N = 26$) slopes and open land ($N = 24$). (b) Slope geometry and the parameters used in the infinite slope analyses for partially saturated conditions

The FoS of a partially saturated slope, as shown in Figure 2(b), can be calculated with Equation 1, where c' and ϕ' are the shear strength parameters of the soil, γ is the bulk unit weight, z and β are the depth of failure surface and angle of the slope, and σ^s is the suction stress, which is dependent on the parameters of the soil-water retention curve (SWRC) (α , n) and matric suction ($u_a - u_w$). The equation defined by Lu and Godt (2008) was modified to define the suction stress as a positive value, for the sake of simplicity for plotting as follows

$$1. \quad \text{FoS} = \frac{c'}{\gamma z \sin \beta \cos \beta} + \frac{\tan \phi'}{\tan \beta} + \sigma^s \frac{\tan \phi'}{\gamma z \sin \beta \cos \beta}$$

$$2. \quad \sigma^s = \frac{(u_a - u_w)}{\{1 + [\alpha(u_a - u_w)]^n\}^{(n-1)/n}}$$

Table 3. Statistical properties of the parameters used in the sensitivity analysis

	Minimum	Maximum	Mean	Standard deviation
β : degrees	23	44	32.3	5.24
z : m	0.6	2.5	1.22	0.38
γ : kN/m ³	18.92	20.83	19.99	0.46
σ^s : kPa	7.83	42.5	15.3	8.08

2.3 Sensitivity analysis

A sensitivity analysis was performed with data from the landslide database and large-scale direct shear experiments, presented in Yildiz (2017) and Yildiz *et al.* (2019), to check the contribution of the variation of the parameters tested on the FoS of a partially saturated slope, as calculated with Equation 1. The shear strength parameters of the Praetigau soil, c' and ϕ' , were taken deterministically as 1.8 kPa and 17.6° from the direct shear experiments under saturated conditions, presented in Yildiz *et al.* (2019).

The geometry of the slopes was defined from the landslide database, while the unit weight and suction stresses were taken from the experiments with Praetigau soil. Matric suctions measured with tensiometers from the experiments were converted to suction stress values using Equation 2. Table 3 shows the mean, standard deviation and the range of each parameter used in the sensitivity analysis. Each parameter, except c' and ϕ' , was varied within its own minimum–maximum, while the other parameters were kept at their mean values.

Figure 3(a) depicts the results of the sensitivity analysis. Θ_i on the x -axis defines the range of the parameters tested – for example, ‘0’ shows the minimum value, while ‘1’ shows the maximum value. It can be deduced that the slope angle, depth and suction stress contribute more to the variation in the FoS, while the sensitivity of the FoS of a partially saturated slope was related less to the unit weight for the range of the parameters tested.

Figure 3. (a) Sensitivity analysis of FoS for Praetigau landslides ($N = 50$) based on infinite slope analysis, the frequency densities and fitted distributions of (b) suction stress and (c) slope angle

2.4 Statistical distributions

The frequency densities of the natural logarithm of the suction stress from the experiments and the slope angle from the landslide database are given in Figures 3(b) and 3(c), respectively. Types of distributions of data were decided using a Cullen–Frey graph based on the kurtosis and skewness of the data (Cullen and Frey, 1999). A Weibull distribution was fitted to the logarithm of suction stress with a maximum likelihood algorithm, and the shape (λ) and scale factors (κ) of the distribution were found as 6.16863 and 2.81378, respectively. A normal distribution was used for the slope angle with a mean of 32.3° and a standard deviation of 5.24° . Two-sided Kolmogorov–Smirnov tests were applied to these two data sets and the selected distributions in order to test the validity of the choices. p values of 0.3536 and 0.8163 were obtained for the logarithm of suction stress and slope angle, respectively. It can be concluded that the chosen distributions were good approximations as the null hypothesis cannot be rejected. Random data sets were generated with the distribution parameters shown in Figures 3(b) and 3(c) for suction stress and slope angle.

3. Simulations

Monte Carlo simulations were performed using the randomly generated data with varying depth. The effects of size of the randomly generated data and the number of simulations were investigated by calculating the FoS using the results of 10 to 1 000 000 simulations. An increased number of simulations, N , did not cause any significant changes in the mean FoS, or the standard deviation, as illustrated in Figure 4(a). However, the cumulative frequency of the simulations yielding a failure (FoS < 1) increased, when the number of simulations was extended from 10 to 1000 (See Figure 4(b)). Percentages of the simulations with a FoS smaller than 1 remained unaffected if the calculations were repeated 10 000 or 1 000 000 times.

An intermediate value of $N = 100\,000$ was chosen as the final number of simulations.

Three sets of Monte Carlo simulations, each with a data size of 100 000, were performed to define the critical suction stress and slope angle values with varying depth. The deterministic values of shear strength parameters of Praetigau soil under saturated conditions, mean unit weight from the experiments and the randomly generated data sets for suction stress and slope angle were used in the simulations. Each simulation was repeated for the depth values of 0.93 m, 1.22 m and 1.48 m. These depths were chosen from the landslide database to be statistically representative for the Praetigau landslides, corresponding to the first quartile, mean and third quartile values of the critical depths, respectively.

4. Results

Figures 5(a)–5(c) illustrate the frequency distributions and fitted log-normal distributions with increasing depth values. The summary of the distributions can be found in Figure 5(e). The results of the simulations yielded mean FoS values of 1.33, 1.14 and 1.03 for depths of 0.93 m, 1.22 m and 1.48 m, with standard deviations of 0.34, 0.28 and 0.24, respectively. The increase in depth resulted in a higher percentage of simulations with an FoS < 1, as shown in Figure 5(d). A failure scenario was indicated in 15.2%, 34.7% and 51.4% of the simulations.

The slope angles and suction stresses of all simulations are shown in Figures 6(a)–6(c). Two clearly distinct point clouds depict the stable and unstable zones of slope angle–suction stress combinations in each figure. Simulations that yielded a FoS less than 1 and higher than 0.995 were used to perform a regression analysis to separate the stable and unstable zones. Second-order polynomials were fitted ($R^2 = 0.99$, $p < 0.001$),

Figure 4. (a) Change in mean FoS with varying number of simulations (N), error bars show the standard deviation. (b) Percentage of simulations yielding a FoS smaller than 1 according to the number of simulations

Figure 5. Frequency densities of calculated FoS from Monte Carlo simulations with depths of (a) 0.93 m, (b) 1.22 m and (c) 1.48 m. (d) Cumulative frequency distributions of the FoS and (e) the fitted distributions

and the fitting parameters are given in the figures as well. Suction stress values between 0 and 60 kPa, as used on the axes of Figures 6(a)–6(c), were converted first to matric suction values using Equation 2. Then, these values were converted to gravimetric water content by substituting them into the SWRC for Praetigau soil.

5. Discussion

The outcome of this retrospective analysis – that is, the separation between the stable and unstable zones of the slope angle–suction stress graph with varying depth, can be used as a tool to carry out a quick determination of slope stability. It requires the monitoring of volumetric water content or matric suction at different depths, knowledge of the SWRC and determination of the slope angle from geographical information system (GIS) applications or field measurements. This analysis was conducted only for the Praetigau region, and the results in Figures 5 and 6 are particular to these conditions. However, this approach can be transferred to other regions known to be susceptible to shallow landslides, given that a suitable L/z and reasonably consistent soil properties are guaranteed. Furthermore, the shear strength parameters of the soil

should be known, and the fitted distributions of the randomly generated data can be validated for this method to be applied to other locations. This model has the advantage of using real statistical distributions for the randomly generated data instead of assuming a uniform distribution (Lee *et al.*, 2013).

The modelling approach presented herein is mainly sustained by results from the direct shear experiments conducted with and inclinable large-scale direct shear apparatus (Yildiz *et al.*, 2019). Normal stresses at the peak shear stress within that investigation were composed of the applied normal load and overburden pressure due to soil weight, and ranged between 7.2 kPa and 20.7 kPa. This range corresponds to a soil thickness of 0.36–1.04 m in the field, using the average unit weight from the experiments. Although the applied normal stresses in the experiments do not cover the whole range of depths of shallow landslides in Praetigau, they still overlap with the stresses the soil would experience for the lower values of depth in the database.

Conversion of matric suction measurements into suction stress with the parameters of SWRC is essential for the method

Figure 6. Slope angle and suction stresses of the Monte Carlo simulations ($N = 100\,000$ each) that yielded a FoS less than 1 for shear planes at depths below the surface of (a) 0.93 m, (b) 1.22 m and (c) 1.48 m. Solid and dashed lines show the nominal separation between a stable and an unstable slope, and are given as an equation. Gravimetric water contents are converted from matric suction values using the fitted curve from the equation by Van Genuchten (1980)

proposed. The SWRC is normally determined from laboratory specimens (c. 50 mm dia. and 20 mm in depth), which should be sampled to be appropriately undisturbed, should not contain macro drainage features (e.g. channels left by old roots) and should be subjected to relevant boundary conditions. Mayor *et al.* (2018) investigated the differences in the determination of the SWRC for the same soil from field measurements and laboratory specimens. The ground drained more quickly and much more freely in the field, because drainage was not limited to nominal one-dimensional (1D) conditions. He also fitted both sets of data to the SWRC computed by two methods derived from the soil particle size distribution: the modified Kovács (MK) (Aubertin *et al.*, 2003) and the Arya and Paris (1981) equations (A&P). The MK method predicted the measured SWRCs well in the zone between the air entry values and the residual zone, whereas the A&P method performed better in the low-suction zone up to the air entry value.

Consequently, the rather time-consuming and demanding requirements to obtain samples and to carry out laboratory tests for limited benefit, led to a pragmatic approach being adopted in this study to obtain the SWRC of Praetigau soil. The MIT technique, which couples the matric suction measurements from tensiometers with the calculated gravimetric water content values from mass measurements (Toker *et al.*, 2004), was used to determine the SWRC with a simplistic set-up, which provides 1D drainage. Application of this

method to other soils and locations requires determination of the SWRC that is representative of the boundary conditions.

The second part of the analysis focuses on the understanding of the initiation of each landslide in the Praetigau region after the rainfall event in 2005. Initially, the same shear strength parameters in the first part of the analysis were used, while the geometry of each slope, depth and slope angle, was taken from the landslide database. When the FoSs from these slopes, which had already failed, were calculated, based on Equation 1, all the values were less than 1, indicating that the slopes failed when the matric suction was lost due to saturation after the rainfall. Afterwards, the critical suction stresses to keep the slopes marginally stable ($FoS = 1$) were calculated, as shown in Figure 7(a) for forested slopes and slopes on open land. The slopes in the forest would require a mean suction stress of 11.7 kPa, with a standard deviation of 8.87 kPa, whereas those in open land would need a mean value of 11.1 kPa, with a standard deviation of 6.66 kPa. No significant differences were found in the requirement of suction stress for a FoS of 1, even though the geometric parameters of the landslides between the forest and open land were different (see Figures 7(a) and 7(b)).

Figures 7(a) and 7(b) also suggest that the required suction stresses increase with depth and the slope angle, both for slopes in the forest and in open land. The back-calculated values from the landslide database were compared to the suction stresses from experiments with Praetigau soil.

Figure 7. The required suction stress based on infinite slope analyses to keep the Praetigau slopes stable ($FoS = 1$) plotted against (a) the slope angle and (b) the depth. (c) Comparison of the required suction stresses calculated from the database and measured in the laboratory

Figure 7(c) shows that the critical suction values were reached with the same soil and different combinations of vegetation in the experiments – that is, the slopes were stable prior to saturation during rainfall, due to the plant-induced suction. Rickli *et al.* (2019) showed that the study site had a relatively open forest structure – namely, 15–70% of forest cover, with forest gaps of considerable length, which was shown to be a highly critical parameter in terms of landslide susceptibility (Moos *et al.*, 2016).

The results presented in Yildiz *et al.* (2019) showed clearly the increase in the shear strength of Praetigau soil with plant-induced suction. Furthermore, matric suction was correlated with root biomass and root:shoot ratio. The plant-induced suction would be expected to be greater with increasing root biomass, either due to plant age or increasing biodiversity.

Measurements of plant-induced suction that consider the influences of biodiversity, inoculation with mycorrhizal fungi and growth duration have provided valuable insight regarding what range of matric suction values can be obtained with different combinations. This insight can be used in combination with the method depicted in Figure 6 as a quick tool to assess the stability of the slopes in the Praetigau region, as the additional contribution to shear strength from the increase in effective stress is lost progressively during infiltration of rainfall, leading to instabilities, sometimes even before full saturation is reached (Springman *et al.*, 2003).

6. Conclusion

A physically based landslide susceptibility model based on plant-induced suction measurements under laboratory conditions and information from a landslide database is proposed herein. Monte Carlo simulations performed for an infinite slope stability analysis at different depths yielded combinations of suction stress and slope angle, which can cause slope instability. Retrospective analyses of the landslides showed that monitoring a hydrological parameter of the soil, such as water content or matric suction, together with the knowledge of slope angle and critical state friction angle of the soil, can be used as an early warning tool for landslide susceptibility for the Praetigau study site.

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