What forest structure and soil properties account for the protection against shallow landslides

Frank Graf [1)], Christian Rickli [2)], Alexander Bast [1)]

[1)] WSL Institute for Snow and Avalanche Research **SLF**, 7260 Davos Dorf, Switzerland (graf@slf.ch, alexander.bast@slf.ch)

[2)] Swiss Federal Institute for Forest, Snow and Landscape Research **WSL**, 8903 Birmensdorf, Switzerland (christian.rickli@wsl.ch)

Introduction

A Multi FactorAnalysis (MFA) approach was applied for better understanding the influence of forest structure on the triggering process of shallow landslides. From the WSL landslide database, 207 shallow landslides triggered in forests were analysed, considering geotechnical information (Tabs. 1, 2).

Table 1: In the **WSL landslide database** (https://hangmuren.wsl.ch) currently 734 shallow landslides allocated to 8 heavy thunderstorm events are documented by more than 60 parameters, e.g. volume, inclination, soil material, vegetation, … [1]).

Location (inventory number)	**Communities** (investigation region)	**Date of event** (thunderstorm) [dd.mm.yyyy]	**Cumulative rainfall** [mm]	**Duration of rainfall event** [h] (within n days)	**Number of landslides** [n]	**Area of watershed** [km^2]
Sachseln (1)	Sachseln	15.08.1997	150	2 (1)	280	8.2
Appenzell (2)	Rehetobel, Trogen, Wald	31.8.-01.09. 2002	120	9 (2)	100	10.2
Napf (3)	Trub	15.-16.07. 2002	60	3 (2)	64	2.5
** Surselva (4)*		*14.-16.11. 2002*	*252*	*63 (3)*	*34*	*3.2*
Entlebuch (5)	Flühli	18.-23.08. 2005	269	72 (6)	91	5.1
St. Antönien (6)	St. Antönien	18.-23.08. 2005	185	72 (6)	69	4.7
Napf (7)	Trub	18.-23.08. 2005	241	72 (6)	58	1.6
** Eriz (8)*		*04.07. 2012*	*60-100*	*2 (1)*	*38*	*9.5*
Total					**734**	**45.0**

** Not considered in the Multi Factor Analysis*

Conventional structural properties of forests (layering, development, mixture, canopy cover), geotechnical parameters (friction angle, cohesion), water content, void ratio, fines-content [silt, clay]) and environmental variables (altitude, slope-inclination) were included as well as the triggering thunderstorm events and the different affected geographic regions (Tab. 2). Furthermore, the soil material of the shearing zone was determined according to [1, 2, 3] and categorised in three soil stability types, either controlled particularly by friction (F-contr.; n=4), suction (S-contr.; n=133), or a combination of both (n=70).

Table 2: Numeric and categorical variables of the Multi Factor Analysis with the portion of explained variance for Dimension 1 (Dim1: 46.5%) and 2 (Dim2: 21.7%), the correlation (numeric) and R^2 values (categorical), respectively and the corresponding p-values [2]. The individual portions to the explained variance sum to 100%, representing 46.5% and 21.7%, respecticely (light grey filled).
- numeric variables: **dark grey** (geographical); **black** (soil properties)
- categorical variables: coloured according to Fig.1 and filled: **blueish** for soil, location, and thunderstorm or **greenish** for forest structure parameters

	Dim1 [%var] **46.5**	cor // R^2 [0,1]	p-value [0,1]	**Dim2** [%var] **21.7**	cor // R^2 [0,1]	p-value [0,1]
altitude [m asl]	1.6	0.23	$1.0\ e^{-03}$	**36.40**	**-0.74**	$9.7\ e^{-38}$
inclination [°]	0.01	---	---	7.7	0.34	$4.9\ e^{-07}$
water content w [%]	**27.87**	**0.95**	$7.1\ e^{-108}$	2.2	0.18	$8.2\ e^{-03}$
void ratio e_0 [-]	**26.53**	**0.93**	$1.3\ e^{-90}$	2.7	0.20	$3.2\ e^{-03}$
friction Φ' [°]	**23.50**	**-0.88**	$1.5\ e^{-66}$	0.1	---	---
cohesion c' [$kN \cdot m^{-2}$]	0.4	---	---	**40.74**	**0.78**	$6.8\ e^{-45}$
fines content fc [%]	20.00	0.81	$6.1\ e^{-49}$	10.16	-0.39	$4.7\ e^{-09}$
Total [%var] Dim1/Dim2	100.00			100.00		
type of failure (**F**riction, **S**uction, **I**ntermediate)		**0.58**	**$4.3\ e^{-39}$**		---	---
region		0.16	$6.6\ e^{-06}$		**0.56**	**$2.2\ e^{-32}$**
thunderstorm		0.12	$1.3\ e^{-05}$		**0.46**	**$6.0\ e^{-27}$**
development		**0.04**	**$3.5\ e^{-02}$**		---	---
canopy cover		---	---		**0.06**	**$1.6\ e^{-03}$**
layering		---	---		**0.02**	**$3.2\ e^{-02}$**

Results

The input variables account for ≈93% of the explained variance on the first four MFA dimensions (47, 22, 14, 10%). Thereof, ≈69% are allocated on dimension 1 (Dim1) and (Dim2).

Significant and positive correlations with Dim1 are shown for water content, void ratio, and fines-content, contributing 28, 27, and 20%, respectively. The friction angle (Φ') is negatively correlated and accounts for 24%, totalising geotechnical contributions to ≈98%. Further significant correlations with Dim1 were found for altitude (numerical) and the categorical variables **type of failure**, **region**, **thunderstorm**, and **development**.

Main contributions to Dim2 resulted from cohesion (41%) and slope-inclination (8%) both significantly positive as well as altitude (36%) and fines-content (10%) both negatively correlated. Further significance was identified for numerical void ratio and water content as well as categorical **type of failure** (soil stability), **region**, **thunderstorm**, **canopy cover**, and **layering** (Fig. 1).

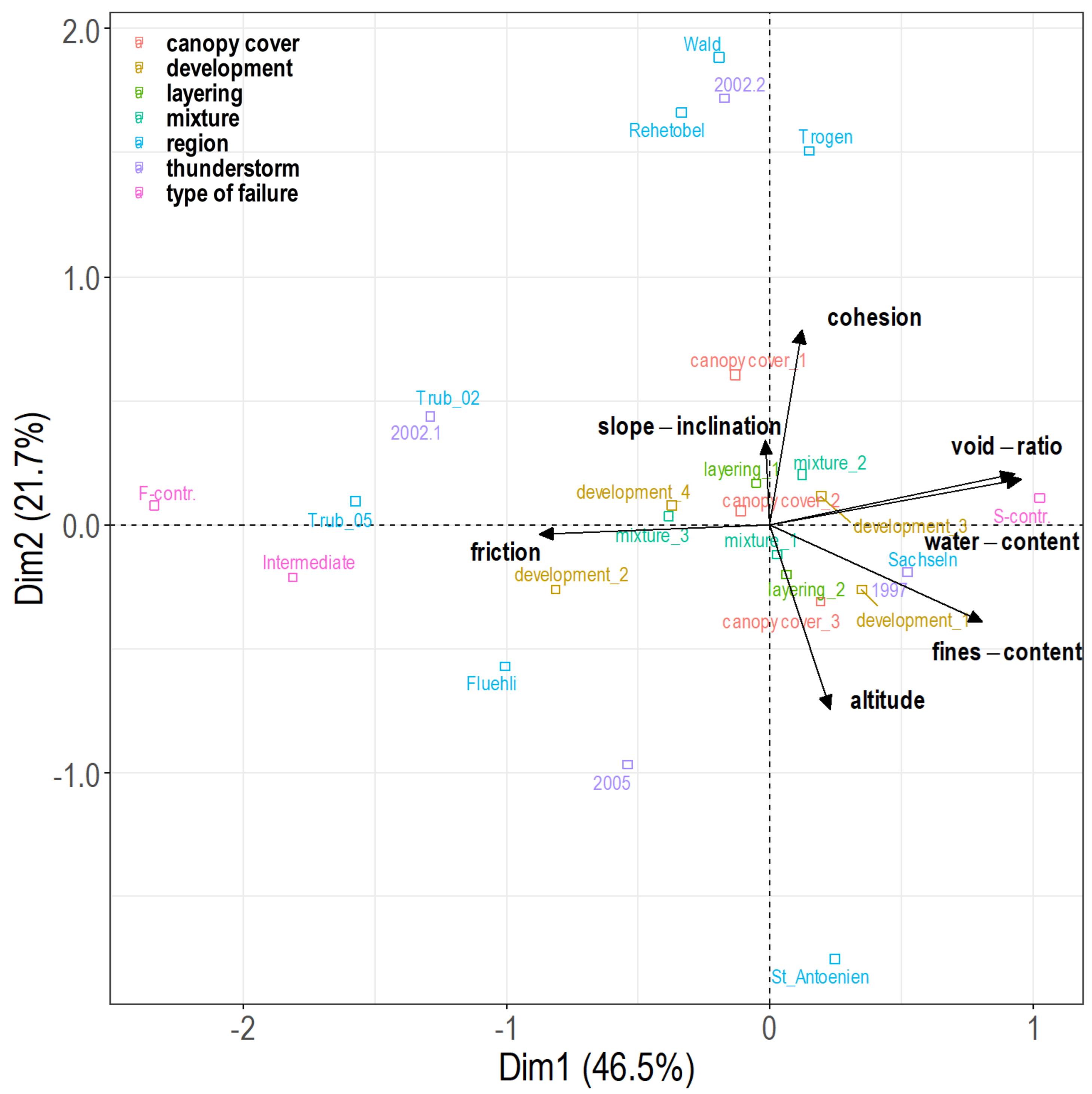

Figure 1: First (Dim1) and second (Dim2) dimension of a Multi Factor Analysis applied to numerical and categorical variables.
Numerical variables are separated in geographical location (altitude, slope-inclination) and soil parameters (friction angle, cohesion, fines-content, water content, void ratio). Categorical variables include the group with region (communities), the corresponding thunderstorm (2 events in 2002: 2002.1, 2002.2), the type of failure* (soil stabilty), and forest structure§ properties (canopy cover, development, layering, mixture).

* type of failure (soil stability)
- **F-contr.**: friction-controlled (GP, SW); n=4
- **S-contr.**: suction-controlled (CL, CL-ML, CM, GC, MH, ML, OL, SM); n=133
- **Intermediate**: intermediate (GM, GC-GM, SC, SC-SM); n=70

Soil classification according to [2, 3].

§ **forest structure** (conventional stand code)
- canopy cover: 1: c > 80%, **2: 60% ≤ c ≤ 80%**, 3: c < 60%
- development: 1: young stand/thicket, **2: pole wood, 3: tree wood, 4: well-structured stand**
- layering: 1: mono-layered, **2: multi-layered/well-structured**
- mixture: 1: > 80% conifers, **2: mixed stand, 3: > 80% deciduous trees**

Bold: Thresholds for well-structured forests in terms of «optimal protection» against shallow landslides after [4]. Forest stand code thresholds according to [1, 4].

Conclusions

The Multi Factor Analysis is a valuable statistical approach to evaluate combined, numerical and categorical variables and confirms the importance of soil properties and forest structure as regards the protection against shallow landslides.

Water content, void ratio, and friction are the most important soil properties. Pure frictional soils (**F-contr.**: n=4) are far less affected by shallow landslides compared to intermediate (**Intermediate**: n=70) and suction-controlled soils (**S-contr.**: n=133).

Well-structured forests meeting the thresholds of the forest stand code (caption of Fig. 1, [1]) are more stable and there are hints on positive correlation between root (forest) structure, friction angle (Φ') as well as soil aggregate stability [4].

Yet, the analysis gives leeway to speculations on the suitability of the conventional forest stand code. Additionally addressing the «health» of forests, including disturbances such as landslides, avalanches, windthrow, fire, calamities by insects and fungi, is likely to improve the results.

Finally, we should bear in mind that the specific region and thunderstorm event have a strong impact on the boundary conditions.

References:
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