AUSTRIAN JOURNAL OF EARTH SCIENCES | VOLUME 102/2 | 90 - 99 | VIENNA | 2009

THE INFLUENCE OF DEFORESTATION ON SLOPE (IN-) STABILITY

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KEYWORDS

slope instability
root cohesion
deforestation
landslides
forest

ABSTRACT

Various studies over the last few decades state an influence of vegetation on slope stability. Statistical analyses of several rainfall induced mass movement events in the Alps occurring in recent years were inconclusive because of the complexity of competing parameters and processes in nature. However, several trends in some of the relevant parameters could be determined and are discussed in the paper. Limit equilibrium analyses were then carried out to quantify root cohesion and tree weight evaluating their influence on slope stability. Clear trends can be recognized which show that in most cases complete deforestation of sliding prone slopes does have a minor effect on slope stability, and that the degradation of roots leads to a decrease in the factor of safety within years and decades. Slightly inclined slopes may even show a decrease in the factor of safety when tree weight is removed from the slope (logging). Even if logging does improve slope stability in the first instance, in the long term, this leads to even bigger problems like fading away of the root cohesion, surface erosion, and soil degradation.

Verschiedene Publikationen der letzten Jahrzehnte konstatieren einen Zusammenhang zwischen Vegetation und Hangstabilität. Eine statistische Analyse von Großschadenereignissen, die durch intensiven und/oder lang anhaltenden Niederschlag ausgelöst wurden, brachte keine eindeutigen Ergebnisse aufgrund der Komplexität der Prozesse und der großen Anzahl an sich gegenseitig beeinflussenden Parametern. Allerdings konnten Trends erkannt werden, die in dieser Arbeit diskutiert werden. Anschließend wurden Grenzgleichgewichtsberechnungen durchgeführt, um Wurzelkohäsion und Baumgewicht zu quantifizieren und deren Einfluss auf die Hangstabilität abzuschätzen. Anhand dieser Berechnungen können eindeutige Ergebnisse aufgezeigt werden, wonach eine völlige Abholzung der Vegetation auf rutschungsgefährdeten Hängen einen kleinen Effekt auf die Hangstabilität hat, die Abnahme der Wurzelkohäsion mit der Zeit jedoch einen klaren Abfall des Sicherheitsfaktors innerhalb von Jahren und Jahrzehnten bewirkt. Bei flachen Hängen kann der Sicherheitsfaktor bereits bei Entfernung des Baumgewichts sinken. Sogar wenn Kahlschlag anfänglich eine Erhöhung des Sicherheitsfaktors bewirkt, so ergeben sich auf lange Sicht Verschlechterungen aufgrund des langsamen Verschwindens der Wurzelkohäsion, der Intensivierung von Erosion und Bodendegradation.

1. INTRODUCTION

A common mitigation measure in dealing with mass movements is the complete deforestation of the affected area (Fig. 1). This is often done routinely and without any scientific or engineering evaluation.

Generally, mass movements are characterized by very complex interaction of different processes and mechanisms, which are further complicated by adding additional factors such as vegetation cover. There have been several authors, most of them from the United States, Canada, New Zealand, Japan and Switzerland, who have worked on mass movements and the impact of vegetation on slope stability. Many of these publications present calculations to quantify the effect of vegetation cover on mass movements. In this paper we compile and reanalyse the findings of various authors on rainfall-induced mass movements and present new results of limit equilibrium analysis evaluating the relationship between hydraulic conditions, vegetation cover and slope stability. Deforestation (log-

FIGURE 1: Deforestation as a mitigation measure for mass movements.

ging, clear cutting) as an immediate mitigation measure for instable slopes is discussed.

2. Reanalyses and Interpretation of previous studies

A comparison of different landslide events at different localities is very difficult because of the great variability of competing parameters and processes in nature, such as slope inclination, soil stratigraphy, micro topography, vegetation cover, as well as triggering factors like precipitation quantity and intensity as well as pre-event soil moisture

Over the last decades, several heavy rain storms triggered clustered mass movement events in alpine regions. All investigated events (Switzerland: Sachseln 1997, Napf and Appenzell 2002, Vorarlberg: Laterns 1999 and 2005, Styria: Gasen and Haslau 2005) were accompanied by intense or long lasting precipitation (see Table 1). According to Rickli (2001), precipitation quantities of about 50 mm or precipitation intensities of about 50 mm/hour, may induce heavy erosion and/or slides. Most of the observed events were shallow seated (0-2 m depth of sliding plane) and can be classified as slides, some developing into flows (BRP, BWW, BUWAL, 1997; Turner and Schuster, 1996; Zangerl et al., 2008).

The investigated slides show slope angles between 23° - 50° and occur at elevations from about 750 to 1600m above sea level. If slope angles exceed 31,5° the likelihood of slope failure decreases (Moser and Schoger, 1989; Rickli, 2001; Andrecs et al., 2002). Several authors find that slides in forested areas occur at steeper slope angles (Rickli and Bucher, 2003; Andrecs et al., 2007). This is due to the fact that forests generally cover steep terrain, whereas smooth areas are used for farming (Rickli and Bucher, 2003). Rickli (2001) excludes slope exposition as relevant parameter as he could not state a preferred orientation of the failed slopes. Moser (1980) states that S and SW exposed slopes show higher activity of slides as a result of increased (pre – event) soil moisture due to snow melt.

There exist contradictory reports about the impact of micro topography. More than 50% of all slides occur at the mid ranges of slopes at localities where inclinations did not significantly change above or below these points (Rickli, 2001; Andrecs et al., 2002; Markart et al., 2007). In general, convex slopes are recognized as more stable, whereas concave slopes are supposed to concentrate subsurface water and therefore to be prone to erosion and mass movements. Rickli (2001) reports that 86% of the slides in Sachseln occur at slopes without any bend in the slope dip line. At the villages of Napf and Appenzell, Rickli et al. (2004) mainly identify slopes with convex dip lines as well as small channels and depressions as the origin of slides and erosion. Markart et al. (2007) and Moser (1980) find that slides are released preferentially underneath points of increasing slope inclination (“edges”) and above and below road cuts. 42% of the slides were released at “homogenous, smooth slopes” and 43% at slopes which showed small channels and ditches in slope dip line (Vorarlberg 2005, Markart et al., 2007).

In Laterns 1999 and Napf 2002, more slides occurred in forested areas whereas in Sachseln 1997, Appenzell 2002, Vorarlberg 2005 and Styria 2005 fewer slides were observed in forests but involved larger volumes (Fig. 2, Rickli, 2001;

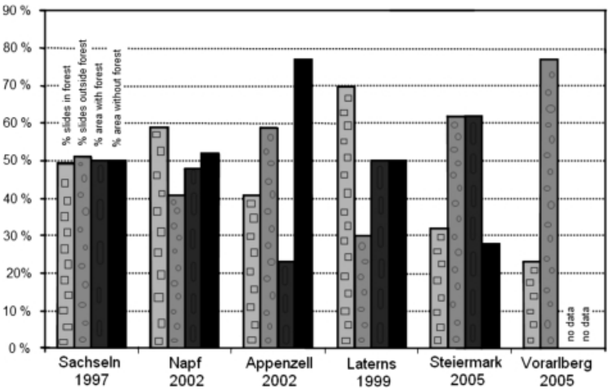

Figure 2: Comparison of % slides occurring in forested areas versus slides occurring on open land, no data for Vorarlberg 2005 (data from various authors: Rickli, 2001; Rickli et al., 2004; Andrecs et al., 2002; Markart et al., 2007; Andrecs et al., 2007).

Locality:	Sachseln (CH) 1997	Napf (CH) 2002	Appenzell (CH) 2002	Vorarlberg (A) Laterns 1999	Styria (A) 2005	Vorarlberg (A) 2005
Reference:	Rickli, 2001	Rickli et al., 2004	Rickli et al., 2004	Andrecs et al., 2002	Andrecs et al., 2007	Markart et al., 2007
Date of event:	15.08.1997	15.-16.07.2002	31.08./01.09.02	20.-21.05.1999	20.-22.08.2005	22.-23.08.2005
Nr. of slides:	280	51	82	147	145	189 - 315
Slope angles of investig. slides:	100%: 28°-45°	100%: 23°-50°	100%: 23°-50°	/	100%: 31°-39°	/
	80%: 34° - 41°	90%: 29°- 44°	90%: 29° - 44°	87%: 27°-36°	/	74%: 20°- 40°
Elev. above s.l. of investig. slides:	~1000 - 1600m	~1000 - 1300m	~750 - 950m	~900 – 1500m	/	~1000-1300m
% rotational	50%	10%	10%	85%	most rotational	28%
% translational	50%	90%	90%	11%	some transl.	66%
Precipitation Quantity and Intensity:	150 mm / 2h	53 mm / 24h	150 mm / 24h	223 mm / 24h	220 mm / 44h	244 mm / 24h

Table 1: Characteristics of some of the clustered slide events in the Alps in recent years after various authors, (CH)...Switzerland, (A)...Austria.

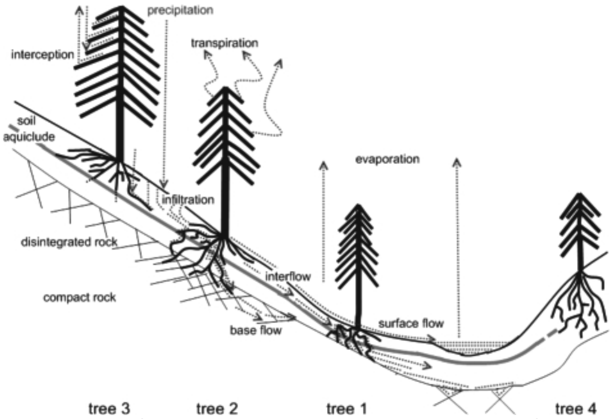

Figure 3: Schematic drawing showing the interactions of vegetation, soil, rock and water (see Table 2 for explanations).

Andrecs et al., 2007).

Rickli (2001) found that as elevation increases, the resulting reduction in the thickness of soil and loose sediment leads to a decrease in the mean depth and volume of slides. Therefore, Rickli (2001) concludes that the likelihood of slides increases with increasing depth of soil and (loose) sediment. He also finds that the contact of soil / loose sediment with the compact rock acts as a distinct boundary which can be activated as a sliding plane, especially when the rock surface is covered with a silty/clayey weathered surface layer of 10 – 20 cm, and the tip of the bedding is slope parallel. He also observes that the number of slides decreases with increasing volume.

The anthropogenic influence on slides is very delicate. Most authors state a significant impact of artificial steepening of slopes, adding weight to the slope, removing support in cut-slope, re-routing and concentrating surface runoff and abandoning farmland (Markart et al., 2007; Rickli, 2001). In Laterns 1999 about 9% of slides were influenced by human activity (Andrecs et al., 2002), in Styria 2005 about 66% of slides showed anthropogenic impact (Andrecs et al., 2007). Moser (1980) states that 36% of slides in Carinthia 1975 occurred at anthropogenic influenced slopes. Proske (1997) concludes on erosion damage in Styria: “The damage done by erosion in the Glein-Valley is predominantly ascribed to the unadapted construction of forest roads and the associated change in the natural slope drainage system”.

3. Mechanical, Hydrological and Hydrogeological Basics

3.1 Influence of Vegetation on Slope Stability

It is widely recognised that vegetation can stabilize steep slopes (Rickli and Graf, 2009). Vegetation cover has an impact on slope stability by:

- Influencing the physical stability of slopes by root arming, weight of trees and wind induced forces (Ziemer, 1981 a/b; Beinsteiner, 1981; Tsukamoto, 1990; Sidle, 1991; Bischetti et al., 2004; Medicus, 2009).
- Influencing the hydrology by reducing the physical force of rain drops, interception, evapo-transpiration, pore pressures, suction power, quantity and volume of pores (Markart et al., 2004; Markart et al., 2006; Thielen, 2007; Tobias, 2003).

However, the quantification of these processes is very difficult. Statistical analysis of several clustered mass movements in the Alps show that there is no simple conclusion such as; “there are less mass movements in forested areas than in grassland” (Fig. 2, Beinsteiner, 1981; Andrecs et al., 2002; Rickli et al., 2004; Markart et al., 2007; Andrecs et al., 2007; Rickli and Graf, 2009). In Table 2 and Fig. 3 relevant interactions between vegetation cover and the basement are demonstrated. Four possible interactions of tree roots and basement can be distinguished (Tsukamoto and Kusabe, 1984; Tsukamoto and Minematsu, 1987; Rickli, 2001).

These four “possible interactions” (Table 2, Fig.3) are further influenced by biological parameters like number and variety of species, age of trees, the density of trees and treetops, depth range of tree root system and “healthiness” of the forest (e.g. Rickli, 2001; Foetzki et al., 2004; Gaertner, 2004). For instance Rickli et al. (2001) find that areas with medium to mature trees and very few clearances (gaps) show minimum sliding activity, whereas sites with very young trees and many clearances or storm damaged sites show the highest (Rickli, 2001; Markart et al., 2007).

3.2 Shear strength

Landslides occur if the driving forces exceed the resisting forces in the critical slip surface of a slope. Wu et al. (1979)

Type:	Description:	Stability effect:	Friction angle:
tree 1	Shallow seated soil cover, reinforced by roots, below: compact, for roots not penetrable rock	Low	If saturated with water decrease of φ and initiation of slides
tree 2	Similar to "tree 1", but rock is slightly disintegrated and can be penetrated by tree roots	Very high	If saturated with water decrease of φ but roots reinforce slope, minor surface erosion possible
tree 3	Medium to deep seated soil cover with a transitional layer, which is more dense and has a greater friction angle, to penetrate this layer increases slope stability	Medium	If forest is "unhealthy" or if roots tend to grow horizontal there may be slides
tree 4	The soil cover is greater than root length, roots may influence hydrology but do not increase mechanical slope stability	Low	If saturated with water decrease of φ and possibly initiation of slides

Table 2: Four possible interactions between tree roots and basement, see Fig. 3; φ …angle of internal friction (modified after Rickli, 2001).

Parameters:	Effect:	Quantification:
Root cohesion c_r: Arming by roots	positive	2 - 22 kPa
Normal stress σ_n: Unit weight of trees	negative/positive	205 - 820 t /~1.66 kPa
Normal stress σ_n: Reducing weight by transpiration	positive	~ 45.000 l/ha/day
Pore pressure u: Increase of suction power	positive	-

Table 3: Parameters of shear strength influenced by vegetation (Beinsteiner, 1981; Sidle, 1991; Medicus, 2009).

introduced a term “c_r” called “root cohesion” to calculate the soil - root composite shear strength τ with the Mohr-Coulomb failure criteria. Root cohesion is the apparent cohesion provided by roots:

$$\tau = (c' + c_r) + (\sigma_n - u) \tan \varphi' \qquad (1)$$

parameters: τ...shear strength; c´...soil cohesion; c_r...root cohesion; σ_n...total normal stress; u...pore pressure; tan φ´...angle of internal friction;

Relevant factors for calculating shear strength are: cohesion, normal stress and the angle of internal friction. Cohesion can act in different ways:

- Cohesion between particles (fine grained material: plasticity, clay content, moisture)
- Suction power (“capillarity cohesion”, Tobias, 2003)
- Arming of particles by roots (Wu et al., 1979)

Normal stress on the slip surface is influenced by

- Pore pressure (buoyant force, weight of water)
- The unit weight of soil and trees
- Density of soil
- Soil depth and
- Slope gradient

The angle of internal friction is a parameter of the degree of interlocking of individual grains or aggregates which itself depends on shape, roundness, size and packing arrangement of the particles. The main parameters influenced by vegetation cover and their roots are given in Table 3.

3.3 Mechanical Reinforcement by Roots

Roots reinforce slopes by three mechanisms: anchoring, lateral support by crossing zones of weakness, and acting as long fibrous binders within a weak soil mass (Ziemer, 1981 b). Roots withstand shearing by tensile strength until the fiber cracks. This depends on diameter and strength of individual roots (Wu et al., 1979) as well as concentration of roots (Abe and Ziemer, 1991). Tobias (2003) shows by shear experiments that extraction of roots (skin friction) is another important failure mechanism influencing not only cohesion but also the friction angle of the soil. Katzenbach and Werner (2006) give the following parameters to assess the influence of roots on slope stability: tensile strength of roots, compound strength between roots and soil (extraction), shear strength of roots as well as length and branching of roots. According to Abe and Ziemer (1991) soil shear strength increases with increasing root concentration and increasing displacement at the shear zone.

Rickli and Bucher (2003) state that mainly wooden roots (mature roots) may act as stabilizers and give depths of the main root system of 5 – 140 cm for forests and 30 – 100 cm for open land (Appenzell and Napf area). Maximum potential root cohesion for different species is given with 2 - 22 kPa by Sidle (1991). Bischetti and Chiardia (2004) analysed shallow landslides near Varese / Northern Italy and calculated the rise of shear strength by roots with 6 – 9 kPa for hazelnut and European ash. Root cohesion seems to be very high in the upper 30 cm of soil (38 – 47 kPa), dropping linearly to values of 10 kPa at 100 cm depth (Bischetti et al., 2004). Katzenbach and Werner (2006) present shearing tests measuring soil before and after root growth. The internal friction angle increased slightly by 0.7° to 1.7°, the cohesion by 1.1 to 4 kN/m² after root growth. Buchanan and Savigny (1990) back-calculated root cohesion values of several slopes at time of failure in Washington State, U. S. They identify four groups of vegetation cover featuring different root cohesion values. Understory vegetation like grasses, sedges and shrubs show c_r values between 1.6 to 2.1 kPa (group I). For a scrub forest (understory with single trees, group II) they calculate c_r values between 2.1 to 2.5 kPa. A mixture of understory vegetation and healthy forest to approximately 15m in height (group III) show c_r values between 2.5 to 3.0 kPa. Group IV, an old growth forest shows values of root cohesion bigger than 3.0 kPa.

The appearance and depth of root systems depend on species and soil development. For instance Spruces (picea abies, Fichte) are shallow root trees (“Flachwurzler”) spreading roots horizontally at shallow depths below ground, developing vertical piles 40-50 years later than roots of first order (Beinsteiner, 1981). Pines (pinus cembra, Zirbe) and firs (abies alba, Weißtanne) grow pile – root - systems (“Pfahlwurzler”) arming the soil faster.

3.4 Hydrological and Hydrogeological Interactions

The hydrology of slopes is as well influenced by vegetation cover (Fig. 3). Precipitation which is blocked by the treetops is called interception. In the Eastern Alps interception can be

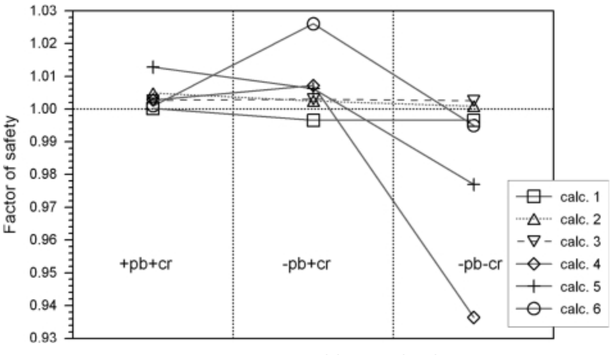

Figure 4: Numerical analyses of factor of safety versus the three calculated states “root cohesion and tree weight present” (+ p_b + c_r), “tree weight removed but root cohesion present” (- p_b + c_r), and “tree weight removed and no root cohesion present any more” (- p_b - c_r), dashed line: factor of safety is 1; data from Medicus (2009).

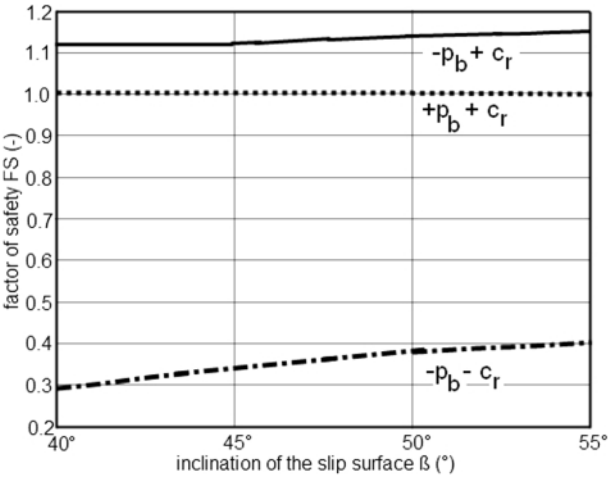

Figure 5: Variation of the slope inclination versus factor of safety, results for calculation 7 with Janbu´s method.

quantified with 1/5 to 1/3 of the annual precipitation (Markart et al., 2006; Moeschke, 1998). Transpiration is the quantity of water which is emitted by plants back to the atmosphere. Markart et al. (2006) shows that depending on precipitation quantity, transpiration may eliminate 21% to 89% of annual precipitation in a spruce forest in Germany. For a pine forest (pinus cembra, Zirbe) in Haggen at the Sellrain-Valley in Tyrol the transpiration could be quantified as 26% to 55% of 400 mm of precipitation from July to September (Markart, 2000). Of course this also depends very much on biological factors (species, age of tree, locality, climate, wind...). Moeschke (1998) investigated forests in Bavaria before and after deforestation and finds that peak runoff increases by 30% after 40% of the trees have been removed. This is caused by the loss of interception and transpiration. Beinsteiner (1981) quantifies transpiration with 43.000 litres / hectare / day for spruces (picea abies, Fichte) and 47.000 litres / hectare / day for larches (larix decidua, Lärche). Additionally, about one year after deforestation, soil degradation (disappearance of micro–organisms, silting up of pores) further inhibits infiltration and increases surface runoff. Vegetation normally inhibits excessive surface runoff by "roughening" the surface and increasing quantity and volume of pores (Markart et al., 2004). Macro– or secondary pores (10 – 50 µm) are important for infiltration, channelizing water into the basement producing interflow, deep interflow and base flow (Fig. 3; Scheffer and Schachtschabel, 2002; Markart et al., 2004).

The parameters influencing the interaction of soil and water are: grain size distribution, per cent fraction of coarse material, density (≈ pore volume), organic inclusions, stratification and thickness of soil / (loose) sediment. Soils with high quantities of fine grained material (silt, clay > 40%) have been identified as being prone to sliding (Moser, 1980; Andrecs et al., 2007). Most of the analysed shallow slides occur within soil, minor cohesive and friable fluvio- / postglacial sediments or at the interface of compact rock with (loose) sediment or soil. Andrecs et al. (2007) identify several soil types as being more prone to erosion and sliding than others. Thielen (2007) reports about suction power ("Saugspannung") increasing maximum

	calculation 1	calculation 2	calculation 3	calculation 4	calculation 5	calculation 6	calculation 7
Short characteristics:	$\varphi >$ ß, $h_w \neq 0$	$\varphi >$ ß, $h_w \neq 0$	ß $> \varphi$, $h_w = 0$	ß $> \varphi$, $h_w = 0$	ß $> \varphi$, $h_w \neq 0$	ß $> \varphi$, $h_w = 0$	ß $> \varphi$, $h_w = 0$
Calculation method:	infinite slope	Bishop/Janbu/ KEM	Bishop/Janbu/ KEM	Bishop/Janbu/ KEM	Bishop/Janbu/ KEM	Janbu/KEM	Janbu/KEM
Slope angle ß:	28°	30°	38.66°	41°	38.66°	45°	40° - 55°
Ground water table h_w:	3.5m	10.5m	none	none	2m	None	none
Depth of sliding plane:	7m	30m	15m	4m	4m	2m	0,4m (organic horizon)
Angle of int. friction φ:	35°	35°	31°	31°	35.5°	20°	5° (o.h.), 32°
Cohesion c:	0	4 kPa	22 kPa	3 kPa	4 kPa	12 kPa	c_1= 1.5 - 4.5 kPa (o.h.) c_2 = 10 - 11.5 kPa
Depth of root system h_r:	sl.pl. > 2m = 0	1m	1.5m	1.5m	1.0m	1.5m	1.5m
Root cohesion c_r:	0	6 kPa	6 kPa	6 kPa	6 kPa	6 kPa	6 kPa
Tree weight p_b:	1.66 kPa	1.66 kPa	1.66 kPa	1.66 kPa	1.66 kPa	1.66 kPa	1.66 kPa
Soil weight γ:	19.5 kN/m^3 - 21.5 kN/m^3	21.5 kN/m^3	19.5 kN/m^3 – 21.5 kN/m^3	19.5 kN/m^3 – 21.5 kN/m^3	19.5 kN/m^3 – 21.5 kN/m^3	19.5 kN/m^3 – 21.5 kN/m^3	19.5 kN/m^3 – 21.5 kN/m^3

Table 4: Assumptions made for generic slope examples by Medicus (2009); the two examples calculating wind induced forces are not shown, for topography models see Fig. 6, abbreviations: φ…angle of internal friction, β…inclination of slope, h_w...depth of ground water table, KEM...Kinematic Element Method, sl.pl....sliding plane; o.h....organic horizon.

shear strength, acting as “apparent cohesion”. Slopes which are too steep for the saturated or dry soil strength are held together by suction effects (Buchanan and Savigny, 1990; Thielen, 2007). Plants increase the suction power by extracting water from the soil and thus decreasing soil saturation (Tobias, 2003). Infiltrating water reduces suction power, which correlates positively with the amount of precipitation. If the upper soil layer is relatively saturated (in winter), the infiltrating water causes a small reduction in suction at all depths. If the upper soil layer is relatively dry (in summer), a rainfall event predominantly causes a large reduction in suction in the upper layer (Thielen, 2007).

Critical situations within unsaturated soil may evolve if the suction power is lost, giving rise to pore water (over) pressures reducing the weight of soils and producing an uplift force (Tobias, 2003). Pore water pressure produced by the head of water in a saturated soil can reduce shear strength by as much as 60% and decrease cohesion of some soils through leaching and eluviations (Ziemer, 1981 b).

4. Limit - Equilibrium Analysis

4.1 Applied Methods and Input Parameters

Medicus (2009) investigated several generic slopes to quantify the influence of vegetation on slope stability by limit equilibrium analyses. The trees were considered in terms of root matrix and weight. The inclusion of the root system in the equation resulted in increased cohesion (≈ 6 kPa, 1 – 1.5 m depth of roots). The weight of trees (1.66 kN/m²) (O´Loughlin, 1974) was added to soil weight (19.5 – 21.5 kN/ m³). The positive as well as the negative influence of vegetation were compared with other parameters like ground water table, slope inclination, friction angle and soil cohesion. Shallow-seated and deep-seated landslides with different slope angles and different soil parameters were analysed. The calculations were mainly performed with the software GGU-Boesch, which determines the critical slip surface and the factor of safety. The results were then interpreted by using sensitivity analyses. Three engineering standard stability analysis methods were used (Bishop´s modified method, Janbu´s method, Kinematic Element Method). The geometry and parameters in all calculations were chosen so that the slope is “just stable” (factor of safety FS ≈ 1) if the distributed load of trees and root cohesion are present. Three states were calculated:

- $+ p_b + c_r$: distributed load of trees (p_b) and root cohesion (c_r) is present
- $- p_b + c_r$: distributed load of trees was removed (logging), root cohesion is still present
- $- p_b - c_r$: distributed load of trees was removed, root cohesion fades by degradation

4.2 Results

Medicus (2009) analysed seven hypothetical slopes with three engineering stability analysis methods. All methods showed the

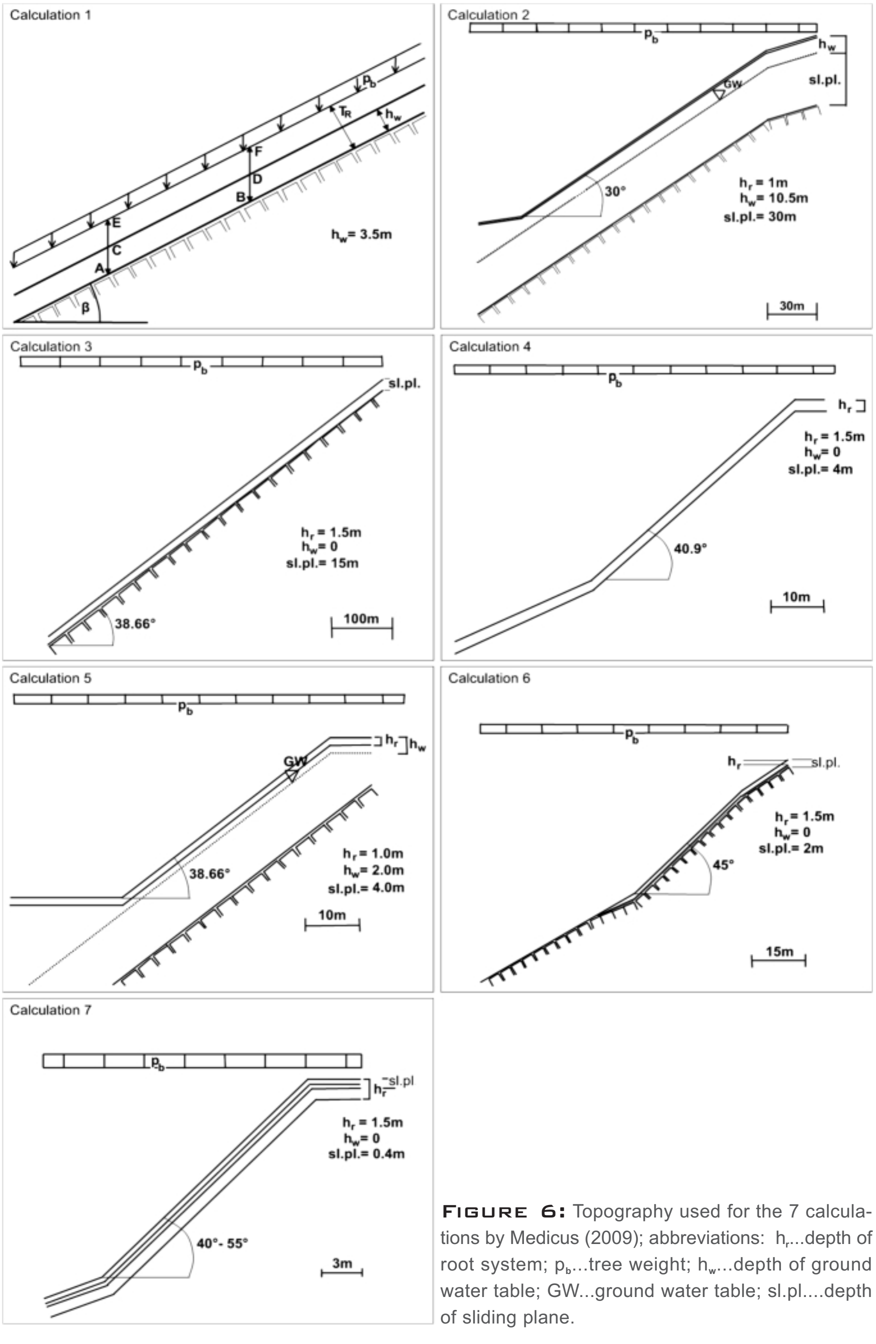

Figure 6: Topography used for the 7 calculations by Medicus (2009); abbreviations: h_r...depth of root system; p_b...tree weight; h_w...depth of ground water table; GW...ground water table; sl.pl....depth of sliding plane.

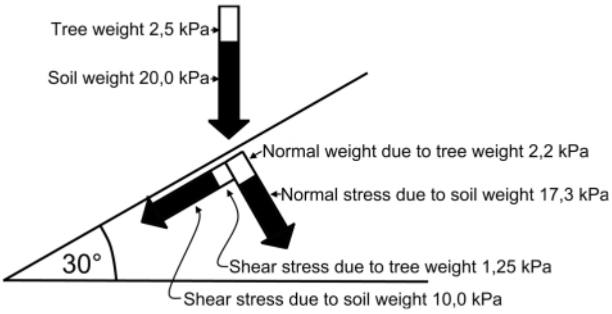

Figure 7: Distribution of shear- and normal stresses for tree and soil weights (redrawn from O´Loughlin, 1974), stresses in a depth of 1m, weight of soil: 20 kN/m^3, bulk density of trees: 2.5 kPa.

same trends even though they predicted slightly different factors of safety. In Fig. 4 the outcome of 6 calculations with Bishop´s modified (calculations 2, 3, 4 and 5) or Janbu's method (calculations 6 and 7) is shown for the three "states" described above: tree weight and root cohesion are present, tree weight is removed and root cohesion is still present, years after logging the root cohesion is fading.

The weight of the trees influences the slope stability in a positive way if the driving force due to the tree weight does not exceed the resisting force due to the tree weight and vice versa. Thus the weight of the trees is not per se negative for slope stability. Fig. 7 shows the distribution of shear- and normal stresses for tree and soil weights in a slope (O´Loughlin, 1974).

Considering an infinite slope with the failure surface parallel to the slope, the driving force due to the load of the trees (p_b) becomes p_b sin (β), with β being the inclination of the slip surface. The resisting force is p_b cos (β) tan (φ). Hence follows that p_b only has a negative effect on the slope stability if $\varphi < \beta$ (i.e if the friction angle in the slip surface is smaller than the inclination of the slip surface, compare Fig. 4, Fig. 7).

As expected in slopes with sliding planes much deeper than the depth of the root system neither the tree weight nor the root cohesion has a significant impact on slope stability. The roots do not reach deep enough to stabilize the slope and the weight of trees is marginal in comparison to the weight of soil or pore water.

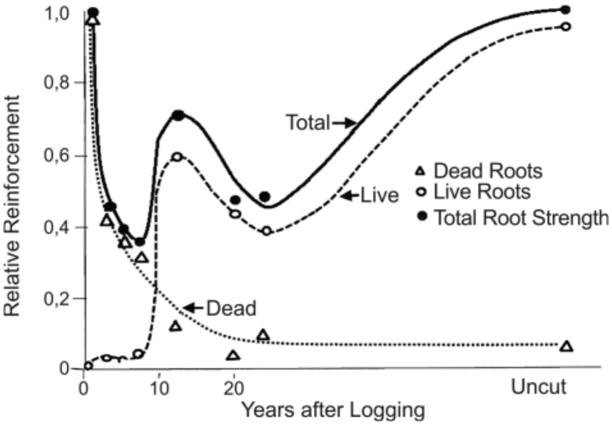

Figure 8: Development of slope stability by living and dead roots after deforestation (redrawn from Ziemer, 1981 a).

Calculation 3 shows an approximately 40° inclined slope with a 15 m deep sliding plane (see Table 4). In this example tree logging changes the factor of safety in the 3rd decimal place. For other deep slip surfaces the influence was similar (compare calculations 1, 2, 4, 5 in Fig. 6). Changes in the 3rd decimal place of the factor of safety can be neglected.

In calculation 6 the slip surface is 2 m below the slope surface. The angle of the sliding plane is bigger than the friction angle in the slip surface. Removing the weight of trees increases the factor of safety in the in the 2nd decimal place, which is still a rather small effect on the slope stability. This slope demonstrates a higher factor of safety with tree weight and root cohesion than the slope does after logging and root decay (Fig. 4).

In calculation 7 the slip surface lies 0.4 m below the surface. The roots are able to penetrate the sliding plane and act as anchors. In this example the friction angle is φ = 5° and the inclination of the sliding plane varies from 40° to 55°, i.e. the inclination of the sliding plane is always much larger than the friction angle. The low friction angle is due to the high organic fraction in the soil of the slip surface. With the trees still alive ("+ p_b + c_r") the factor of safety is around 1.0. The friction angle φ within the slip surface always stays the same; the cohesion c is changing (see Table 4). The steeper the slope, the more significant is the influence of deforestation ("- p_b + c_r"). After logging ("- p_b + c_r") the factor of safety increases in the first decimal place (Fig. 5).

A change of the factor of safety in the 1st decimal place is significant for the slope stability and clear cutting has a slighty positive effect. However, removing the root cohesion c_r reduces the factor of safety much more than logging increases it ("- p_b - c_r", see Fig. 5). The shallower the depth of the sliding plane, the stronger this effect becomes.

Medicus (2009) also quantifies wind-induced forces on slopes using the method by Wu et al. (1979). For deep seated slides (sliding plane at 30 m depth) the influence on the factor of safety is negligible. For shallow seated slides (sliding plane at 2 m depth) the wind induced forces show an influence on the factor of safety which may be relevant in some cases. In both cases, the positive effects of root cohesion are revealed to be bigger than the negative effects of wind induced forces.

4.3 Interpretation of Limit – Equilibrium Analysis

The additional shearing resistance due to the root system always has a beneficial effect on slope stability. The weight of trees increases or decreases the overall slope stability depending on soil and slope parameters. For deep seated slides, the influence of the load of the trees is more or less negligible.

In non-cohesive soils tree weight has a neutral to slightly positive effect for slope parallel or curved sliding planes below the depth of the root system. In reality this may be negligible. Non-cohesive soils with φ = β are in limit equilibrium. For a slope to be stable, slope inclination β must be smaller than the angle of internal friction φ, if a ground water table is present.

This implies an even more positive impact of the tree weight.

For cohesive soils it is not possible to give general conclusions about the positive or negative influence of tree weight on slope stability. Very steep slopes with shallow sliding surfaces should be investigated and analysed. However, the performed calculations show that a positive effect is expected to be very small. In the long term complete deforestation in most cases tend to worsen slope stability by loss of root cohesion.

5. Discussion

Vegetation cover influences slopes physically and hydrologically. The hydrological influence is mostly positive by reducing the overall amount of water infiltrating into the soil or acting as surface runoff. Plant roots do act, apart from giving physical stability, as water consumers extracting water from soils and increasing suction power, which additionally improves shear strength and reduces overall weight acting on the slope. Physical impact is more complicated to assess as many different parameters are involved. In simple terms, the depth of the sliding plane is the crucial factor. Forested areas are mostly effective in preventing shallow seated slides. Slides presenting deep seated sliding planes, the effect of vegetation fall off (Moser, 1980). In Fig. 8 Ziemer (1981a) shows a decrease in relative root reinforcement after deforestation by decaying roots within 10 years to about 20%. Upcoming new trees, if planted, regain 20% of relative root reinforcement in the same time. A significant trough in root reinforcement within this time span of nearly 10 years makes a slope vulnerable for mass movements. Sanktjohanser (1964) showed by comparison of three forest operating modes, that complete deforestation leads to a “critical phase” of reduced slope stability lasting for 20 years. In Fig. 9 a diagram by Ziemer (1981 b) shows the factor of safety versus time after timber harvest. The most important fact is that the slope would not fail because of either changes in seasonal pore water pressure or loss of root reinforcement alone, but when both factors are considered together, the loss of root strength following deforestation lowers the factor of safety to a level where a moderate rain storm and associated rise in pore water pressure can result in slope failure – even though root reinforcement is past the minimum and is increasing (Ziemer, 1981 b).

Complete deforestation as a mitigation measure (“weight release”) for slopes being prone to sliding is common in alpine regions. Beinsteiner (1981) quantified the relationship between weight of trees, pore water and soil weight (see Table 5).

The weight for the forest stand ranges between 2 and 8 per cent of the total weight for one hectare of forest and 0.25 – 1 m soil thickness. Taking this into account, deforestation as a mitigation measure for mass movements should be carefully scrutinised and numerical analyses should be carried out for every endangered slope before logging.

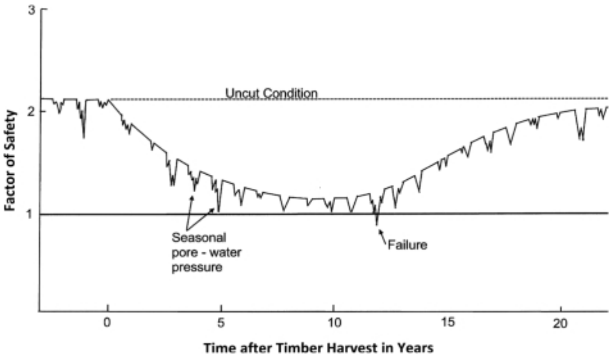

Figure 9: Factor of safety versus time after timber harvest: in a critical phase of 20 years after deforestation the slope is vulnerable to mass movements by seasonal induced pore water pressure changes (redrawn from Ziemer, 1981 b).

6. Conclusions

We draw the following conclusions on how vegetation cover does influence slope stability and the benefit of complete deforestation as a mitigation measure for slopes prone to sliding:

(1) Vegetation does have physical impact on slopes. Tree weight as a negative impact may be neglected in most cases. Root cohesion has a positive impact by increasing cohesion and anchoring. However, the significance on the factor of safety is in the 2nd to 3rd decimal place in typical examples. Only for very steep slopes the factor of safety could change in the first decimal place.

(2) The shallower the location of the sliding plane, the bigger the impact of vegetation displays. Note, that the location of the sliding plane is not apriori given, exept in cases with exceptionally weak layers.

(3) Vegetation does also influence slopes hydrologically. This impact is mostly positive. Erosion is diminished, water is blocked in treetops, pore pressure is reduced and suction is increased.

(4) In the long term, fading of root cohesion after logging has a negative impact on slope stability. A significant trough of slope stability lasting for 10 – 20 years evolves. This time of weakness together with other, seasonal changing factors like suction, pore water pressure or water table fluctuations may lead to landslides.

(5) There may be cases deforestation of landslide affected areas is inevitable i.e. if a monitoring program has to be installed or trees may cause hazard by blocking waterways.

(6) Therefore, deforestation as a mitigation measure for a landslide affected area must be investigated very carefully in

Parameters:	deep soil developed (1m):	%	shallow soil developed (0,25m):	%
Weight of soil:	18.000 - 22.000 t	85	4.500 - 5.500 t	79
Pore water (field capacity saturated):	2.100 - 4.200 t	13	525 - 1.050 t	13
Forest stand (trees):	205 - 820 t	**2**	205 - 820 t	**8**
TOTAL:	20.305 - 27.020 t	100	5.230 - 7.370 t	100

Table 5: Quantification of soil, water and tree weights for 1 hectare (Beinsteiner, 1981).

advance and performed only with exact knowledge of all relevant local characteristics.

ACKNOWLEDGEMENTS

This work was funded by the Center for Natural Hazard Management – GmbH, Grabenweg 3, Innsbruck. Thanks to Markus Wallner (County Forest Department Tyrol) and Christian Zangerl (alps) for drawing our attention to the topic. Thanks to all authors for a very good cooperation. Thanks to Kirsty Stone for correcting English spelling and to Florian Weiler giving me shelter at Washington D.C. where this paper has been written partially.

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Received: 29. May 2009
Accepted: 2. November 2009

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