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SlideforNET

User Manual v0.1

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1 Introduction

SlideforNET is a web application designed for field assessment of rainfall-induced shallow landslide probability in vegetated slopes. Specifically, this tool is designed to quickly quantify the stabilizing effects of different types of vegetation through the basal and lateral root reinforcement. The web application allows the user to enter information about the slope characteristics, the soil properties, and the vegetation cover, and obtain relevant information about the slope stability, the state of the forest stand, and other useful detailed information. Default values are provided for all properties when certain information is not readily available to the user in the field. SlideforNET is particularly well suited to applications such as the evaluation of silvicultural interventions and the assessment of bio-engineering measures.

The main features of SlideforNET that distinguishes it from other available applications are:

- Implementation of a unique large dataset of root reinforcement for several tree species from field measurements of root distribution and root pullout tests;
- Consideration of a realistic force balance calculation for limit equilibrium conditions that includes passive earth pressure forces, lateral root reinforcement in both tension and compression, and basal root reinforcement, where these forces are active at different timings of the slope failure process;
- Implementation of two models for the quantification of the probability of landslide failure: (i) a probabilistic (random) model for soil properties and (ii) a deterministic model with characteristic soil properties and partial safety factors for both soils and root reinforcement.

The random and deterministic models are available to give both foresters and engineers useful information about the stability of a slope. In the random model, values of soil thickness and soil properties such as cohesion, friction angle, and soil dry density are randomly generated to take into account the variability of these properties on a slope. In the deterministic model, used more for engineering applications, design values of soil properties are calculated based on characteristic values and partial safety factors, and a partial safety factor is also used for root reinforcement calculations.

The SlideforNET web application outputs a number of useful information about the slope in addition to the probability of failure:

- Summary of properties for both the random and deterministic cases;
- Root reinforcement as a function of soil thickness;
- Effect of soil thickness on slope failure;
- Stand state diagram for forest management that includes estimates of canopy cover and tree age when data is available.

2 Features

SlideforNET is a probabilistic model that computes the probability of occurrence of a shallow landslide (simply called landslide from thereon) at a specific location on a slope. To obtain this failure probability, the model generates a large number of hypothetical landslides with variable properties to take into the account uncertainties in landslide area, and in soil and vegetation characteristics. The probability of failure of these hypothetical landslides is then the ratio of failed landslides (factor of safety less than 1) to the total number of hypothetical landslides. Landslide failure is based on the factor of safety being less than one where the factor of safety is the ratio of resistive forces to driving forces. In the calculation of the factor of safety, the model includes the effects of hydrology and root reinforcement. Calculation of factor of safety in SlideforNET is based on a description of

- the slope angle,
- the soil thickness,
- the soil water saturated thickness,
- the soil properties (e.g., cohesion, friction angle),
- the stand characteristics.

Failure probability is calculated by considering an ensemble of landslides on a slope at a given location (i.e. with a fixed slope gradient). Vegetation characteristics, slope angle, soil thickness, soil properties, and water-saturated soil thickness are quantities required to compute the limit-equilibrium force balance to obtain the factor of safety (FOS). The water-saturated soil thickness is used as a single-parameter hydrological model to describe the available water in the soil column from which water pressure at the failure surface (soil thickness) can be calculated

The model calculates failure probability for both a vegetated and a non-vegetated slope to show the effects of vegetation on slope stability. Vegetation is assumed to consist of a number of tree species, each having a defined tree density (trees per hectare) and diameter at breast height (DBH). Each species has its own root reinforcement characteristics that has been obtained from detailed measurements of root distribution and root pullout tests and calibrated to the model of [8]. The user can choose any combination of tree species among the ten species available:

- Ailanthus altissima (Tree of heaven)
- Betula pendula (Birch)
- Castanea sativa M. (Chestnut)
- Fagus silvatica (Beech)
- Picea abies (Spruce)
- Pinus radiata (Radiata pine)

- Pinus sylvestris (Scots pine)
- Populus nigra (Black poplar)
- Quercus pubescens (Pubescent oak)
- Trachycarpus Fortunei (Chinese windmill palm)

Calculation of tree age and canopy cover is not available for all species.

3 General framework

SlideforNET calculates the factor of safety (FOS) of a large number of hypothetical landslides at a given location on a slope to determine the probability of failure as a function of the landslide area.

Two models, random and deterministic, are used to compute the FOS. The random model assumes random values of soil properties (e.g., cohesion, friction angle) while the deterministic model uses characteristic values for soil properties and partial safety factors to obtain design values used in the calculation of the FOS.

The FOS is calculated from the ratio of resistive to driving forces. Shallow landslide triggering is characterized by differential deformation that indicates localized activation of forces in tension, compression, and shear in the soil at different moment during the failure process [2]. Maximum root reinforcement in tension does not occur at the same time as maximum compressive forces at the toe of the landslide. Based on these observations, we compute the resistive forces for two cases: (1) when root reinforcement in tension is at a maximum; (2) when compressive forces are at a maximum. The FOS is then calculated using the maximum of either (1) or (2).

Calculation of root reinforcement is at the heart of SlideforNET. The model uses a unique data set of root density and pullout tests for several tree species obtained from field measurements. Data are compiled to obtain the maximum root reinforcement as a function of tree DBH and distance from the tree trunk [8]. The distance from the tree trunk is directly related to the tree stand density and the arrangement of trees on the slope, here assumed to be on a triangular array.

The calculation process of SlideforNET is as follows:

1. Generate landslide geometry from random area distribution
2. Generate soil properties, either random or deterministic
3. Calculate water pressure from soil water-saturated thickness
4. Compute water content and other properties to estimate resistive and driving forces
5. Compute FOS without vegetation
6. Calculate root reinforcement
7. Compute FOS with vegetation
8. Compute failure probability

The details of the calculations are described in Section 9.

4 Installation instructions

SlideforNET is a progressive web application (Progressive Web Apps! or PWA for short, see `https://web.dev/learn/pwa/`) that can be accessed via any web browser on a computer, a tablet, or a smart phone, by typing this address in the address bar:

`https://slidefornet.cosci-llc.com`.

At the time of publication of this User Manual, the version of SlideforNET available is version 0.1. Reloading the web page in your browser may be necessary to obtain the latest version of SlideforNET.

PWA can be used directly in the web browser or installed on your device. Installation instructions may depend on your device and your operating system, as well as the browser being used. Detailed instructions for different platforms can be found on `https://web.dev/learn/pwa/installation/`. Instructions for Android and iOS and iPadOS are summarized below.

4.1 Android installation

On Android devices, installation prompt for PWA differs by device and browser. On the Google Chrome browser:

1. Open the page of the SlideforNET PWA
2. Click on the three vertical dots in the upper right of the page
3. Select **Install**.

4.2 iOS and iPadOS installation

On iOS and iPadOS, installation of the PWA can only be done with the Safari browser. Other browsers available in the App Store, such as Google Chrome, Firefox, Opera, or Microsoft Edge, cannot install a PWA on the home screen.

1. Open the Share menu, available at the bottom or top of the browser
2. Click **Add to Home Screen**
3. Confirm the name of the application; the name is user-editable
4. Click **Add**. On iOS and iPadOS, bookmarks to websites and PWAs look the same on the home screen.

5 Description of the user interface

The user interface (UI) is the way the user interacts with the application by selecting values of parameters and choices for the tree species in the stand. Figures 1 and 2 show the user interface on a laptop computer and an Android phone, respectively, using Google Chrome.

At the bottom of the application web page, the button **Calculate** launches the simulations (see Figure 1).

The UI has 6 tabs that are accessible at the top of the application: one tab for input and 7 tabs for output. The input tab consists of three parts (or windows):

1. Slope Characteristics
2. Soil Properties
3. Forest Characteristics

The 7 output tabs are:

1. Landslide Probability
2. Tabulated Results
3. Basal Root Reinforcement
4. Landslide Thickness
5. Stand State Diagram
6. Download
7. User Manual

The info button in the upper right corner of the web application displays SlideforNET version number, copyright information, and license agreement. Questions about the software can be sent to `software@cosci-llc.com`.

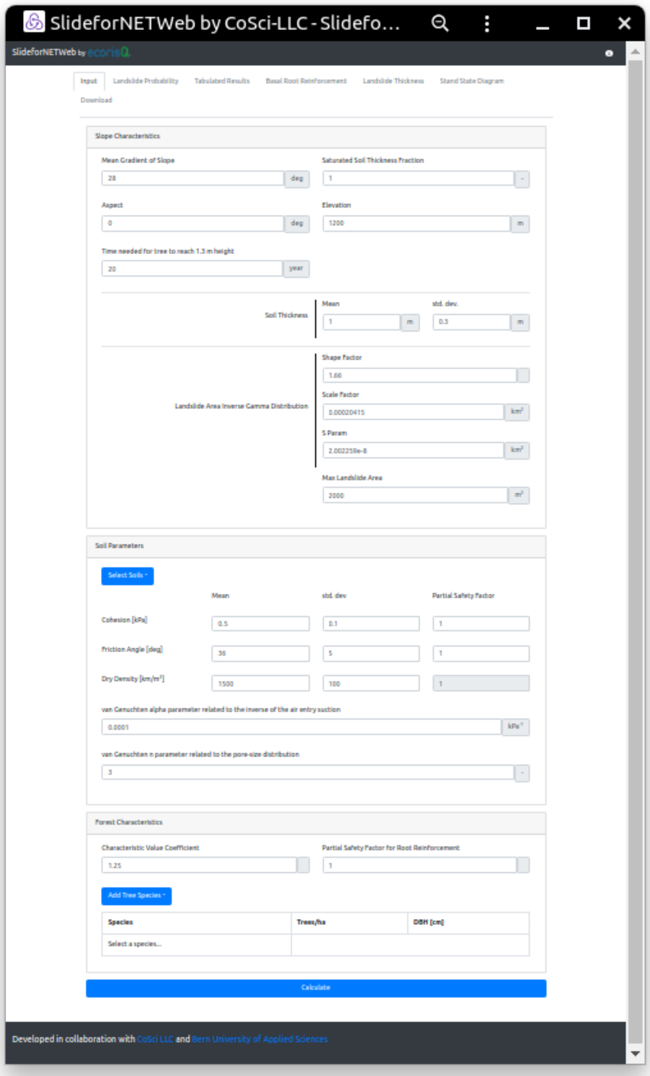


Figure 1: User interface on a 15-inch laptop using Google Chrome

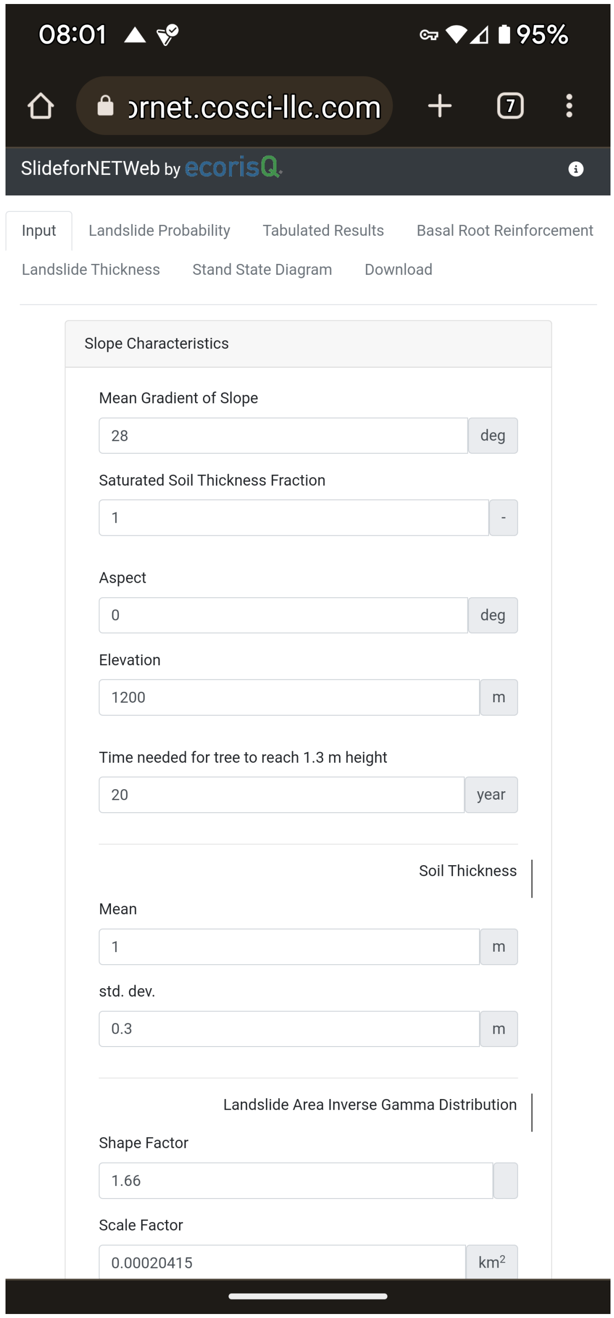


Figure 2: Part of the user interface on an Android phone using Google Chrome

6 Model inputs

6.1 Slope Characteristics

The first window at the top of the UI is the **Slope Characteristics** (Figure 3) and is used to enter values of parameters that describe the slope. Table 1 describes the different parameters available to the user and their default values.

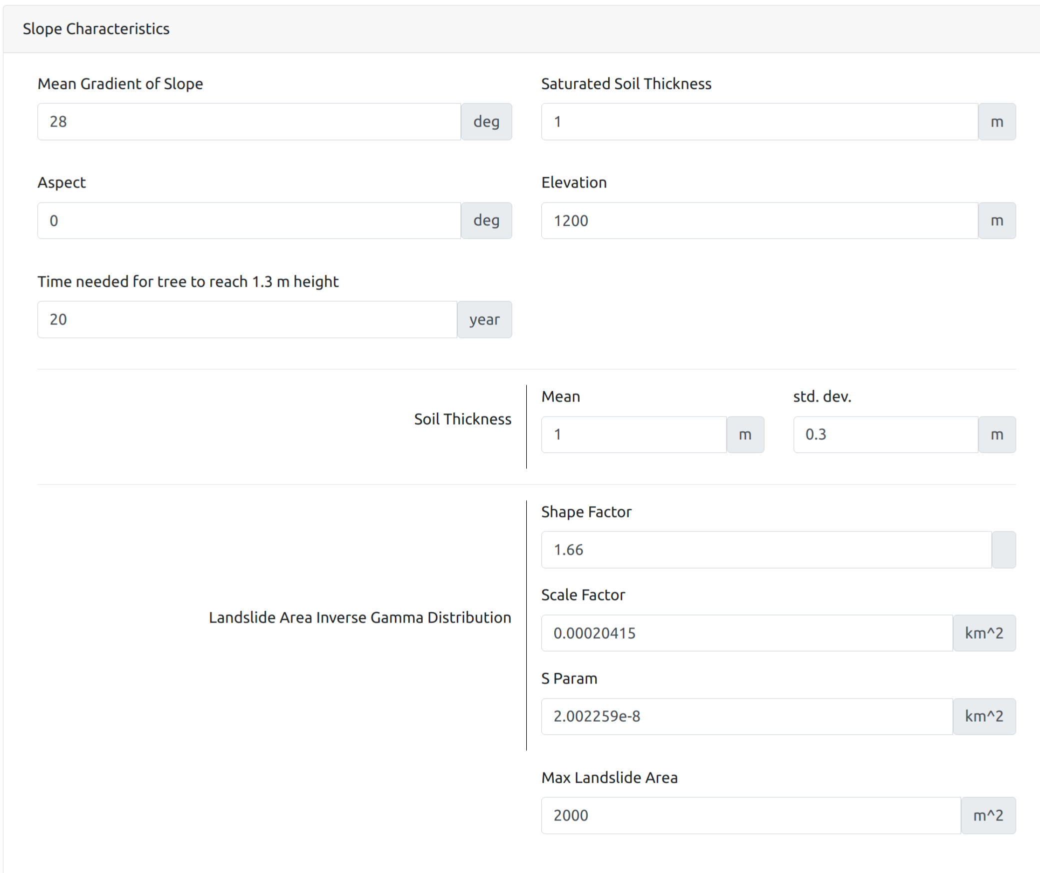


Figure 3: Slope characteristic window with default values

Characteristic	Description	Default value	Unit
Mean Gradient of Slope		28	degree
Saturated Soil Thickness Fraction	Fraction of the soil thickness measured vertically that is water saturated	1	-
Aspect	Orientation of slope with respect to north (0 deg). East is 90 deg, south is 180 deg, west is 270 deg.	0	degree
Elevation	Elevation of the slope	1200	meter
Time needed for trees to reach 1.3 m	This is used to compute the age of the stand. Identical for all tree species	20	years
Soil Thickness	The soil thickness is measured vertically from the soil surface. Mean and standard deviation are used to obtain random values of soil thickness for each of the landslides (both Random and Deterministic landslides)		
Mean	Average value of soil thickness	1	meter
Std. Dev.	Standard deviation value of soil thickness. Use 0 for a constant value of soil thickness	0.3	meter
Landslide Area Inverse Gamma Distribution	Parameters used to describe the area distribution of landslides in a particular geographical area using the three-parameter inverse gamma distribution described in [6], Equation (3). See also Equation (12) in this user manual		
Shape Factor	ρ, Equation(12)	1.66	-
Scale Factor	a, Equation(12)	2.0415E-04	km^2
S Param	S, Equation(12)	2.002259E-08	km^2
Max Landslide Area	This option prevents sampling landslides with too large areas	2000	m^2

Table 1: Variables describing the slope characteristics

6.2 Soil Parameters

In the **Soil Parameters** window (Figure 4), the user can select a soil type under the drop-down menu **Select Soils**. The list of soils available is given in Table 2 below with the default values of cohesion (mean and standard deviation), friction angle (mean and standard deviation), dry density (mean and standard deviation), and van Genuchten parameters (the air-entry pressure, α, and the exponent, n). Once a soil has been selected, the user can modify in the table the values of any of the parameters. The value of cohesion should be the value of soil cohesion without any root material. In addition, for Deterministic landslides, the user can enter a partial safety factor for the cohesion and the friction angle (default value of 1). This option is not available for the dry density (grey cell).

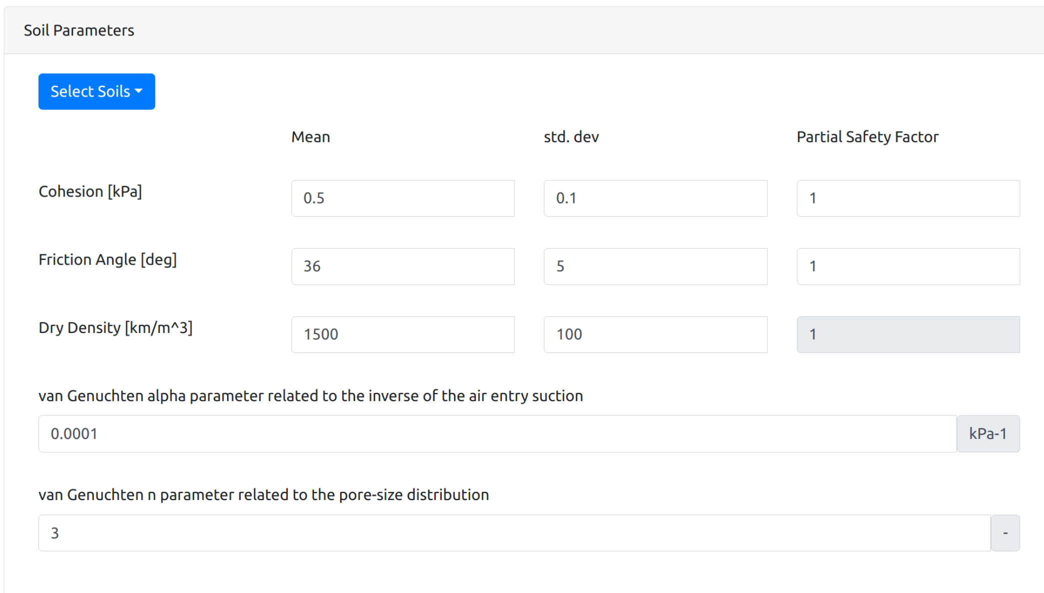


Figure 4: Soil parameter window with default values

		Cohesion (kPa)		Friction angle (deg)		Dry density (kg m^{-3})		van Genuchten parameters	
Name	Code	Mean	Std dev	Mean	Std dev	Mean	Std dev	α (kPa^{-1})	n
Clay of high plasticity, fat clay	CH	25	5	22	5	1100	200	0.00051	2.6
Clay of low plasticity, lean clay	CL	25	5	22	5	1100	200	0.00051	2.6
Clayey gravel	GC	0.5	0.05	34	2	1680	100	0.00051	2.6
Silty gravel	GM	0.5	0.05	36	5	1720	100	0.00051	2.6
Silty gravel	GM-GL	0.5	0.05	36	5	1720	100	0.00051	2.6
Poorly graded gravel	GP	0.5	0.05	38	4	1580	100	0.0001	3.3
Well-graded gravel, fine to coarse gravel	GW	0.5	0.05	40	2	1800	100	0.0001	3.3
Silt of high plasticity, elastic silt	MH	5	3	24	3	900	200	0.0001	3.3
Silt	ML	0.5	0.25	33	2	1430	100	0.00013	1.46
Organic clay, organic slit	OH	10	5	22	5	900	200	0.0001	3
Organic silt, organic clay	OL	10	5	25	2	1130	100	0.0001	3
Clayey sand	SC	0.5	0.25	32	1	1500	100	0.0002	2
Silty sand	SM	0.5	0.25	34	1	1530	100	0.00017	2.2
Poorly graded sand	SP	0.5	0.05	36	1	1470	50	0.00051	1.7
Well graded sand, fine to coarse sand	SW	0.5	0.05	38	1	1540	50	0.00167	2.35

Table 2: Default values of soil parameters

6.3 Forest Characteristics

In the last input window, **Forest Characteristics** (Figure 5), the user can select species that are present on the slope. Ten species are available from the database (see Section 2, Features). All ten species have root reinforcement data but not all species have canopy cover and age data such that the Stand State Diagram (described below in Section 8.5) will not show these information.

The user can add a tree species using the drop-down menu **Add Tree Species** and then enter the average tree density in trees/ha and the DBH in cm. Default values are 100 and 10, respectively.

Above the **Add Tree Species**, the user can enter a value for the **Characteristic Value Coefficient** and for the **Partial Safety Factor for Root Reinforcement** for the calculation of root reinforcement for Deterministic landslides. The characteristic and design values for the root reinforcement are calculated as follows:

$$\mathrm{RR}_{\mathrm{char}} = \phi_{\mathrm{RR}}\,\mathrm{RR}, \tag{1}$$

$$\mathrm{RR}_{\mathrm{design}} = \frac{\mathrm{RR}_{\mathrm{char}}}{\gamma_{\mathrm{RR}}}, \tag{2}$$

where RR is the computed value of root reinforcement (whether lateral or basal), $\mathrm{RR}_{\mathrm{char}}$ is the characteristic value of root reinforcement, $\mathrm{RR}_{\mathrm{design}}$ is the design value of root reinforcement, ϕ_{RR} is the characteristic value coefficient, and γ_{RR} is the partial safety factor.

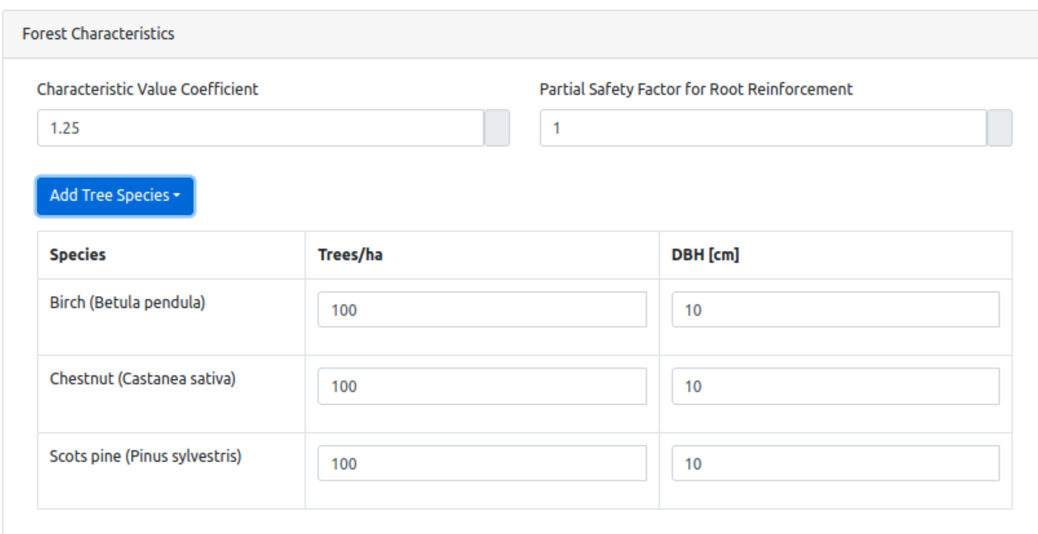


Figure 5: Forest characteristic window with three tree species added.

7 Model outputs

Model outputs are separated under five different tabs. By default, once the SlideforNET calculations are finished, the web application displays the **Landslide Probability** tab. Each of these tabs and their outputs are discussed in the sub-sections below.

7.1 Landslide Probability tab

The landslide probability figure is a bar graph that gives the probability of landslides as a function of landslide area in bins of 100 m^2 for the random and deterministic models and for vegetated and non-vegetated slopes. The user can click on the legend to remove or add specific results to the graph. Below the landslide probability graph are shown tabulated the overall landslide probability for non-vegetated and vegetated cases, as well as the current degree of protection obtained from vegetation. Figure 6 shows an example of this output.

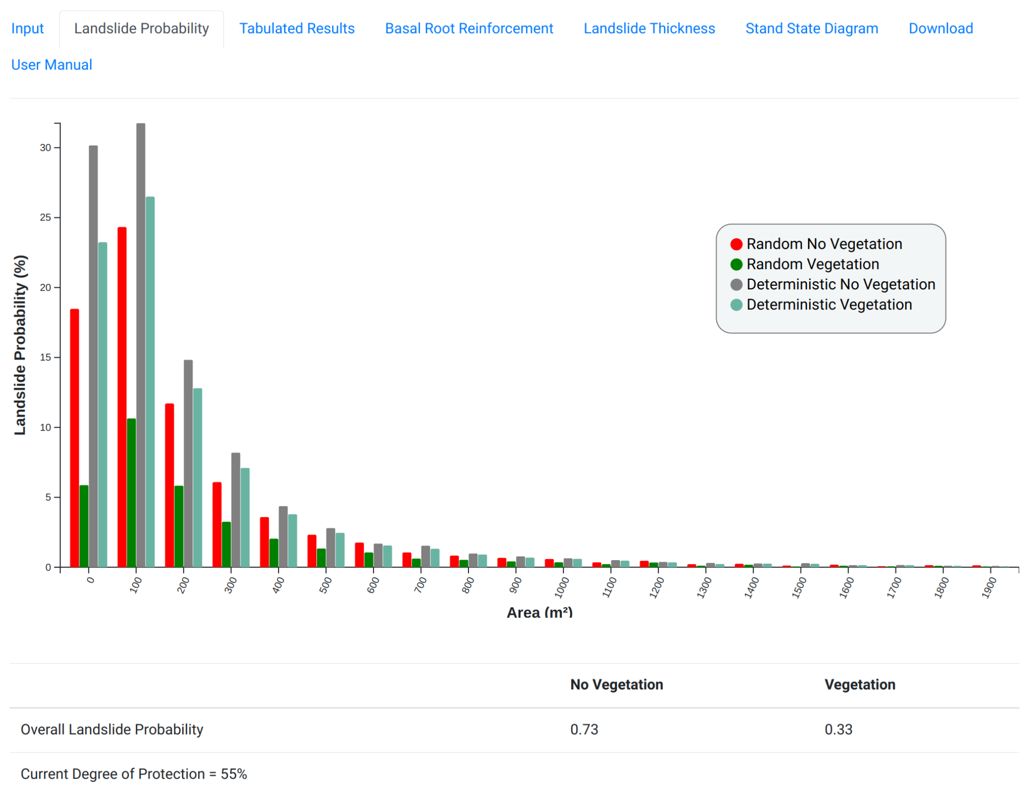


Figure 6: Bar graph of probability for random and deterministic landslides, and for vegetated and non-vegetated slopes with overall landslide probability and current degree of protection

7.2 Tabulated Results tab

Under this tab is a summary of computed values for the simulation for the random and deterministic cases. Figure 7 shows an example of this output.

Input | Landslide Probability | Tabulated Results | Basal Root Reinforcement | Landslide Thickness | Stand State Diagram | Download

Tree Stand	**Value**	**Unit**
Density	550.000	trees/ha
Volume	58.676	m^3/ha
Weight of vegetation	0.005	t/m^2
Weight of vegetation in equivalent soil thickness	0.251	cm
Random landslides		
Mean lateral root reinforcement	5.136	kN/m
Mean basal root reinforcement	0.630	kPa
Reliability Index for vegetation	0.178	-
Reliability Index for no vegetation	-0.511	-

Deterministic landslides	**Characteristic Value**	**Design Value**	**Unit**
Cohesion	0.354	0.354	kPa
Friction angle	15.781	15.781	deg
Basal root reinforcement	0.083	0.083	kPa
Lateral root reinforcement	4.315	4.315	kN/m

Figure 7: Example of tabulated results

The reliability index is defined as [10]

$$\beta = \frac{\mu_{\mathrm{FOS}} - 1}{\sigma_{\mathrm{FOS}}}, \tag{3}$$

where μ_{FOS} and σ_{FOS} are the mean value and standard deviation of the FOS, respectively. Here, it is an assessment of the effectiveness of the effects of vegetation on slope stability. According to [10], *the reliability index indicates how many standard deviations separates the mean factor of safety from the critical value of* $\mathrm{FOS} = 1$. Negative values of β are possible indicating that the mean value of the FOS is less than 1.

Also under the same tab is a boxplot of the factor of safety for both vegetated and non-vegetated cases. Figure 8 shows an example.

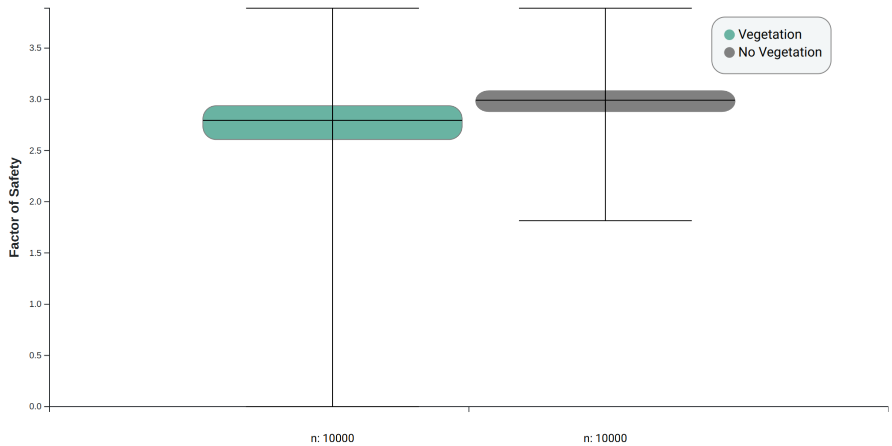


Figure 8: Example of boxplot for factor of safety

7.3 Basal Root Reinforcement tab

This tab shows the basal root reinforcement as a function of soil depth for both the random and deterministic models. The graph indicates how rapidly basal root reinforcement decreases as a function of depth. Figure 9 shows an example of this result.

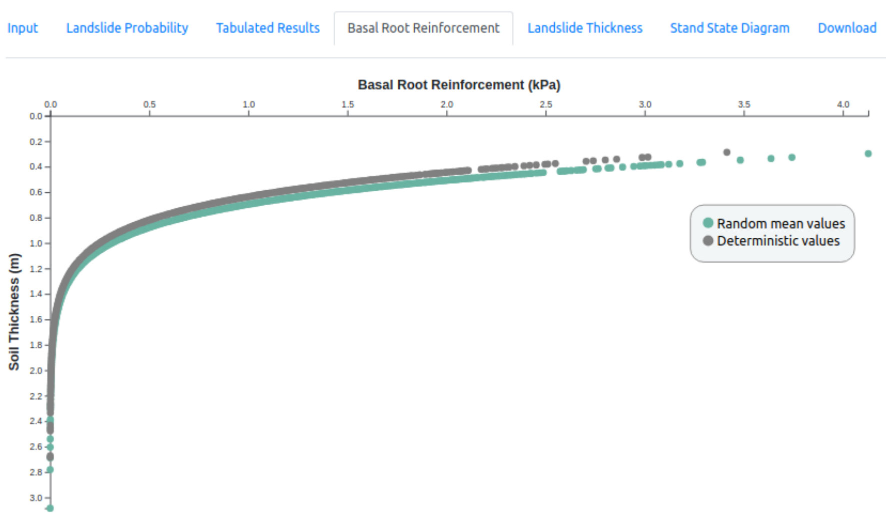


Figure 9: Plot of basal root reinforcement as a function of soil thickness for random and deterministic landslides

7.4 Landslide Thickness tab

This tab shows the statistics of landslide failure for the different cases of vegetation/no vegetation, random/deterministic landslides in the form of box plots. For each case, the number of failed and stable landslides is indicated (total is always 10,000 landslides).

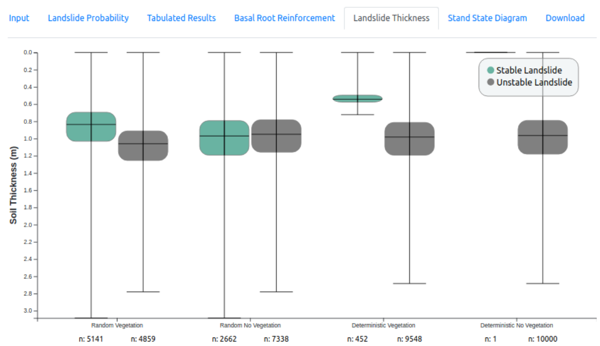


Figure 10: Box plots of basal root reinforcement as a function of soil thickness for random and deterministic landslides

7.5 Stand State Diagram tab

The tab shows a stand state diagram (see Figure 11 below), with lines of constant root reinforcement and lines of constant canopy cover (when available) for a range of DBH and tree stand density. On the upper y-axis, average age of the stand is also indicated when data is available for the species that have been selected. The purple cross indicates the present state of the stand in terms of average DBH and stand density. The average DBH is calculated using values entered in the table and weighted by the density of the species. Also, the mean horizontal distance between trees and the mean distance between trees parallel to slope are shown on two separated y-axes on the right side of the diagram.

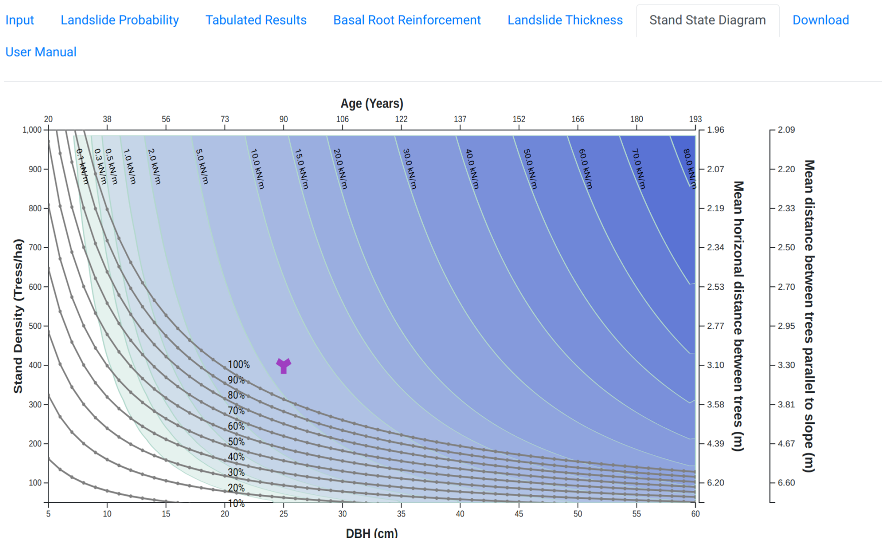


Figure 11: Stand state diagram

7.6 Download

This tab allows the user to download input data and output results to its own device.

7.7 User Manual

This tab gives access to the User Manual as a PDF (Portable Document Format).

8 Case studies

Protection forests are an important element in the integrated risk management for gravitational natural hazards. In the practical implementation of this concept, three main types of applications can be identified:

- Evaluate if present forest condition can be considered in the hazard assessment (see PROTECT-Praxis in Switzerland as an example): **Reliability of protection forests**.
- Maintenance of the protective effects of forests (see NaiS in Switzerland as an example): **Sustainable silvicultural measures**.
- Planification of new eco- or bio-engineering measures (see STEC in New Zealand as an example): **Quantitative eco- and bio-engineering**.

SlideforNET can be used for all three types of applications but only at the spatial scale of a forest stand or a slope. For a more detailed spatial resolution analysis that uses similar model calculations, the model SlideforMAP is better suited.

The case studies presented below show examples of applications of SlideforNET with different degrees of complexity.

8.1 Reliability of protection forests: Hazard mapping of shallow landslides above a village: example of Diemtigen (Switzerland)

8.1.1 Objective

During the revision of the hazard maps in the commune of Diemtigen (Switzerland), authorities (cantonal) and experts discussed whether the forest should be considered in the hazard mapping and how much is the reliability and contribution of the forest to slope stability. The central questions are: **how much does the actual forest contribute to slope stability? How reliable is protective effects of forests?**

8.1.2 Description of the study area

The slope above the village is partly used as pasture/meadow, and part of it is a homogeneous forest dominated by beech trees (350 stems/ha with a mean DBH of 40 cm)(*Milio-Fagetum stachyetosum sylvaticae*). The cadaster of events shows that several landslides took place in 2005 (see Figure 12).

From a geological point of view, the area is located in the zone of the Simmen-Decke and is covered with calcareous moraine material. The soil is a brown earth without clay enrichment or hydromorphological

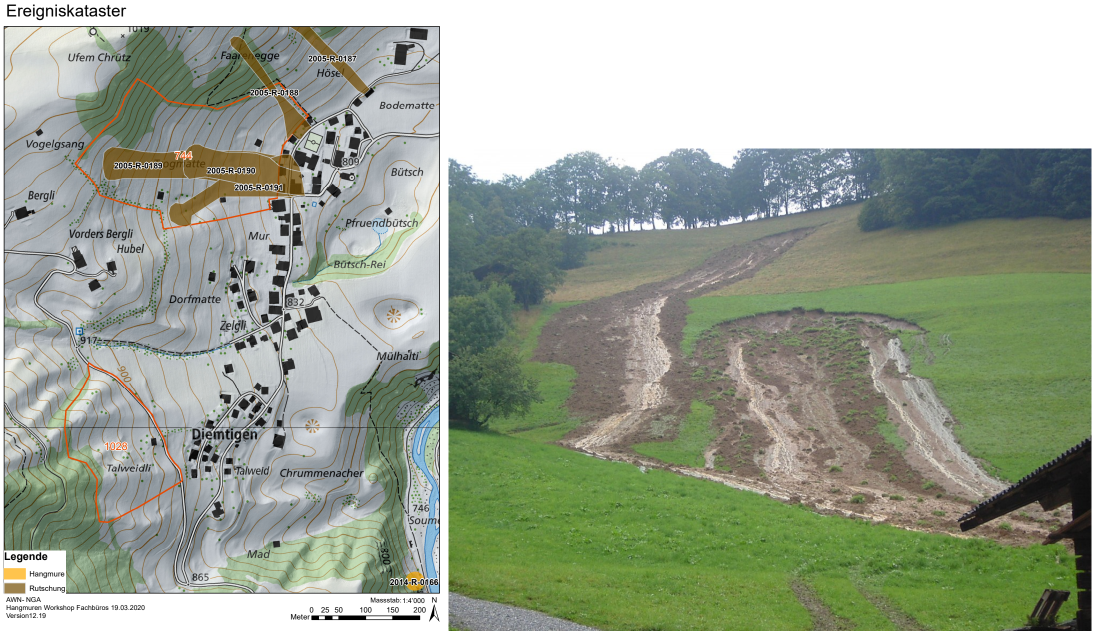


Figure 12: Map of the cadaster of events and a photograph of the landslide event in 2005

characteristics. Browning is caused by chemical alteration of primary minerals (e.g., clay minerals in the sedimentary rocks). The soil material of the B-C horizons is classified as silty gravel with sand (GM) (our sieve analysis showed: 35% gravel, 25% sand, 36% silt, 4% clay).

The silt fraction, with a plasticity index of 11.1, has a low plasticity (ML, yield point WL<50%). The soil mechanical parameters cohesion (c') and friction angle (ϕ') are estimated as $c' = 0$–0.5 kPa and $\phi' = 30$–$32°$.

The one-hour precipitation intensity for a 100-year return period event is about 80 mm/h according to hydrological statistics. The areas contributing to the cumulative lateral runoff in the landslide zone are relatively small (up to maximum of 5000 m^2). However, there are large uncertainties in the assessment of this process in the area due to the hydrogeological processes in the rock layer. The anthropogenic influence on the water runoff on the slope due to drainage and unrecorded water drains and terrain adjustments, is significant. It can be assumed that in the worst case the soil profile is fully saturated.

The estimated landslide areas are 200 to 900 m^2 with a soil thickness between 0.5 and 1.5 m. These values were obtained in the field and based on the description of past events.

8.1.3 Inputs for SlideforNET

In a first step, the inputs of slope characteristics are needed such as mean inclination gradient (deg), and soil thickness (m) (Figure 13). The values of Aspect (deg), Elevation (m), "Time to 1.3 m" (years) are only needed to estimate the stand age in the Stand State diagram. The saturated soil thickness can be set assuming different scenarios of triggering rainfall. As worst case scenario, this parameter can be kept equal to 1. If needed, a detailed estimation of this parameter can be performed considering the soil permeability, the slope inclination, the rainfall intensity, the hydrological contributing catchment area, and a mean runoff coefficient for the catchment area. As an alternative, available water runoff maps can be consulted (Figure 14).

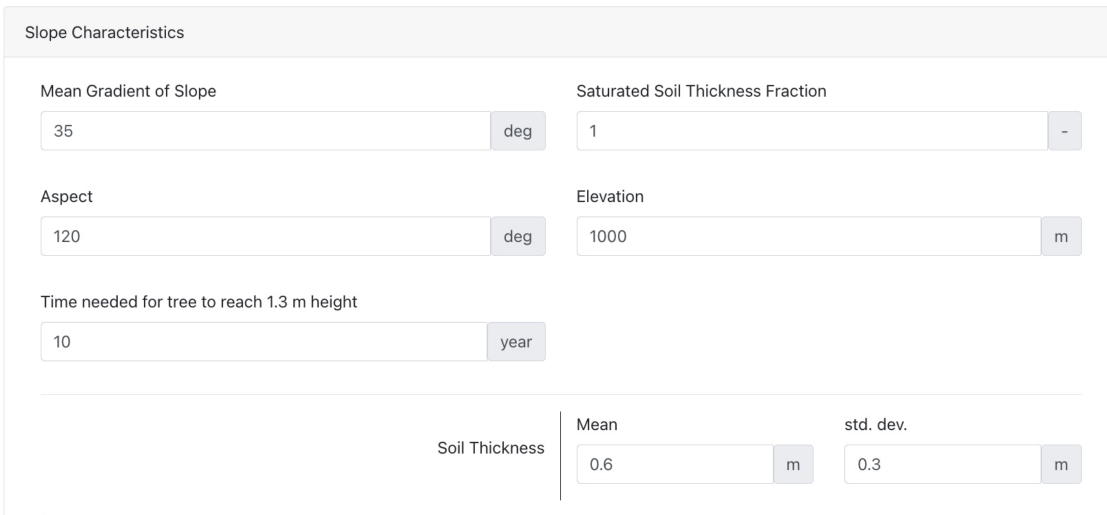


Figure 13: Input parameters for the slope.

The values of the soil parameters can be estimated based on the type of soil (see drop down list). It is important that the chosen properties are representative of the soil along the potential shear plane of the landslide. Once the soil type is choosen, single parameter values can be modifies if needed (Figure 15).

The structure of the forest stand is quantified in a simplified way. In an heterogeneous forest stand, only the dominant tree species can be considered. The stand density (number of trees per hectare) is estimated considering the horizontal projection of the area. The value of the DBH can be estimated in a conservative way, choosing the lower range of values of the dominant tree species in the stand (Figure 16).

8.1.4 Outputs of SlideforNET

The first tab of the output is the "Landslide Probability". This shows the landslide probability for each class of landslide area, for the conditions with or without vegetation (Figure 17).

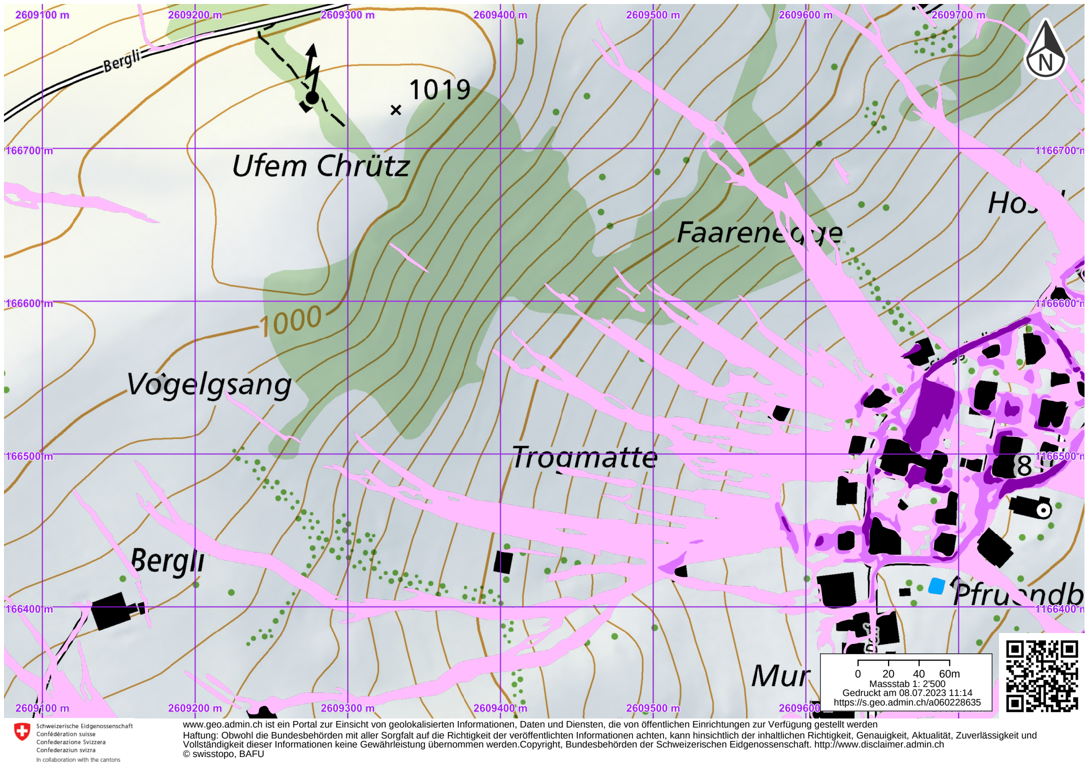


Figure 14: Example of available water runoff map (`https://map.geo.admn.ch`). Pink colors indicate saturated overland flow for a 100-year rainfall event.

The tab named "Tabulated Results" shows the list of parameter values used for the probabilistic (random) and deterministic calculations (Figure 18). For the assessment of protection forest reliability, the random calculations are used. The value of wood volume per hectare is useful to compare the estimation of stand density used as input.

The weight of vegetation in equivalent soil thickness is useful to evaluate the influence of vegetation weight on slope stability compared to the uncertainty in the estimation of the landslide thickness. Generally, this corresponds to only a few centimeters, meaning that vegetation weight has a limited influence on slope stability.

The values of calculated lateral and basal root reinforcement are important to understand the mechanism through which roots contribute to slope stability. In this case both values are quite high. In particular, basal root reinforcement plays a major role under these given conditions. Increasing the soil thickness of the potential landslide would considerably reduce the effect of the basal reinforcement (Basal Root Reinforcement tab, Figure 19).

The output tab "Landslide Thickness" is useful to analyze how the probability of failure is distributed

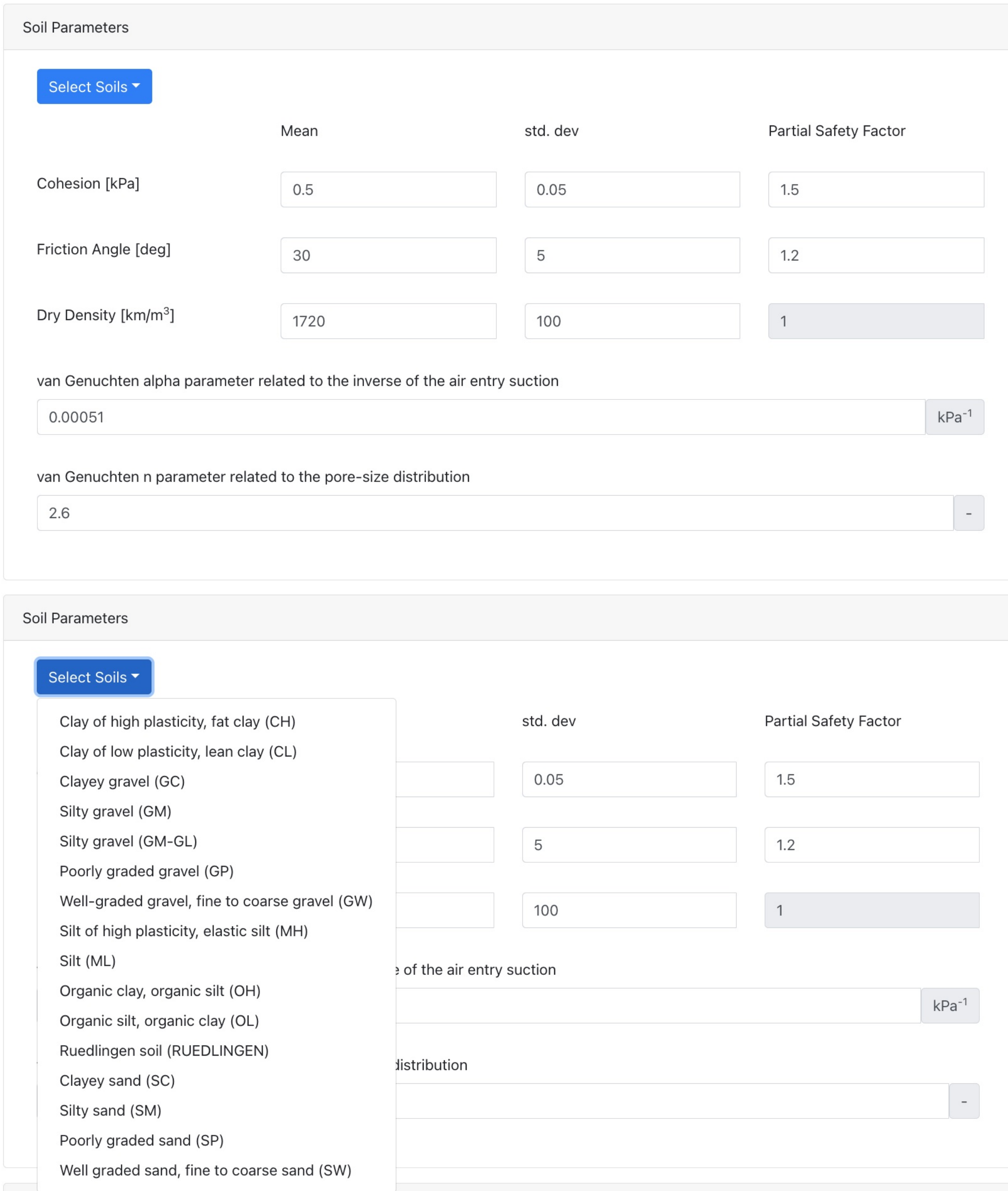


Figure 15: Input parameters for the soil characteristics. As a fist estimation, the drop-down list of soil types can be used (bottom figure).

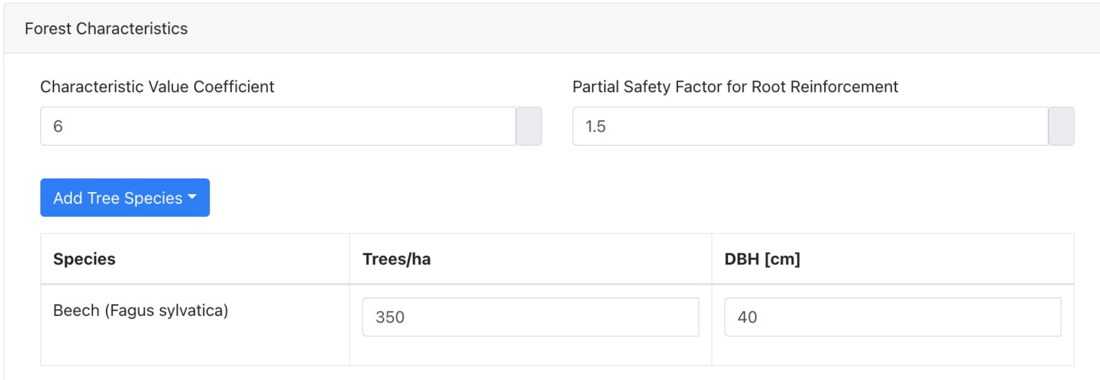


Figure 16: Input parameters for the forest characteristics.

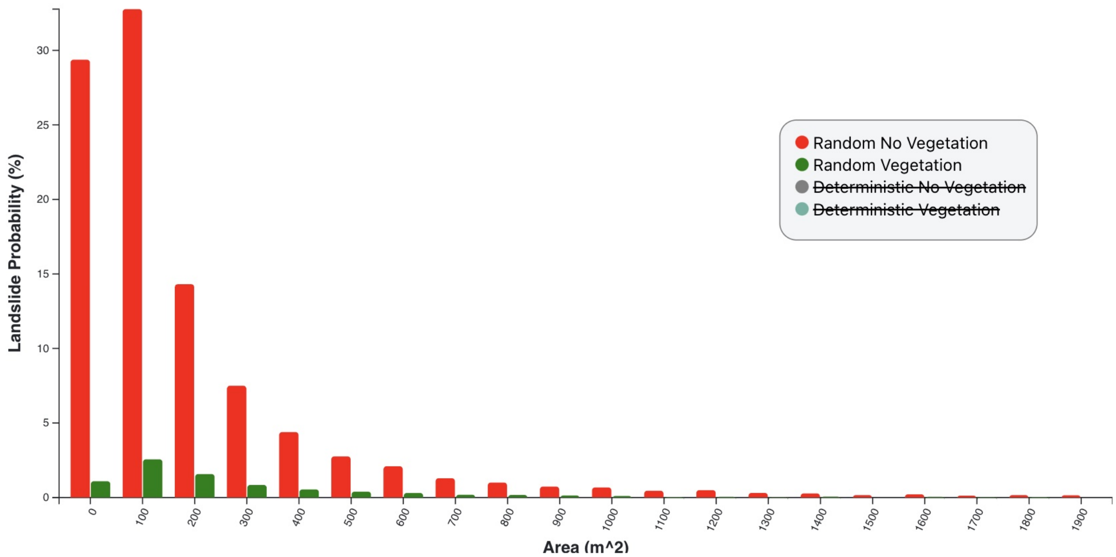


Figure 17: Output values of landslides probability for different classes of landslide areas.

between different random generated landslide thickness. In this case study it is evident that in vegetated condition, the most unstable conditions are given when the landslide thickness is higher than 1 m. This confirm that the basal root reinforcement play a major role in slope stabilization (Figure 20).

The "Stand State Diagram" is an important output to evaluate the sustainable condition of the forest stand. Sustainable protection forests need to fulfill several criteria, of which two are particular importance:

1. Forest stand should be resistant/stable against storms and snow-loads. To fulfill this criteria single trees or groups of trees need to be stable, having long canopy crowns (low barycenter), high

Input | Landslide Probability | Tabulated Results | Basal Root Reinforcement | Landslide Thickness | Stand State Diagram | Download

Tree Stand	Value	Unit
Density	350.000	trees/ha
Volume	280.417	m^3/ha
Weight of vegetation	0.024	t/m^2
Weight of vegetation in equivalent soil thickness	1.122	cm
Random landslides		
Mean lateral root reinforcement	15.879	kN/m
Mean basal root reinforcement	13.825	kPa
Reliability Index for vegetation	0.897	-
Reliability Index for no vegetation	-3.009	-

Figure 18: Output of the values of the main calculated parameters.

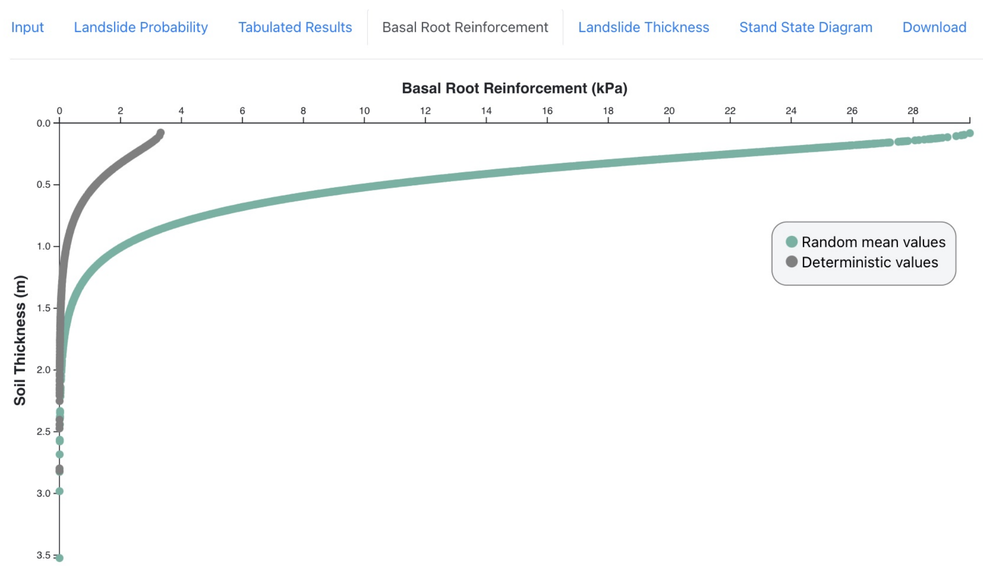


Figure 19: Output values of calculated mean basal root reinforcement as function of soil thickness.

proportion between tree height and DBH (H/D quotient), and a vertical growing stem.

2. Forest stand should be resilient against disturbance. This criteria is fulfill assuring enough tree renovation above the dominating trees of the stand.

Both criteria are usually fulfill mainly through the constant regulation of the canopy cover of the dominating trees. Canopy cover between 50 and 70% allows trees to grow stable (large and long crowns)

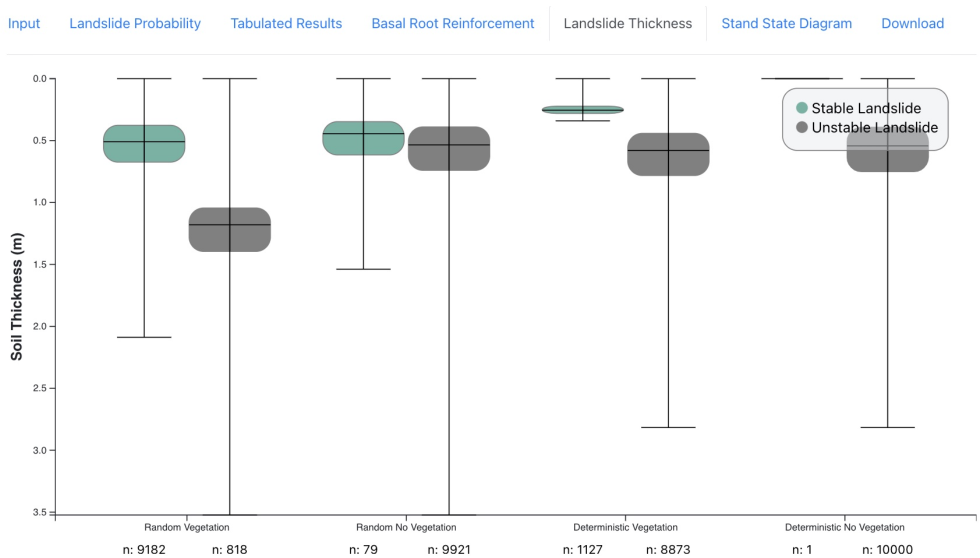


Figure 20: Boxplots of the landslide thickness for different categories (with or without vegetation, stable or unstable).

and to insure enough light for the the growth of young trees.

In the present case study the stand density is much too high. Indeed, no vegetation is growing on the floor (Figure 21).

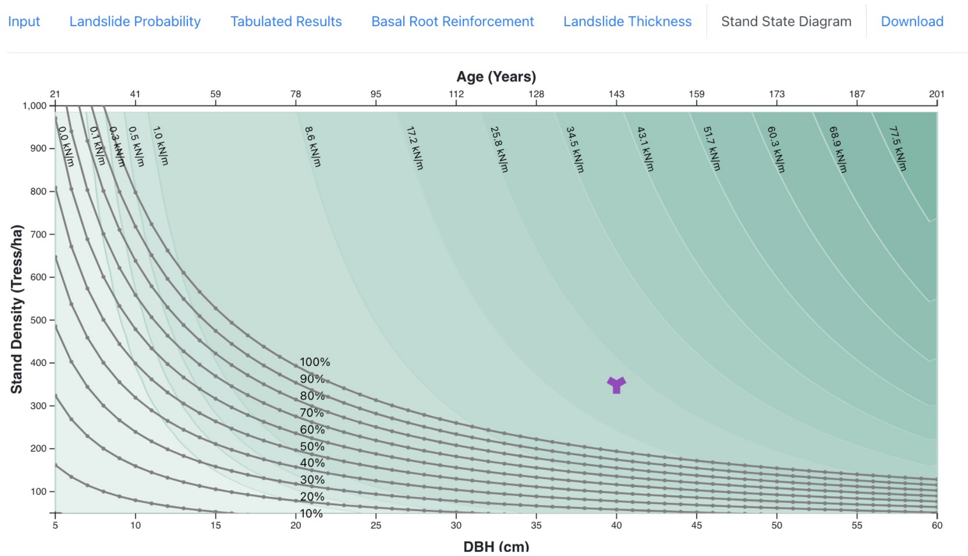
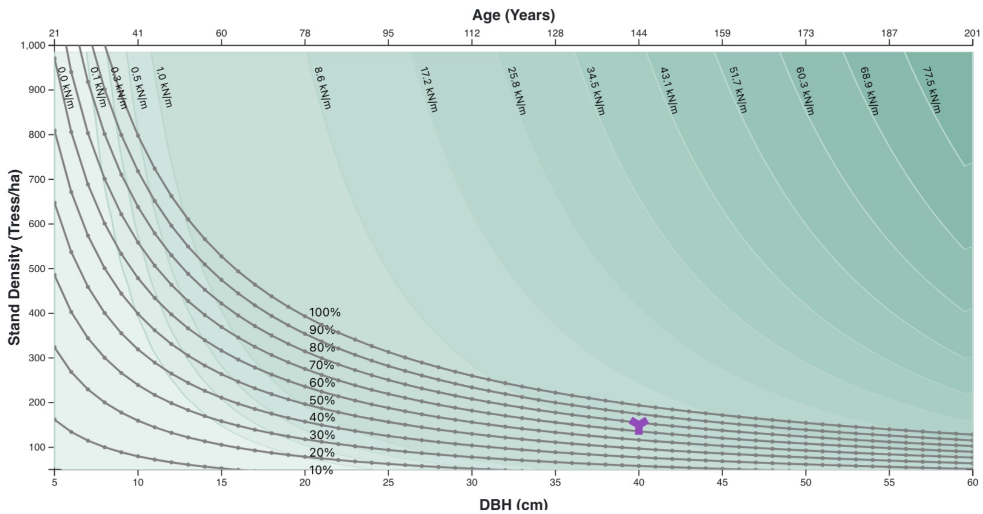


Figure 21: Stand state diagram of the forest stand.

For a long-term evaluation of the protection forest reliability, the stand density needs to be reduced to values corresponding to 70% of the canopy cover (Figure 22 and 23). The type of silvicultural measures needed to reach this defined target is not the aim of discussion in this case study. The objective is to focus on the assessment of the reliability of protection forests in hazard mapping.



Random landslides

Mean lateral root reinforcement	7.513	kN/m
Mean basal root reinforcement	8.620	kPa
Reliability Index for vegetation	0.762	-
Reliability Index for no vegetation	-3.009	-

Figure 22: Stand state diagram and calculated root reinforcement results considering a reduction of stand density to 150 stems per hectare in order to fulfill sustainability criteria of protection forests in the long term.

8.1.5 Interpretation of results and conclusions

The results of SlideforNET shows that:

- **The actual condition of the forest reduce the landslide probability of almost of 92% (99% without vegetation versus 8% with vegetation), meaning an important protective effect of vegetation. Even in a stand with 150 stems per hectare the protective effect of the forest is high.**
- **The reliability index with vegetation is almost 0.9 (and 0.76 in the calculation with reduced stand density). This means that the actual condition of the forest and a long-term scenario**

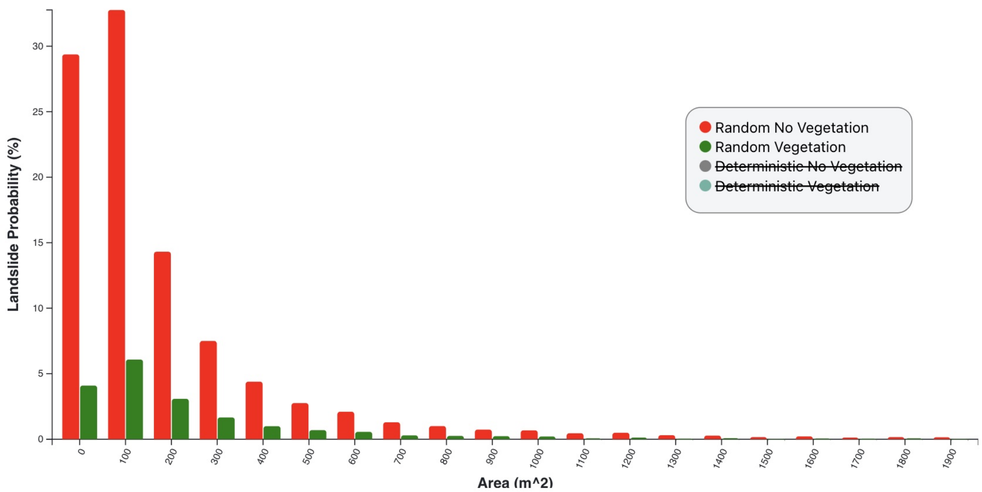


Figure 23: Landslide probability considering a reduction of stand density to 150 stems per hectare in order to fulfill sustainability criteria of protection forests in the long term.

guaranties an increment of the factor of safety above 1, almost as much as the equivalent of its standard deviation. In general the larger the reliability index is, the smaller is the probability of failure. (REMARK: The distribution of the random calculated factors of safety in NOT necessary normal distributed!). In conclusion, the reliability index lower then 2, in general indicates that a small change in mean value of the input parameters may correspond to a large increase in failure probability.

8.2 Sustainable management of protection forests: Management of protection forests along power lines: example of Pradiron (Switzerland)

8.2.1 Objective

In some situations protection forest management need to consider conflicts due to risks related to the presence of trees. For example, large trees on slopes along roads may fall and hit vehicles, or trees along streams may be mobilized during flood as large woody debris and increase the intensity of floods. In this case study we consider an analog situation along power lines. In this case, trees stabilize the steep slopes along power lines, but at the same time trees are not allowed to growth too much in order to avoid the contact with the cables. Currently, clear-cut is the common adopted practice, but it can lead to high frequency of landslides that damage the infrastructures (Figure 24) or increase the risk due to other type of damages. The main objective of the silvicultural management in this case is to assess the minimum needed protective effect of the forest in order to stabilize slopes, and at the some time keep the tree high as low as possible, optimizing the costs of interventions.

Figure 24: Landslide occurred after clear-cut under the power line in Pradiron (GR).

8.2.2 Inputs

The values of the input parameters where estimated in the field, based on the observation of recent shallow landslides occurred few months after clear-cutting. Figure 25 shows the input parameters for SlideforNET.

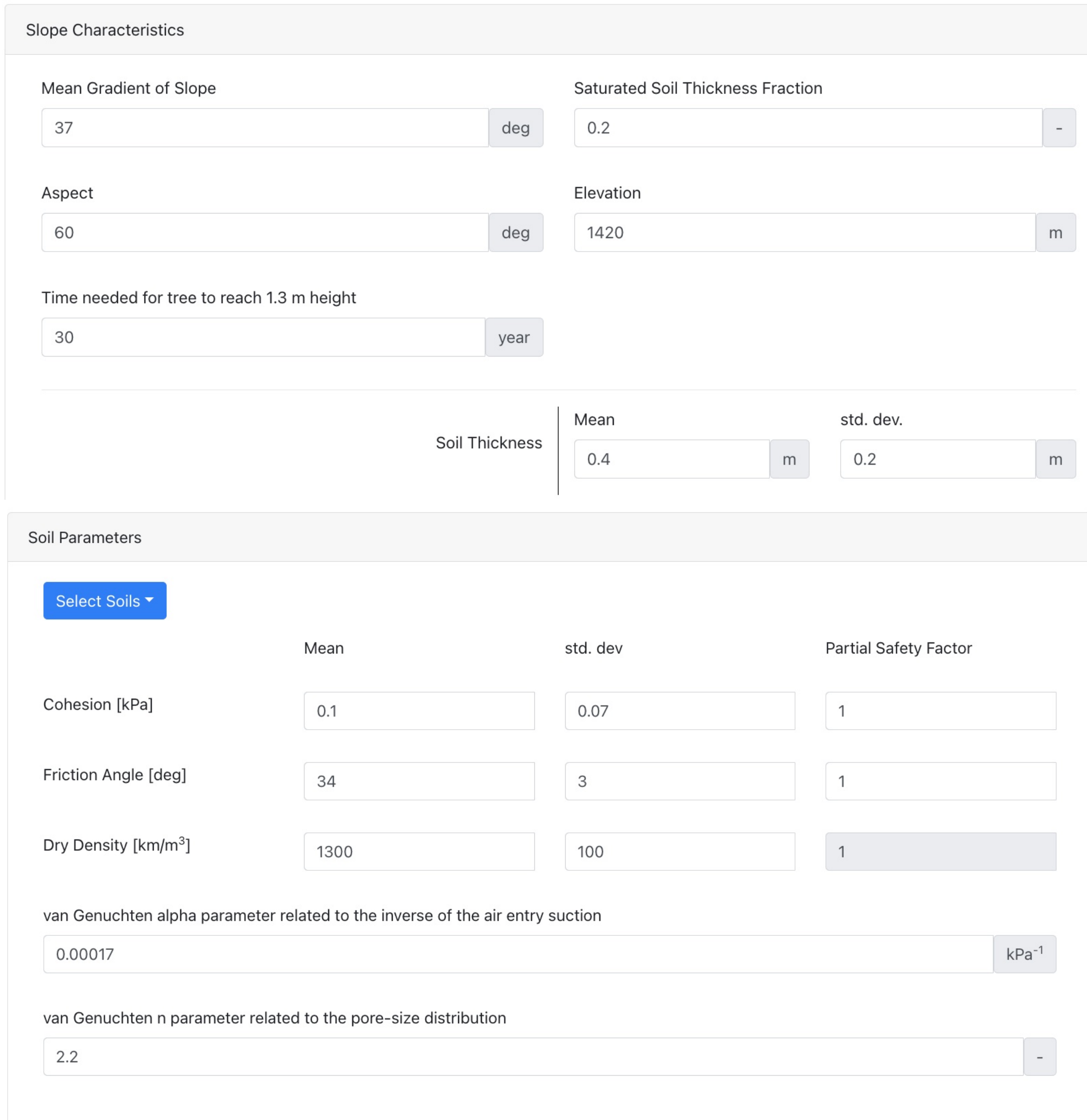


Figure 25: Inputs for the calculations in Pradiron.

8.2.3 Outputs

The results of SlideforNET for the condition of the forest before the clear-cut (stand density = 800 trees per hectare, mean DBH = 30 cm) (Figure 26) indicate that the spruce forest has a significant influence on slope stability (Figure 27). Indeed, the condition of the forest stand are not sustainable, and silvicultural interventions are needed.

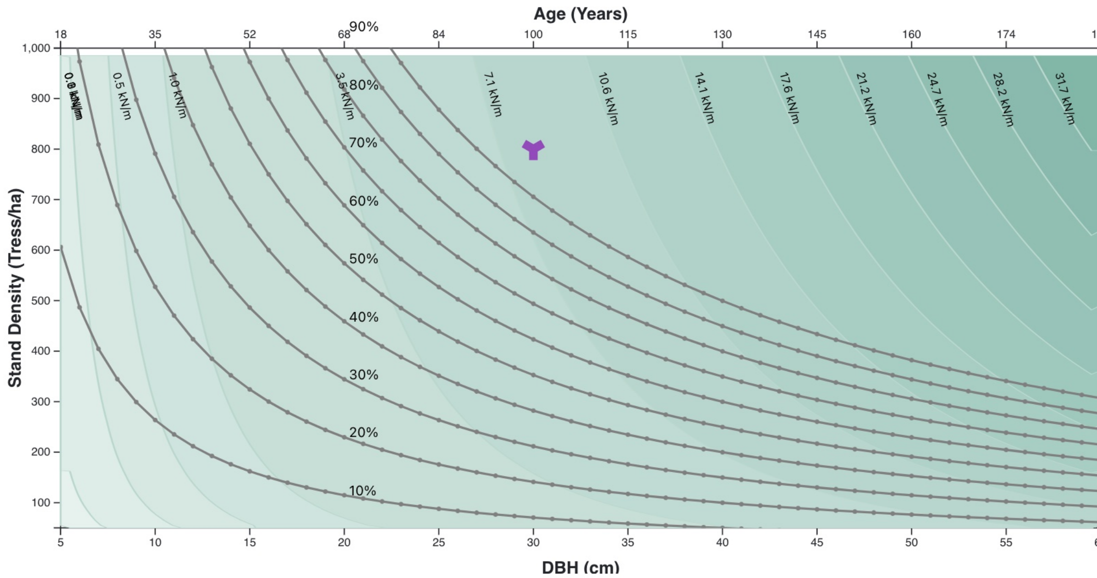


Figure 26: Stand state diagram of the forest before clear-cutting in Pradiron.

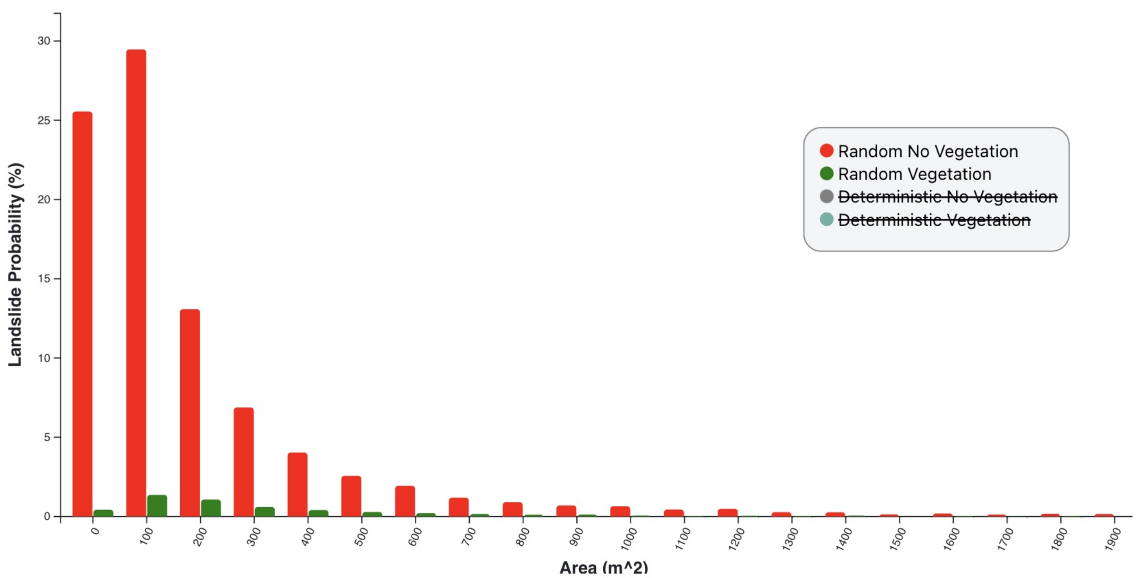


Figure 27: Landslide probability influenced by the vegetation before clear-cutting in Pradiron.

8.2.4 Interpretation of results and conclusions

Based on the values in the graph in Figure 26, it is possible to formulate a silvicultural objective for areas with high landslide hazards under power lines. In the specific case of Pradiron, it would be necessary to manage the stand in such a way that the maximum diameter (DBH) present does not exceed 25 cm (corresponding to a maximum height of about 10-15 m for spruce ($Picea\ abies$) in this area, with a degree of canopy cover of the dominant trees not exceeding 50% (achieved by small cuts or thinings from above, about every 15 years)(Figure 28). In this way it would be possible to maintain a level of root reinforcement sufficient to stabilize landslides (about 4 kN/m) (Figure 29) and at the same time contain the maximum stand height. Although the intervals of intervention are relatively short, the additional costs of such interventions would in many cases be less than the costs of restoring the damage done by landslides. In addition, if it were possible to favor other tree species in secondary successions, this would ensure greater resilience of the forest community and probably increase silvicultural management margins.

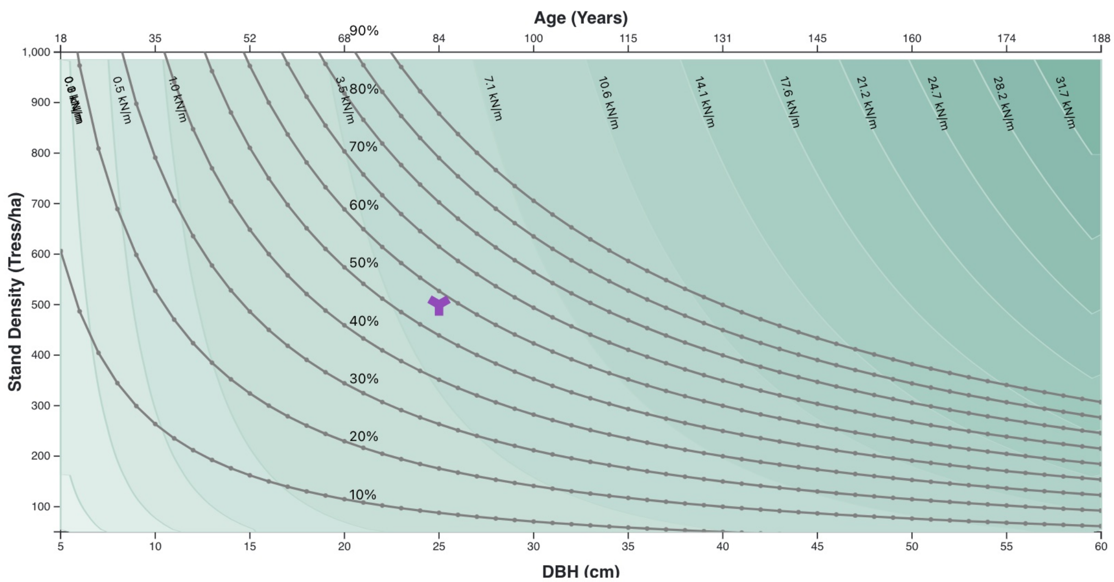


Figure 28: Stand state diagram of the managed forest corresponding to silvicultural target in Pradiron.

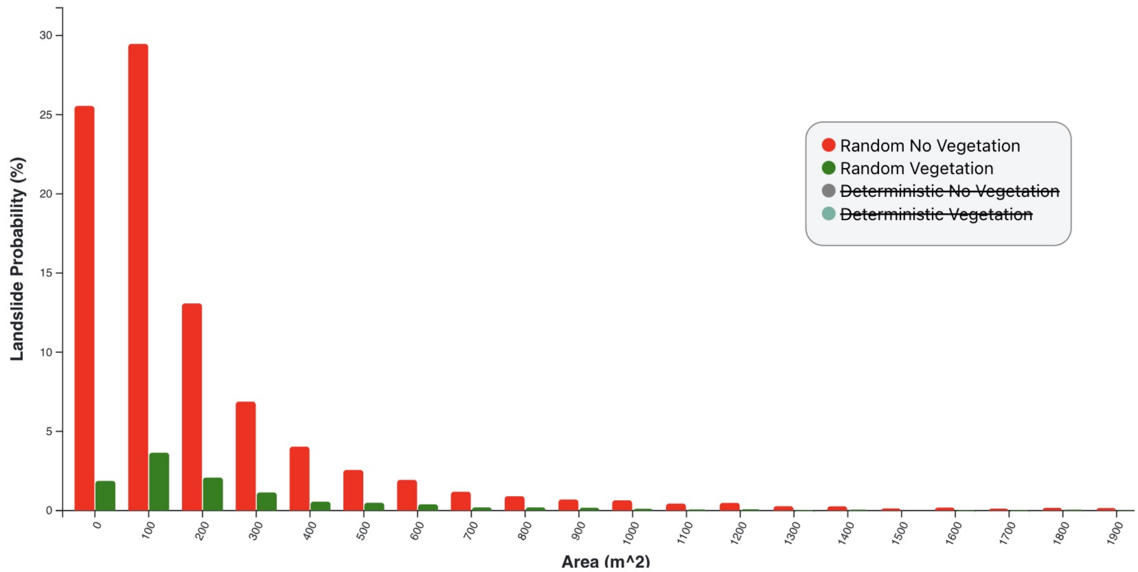


Figure 29: Landslide probability influenced by the vegetation corresponding to silvicultural target in Pradiron.

8.3 Quantitative eco- and bio-engineering: Design of bio-engineering measures for "object-protection" in Tannen, (Morschach, Switzerland)

8.3.1 Description of the case study and objectives

The Tannen farmhouse (Morschach, SZ) was built in 1341 and is one of the oldest wooden houses in Europe. In 2015, the owner began planning the renovation and conversion of the building. According to the hazard map, the house is located on a hazard area with a medium hazard level (blue color in the Swiss standards) due to shallow landslides (Figure 30). In this area of "medium hazard", protection measures to reduce hazard intensities are needed to obtain the building permits. The morphology of the slope in Tannen indicates possible past events. However, although the house has been standing for more than 675 years, it is difficult to estimate whether it has already been affected by minor events or even been partially repaired. Additionally, it is no longer possible to assess how land use has changed over the years and how significant the influence of this factor is on the disposition of shallow landslides (the field name "Tannen" indicates that the slope was once probably forested). The Tannen House is a small and relatively light wooden house, which stands on dry stone walls without rigid connections / interlocking. Therefore, it is basically not capable of absorbing large lateral loads. Due to the special construction of the building, an "object protection measure" must be designed in such a way that it prevents the direct impact of a landslide against the rear wall of the building. In a first phase, it was proposed to build an angular retaining wall along the rear side of the building or a debris flow protection net above the house. These measures were rejected mainly because of the negative aesthetic impact on the landscape. Drainage measures were also rejected due to large uncertainty about the effect on the stability of the slope. Another option proposed was reforestation of the slope, which had to be discussed with the neighboring landowner. Finally, a compromise was reached for single tree plantation (analog to the practices in NZ, [11, 9]). At this point, the design of the bio-engineering measures needed to be formulated to fulfill the criteria of the standards used for technical measures. In particular, the introduction of the partial security factors for rooted soil needed to be implemented in order to define the characteristic and design values used in slope stability calculations.

The objective of the study is to show how to verify the design a bio-engineering measure using the approach of partial security factors in the preliminary phase of the project.

Figure 30: Detail of the Hazard map of Tannen and picture of the slope behind the Tannen house. The small red rectangle shows the position of the house on the hazard map.

8.3.2 Inputs

The slope inclination above the house is quite regular around 27 ^{o}. The average thickness of past shallow landslides in the area is 0.5 m. The soil along the potential slip surface was classified as silty gravel (GM-GL), with a friction angle of 35°, a cohesion of 0.5 kPa, and a soil density of 1.7 t/m^3. Following the principle of partial safety factors, the coefficients 1.2 for the tangent of the drained friction angle and 1.5 for the drained cohesion were used (Figure 31).

As possible biological measures, a minimal variant was investigated in detail, which acts through the effect of root reinforcement of a wedge-shaped forest area above the house. A plantation with 200 trees per hectare and a mean DBH of 25 cm, should reach the maximum expected protective effect about 40 to 50 years. It was proposed to manage the tree stand in such a way that the tree height is never greater than the distance between each tree and the house (to avoid risks due to falling trees). In view of the climatic station and the possible scenarios of climate change, the proposed tree species was the pubescent oak (*Quercus pubescens*). Due to the fact that no "characteristic values" are available, these needed to be calculated based on the average root reinforcement values calculated by SlideforNET. Considering the available analysis on the variability of root reinforcement [5], a factor of 6 can be used to define the "characteristic value" that corresponds to the lower 5 percentile of the probability distribution.

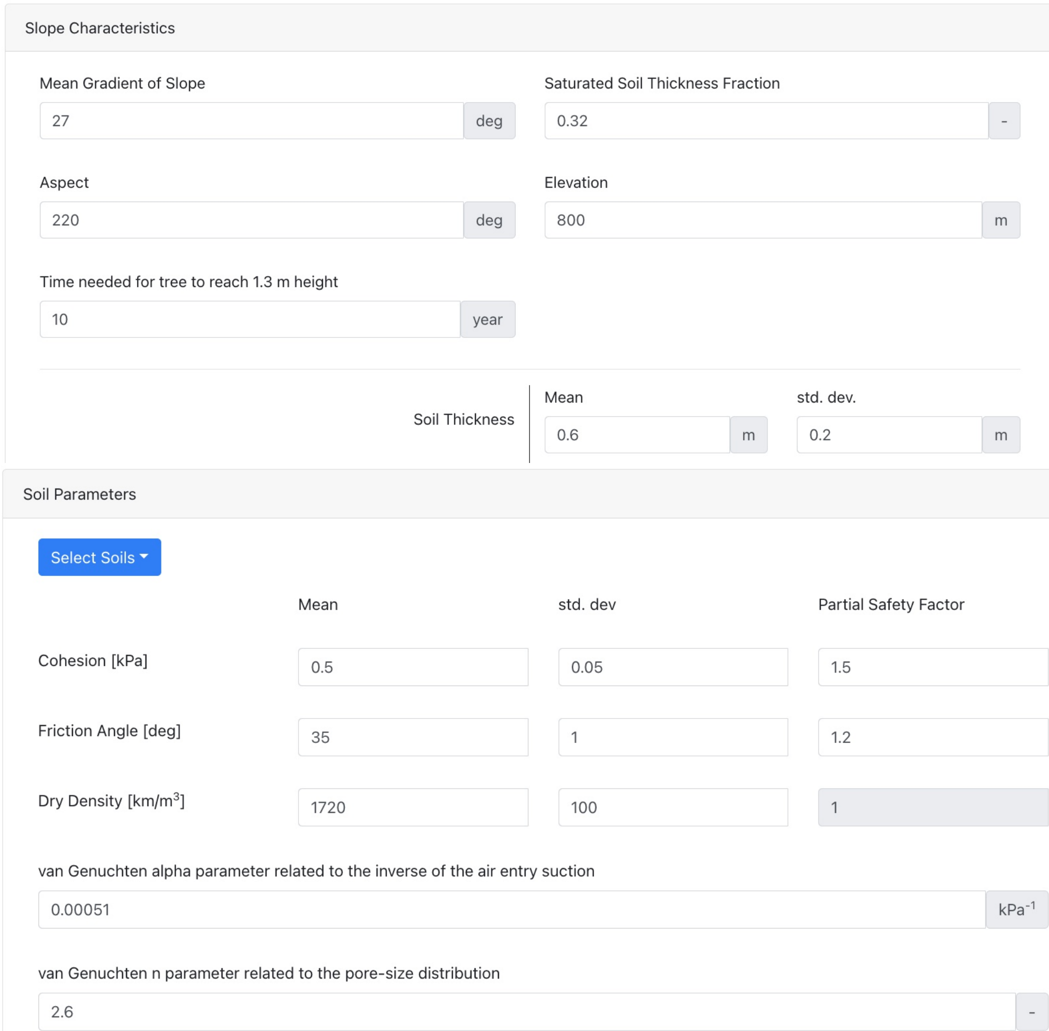


Figure 31: Tables of the slope and soil inputs parameters for Tannen.

The design value for root reinforcement is calculated with a partial factor of 1.5, analog to the factor used for soil cohesion (Figure 32).

8.3.3 Outputs

The "Tabulated Results" of SlideforNET for the "deterministic" calculations using the partial security factors show that the design values of friction angle and cohesion are reduced to 27.8 ^{o} and 0.281 kPa, respectively (Figure 33). The values of lateral root reinforcement are reduced from 12.4 kN/m

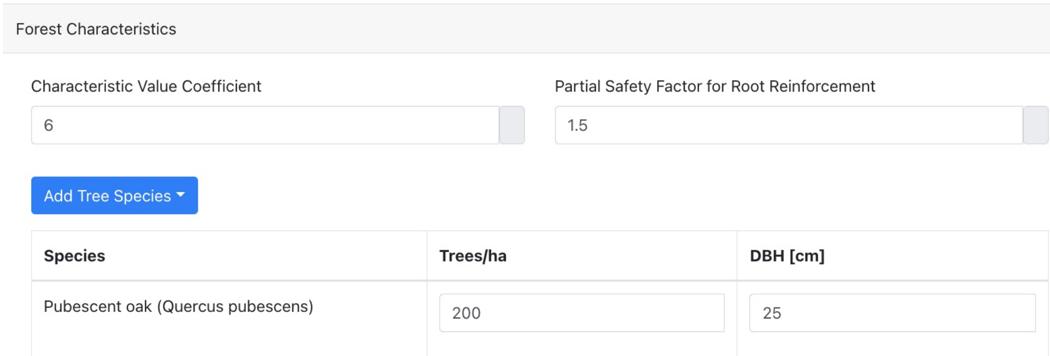


Figure 32: Tables of the parameters of planed bio-engineering measures.

to 2.9 kN/m as "characteristic value" and to 1.9 kN/m as "design value". The values of basal root reinforcement are reduced from 11.2 kPa to 0.6 kPa as "characteristic value" and to 0.45 kPa as "design value".

Tree Stand	**Value**	**Unit**
Density	200.000	trees/ha
Volume	42.976	m^3/ha
Weight of vegetation	0.004	t/m^2
Weight of vegetation in equivalent soil thickness	0.172	cm
Random landslides		
Mean lateral root reinforcement	12.402	kN/m
Mean basal root reinforcement	11.251	kPa
Reliability Index for vegetation	1.808	-
Reliability Index for no vegetation	5.990	-

Deterministic landslides	**Characteristic Value**	**Design Value**	**Unit**
Cohesion	0.422	0.281	kPa
Friction angle	33.380	27.816	deg
Basal root reinforcement	0.680	0.454	kPa
Lateral root reinforcement	2.936	1.958	kN/m

Figure 33: Table of output results for Tannen house.

The visualization of the landslide probability for the "deterministic" calculations (selection is possible clicking on the legend!) show that almost no landslides are possible in vegetation condition, whereas without vegetation, the total landslide probability is about 40% (Figure 34).

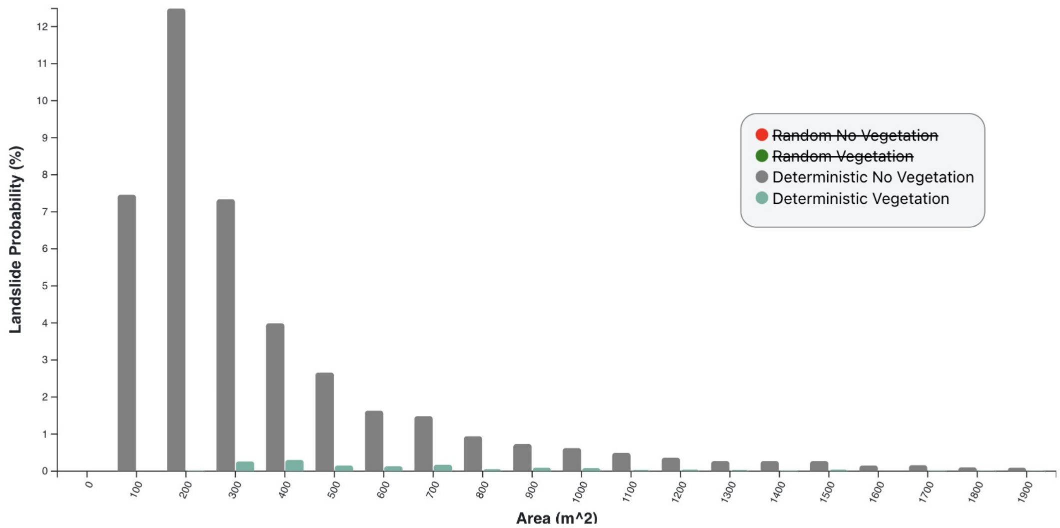


Figure 34: Output probability for the Tannen house.

The distribution of landslides thickness indicates that root reinforcement in generally enough to ensure stability with a probability of 99% (against a probability of stable condition of 58% without vegetation) (Figure 35). Moreover, the boxplots show that the effect of root reinforcement are limited to a landslide thickness less than 0.8 m.

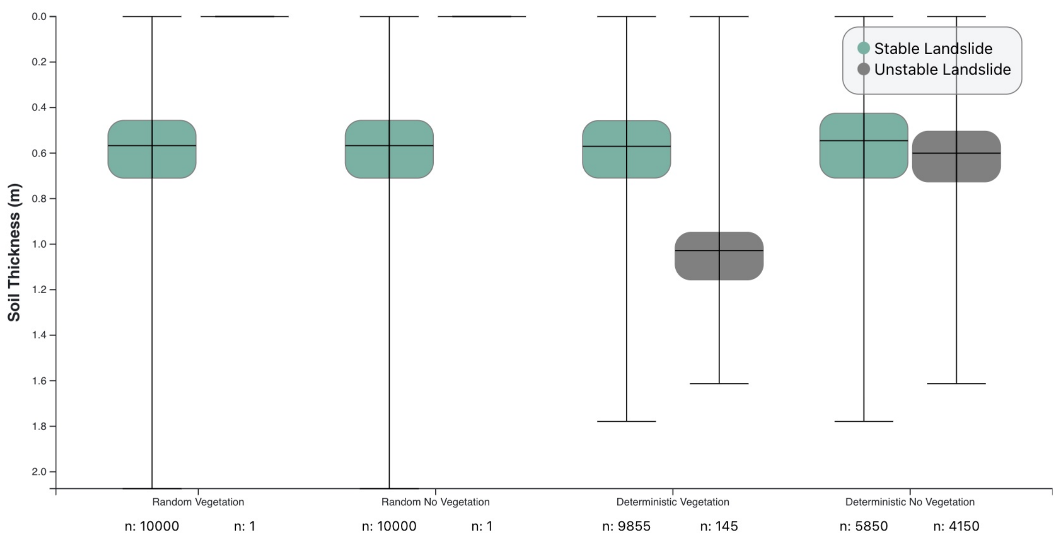


Figure 35: Soil thickness boxplots for the different scenarios.

The stand state diagram shows that the "total" mean calculated lateral root reinforcement is about 20 kN/m. "Total" means that it considers an infinite vertical integration along the soil thickness (Figure 36). The value of lateral root reinforcement shown in the "Tabled Results" corresponds to the vertical integration down to the mean soil thickness (in this case equal to 0.6 m). The grey points in Figure 37 correspond to the design values of basal root reinforcement.

The lines of the canopy cover values are not shown because not such data are available at the moment for the selected tree species.

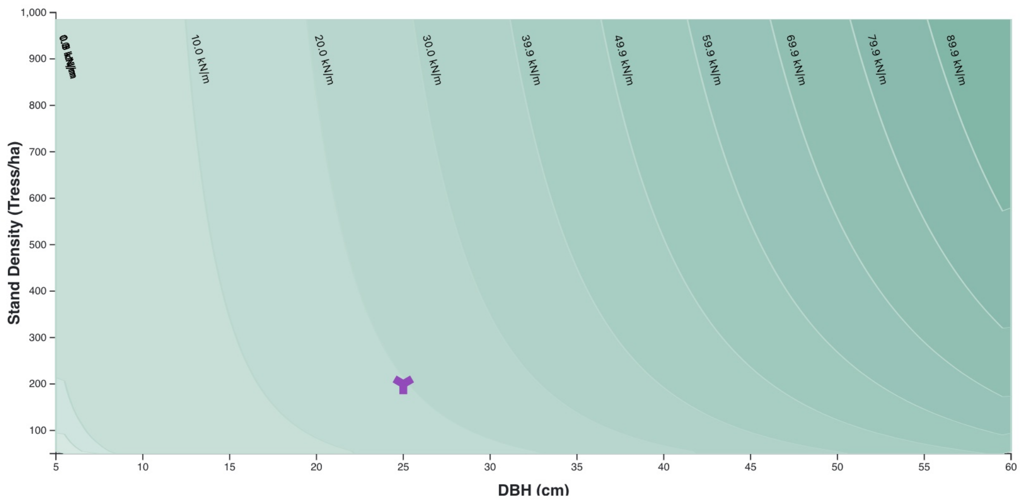


Figure 36: Stand state diagram for the Tannen house.

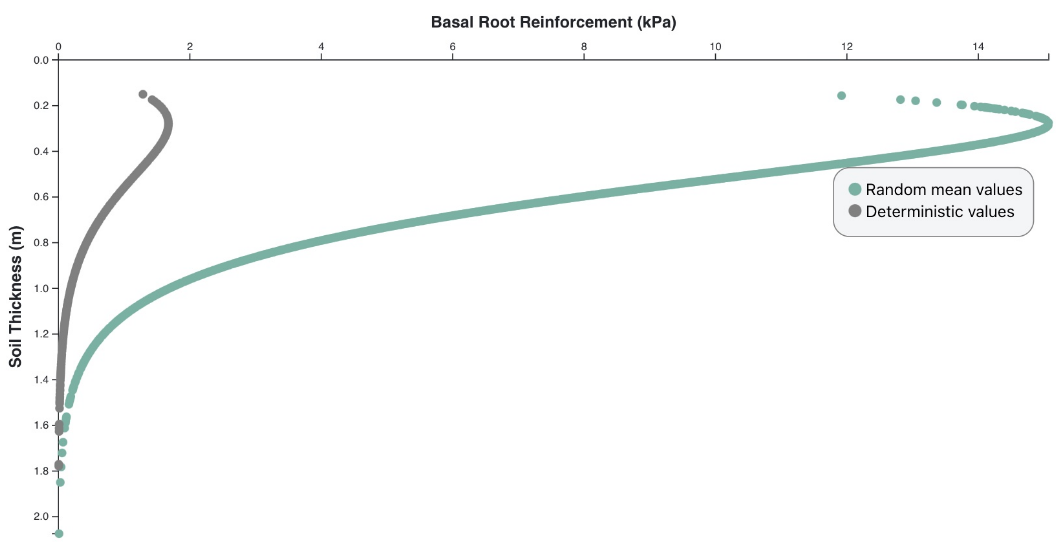


Figure 37: Basal root reinforcement as a function of soil thickness for the Tannen house.

8.3.4 Interpretation of results and conclusions

This one of the first examples documented in the literature for the quantitative design of bio-engineering measures. The application of partial security factor in SlideforNET calculations shows that a developed plantation of pubescent oaks will guarantee enough slope stability to avoid risks in Tannen. However, the temporal dynamic of the stand needs to be considered too. Changing the values of DBH and stand density in the inputs, it is possible to evaluate how the stabilization effects of roots would change in time. For example, considering a DBH of 12.5 cm and a stand density of 500 trees per hectare (Figure 38), the lateral root reinforcement is about half of the final designed value. Nevertheless, even under these conditions, slope stability for soil thickness less than 0.8 m is guaranteed (Figure 39). For the design of the measure in the final phase of the project, a more detailed modeling approach using the package SOSlope can be used.

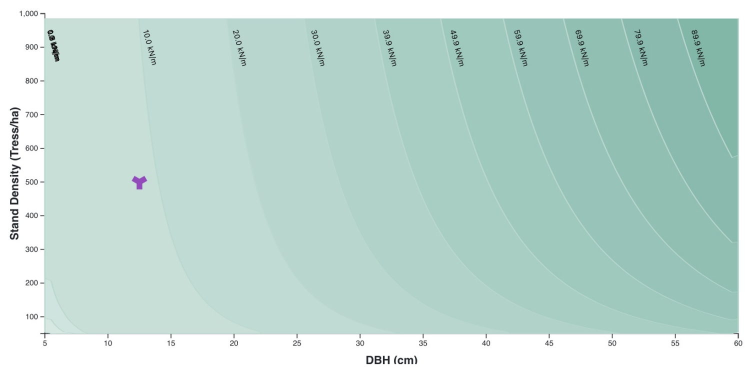


Figure 38: Stand state diagram for the Tannen house.

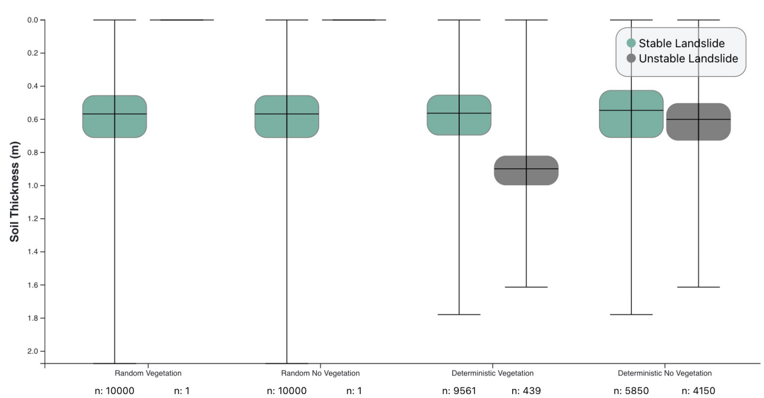


Figure 39: Soil thickness box plots for different scenarios.

The designed measure was only partly implemented. Figure 40 shows the areal view of the slope in 2023 with recently planted trees above the Tannen house. At the moment trees have a distance between 4 and 10 m.

Figure 40: Aerial view of the actual implemented measure.

In this case study, only the effect of root reinforcement was considered, although other positive vegetation effects can also be mentioned: 1) The root system at the foot of the slope has a draining effect and thus reduces the building of pore water pressure during intense precipitation; 2) The evapo-transpiration of the trees is higher than in the meadow, reducing the water saturation of the soil before a precipitation; 3) Interception (of water and snow) reduces the amount of water that can infiltrate into the soil before an intense rainfall; 4) A healthy and stable stand structure has a protective effect against the impact of small shallow landslides or snow pressure.

9 Theory and methods

SlideforNET calculates the factor of safety of a large number of hypothetical landslides, $N_{\mathrm{L}} = 10,000$, at a given location on a slope to determine the probability of failure in the case with and without vegetation. The slope is assumed to have some mean characteristics, such as slope gradient, soil thickness, soil properties, forest cover, etc. The probability of failure of that slope is calculated as a function of the landslide area, A_L, a probabilistic quantity randomly chosen from a distribution for each hypothetical landslide. The probability of failure, $p_f(A_L)$, is defined as the ratio of the number of hypothetical landslides that failed (factor of safety less than 1) to the total number of hypothetical landslides:

$$p_f(A_L) = \frac{N_{\mathrm{L}}(A_L, \mathrm{FOS} < 1)}{N_{\mathrm{L}}(A_L)}, \tag{4}$$

where $p_f(A_L)$ is the probability of failure of landslides, A_L represents the area interval between A_L and $A_L + \delta A_L$ (δA_L is the bin size set to 100 m^2), $N_{\mathrm{L}}(A_L)$ is the total number of simulated landslides of area A_L, and $N_{\mathrm{L}}(A_L, \mathrm{FOS} < 1)$ is the number of landslides of area A_L that failed, i.e. their factor of safety (FOS) is less than 1.

The model uses two different approaches to compute the factor of safety and the probability of failure: (i) assuming random values of soil properties for each of the landslides or, (ii) using constant characteristic values with partial safety factors for soil and root properties.

9.1 Calculation of factor of safety

The factor of safety is the ratio of resistive forces to driving forces. Because resistive forces in the soil and in the roots are activated and reach their maximum values at different times during the failure process (root maximum tensile forces usually occur before the soil maximum compressive resistance, see [3]), we compute the factor of safety for two different cases of resistive forces:

1. F_{r_1}: when lateral root reinforcement is maximized and soil compressive resistance is a fraction κ of its maximum value;
2. F_{r_2}: when lateral roots have all failed and support no force, and soil compressive resistance is at its maximum value.

The factor of safety is then calculated using the maximum value of either F_{r_1} or F_{r_2}, i.e.,

$$\mathrm{FOS} = \frac{\max\left(F_{r_1}, F_{r_2}\right)}{F_d}, \tag{5}$$

where

$$F_{r_1} = F^{\mathrm{basal}} + F^{\mathrm{lateral}} + \kappa W \left(E_p + \frac{F^{\mathrm{lateral}}}{10} \right), \tag{6}$$

$$F_{r_2} = F^{\mathrm{basal}} + W \left(E_p + \frac{F^{\mathrm{lateral}}}{10} \right), \tag{7}$$

and F_d, the driving force, is

$$F_d = g \cos\beta (M_S + M_W + M_T). \tag{8}$$

In these equations, g is gravity, β is the angle of the slope with the horizontal, M_S, M_W, and M_T are, respectively, the masses of the dry soil, the water in the soil, and the trees, in the elliptical landslide of area A_L, soil thickness h, and width (minor axis of ellipse) W (see Fig X and Equation 13 below). E_p is the earth pressure force (see Equation 30 below), $\kappa = 0.3$ is a reduction coefficient of the earth pressure force when not at its maximum, and F^{basal} and F^{lateral} are the basal and lateral forces, respectively, given by

$$\begin{aligned} F^{\mathrm{basal}} &= A_L\, c' + F_{\mathrm{eff}} \tan\phi' + F^{\mathrm{rootbasal}}, && (9) \\ F^{\mathrm{lateral}} &= F^{\mathrm{rootlateral}}, && (10) \end{aligned}$$

with

$$F_{\mathrm{eff}} = g\ \cos\beta\ (M_S + M_W + M_T) - A_L\, P_w\ \cos\beta, \tag{11}$$

where F_{eff} is the effective normal force, c' is the soil cohesion, ϕ' is the soil friction angle, $F^{\mathrm{rootbasal}}$ and $F^{\mathrm{rootlateral}}$ are the basal and lateral root reinforcement, respectively.

The lateral force in Equations 6 and 7 in the last term of these equations is divided by 10 to represent lateral root reinforcement under compression, i.e., 10 times less than in tension. Details of all the terms of these equations and their calculations are given in the subsections below.

9.2 Calculation of landslide geometry

Hypothetical landslides are assumed to be elliptical in shape with area A_L and constant soil thickness h and with the major axis of the ellipse pointing downslope. The area of each landslide is a random variable generated from the inverse 3-parameter gamma distribution (MALAMUD ET AL 2004). The landslide thickness is also a random variable generated from a normal distribution based on a given mean and standard deviation.

9.2.1 Landslide area

The landslide area distribution is given by the 3-parameter inverse gamma distribution (see Equation 3 in [6]):

$$p(A_L, \rho, a, S) = \frac{1}{a\Gamma\rho}\left[\frac{a}{A_L - S}\right]^{\rho+1} \exp\left[\frac{-a}{A_L - S}\right], \tag{12}$$

where A_L is the landslide area, ρ is a parameter controlling the power-law decay (the shape factor), a is a parameter controlling the location of the maximum probability (the scale factor), and S is a parameter controlling the exponential roll-over for small values of landslide area.

9.2.2 Landslide width, circumference, and volume

In SlideforNET, hypothetical landslides are assumed to be ellipses with their major axis equal twice their minor axis. Then, the width W of the landslide (twice the length of the minor axis) is

$$W = \sqrt{\frac{2\,A_{\mathrm{L}}}{\pi}}. \tag{13}$$

The circumference is approximated as

$$C = 1.211056 \times 4\,W. \tag{14}$$

Finally the landslide volume is

$$V_{\mathrm{L}} = h\,A_{\mathrm{L}}. \tag{15}$$

9.3 Calculation of soil properties

9.3.1 Random landslides

For random landslides, values of cohesion, c, friction angle, ϕ and dry density, ρ_{dry} are randomly generated from log-normal distributions using the mean and standard deviation of each property. From the dry density and assuming a solid grain density of $\rho_s = 2650$ kg m^{-3}, we compute the saturated water content θ_{sat}, the soil wet density ρ_{wet}, the residual water content, θ_r, and the field capacity θ_{fc} as:

$$\begin{aligned}
\theta_{\mathrm{sat}} &= 1 - \frac{\rho_d}{\rho_s}, && (16)\\
\rho_{\mathrm{wet}} &= (1 - \theta_{\mathrm{sat}})\rho_s + \theta_{\mathrm{sat}}\,S\,\rho_{\mathrm{water}}, && (17)\\
\theta_r &= 0.1\,\theta_{\mathrm{sat}}, && (18)\\
\theta_{\mathrm{fc}} &= \theta_r + \frac{\theta_{\mathrm{sat}} - \theta_r}{\left[1 + (\alpha P)^n\right]^{1-1/n}}, && (19)
\end{aligned}$$

where S is the saturated soil thickness ratio (between 0 and 1), $\rho_{\mathrm{water}} = 1000$ kg m^{-3} is the density of water, α and n are the van Genuchten air-entry pressure (units of one over pressure) and exponent, respectively, and $P = 33$ kPa is the pressure at which the field capacity is calculated (REF).

9.3.2 Deterministic landslides

For deterministic landslides, characteristic values of the three quantities cohesion, friction angle, and dry density are calculated at the 5% (cohesion, friction angle) and 95% (dry density) percentile from a log-normal distribution:

$$
\begin{aligned}
c^{\mathrm{c}} &= \exp\left(\mu_c^\star - 1.645\,\sigma_c^\star\right), && (20)\\
\phi^{\mathrm{c}} &= \exp\left(\mu_\phi^\star - 1.645\,\sigma_\phi^\star\right), && (21)\\
\rho_d^{\mathrm{c}} &= \exp\left(\mu_{\rho_d}^\star + 1.645\,\sigma_{\rho_d}^\star\right), && (22)
\end{aligned}
$$

where μ and σ designate the mean and standard deviation, respectively, the underscore symbol indicates the variable, the c superscript indicates a characteristic value, and the superscript $\star$ indicates the value for the log-normal distribution obtained by the following transformation:

$$
\begin{aligned}
\mu^\star &= \ln\frac{\mu^2}{\sqrt{\mu^2+\sigma^2}}, && (23)\\
\sigma^\star &= \sqrt{\ln\left(1+\frac{\sigma^2}{\mu^2}\right)}, && (24)
\end{aligned}
$$

where μ and σ are the mean and the standard deviation.

Design values for the cohesion, the friction angle, and the dry density are the characteristic values divided by their respective partial safety factor, γ, i.e.

$$
\begin{aligned}
c^d &= c^c/\gamma_c, && (25)\\
\phi^d &= \phi^c/\gamma_\phi, && (26)\\
\rho_d^d &= \rho_d^c/\gamma_{\rho_d}, && (27)
\end{aligned}
$$

where the superscript d indicates the design value. In SlideforNET $\gamma_{\rho_d} = 1$.

Saturated water content, soil wet density, soil residual water content and field capacity are calculated as in the random case using Equations 16 to 19

9.4 Calculation of landslides soil and water masses

The soil and water masses in each landslide is

$$
\begin{aligned}
M_S &= \rho_{\mathrm{dry}}\,V, && (28)\\
M_W &= \rho_{\mathrm{water}}\,V\ \left[\theta_{\mathrm{sat}}\left(S+(1-S)\,\theta_{\mathrm{fc}}\right)\right]. && (29)
\end{aligned}
$$

9.5 Calculation of passive earth pressure force

In SlideforNET the passive earth pressure force, E_p (units of force per unit length) is assumed active on the lower half of the landslide acting on the maximum width of the landslide and is given by

$$
E_P = \frac{1}{2}\,\rho_d\ g\ h^2\ K_P, \qquad (30)
$$

where K_P is the coefficient of passive earth pressure calculated using the gen-Rankine model described in [1] and based on based on a closed-form solution by [7].

9.6 Calculation of lateral and basal root reinforcement

In SlideforNET, lateral root reinforcement is computed using the model of [8] (see also [4]). The model estimates the maximum value of root reinforcement (as a force per meter) for a particular species s during root pullout in tension as a function of the distance from the tree trunk (d) and the tree species DBH (ϕ_s),

$$R_s^{\text{lateral}}(d) = \begin{cases} \gamma_s\, \phi_s\, f_\Gamma\left(\frac{d}{d_s^{\max}}; \alpha_s, \beta_s\right), & d \leq d_s^{\max} \\ 0, & d > d_s^{\max} \end{cases} \tag{31}$$

where f_Γ is the gamma distribution function, d is the distance from the tree trunk where root reinforcement is at a minimum, $d_s^{\max}$ is the maximum root extent measured from the tree trunk, and γ_s, α_s and β_s are parameters that depend on the type of species. The parameters α_s and β_s are the shape and scale (inverse of rate) parameters of the gamma distribution

$$f_\Gamma(x; \alpha, \beta) = \frac{x^{\alpha-1} \exp^{-x/\beta}}{\beta^\alpha \Gamma(\alpha)}. \tag{32}$$

The values of the four parameters $d_s^{\max}$, γ_s, α_s and β_s are determined empirically for each species s.

The distance d from the tree trunk where root reinforcement is at a minimum for a arrangement of trees on a triangular grid, is:

$$d = \sqrt{\frac{2\cos\alpha}{3\sqrt{3}} \frac{10000}{\rho_s}}, \tag{33}$$

where ρ_s is the density of tree of species s in trees per hectare.

Because root density is not uniform with soil thickness and usually decreases rapidly with soil thickness, the actual lateral root reinforcement is calculated by multiplying the lateral root reinforcement (Equation 31) with the cumulative distribution function at thickness h, i.e.,

$$R_s'^{\text{lateral}}(d, h) = F_\Gamma(h; k_s, \theta_s)\, R_s^{\text{lateral}}(d), \tag{34}$$

where $F_\Gamma(x; k_s, \theta_s)$ is the cumulative gamma distribution function with shape and scale parameters k_s and θ_s respectively. Both shape and scale parameters are determined empirically for each species s from measurements of root distribution with soil thickness.

The basal root reinforcement is computed at the failure surface at soil thickness h from the maximum lateral root reinforcement (Equation 31) at a distance $0.6\,d$ (instead of d, see Equation 33), to account for the average value of basal reinforcement over the base of the sliding surface) times the gamma distribution function at that thickness, i.e.

$$R_s^{\text{basal}}(d, h) = f_\Gamma(h; k_s, \theta_s)\, R_s^{\text{lateral}}(0.6\,d). \tag{35}$$

The value of root reinforcement is then calculated as the sum of the root reinforcement for each tree species s:

$$F^{\text{rootlateral}} = 3\,\frac{C}{2}\,\sum_{s=1}^{n_s} R_s^{\prime\text{lateral}}, \tag{36}$$

$$F^{\text{rootbasal}} = A_L\,\sum_{s=1}^{n_s} R_s^{\text{basal}}, \tag{37}$$

where the coefficient 3 in Equation 36 comes from the assumption of a triangular arrangement of the trees on the slope, A_L and C area the area and circumference of the landslide, respectively.

9.7 Probability of failure of landslides as a function of area

The factor of safety is calculated for each hypothetical landslide and the probability of failure (Equation 4) is then normalized and binned based on landslide area using a 100 m^2 bin size.

10 Glossary

Basal root reinforcement Root reinforcement acting at the base of the landslide along its failure surface.

DBH Tree diameter at breast height.

Deterministic landslide A hypothetical landslide whose soil characteristic properties are calculated based on the 5% percentile of the log-normal distribution with design values computed using a partial safety factor.

Lateral root reinforcement Root reinforcement acting along the circumference of the landslides, in tension at the upper end, in compression at the toe.

Probability of failure The probability that a landslide of area A_L will occur.

Random landslide A hypothetical landslide whose soil properties (e.g., cohesion, friction angle, dry density) are generated from log-normal distributions.

Web application A web application (web app) is an application program that is stored on a remote server and delivered over the internet through a browser interface.

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