UNIVERSITÄT FÜR BODENKULTUR

INSTITUT FÜR GEOTECHNIK

Lorenzo Holsworth

Numerical analysis of vegetation effects on slope stability

2014

SUPERVISOR: Prof. Dr.-Ing. Wei Wu

MASTER THESIS No. 367

Table of contents

List of figures

Abstract

Landslide is a major form of natural hazards with huge loss to life and property. Vegetation plays an important role in slope stabilization. However, it is rarely included in slope stability calculations nor in the development of engineering solutions. This thesis studies the influence of three types of root morphology, given typical properties for clay and sand soils and two different sets of atmospheric conditions.

Slope stability in areas prone to shallow landslides is improved by considering the effect of vegetation, since it provides additional cohesion in the root zone. On the other hand, the presence of a bedrock, has a large influence on the factor of safety in clay slopes, but the effect is less obvious in sandy slopes.

Vegetation helps to drain soil before and after rainfall, increasing soil suctions and reducing pore pressures. Most sandy slopes saturates and desaturates relatively fast, and thus pore water pressure distribution is less affected by root water uptake. In general, vegetation with cylindrical root architecture contributes to the development of the highest suctions in the shear zone and is more effective in slope stabilization than other root architectures. This effect is the most evident for clay slopes.

The deformation of slopes as well as root reinforcement and its distribution models are still necessary for a better understanding and sufficient accuracy. However, this requires complex models and detailed information. Simple models are very useful as first approximations, for large scale simulations, or in situations where data is inaccurate or insufficient.

Zusammenfassung

Hangrutschungen stellen eine Gefährdung für Menschen und Infrastruktur dar. Derzeit findet die Vegetation eines Hanges selten Eingang in die Berechnung der Hangstabilität oder die Bemessung eines konstruktiven Schutzbauwerks. Die vorliegende Arbeit untersucht durch Simulation den Einfluss dreier Wurzelmorphologien für Böschungen aus Ton- und Sandböden unter zwei verschiedenen atmosphärischen Bedingungen.

Unsere Berechungen zeigen, dass die Berücksichtigung der Vegetation bei den, seichten Hangrutschungen zu einer höheren, Stabilität aufgrund des zusätzlichen Zusammenhalts in der Wurzelzone führt. Darüber hinaus wurde auch der Einfluss von anstehendem Festgestein untersucht. Dabei zeigen Böschungen aus bindigen Böden deutlich höhere Stabilitäten bei Vorliegen eines Felsuntergrundes Bei Hängen aus sandigem Material ist der Einfluss der Untergrunds geringer.

Vegetation erhöht die Drainage von Böden sowohl bei Niederschlagsereignissen. Dies hat zur Folge, dass die Die vaugspannung erhöht und der Porenwasserüberdruck reduziert wird. In Böschungen aus sandigen Böden ist der Boden meist teils gesättigt. In diesem falle spielt die Wasseraufnahme von Wurzeln nur eine untergeordnete Role für die Verteilung des Porenwasserdruckes bei. Generell erhält man für die Vegetation mit zylindrischer Wurzelarchitektur der Porenwasserüberdruck reduziert wird. Die höchsten Saugspannungen in der Scherzone. Somit ist diese Wurzelarchitektur effektiver für die Hangsicherung als die anderen Architekturen, insbesondere auf Tonhängen.

Die Wechselwirkung zwischen Böden un Vegetation ist hoch komplex. Eine genaue Untersuchtung erfordert komplexere Modelle und Detailinformationen. Einfache Modelle, wie in dieser Arbeit angewendet, eignen sich hervorragend als erste Annäherungen, für Simulationen großer Gebiete oder in Situationen, in denen Daten in nicht ausreichendem Umfang vorliegen.

1 Introduction

Slope instability represents a major threat to human life and property. The risk is considerable, as landslides often evolve from a mass movement into debris flows and affect infrastructure, buildings, and even cause fatalities (Avanzi et al., 2004). Moreover, in many catchments, landslides are a substantial part of the sediment delivery which often contributes to the increase of the flood risk.

Landslides consist of soil and debris which move by sliding or flowing due to the action of the complex driving forces. If they are less than 2 m deep they are classified as “shallow” landslides (Rickli and Graf, 2009). These are often triggered by rainfall events and generally involve only a relative thin layer of soil, but sometimes can affect large areas and lead to catastrophic situations. Typical rainfall-induced shallow landslides have depths between 0.5 to 1.5 m, a scar area of 50 to 1000 m², volumes that range from few to several hundred cubic meters and are triggered either by short high intense rainfall or long low intense precipitation (Ceriani et al, 1992, Crosta, 1998).

Consequences of landslides often lead to catastrophic events. Only in 2010, hundreds of fatalities are attributed to this phenomena. The most noticeable catastrophes are a mudslide in Shouqu County in Gansu (China) in August, a landslide in Bududa (Uganda) in March or another one in Leh (Ladakh, Indian Kashmir) in August (Kirschbaum et al, 2012).

Concerning impacts of landslides, they are of a major concern for all people and organizations responsible for the protection of human lives and infrastructure from natural hazards (Graf et al, 2009). Thus a deep understanding of the driving forces of slope instability is fundamental for risk prevention and management associated with this phenomena.

Protection measures concerning landslide prevention are critically needed. They should involve precise suitable measures and reliable models, which allow estimation and prediction of slope stability and calculation of factors of safety. However, classical civil engineering methods of slope stabilization face major disadvantages, as they compromise only technical solutions. These solutions can be improved if they are combined with biological measures (bioengineering), which consider ecological and environmental aspects. Bioengineering is particularly suitable as it combines environmental compatibility with cost effective solutions.

A frequent tool for risk management is the use of landslide-hazard maps. Accurate information about the factors which influence slope stability is required for the hazard maps preparation and performance, hence the importance of landslides research and investigation.

Landslide hazards can be assessed through physically based models, multivariate analyses, or investigation of landslides, scars and deposits. Physically based models suffer from insufficiently accurate hydrological, vegetation, geological and topographical data and classify unreasonably large areas susceptible to landslides.

Although extensive research has been performed on shallow landslides, little is known about the contribution of the vegetation to the slope stability. Moreover, vegetation is very rarely included in safety calculations, either for hazard maps or “bioengineering” solutions (Graf et al, 2009, Rickli and Graf, 2009).

Numerous studies have shown positive effects of forests and tree roots on slope stability. These studies prove an increase in landslide frequency to be the result of intensive harvesting, which often occur a few years after the deforestation, when the roots start to decay (Kirschbaum et al, 2012).

The importance of these additional modeling factors is essential in making slope stability calculations more efficient. Mathematical models are the basis of our technological world. Forecasting and slope stability studies must be advanced to take into account more of the factors involved in the stability of soil masses. When studying and offering solutions to slope stability measures, it is absolutely essential to increase the efficiency and reliability of these applications by including not only different soil types, slope geometries, hydrological conditions, and other traditional factors, but also vegetation root structure types. This would apply both before and after land adjustment or reconstruction.

2 Research objectives

This project aims to explore the effects of vegetation on slope stability through numerical analysis of a standard slope. More specifically:

1. Identification of mechanical and hydrological effects of different types of vegetation with various root distributions on slopes with different soils.
2. Identification of the influence on slope stability of a shallow, impermeable and strong material underlying the vegetated soil layer.
3. Identification of mid-long term effects on slope stability under fluctuating atmospheric conditions.
4. Identification of effects on slope stability subjected to a heavy rainfall event.
5. Assessment of the capabilities of a commercial software to simulate the stability of 2D slopes, including vegetation and applying atmospheric conditions.

3 Fundamentals and literature review

Landslides occur if the driving forces in the soil mass exceed the resisting forces on the critical slip surface. This is characterized by very complex interactions of different processes and mechanisms. Understanding the mechanics of such mechanisms and forces is crucial for modeling, designing and assessing slope stability. Consequently, analysis of slopes and earth structures stability is the oldest type of numerical analysis in geotechnical engineering.

3.1 Slope stability calculation methods

Within a homogeneous soil, a force acting in a plane with inclination α generates a normal stress (σ_α, perpendicular to the plane considered) and shear stress (τ_α, parallel to the plane). For each angle of the plane, stresses are calculated, and corresponding Mohr circle can be drawn, from which it is possible to delineate the applied normal and shear stress along any potential failure plane in a soil element (Figure 3.1, left). Failure occurs when the Mohr circles associated to a stress are tangent to Coulomb's soil strength equation (Figure 3.1, right).

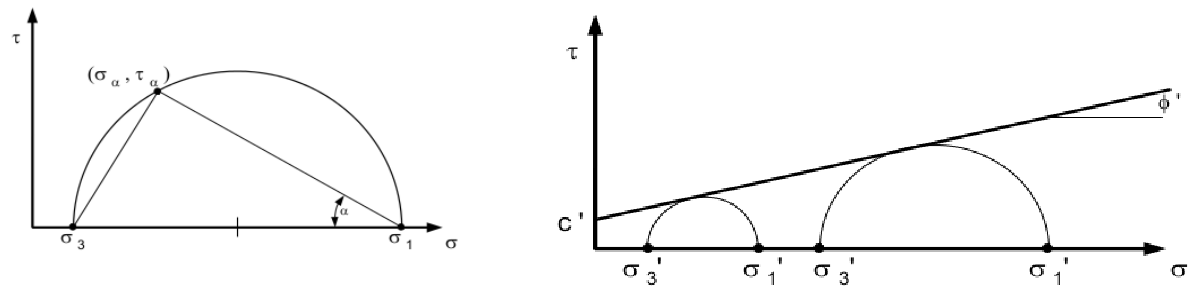

Figure 3.1. Mohr stress circle and Mohr-Coulomb failure criteria.

3.1.1 Infinite slope stability analysis

For a long planar failure, a one-dimensional limit-equilibrium model using a modified Mohr–Coulomb failure criterion can be readily applied to calculate a safety factor (Figure 3.2). This type of simple analysis assume an infinitely long homogeneous slope and a constant depth of the failure surface.

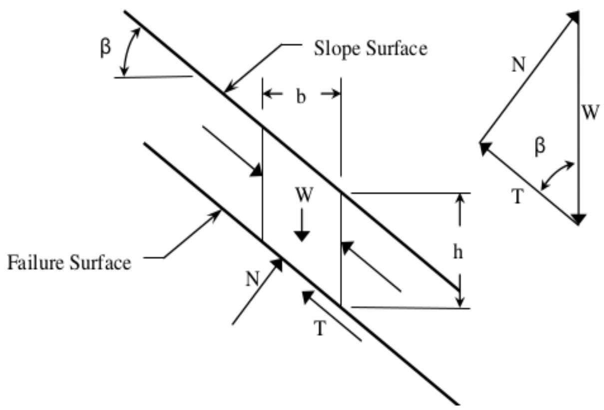

Figure 3.2. Infinite slope model diagram for a dry soil (Jordan, 2011).

For many rainfall-induced landslides, the failure surfaces are usually shallow and parallel to the slope surface (Fredlund and Rahardjo, 1993a). Under such conditions, a one-dimensional infinite slope stability analysis is the preferred method to assess slope stability due to its simplicity and practicability (Yeh and Lee, 2013).

3.1.2 Limit equilibrium methods

In early decades of 20th Century, Fellenius (1936) introduced the Ordinary or Swedish method of slices, the first method that uses the idea of discretization of a potential sliding mass into slices (Figure 3.3a). In the mid-1950s. Janbu (1954) and Bishop (1955) developed advances in the method. Finally, with the advancement of computers, iterative methods were developed, such as Morgenstern and Price (1965) or Spencer (1967), and implemented into the computer software (Geo-Slope international, 2008a).

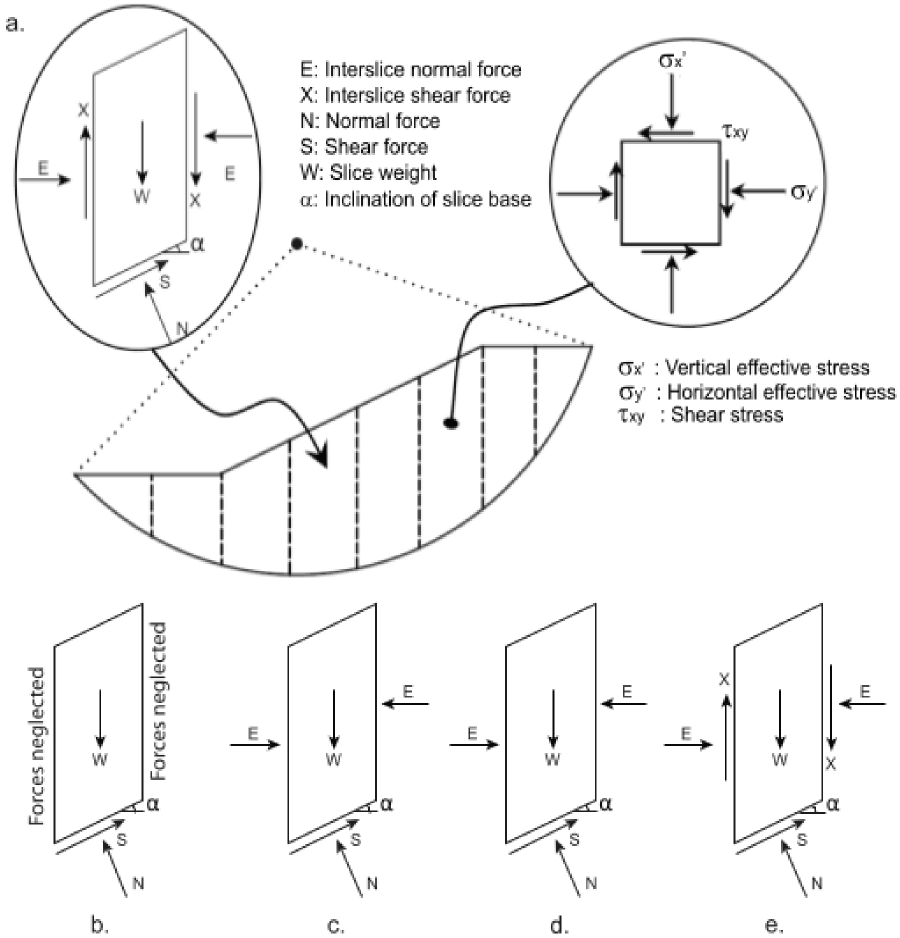

Figure 3.3. (a) Slice discretization of a potential sliding mass and forces acting on a typical slice used in limit-equilibrium methods. (b) Ordinary (Fellenius) Method, (c) Bishop's Simplified Method (vertical force equilibrium),(d) Janbu's Simplified Method (horizontal force equilibrium), and (e) Morgenstern-Price Method (Lu et al, 2012).

Modern software allows dealing with complex stratigraphy, irregular pore-water pressure conditions and complex slip surface shapes. Still, limit equilibrium models are conceived for situations where the normal stress along the slip surface is influenced by gravity, which limits the model capabilities to such conditions. However, with the understanding of limitations it is possible to efficiently use the models. The most important consideration is that these methods are strictly formulated from a static point of view.

Solutions of the methods differ in terms of considered equilibrium equations. The Ordinary, or Fellenius method dismisses all inter-slice forces and satisfies only moment equilibrium (Figure 3.3b, Fellenius, 1936). This is the best solution, when all calculations have to be done manually. Later Bishop included inter-slice normal forces, but ignored the inter-slice shear forces (Figure 3.3c, Bishop, 1955). Again, Bishop's Simplified method satisfies only moment equilibrium. Janbu's Simplified method is similar to that of Bishop, but satisfies only horizontal force equilibrium (Figure 3.3d).

With development of computer power it becomes possible to conduct iterative calculations that allow the inclusion of all inter-slice and equilibrium equations (Figure 3.3e, Morgenstern and Price, 1965). Two such methods are the Morgenstern-Price and Spencer methods. However, none of the described methods consider the development of strain and displacement in the soil. Therefore, local variations of these quantities cannot be considered and computed stress distributions are often unrealistic. This does not mean that the overall factor of safety is necessarily unrealistic. Some caution is required when stress concentrations exist due to slip surface shape or soil-structure interaction (Geo-Slope international, 2008a).

3.1.3 Finite element methods

To overcome the limitations of limit equilibrium methods, strain-displacement procedures have to be included. This requires the use of the finite-element methods such as the Janbu's generalized method or strength reduction methods (SRM).

Finite element methods calculate the stress of each element of a discretized slope according to the computed strain and displacement. Coupled within the limit equilibrium methods or the modified Mohr-Coulomb equations, it is possible to accurately calculate local factors of safety, effects of point loads or soil-structure interactions. This methods are used when the slope is very steep and has sharp edges or when geometry and boundary conditions are complex. However, in homogeneous, smooth slopes without significant stress concentrations, results can be very similar to those obtained with the limit equilibrium methods.

Finite element methods, e.g. SRM, are accurate and reliable in the calculations of the complex slope stabilities. However, they require high computational efforts and often they are highly sensitive to initial conditions and prone to errors due to the nonlinear solution algorithm. In the other hand, limit equilibrium methods are limited because of an inter-slice shear force assumption. Both methods have their own merits and limitations, and the use of one or other does not provide superior results (Cheng et al, 2007).

In natural slopes, where it is not easy to determine the stresses in the slope due to the complex processes that created the slope, the conventional limit equilibrium method is more adequate in spite of its limitations (Geo-Slope international, 2008a).

3.2 Pore water pressure

Soil can be considered granular material, as it consists of a collection of distinct macroscopic particles (Bagi, 1996). Most studies concentrate on dry granular media, however most of real soils have voids filled with water and gas, which modifies significantly soil behavior.

Liquid in granular media has different effects depending on its quantity relative to the soil bulk volume. When liquid fills only small pores (unsaturated soils), so called "apparent cohesion" develops within the media due to the capillary forces and surface tension of water, acting as negative pore water pressures. When the media is fully saturated (liquid is present in all pores), positive water pressures start to develop. Consequently, different mechanical effects appear depending mainly on the relative water content and particle size.

3.2.1 Soil Suction

Energy state of soil water in unsaturated conditions is described as suction. Total suction has two main components, matric and gravitational, while other suctions (osmotic) are comparatively smaller and they can be neglected (Fredlund and Rahardjo, 1993b, Richards, 1967).

Osmotic suction is the difference between the partial pressure of water vapor in equilibrium with pure water to that in equilibrium with the groundwater as result of different chemical contents. Osmotic suctions can be significant, but are normally neglected, as in the absence of salts or uniform unchanging concentrations the osmotic pressure is very low (Gardner, 1961, Richards, 1967).

Matric suction develops in consequence of tension between water and air surface leading to a pressure difference between the two fluids. The pressure difference is inversely proportional to the size of the pore where the water is located. Matric suction is usually defined as the difference between pore pressure of air and pore pressure of water (Fredlund and Rahardjo, 1993a). Since matric suction is dependent on the radius of the void (or pores), it is evident that the suction in a soil will be dependent on its particle size distribution.

Consequently, fine grained soils, which have small pores, can have large suction pressures, while coarse grained soils, which have larger voids, will tend to maintain lower suction pressures. In heterogeneous soils, water might have different pressures depending on which pores are filled with water. Large voids (with low matric suction) tend to empty first, and the smallest pores, the last. Thus a well known relationship between the matric suction and the water content of the soil is created, known as the soil water retention curve.

3.2.2 Mechanical effects of pore water pressure

In order to take into account the mechanical effects of the pore water pressure, the principle of effective stress is introduced into the classical Mohr-Coulomb equation of soil strength (Terzaghi, 1943). Since then, it has been widely used in soil mechanics problems, but only for the cases when soil is fully saturated or completely dry. The effective stress is the result of the difference between the normal stress and pore water pressure.

For unsaturated conditions, this principle was slightly modified to introduce the suction effect of soil moisture (Bishop, 1959, Lumb, 1962, Fredlund et al, 1978). The matric suction, net normal stress and shear strength interrelate to give a three dimensional failure surface for the Mohr-Coulomb failure envelope. In Figure 3.4 the effect of matric suction is shown as an increase in cohesion. However, this is merely a presentational effect.

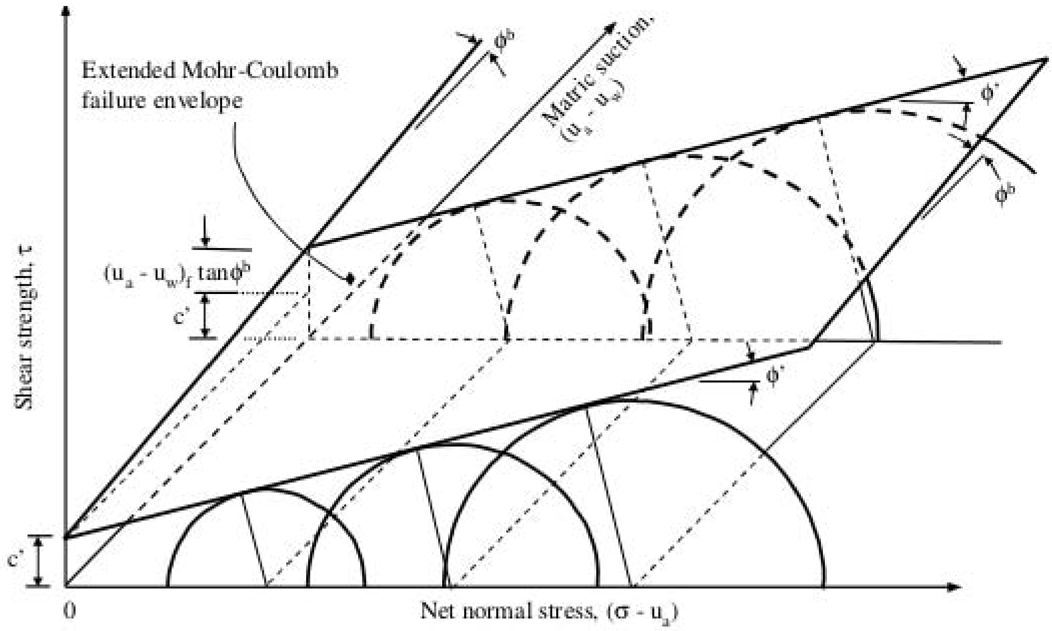

Figure 3.4. Shear strength failure surface for unsaturated soils (Fredlund and Rahardjo, 1993a).

For high soil water contents (thus, low values of matric suction) the negative pore water pressure provides a direct increase in effective stress. However, at lower soil water contents, the effect of suction on strength is reduced. Thus, the effective stress for unsaturated conditions is adjusted by the matric suction (Vanapalli et al, 1996), dependent on water content, and introduced to the Mohr-Coulomb criteria.

This modified Mohr-Coulomb equation allows introducement of the mechanical effects of pore water pressure which contributes to the increase of the shear strength of the soil. In case of saturated soils, with positive water pressures, the effective stress is decreased and the slope is destabilized. For unsaturated soils pore water pressures are negative, hence the effective stress increases and stabilizes the soil. Moreover, suction can cause changes in the soil cohesion and affect in the process of dissipation of excess pore pressures (see section “Slope stability analysis“ for details).

3.2.3 Soil water flow

Understanding water movement in the soil, from the geotechnical point of view, is essential for modeling and predicting pore water pressures, necessary for modeling behavior of soils subjected to load. The flow of soil water comprehends storage, infiltration, evaporation and saturated and unsaturated flow regimes.

Flow equations are used to calculate, at a given instance of time, the volumetric content of water in the soil. This water content is directly related to the pore water pressure. A graph, which presents this relationship is named water retention curve or soil water content curve (Figure 3.5), and it can be derived from measured data, or by using empirical functions that require less measurements (Van Genuchten, 1980, Fredlund and Xing, 1994, Aubertin et al, 2003).

The water content and soil water retention curve are not universal for drying and wetting, but are characterized by a hysteretic behavior (Bear, 1972). The relationship depends on whether soil is getting wet (adsorption curve) or dry (desorption curve), this is attributable to air bubbles trapped in soil. As shown in Figure 3.5, suctions are lower during adsorption. When desorption, or drying, begins again, suctions return to the desorption curve, thus it creates a closed loop (Bear, 1979).

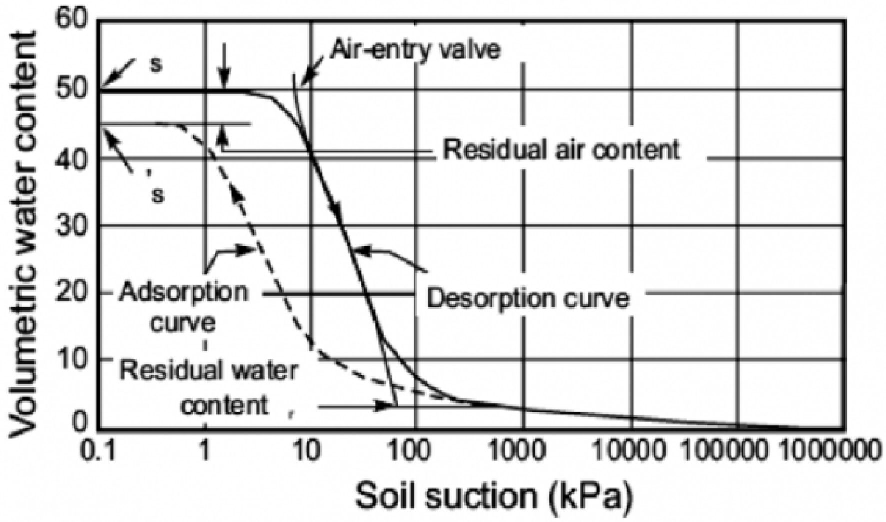

Figure 3.5. Soil water content curve (Fredlund and Xing, 1994).

In the past, analyses related to groundwater were concentrated on saturated flow. The phreatic surface was considered an upper boundary and any flow that may have existed in the capillarity zone above the phreatic line was ignored.

Saturated groundwater flow, described by Darcy's law, depends on hydraulic gradient and a constant hydraulic conductivity, an inherent soil property. In case of unsaturated flow, the hydraulic conductivity changes along with the water content and is lower when water content decreases. Coupling the shifting hydraulic conductivity with water flow laws is done within the Richard's equations for transient flow in unsaturated soils (Richards, 1931, see section “Vadose zone simulation“ for details). Adaptations were made to account for water vapor flow (Milly, 1982 and Wilson, 1990), and heat transfer (Edlefsen and Anderson, 1943).

Different methods can be used for estimating, if necessary, the relation between hydraulic conductivity and water content from the saturated hydraulic conductivity and soil water retention curve (Green and Corey, 1971, Van Genuchten, 1980, Fredlund and Xing, 1994).

3.3 Vegetation and its influence on slope stability

Soil water content in real slopes depend on the climatic-hydrological conditions. For mid and long term analysis, factors such as solar radiation, precipitation, infiltration, evapotranspiration and interception, have to be included in the stability analysis. Particularly, the impact of evapotranspiration on ground water flow is recognized to be of vital importance (White, 1932, Saxton, 1982).

Vegetation affects soil water content, due to transpiration, interception of precipitation, drainage effect and also it reduces pore water pressure. In the other hand, vegetation influence physical behavior of soils by mechanical effects of root reinforcement (Wu, 1976, Ziemer, 1981). Accordingly, it is widely recognized that vegetation can stabilize steep slopes (Rickli and Graf, 2009). However, the fact is not a simple statement. Biological parameters like number and variety of species, age of trees, the density of trees and treetops, depth of tree root system and "healthiness" of the forest are factors of influence (Rickli et al, 2001).

3.3.1 Atmospheric and Hydrological effects of vegetation

The most significant variables to quantify are the magnitude of surface infiltration and actual evaporation, which can be coupled with flow regime equations and given as the boundary conditions.

a. Potential and actual evaporation

Evaporation is the process whereby liquid water is converted to water vapour and removed from the surface. Energy is required to change the phase from liquid to vapour, which is provided by direct solar radiation and, to a lesser extent, ambient temperature. The driving force is the difference between the water vapour pressure at the surface and that of the atmosphere. Hence, solar radiation, air temperature, air humidity and wind speed are climatological parameters which should be taken into account.

Transpiration consists of the evaporation of water contained in plant, previously absorbed via the roots from the soil, and transferred to the atmosphere. It is governed by the same parameters that control evaporation and regulated by the stomata of the leafs. Evaporation and transpiration occur simultaneously, thus it is hard to separate them (Allen et al, 1998).

Thereby, evapotranspiration is a sink term that removes water from soil and has to be included in soil water balances and soil water flow in mid and long-term studies (Figure 3.6).

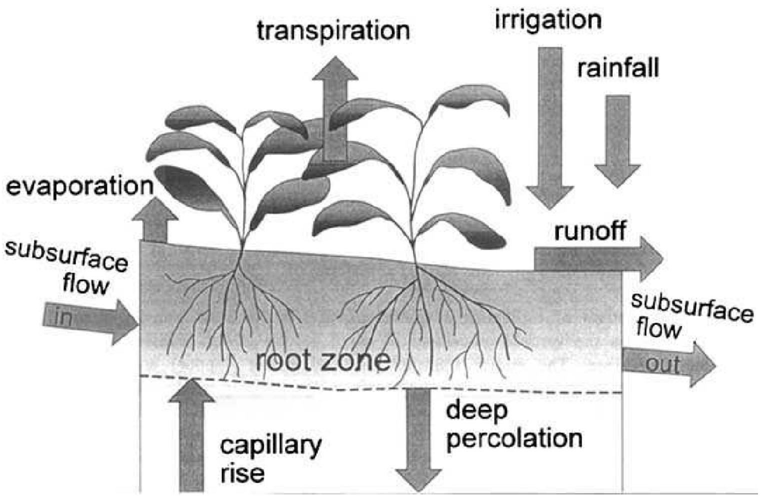

Figure 3.6. Soil water balance and flows (Allen et al, 1998).

Traditionally, evaporation modeling has been limited to methods based on potential evaporation, function of a turbulence mixing parameter multiplied by the difference between the saturation vapor pressure at the ground surface and that in the air above the ground (Penman, 1948). This approach assumes the ground surface is always saturated. Other existing methods also predict potential evaporation, but they are site specific (Thornthwaite, 1948, Priestly and Taylor, 1972).

For unsaturated soils, Wilson (1990) determined the relation between actual and potential evaporation, based on matric suction. The dryer is the soil, the energy state of the water is lower, thus more energy is required for the water to evaporate.

The most popular method for calculating the actual evaporation is the Penman-Wilson method. Potential evaporation equation is modified to account for net radiation, wind speed, and the relative humidity of both the air and soil surface allowing the calculation of the evaporation from an unsaturated soil surface (Wilson, 1990). Soil relative humidity is determinated by coupling moisture-water vapor and heat flows.

b. Plant transpiration

Vegetation plays a significant and dynamic role in the overall evapotranspiration process (Saxton, 1982). Water moves from higher to lower potential and from soil to plant stomata (Gardner, 1960). As plants draw water from the soil, the matric suction in proximity to the root zone increases, becoming increasingly more difficult for a plant to extract water from the soil until the process ceases completely at the wilting point (Tratch, 1996, Nyvall, 2002).

When plant suffer from water stress due to high evaporative demand or lack of available water, it reacts by closing stomata and reducing transpiration and slowing down its metabolism (Saxton, 1982). Under continued increase of water stress, the plant reaches its wilting point (usually, point when all the root zone reaches pore water pressures of -1500 kPa) resulting in leaf drop and tissue death.

Different plants have different transpiration rates as a function of growth stage, environment and maintenance (Allen et al, 1998). The process is included in evapotranspiration models as plant moisture limiting factor. This factor controls how much of the energy received by the canopy is actually used for transpiration.

Amount of energy received by the canopy depends on the surface that leafs cover, or leaf area index (LAI). Thus, LAI controls how energy at the surface is divided between that available for direct evaporation from the soil and that which is accessible for transpiration (Tratch, 1996).

Transpiration demand is supplied by root uptake. In general terms, three independent factors influence root water uptake: soil suction, root distribution, and potential transpiration (Fatahi, 2007, Fatahi et al, 2010, Rees and Ali, 2006). Root water uptake increases soil matric suction, leading to significant soil strength increase. Therefore, when giving appropriate root water uptake models, it is possible to include transpiration of plants in slope stability analysis (Rees and Ali, 2012).

Coupling is done by including the root water uptake as a sink term in the Richard's soil water flow equation in the root zone. This depends on root distribution that can be represented by a simple linear function of soil depth, or be a complex expression, including two or three-dimensional root distribution models. Different models depend on purpose of the user, computational power, and data availability (Willigen et al, 2012).

c. Infiltration and run-off

It is clear, that when rainfall penetrates into the soil, soil water content above the phreatic surface will increase (thus, reducing suctions in this area). The process includes diffusion of water due to differences in the moisture content, and also a pressure effect raised from gravity and pore water pressure difference (Philip, 1957a, Lumb, 1962).

With time, the diffusion process becomes insignificant compared to the pressure effect, thus it can be ignored. In unsaturated soils, infiltration rate can exceed saturated permeability as consequence of water storage capacity (Lumb,1975). Infiltration rate then reduces rapidly over time tending towards the saturated permeability. This implies that the process is controlled by porosity, changes in saturation of the soil and storage capacity.

During infiltration, a wetting front develops and moves downward. Near the surface, a thin layer of soil becomes fully saturated. Afterwards, in the transition zone, saturation drops to 80-90% (Lumb, 1962) and is approximately constant until the ‘wetting front’ is reached, at which, saturation drops sharply to the original value. The advancing wetting front causes reduction of suction and decrease in slope stability. The velocity at which the wetting front advances is greater when water storage capacity of the soil is small (Sun et al, 1998).

Soil remains unsaturated while infiltration rates are lower than saturated permeability, with suction pressures close to the ones when hydraulic conductivity is equal to infiltration rate (Rubin, and Steinhardt, 1963, Rubin et al, 1964, Kasim et al, 1998). If the infiltration rate exceed the saturated permeability, runoff occurs (Sun et al, 1998).

For modeling purposes, infiltration is treated as constant flux of water into the soil when the precipitation is higher than evapotranspiration demand during the time step considered. When positive pore water pressures start to develop, precipitation that exceeds saturated permeability is considered as runoff. To avoid unrealistic excessive positive pore water pressures, small time steps are necessary (Smith, 2003, Geo-Slope international, 2008b).

3.3.2 Mechanical Root reinforcement

Although root systems are designed to anchor the plant in the soil mass and provide access to nutrients and water, interactions between root and soil enable understanding and managing unstable slopes (Stokes et al, 2009). As shown in Figure 3.7, tree roots may penetrate the entire soil profile and anchor the soil into more stable substrate. In the other hand, lateral roots form a membrane that stabilizes the soil (Schmidt et al, 2001).

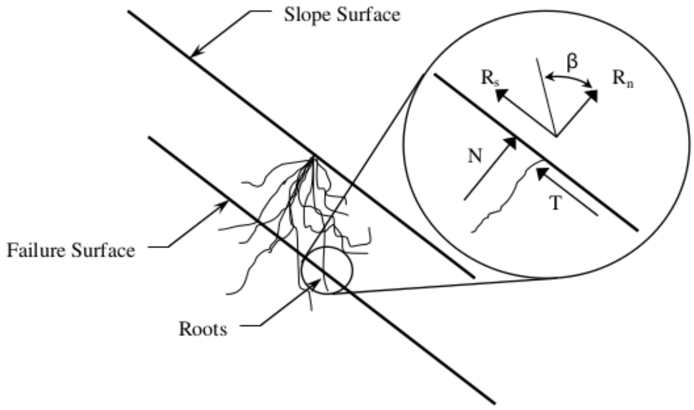

Figure 3.7. Root forces at the failure plane (Jordan, 2011).

Thick roots act like soil nails on slopes, reinforcing soil in the same way that concrete is reinforced with steel rods. Thin and fine roots act in tension during failure on slopes and if they cross the slip surface, provide a major contribution to slope stability (Stokes et al, 2009). In the other hand, thinner roots are significantly stronger than thick roots, due to changes in cellulose content. But it is suggested that differences in tensile strength have little influence on slope stability and that root distribution will affect slope stability more significantly (Genet et al, 2010).

First attempts to model root reinforcement were simple and based on a number of assumptions. Mechanical reinforcement was included as additional soil cohesion to the Mohr-Coulomb criterion. The cohesion was dependent on average tensile strength and the fraction of soil occupied by roots (Wu, 1976, Waldron, 1977). This model assumes that roots are perpendicular to the slip surface, all roots reach at once maximum tension and thus brake at the same time. Failure due to the pull-out cannot be accounted for.

Later on, a fiber bundle model was introduced which allows modeling a progressive failure of the roots, depending on its individual tensile strength and redistribution of loads (Pollen-Bankhead et al, 2010, Tiwari et al, 2013). Roots may also fail by slipping due to root-soil interface failure, or pullout. This creates the possibility that the load withstood by the roots is less than the sum of their individual strengths.

More detailed models take into account spatial distribution of root fibers and enable the pullout failure. Moreover, the model developed by Schwarz et al, 2010, allows modelling a progressive loading and failure of the roots. The model is very complex and assumes that root distribution is radially symmetric, it is not influenced by neighboring trees and lateral reinforcement is isotropic (Schwarz et al, 2012).

Root reinforcement models rely on a correct description of root distribution. But architectural characteristics are complex and rarely included in models. Some commonly used architectural characteristics are the root depth, the spatial distribution of root area and root density. Other architectural features, such as the branching pattern, root orientation and fractal characteristics, seem to also affect soil properties (Reubens et al, 2007). However, direct assessment of individual root characteristics in the field is very time consuming and difficult.

3.3.3 Other effects of vegetation

Other effects, which may negatively influence slope stability is surcharge of the mass of the vegetation and wind forces transmitted to the soil. Surcharge of vegetation only plays a significant role when large trees are present (diameter at breast height greater than 0,3 m) on the slope (Greenwood et al, 2004). The weight of a typical tree, 30 m high and 80 cm breast height diameter, might vary from 10 to 15 kN.

Early simple models, include surcharge of trees as a distributed surface load (Hammond et al, 1992), assuming the site has homogeneous properties. In reality, tree surcharge is point load, thus, effects can spatially vary depending on the position of a single tree. This method is a good way to identify the mechanical effects of trees in a regional scale (Kim et al, 2013), but more data and, perhaps, a different model is needed for detail, local studies.

Other methods, distribute the weight of the tree through the root zone, by increasing the density of the soil by an amount corresponding to the average load from the trees, divided by the root plate area (Simon and Collison, 2002). This can result an increase of 2-3 kN/m^3 of the soil unit weight.

The effect of the presence of the tree on overall slope stability depends on its position. A tree growing at the toe of a slope, increases stability and may increase the factor of safety up to 10%. Conversely, the same tree at the top of the slope, may decrease stability, reducing the factor of safety up to 10% (Greenwood et al, 2004).

Influence of wind is significant when considering the stability of a single tree and could be critical on slopes of marginal stability. However, in fully forested slopes, where clusters of trees protect themselves, wind forces are not significant compared to other parameters which may contribute to the slope instability.

3.4 Numerical modeling

Numerical modeling is a mathematical simulation of real physical processes. It is a purely mathematical instrument different from physical modeling. The use of mathematics to model, allows better understanding of the underlining physical processes.

Numerical models are relatively easier, safer and faster to set up than real physical models. Moreover, a numerical model can be used to investigate a wide variety of scenarios, what otherwise would be impossible, since there is a limitation due to scaling effects or safety issues during the experiments. Obtaining results at any location of the experiment is possible.

Numerical models are limited to the correct use. It is necessary to formulate and adjust appropriate parameters and boundaries as well as to understand the mathematical limitations, due to complex algorithms and relations. Some limitations result from the capabilities of hardware and formulation used, since they are developed under specific conditions.

In summary, “a mathematical model is a replica of some real-world object or system. It is an attempt to take our understanding of the process (conceptual model) and translate it into mathematical terms” (National Research Council, 1990). Modeling is useful for quantitative predictions, to compare alternative solutions, identify governing parameters and understand processes.

Equations describing physical processes can be very complex and may not have a simple analytical solution. Non-linear, complex equations require iterative process to solve them, within a given tolerance. Different methods, such as the finite element method, solve differential and partial differential equations numerically, for a given space discretization, boundary and initial conditions. This allows finding an approximated solution for the numerical problem. The finite element method is the most common technique for solving highly non-linear flow equations.

4 Research methods

In the previous sections, and overview and literature review of the different factors that influence slope stability is presented. In this section a more detailed description of the specific methodology used in this study is shown.

All numerical simulations are made with the commercial software *Geo-Slope 2007*. This software package includes vadose zone and slope stability analysis modules. The methodology adopted in this project, therefore, is accommodated to the software work-flow. This includes, slope definition, material properties and boundary conditions. A procedure of the calculations is as follows: first simulation of unsaturated water flow (vadose zone) is made in cases where it is needed. Then, with the computed pore water pressures, slope stability analysis is done.

4.1 Mathematical background

In this section the specific theory and mathematical equations used are explained. This includes vadose zone simulations and slope stability analysis.

4.1.1 Slope stability analysis

For slope stability analysis, the widely used limit-equilibrium method is the basis for calculation. The methodology calculates two different factors of safety, one based on the equilibrium of forces and other one based on momentum equilibrium.

Factor of safety (Eq. 1) is the relation between stabilizing forces (soil strength) and mobilizing factors (soil stress). In other words, factor of safety is the proportion of the soil strength, which should be modified to reach a limit-equilibrium state along a slip surface.

[redacted] Eq. 1

Soil strength is described by Coulomb's equation. Through effective stress analysis, shear strength is defined as:

[redacted] Eq. 2

Where:

s = shear strength.

c' = effective cohesion.

Φ' = effective angle of internal friction.

σ_n = total normal stress.

u = pore-water pressure.

Limit equilibrium methods require a known or estimated slip surface (Figure 4.1) This surface can be circular, planar or of complex shapes. The sliding mass is divided into slices, and for each, force or momentum equilibrium is computed, depending on the method used. The most complex models, assume both equilibriums, and take into account forces within and between slices (inter-slice forces).

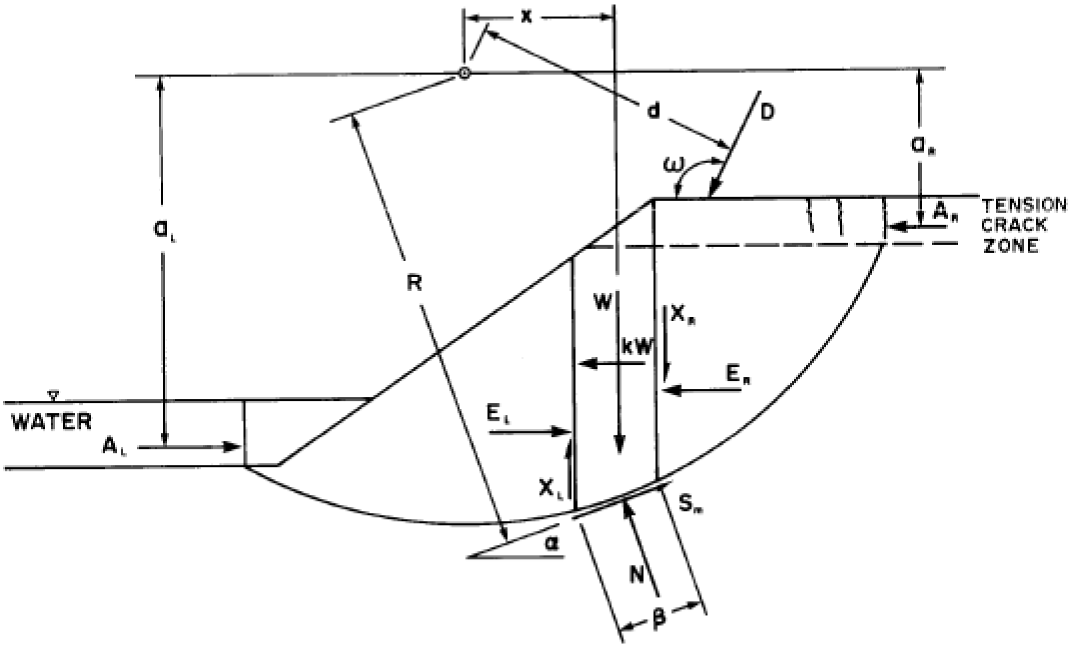

Figure 4.1. Diagram of forces in a slice of a slope. (Geo-Slope international, 2008a).

Applying Eq. 2 and momentum equilibrium with respect to the center of rotation, factor of safety becomes:

[redacted] Eq. 3

And for force equilibrium:

[redacted] Eq. 4

Where:

W = the total weight of a slice.

N = the total normal force on the base of the slice.

D = an external point load.

kW = the horizontal seismic load applied through the centroid of each slice (not present in this project).

R = the radius for a circular slip surface or the moment arm associated with the mobilized shear force.

A = the resultant external water forces.

d, a = distances from the center of rotation to point load and resultant of external forces respectively.

f, x = perpendicular offset of the normal force from the center of rotation and horizontal distance from the center line of each slice to the center of rotation.

e = vertical distance from the centroid of each slice to the axis.

β = base length of each slice.

ω = the angle of the point load from the horizontal plane.

α = the angle between the tangent to the center of the base of each slice and the horizontal plane.

The normal force at the base of each slice is defined by Eq. 5

[redacted] Eq. 5

The inter-slice forces have two components: E, horizontal or normal component (Eq. 6) and X, vertical or shear component (Eq. 7). The relation between this two components can be considered to be the same in all slices (Spencer method, 1967), or it can vary (Morgenstern and Price method, 1965) In this project, the Spencer method is used.

[redacted] Eq. 6

[redacted] Eq. 7

Where:

F = factor of safety.

λ = the percentage (in decimal form) of the function used.

f(x) = inter-slice force function representing the relative direction of the resultant inter-slice force.

E = the horizontal inter-slice normal forces. Subscripts L and R designate the left and right sides of the slice, respectively.

X = the vertical inter-slice shear forces.

The value of λ is optimized, so the factors of safety from momentum and force equilibrium are equal. The fact that inter-slice forces and normal forces depend on the value of factor of safety, requires an iteration process for the calculation.

In most engineering cases, only positive pore water pressures are considered during safety calculations. In reality, when soil is unsaturated, negative pore water pressures, or suctions, appear. When suctions need to be taken into account, Eq. 2 is modified to Eq. 8 (Vanapalli et al, 1996). Eq. 3, Eq. 4, Eq. 5 and Eq. 6 are accordingly modified to add the suction term.

[redacted] Eq. 8

Where u_a is pore air pressure, u_w pore water pressure, θ_w is the volumetric water content, θ_s is the saturated volumetric water content and θ_r is the residual volumetric water content .

4.1.2 Vadose zone simulation

Saturated groundwater flow is described by Darcy's law (Eq. 9) For unsaturated conditions, partial differential equations have to be used, such as Richard's equations (for two dimensions, Eq. 10, Richards, 1967 and Wilson, 1990).

[redacted] Eq. 9

[redacted] Eq. 10

Where:

q = the specific flux.

i = the gradient of potential.

P = pressure.

P_v = vapor pressure of soil moisture.

m_v = slope of the volumetric water content function.

K_x = hydraulic conductivity in the x-direction.

K_y = hydraulic conductivity in the y-direction.

Q = applied boundary flux.

D_v = vapor diffusion coefficient (Wilson, 1990).

y = elevation head.

ρ = density of water.

g = acceleration due to gravity.

t = time.

Soil moisture also depends on water vapor pressure which depends on temperature. Therefore, the standard Fourier equation for conductive heat transfer (Eq. 11) is needed when temperature changes are considered. Water vapor pressure makes it possible for both partial differential equations to be fully coupled.

[redacted] Eq. 11

Where:

L_v = latent heat of vaporization.

T = temperature.

ρc = volumetric specific heat value.

K_{xy} = thermal conductivity in the x and y directions.

V_{xy} = the Darcy water velocity in x and y directions.

Q_t = applied thermal boundary flux.

λ_t = volumetric heat capacity.

In order to solve Eq. 10 and Eq. 11, the saturated vapor pressure of water in air curve is needed (Edlefsen and Anderson, 1943). The differential equations are solved with the finite element technique, for which spacial and temporal discretization is required.

When atmospheric conditions have to be taken into account, boundary fluxes are used to add or remove water from the soil or change soil temperature due to external factors.

a. Actual evaporation

Evaporation is calculated through Penman-Wilson formulation (1990):

[redacted] Eq. 12

$$E_a = f(u) P_a (B - A) \quad \text{Eq. 13}$$

$$f(u) = 0{,}35 (1 + 0{,}15 U_a) \quad \text{Eq. 14}$$

Where:

AE = actual vertical evaporative flux (mm/day).

Γ = slope of the saturation vapor pressure versus temperature curve at the mean temperature of the air (kPa/ºC).

Q_r = net radiant energy available at the surface (mm/day).

υ = psychrometric constant.

f(u) = function dependent on wind speed, surface roughness, and eddy diffusion.

U_a = wind speed (km/h).

P_a = vapor pressure in the air above the evaporating surface (kPa).

B = inverse of the relative humidity of the air = $1/HR_A$.

A = inverse of the relative humidity at the soil surface = 1/HR.

Eq. 12 accounts for net radiation, wind speed, and the relative humidity of both the air and soil surface when calculating the evaporation. For saturated soils, this formulation reduces to the conventional Penman formulation (Penman, 1948).

b. Temperature

The surface temperature may be estimated (for conditions where no snow pack is present) with the relation formulated by Wilson (1990)

[redacted] Eq. 15

Where T_s is the temperature at the soil surface (ºC) and T_a, temperature of the air above the soil surface (ºC). Temperature is increased by energy that was not consumed in the evaporation or transpiration process.

c. Transpiration

Transpiration depends on root distribution (density and depth), soil moisture, potential evaporation and stress state of the plant. Lack of water available for the plant causes the closure of the stomata and reduction of the transpiration (in the calculations this is defined by the plant moisture limiting factor).

Free energy is distributed between actual evaporation on soil surface and transpiration. This distribution depends on the leaf area index (LAI). The leftover energy increases soil surface temperature. This project uses Eq. 16, Eq. 17, Eq. 18 and Eq. 19 to calculate the adjusted actual evaporation and actual plant transpiration(Tratch, 1996, Allen, et al, 1996 and Geo-Slope international, 2008b).

[redacted] Eq. 16

[redacted] Eq. 17

[redacted] Eq. 18

[redacted] Eq. 19

Where:

AE = actual evaporation.

PT = potential transpiration.

PE = the potential evaporation.

LAI = leaf area index for the day in question.

AT = the actual nodal transpiration.

R_T = total thickness of root zone.

R_n = the depth to the considered node.

A_n = the nodal contributing area of the considered node.

PML = plant moisture limiting function value at the current nodal soil negative pore water pressure.

PRU = Plant root uptake function (depends on root distribution model).

d. Infiltration and runoff

In rainy days, actual evaporation is subtracted from the precipitation. If the result is positive, infiltration rate is calculated by applying the excess precipitation as positive surface flux boundary condition in Richard's equations.

If the calculated infiltration rate is smaller than precipitation intensity, the excess of precipitation is considered as runoff (Eq. 20). Runoff can be pounded in sink holes at the surface and re-infiltrated in the next time step. In this project, it is assumed that flat areas do not accumulate water.

$$Runoff = Precipitation - AE - Infiltration \quad \text{Eq. 20}$$

4.2 Experimental design

Different scenarios are tested to investigate mechanical and hydrological effects of vegetation. Studied factors are: soil type, presence of impermeable rock layers, different root architectures and various atmospheric conditions.

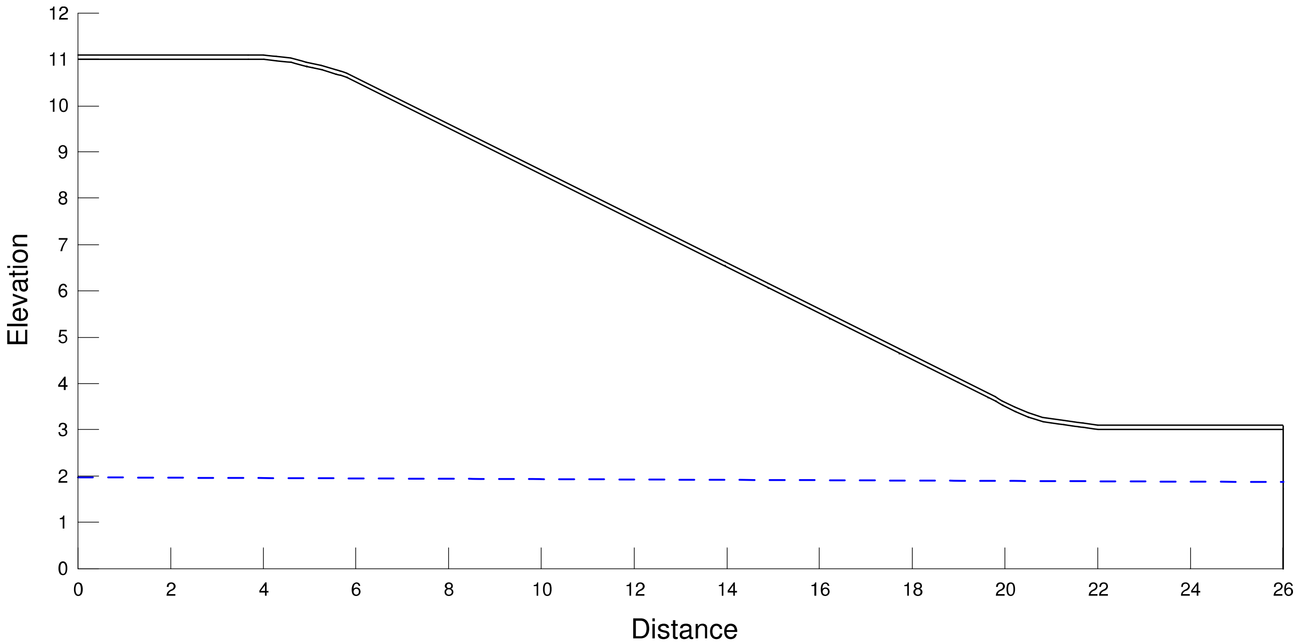

Figure 4.2. Slope design and water table of the scenario without an impermeable rock layer. All dimensions are measured in meters.

Considering a 1H / 2V slope (approximately 26º) two scenarios are built: one with an impermeable rock layer 1,35 m parallel to the surface, and other one slope without this impermeable layer (Figure 4.2). In the first scenario an initial water table is considered to be situated 0,1 m above the impermeable layer, and in the second scenario is 1,25 m deep in the lowest part of the slope.

Depending on type of vegetation, different root morphology has to be considered. Average root distribution can be approximated with the geometrical shapes as shown in Figure 4.3 (Köstler et al, 1968 and Kokutse et al, 2006).

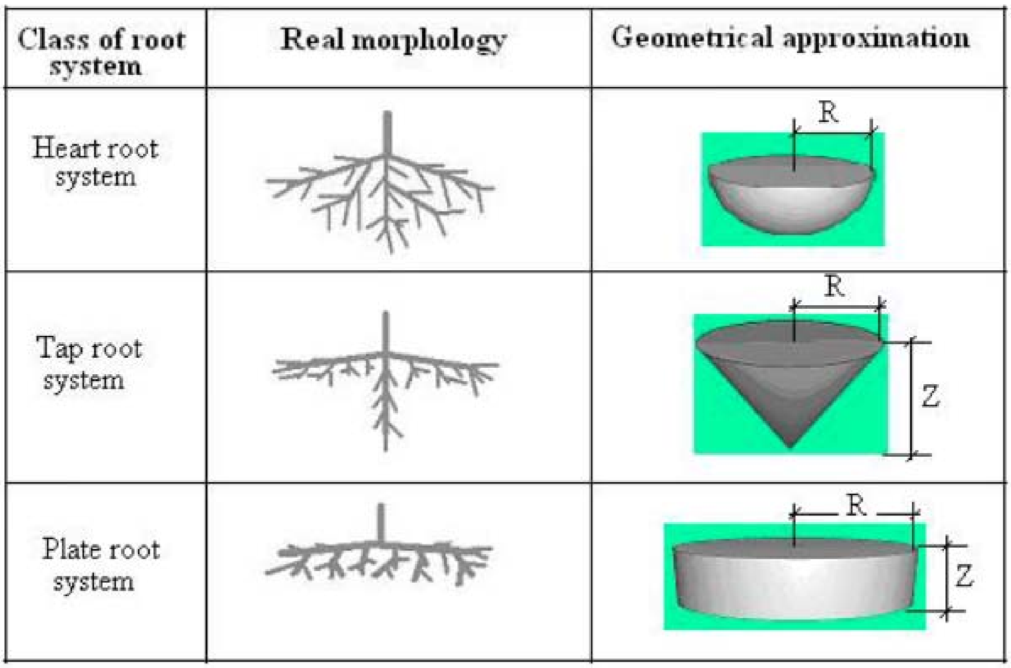

Figure 4.3. Geometrical approximations of roots systems according to Köstler's classification (Kokutse et al, 2006).

Three types of root morphology are considered: uniform 0.5 m deep plate root system, 2 m diameter and 1,5 m deep cylindrical system, and 1,35 m radius semi-spherical system. In addition to the three types of vegetation, a slope with no vegetation as a reference is also analyzed. A 10 cm of a weathered surface layer with higher hydraulic conductivity is defined in all the models (Figure 4.4).

To account for the effects of soil properties, each scenario is tested for sand and clay soils. All these variations lead to 8 different calculation cases.

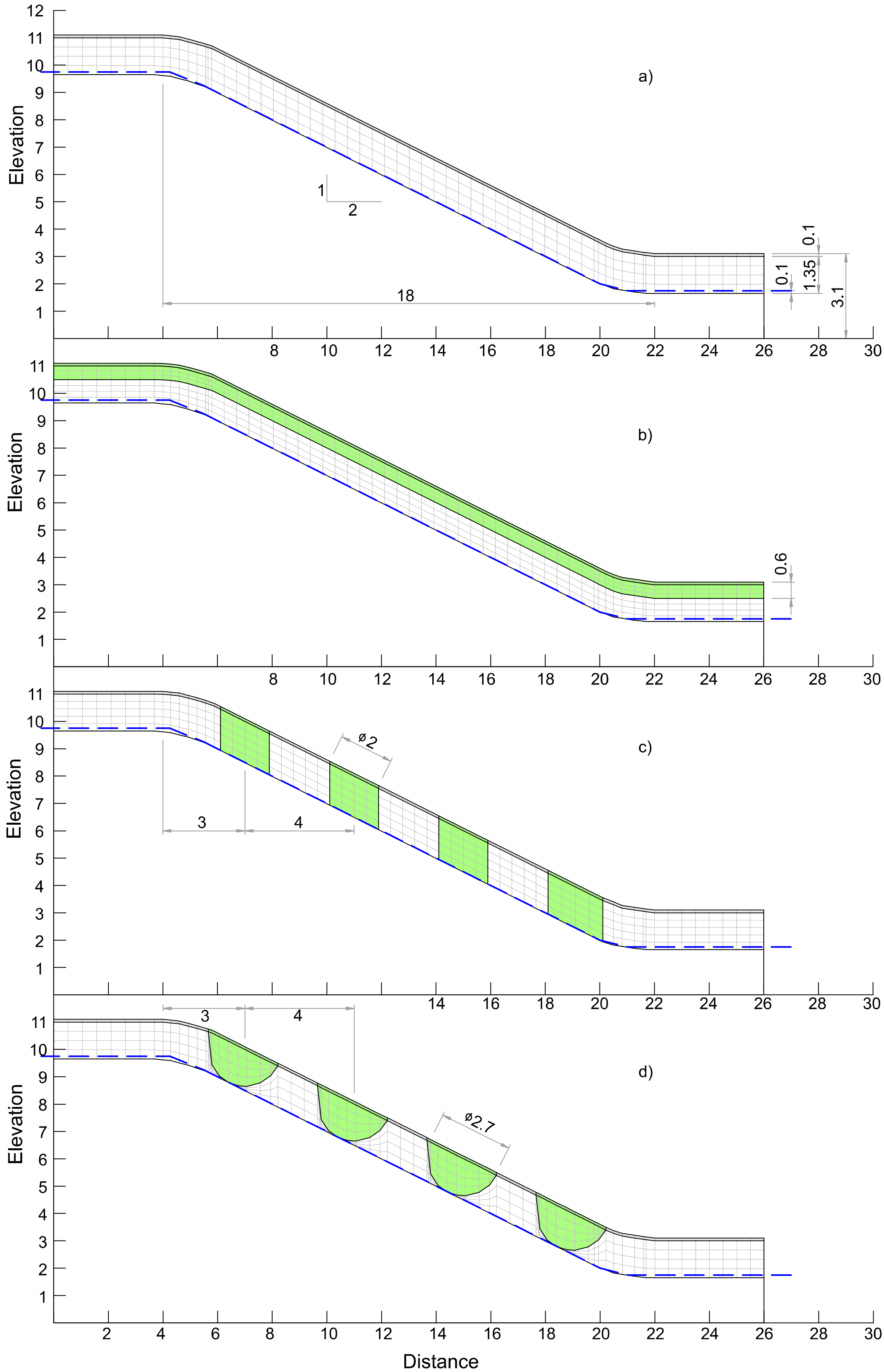

Figure 4.4. Slope models with an impermeable layer: a) no vegetation, b) uniform vegetation layer, c) cylindrical vegetation layer and d) semi-spherical vegetation layer. All dimensions are in meters.

Firstly, scenarios with and without the impermeable rock layer are simulated without taking into account atmospheric conditions nor negative pore-pressures. Later, matric suctions and sets of atmospheric conditions are added to study hydrological effects. To study rainfall-induced-landslides, two different sets of atmospheric conditions are used, one with regular atmospheric conditions from Paris, and other with an extreme event from Vienna (Figure 4.5).

For each of the two soil types, sand and clay, there are 8 cases where matric suctions are not taken into account: 3 models with different root architectures plus the non vegetated control slope, simulated for two scenarios: with the presence or absence of an impermeable rock layer. Other 16 cases take into account atmospheric conditions and matric suctions, 8 of which correspond to the extreme precipitation event and the other 8 to regular precipitation regime, all of them with a rock layer.

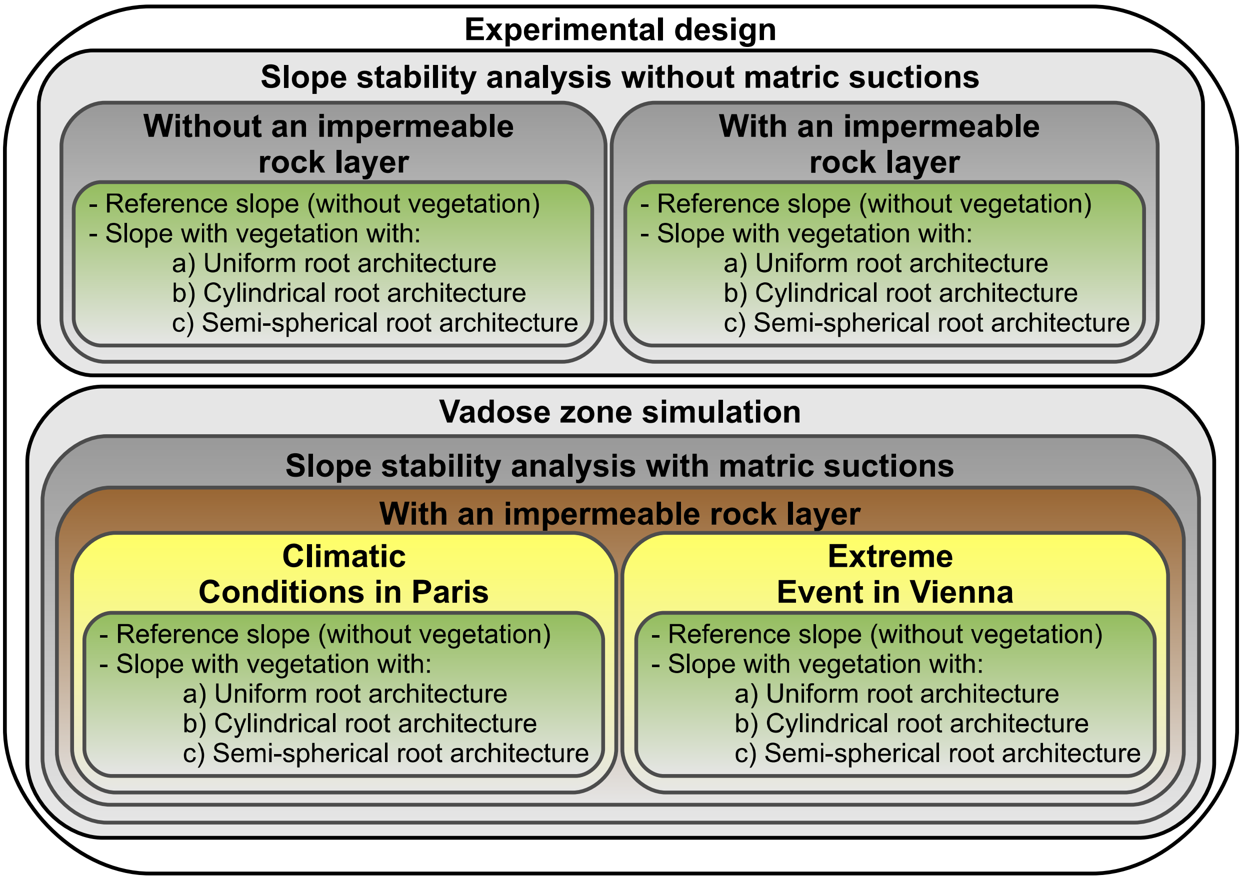

Figure 4.5. Diagram of the experimental design. The experiment is done with sand and clay slopes.

The duration of the extreme event simulations is 15 days and the regular climatic conditions simulations 40 days. For each day slope stability is calculated.

Considering both materials, in total, there are 16 slope analyses, where the unsaturated conditions are not taken into account. In the other hand, 440 slope analyses correspond to calculations where suctions are considered.

4.3 Material properties

Two different materials are used in the simulations, sand and clay. Mechanical properties of these soils are modified when roots are present. In the second scenario, an impermeable rock layer and a weathered surface layer are also added.

4.3.1 Mechanical properties

Average values of mechanical properties of sand and clay are used (Table 4.1). A minimum cohesion of 1 kPa for sand is assumed to avoid numerical and convergence problems. Extra cohesion in soils with roots represents the tensile strength of roots according to the classical method proposed by Wu (1976), best suited for the software used in this project.

Table 4.1. Mechanical properties of each soil type.

Material	Young Modulus	Poison's ratio	Angle of friction	Cohesion	Density
[-]	E [kPa]	υ [-]	φ [º]	C [kPa]	ρ [kg/m³]
Sand	2000	0,30	30	1	1631
Clay	6000	0,25	20	8	1300
Clay with roots	6000	0,25	20	18	1300
Sand with roots	2000	0,30	30	11	1631

Tensile strengths of roots are typically measured with direct shear tests (Turmanina, 1965, Burroughs and Thomas, 1976 and Gray, 1978). Semi-empirical equations transform tensile strength to cohesion (Hausmann, 1978 and Wu, 1984). For this project, an average value of 10 kPa for additional cohesion provided by roots is applied.

4.3.2 Hydrological and thermal properties

Due to the energy state, water behaves differently depending on the amount, size and connectivity of the pores, through which it flows. In Figure 4.6 typical curves for clay and sand of water content in relation to matric suctions are shown.

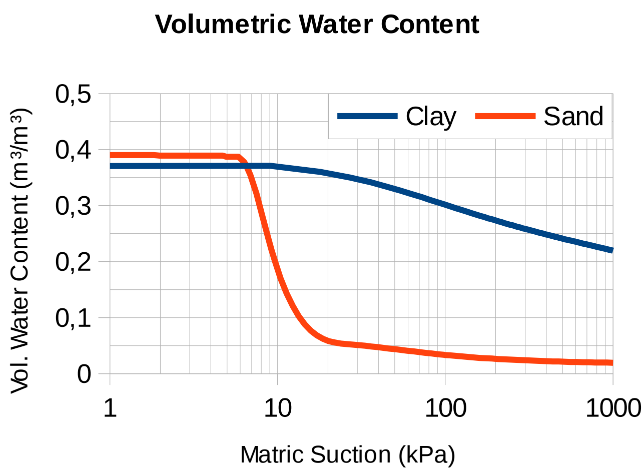

Figure 4.6. Volumetric water content of clay and sand.

Hydraulic conductivity represents how fast the water moves through soil.Figure 4.7 shows values for clay and sand which are taken into account in this thesis. The fastest flow happens when the soil is saturated (saturated hydraulic conductivity, *ksat*).

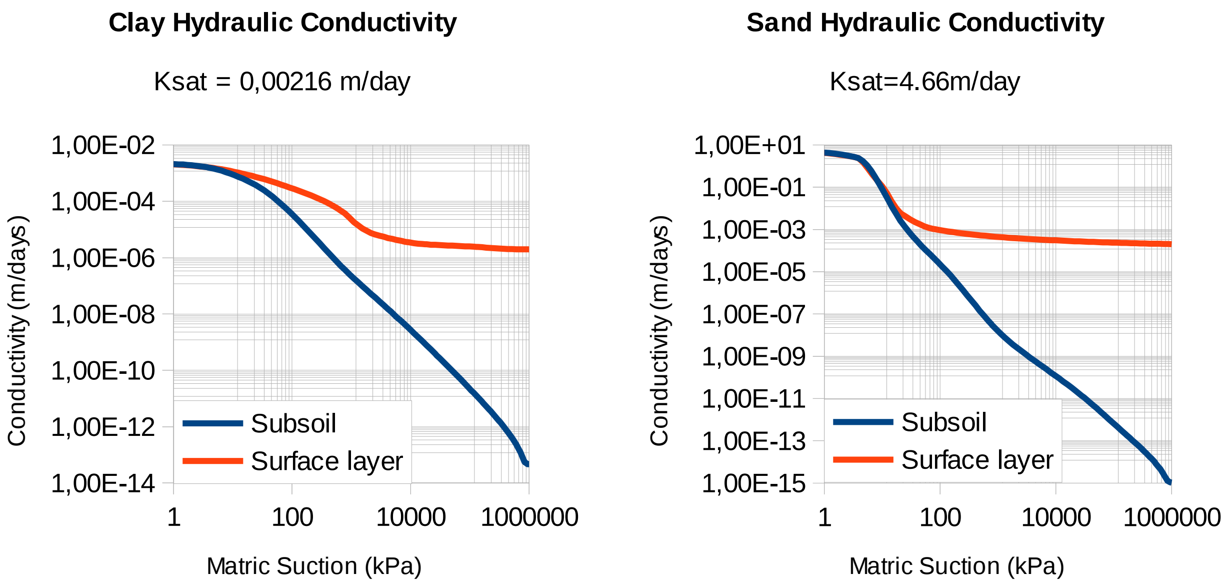

Figure 4.7. Hydraulic conductivity of clay and sand in the surface layer and subsoil.

Surface layer, first 10 cm of soil, is weathered, thus water flows faster and different values of unsaturated hydraulic conductivity are considered. In the other hand, possible numerical problems would cause the acceleration in drying of the top layer, extremely slowing down water flow in this region. Allowing higher conductivity in the top layer, more realistic flows and infiltration rates are calculated.

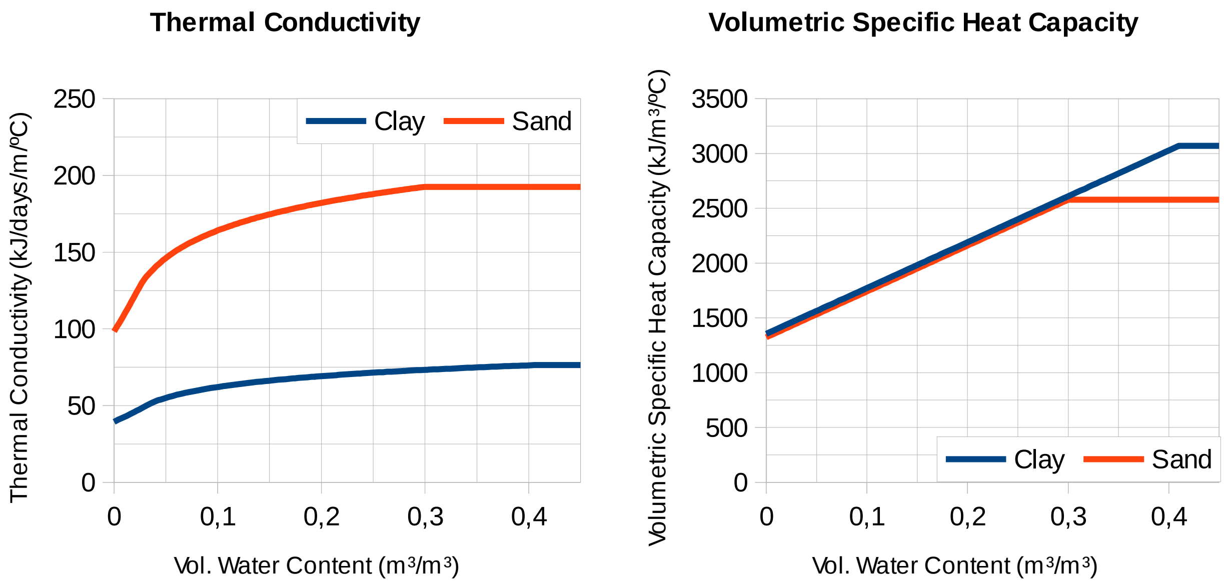

Figure 4.8. Thermal conductivity and heat capacity of clay and sand.

Water can also move as a gas phase. Rates of evaporation-condensation of soil water and diffusion of water vapor is calculated depending on temperature. Heat transport and storage varies with soil water content and soil type. For higher accuracy, soil temperature change is allowed and values of thermal conductivity and heat capacity of clay and sand are needed (Figure 4.8).

4.4 Boundary conditions

Simulation of soil water flow in unsaturated conditions requires an introduction of new boundary conditions. Two of them are constant hydraulic head of water on the right and left sides of the slope and a third one stands for climatic conditions on the slope surface.

a. Hydraulic boundary conditions

In the upper and lower part of the slope, a constant head of water pressure, 1,35 m deep form the surface at each side is set as a lateral boundary. Water accumulation due to "bathtub-effect" is avoided, and a constant soil water flux enables numerical procedures to work properly. To minimize influence of boundaries on slope stability, the lateral limits of the mesh that forms the slope, are extended out several meters during the simulation.

b. Climatic boundary conditions

Values of precipitation, wind speed, relative humidity and temperature from Paris are used for the mid-term simulations (Figure 4.9). Simulation starts on May 1996 and lasts 40 days. Solar radiation is calculated knowing the latitudinal longitude of Paris is 48,4º. Excessive, non realistic suctions on the surface layer develop during calculations. To avoid it, an extra 1 mm of precipitation each day is added to the data set.

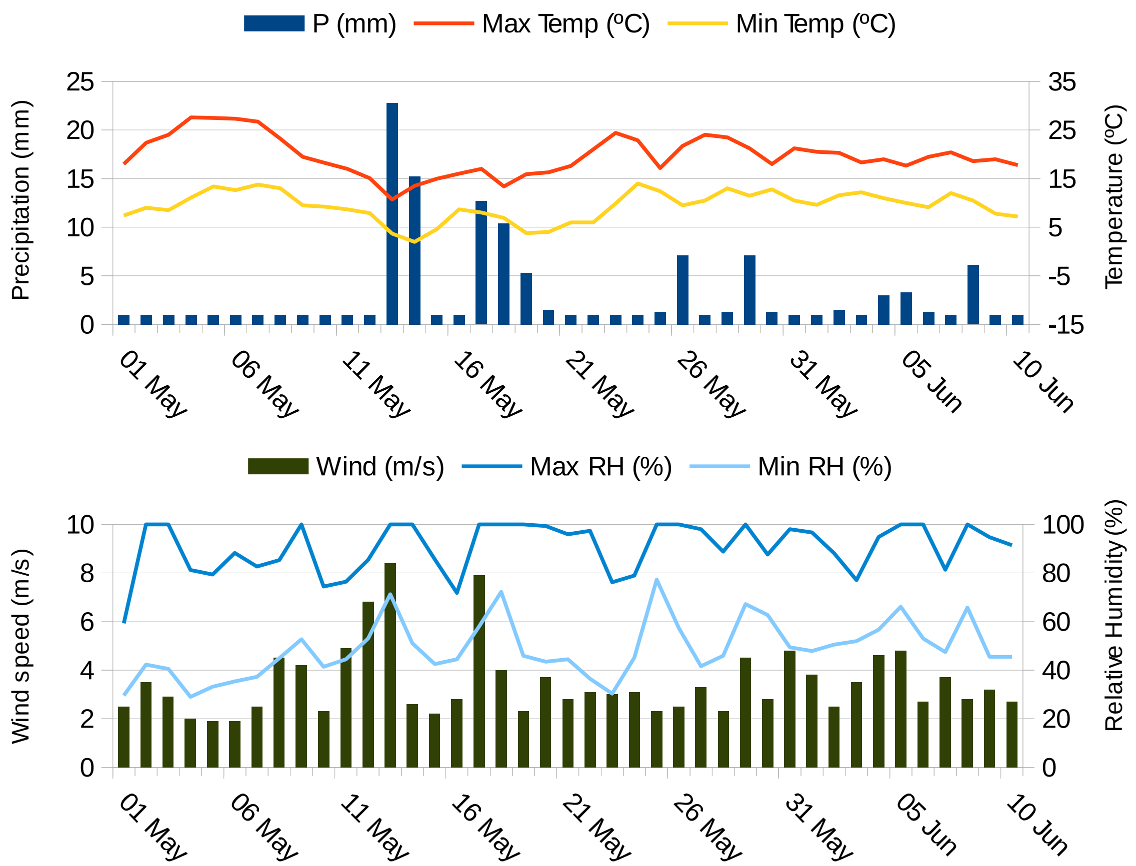

Figure 4.9. Climatic data from Paris (France) for the simulation period of 40 days.

In 2013 severe floods occurred in Austrian Danube basin, caused by extreme precipitation. From the 29th of May to the 4th of June, 232 mm of total precipitation were observed in Lofer, 244 mm in Kössen (25 km north- west of Lofer) and 270 mm in Samerberg (40 km northwest of Lofer). The northern ridge of the Alps in Austria (Tirol, Salzburg and Upper Austria), rain gauges records exceeded 300 mm during this time period (Blöschl et al, 2013). Data of this event is used as an example to simulate slope stability under extreme rainfall.

In this project, the event duration is 15 days. In the first 5 days, no precipitation is assumed to occur in order to allow the model to reach an equilibrium. Then for 5 days extreme precipitation is applied and for the last 5 days, again no rainfall is assumed, to allow drainage (Figure 4.10). Other climatic data, such as temperature and wind conditions, are assumed Vienna's climatic conditions in the same time period (data from Vienna Schwechat, source *http://www.wunderground.com*). Also in this case, an extra 1 mm of precipitation is added in order to avoid numerical problems.

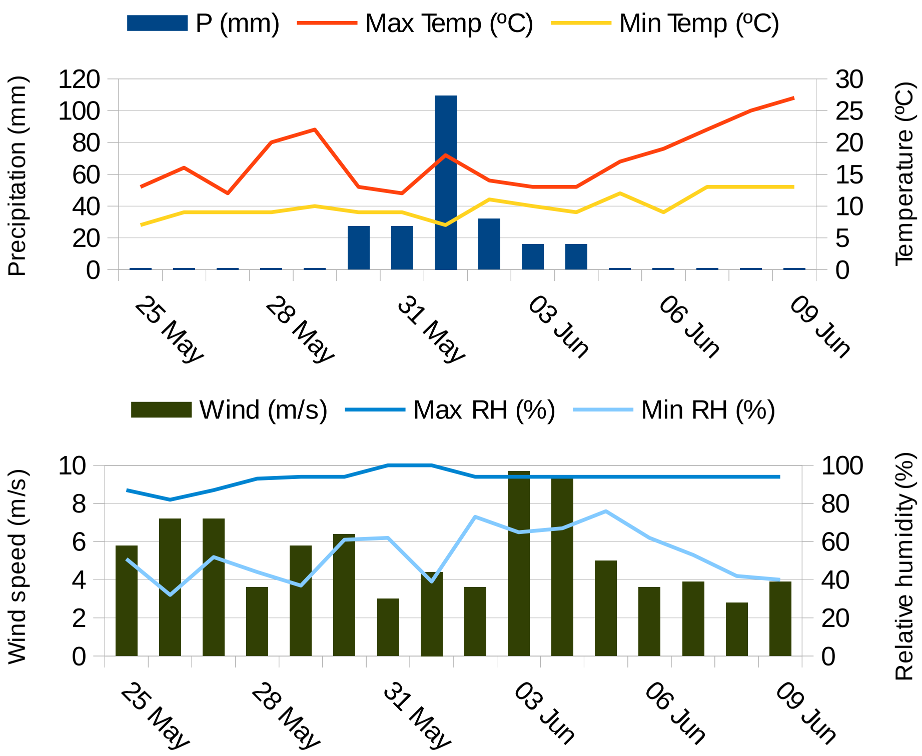

Figure 4.10. Climatic data for the extreme event. Temperatures, wind speed and relative humidity correspond to Vienna's climatic data (latitude 47,33º) in the same time period.

c. Vegetation boundary conditions

In areas where vegetation is present, climatic boundary is affected by vegetation characteristics which determinate transpiration and evaporation. Growth of vegetation is not considered in this project, and all its characteristics remain constant through time.

The amount of the available energy used for transpiration or evaporation depends on the leaf area index (LAI). A well covered surface with a LAI of 2 is assumed. Other factor, which has to be determined, is plant capacity to regulate transpiration when soil water is not available. It is usually assumed, that when water pore pressures reach -1500 kPa, plants stop transpiration (wilting point is reached), and when it is higher than -100 kPa, plants don't limit transpiration (Figure 4.11).

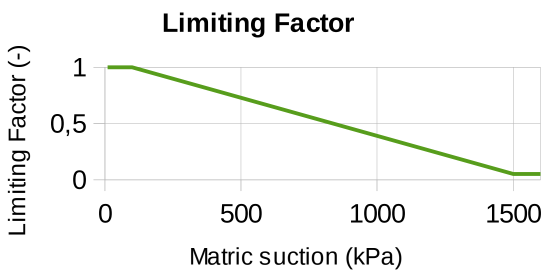

Figure 4.11. Limiting factor of plant transpiration.

Transpiration is supplied by root water uptake, therefore, drying of the soil is dependent on the root depth and distribution. Each root architecture is represented by different root distribution models. The plate root system has a constant root depth (counting the surface layer) of 0,6 m and has a rectangular distribution, consequently water uptake is uniform in the root zone. The cylindrical system also has a rectangular distribution and is approximately 1,5 m deep.

In the semi-spherical system, the bottom of the root zone reaches the impermeable layer and root distribution is assumed to be triangular, meaning that the surface has higher root density and water uptake than at maximum root depth (see Figure 4.4).

4.5 Other considerations

Numerical simulations are sensitive to initial conditions and in the case of transient analysis, where variables change over time, an accurate time step has to be chosen.

4.5.1 Initial conditions

For the vadose zone simulation, initial soil temperature and pore water pressures have to be assigned to the model. In all simulations, soil temperature is assumed to be 10ºC and once calculations begin, it is allowed to change accordingly. Initial pore water pressures are set by the water table. The phreatic level is set up 10 cm above the impermeable layer (Figure 4.4), and is fed by the hydraulic boundary conditions.

If during the calculations, when rainfall is applied, soil moisture capacity is not large enough to absorb the total amount of precipitation, and runoff is produced, then excess water is not allowed to pond on flat areas and is lost.

The limit-equilibrium method used for slope stability calculations. requires a set of values representing potential slip surfaces, which can be later optimized. In sand usually shallow planar slip surfaces develop. In order to define a position of the slip surface in sand slope, a net with 24 nodes is constructed (6x4) with 3 angles of the entrance and exit of the failure line. Factors of safety for each combination are calculated and the most unfavorable conditions are chosen to define a failure surface. Clay has circular slip surfaces. Four radius are tested in each of the 10 entrance and exit points.

In scenarios, in which suctions are considered, computed negative pore pressures are used in the calculations of slope stability. Otherwise, a water table is used to estimate pore water pressures distribution. In the scenario with an impermeable layer, the same phreatic level used in the vadose zone simulations is set up. In the other scenario (cases without an impermeable layer) a water table with a 4 ‰ slope is present at 1,35 m deep in the lowest part of the model (Figure 4.2).

4.5.2 Time steps

In transient analysis, appropriately chosen time steps are of special importance. Time scale can influence results, and depending on the objective, its adequate precision is required. For mid-long term studies, daily values are sufficient. Also, in order to minimize the influence of initial conditions, simulations begin few days prior to the event studied.

Climatic data is presented with daily values, but during calculations of water flows, smaller time steps are required. It is assumed that climatic data within a day, can be extrapolated following a sinusoidal pattern. Adaptations of the time steps are done automatically by the software, but only daily values are recorded for a later use in slope stability analysis.

4.5.3 External forces

In slope stability, external forces such as extra loads or seismic phenomena can lead to slope failure. The effect of external forces can vary depending on the location of application. Assessment of slope failure requires the evaluation of these situations.

It is not the objective of this project to study the effect of such forces. Therefore, external loads, such as weight of trees or forces transferred from wind are not considered.

4.5.4 Mesh

Water flow differential equations are solved through the finite-element method. Thus, the calculations domain has to be divided into finite elements. In this project, the mesh is only constructed in the scenarios where the impermeable layer is present and where vadose zone simulations are made.

The constructed mesh is quadrilateral, subdivided into sections of 0,5 m wide. The surface layer is subdivided vertically into two finite elements, and the rest of the layers into four. These subdivisions are equal in all vegetated and non-vegetated areas to ensure good connectivity of the mesh and the continuity of the domain. See Figure 4.4 for details.

5 Results

5.1 Slope stability analyses without accounting for negative pore water pressures

Factors of safety (FOS) for each scenario and case, where negative pore water pressures are not taken into account during calculations are listed in Table 5.1. There is a clear influence of the soil material: clay slopes, with large cohesion, have larger FOS values than sand slopes, for which stability mostly depends on internal friction.

Table 5.1. Factors of Safety of slopes calculated without accounting for negative pore water pressures.

Material	No rock layer present		With a rock layer	
	Clay	Sand	Clay	Sand
Reference slope	1,62	1,36	2,03	1,37
Cylindrical root architecture	1,62	1,50	2,67	1,92
Semi-spherical root architecture	1,62	1,42	2,10	1,55
Uniform root architecture	1,68	1,50	2,17	1,53

The effect of vegetation and the rock layer are different for each material. For clay, the presence of a rock layer improves significantly stability. Influence of vegetation on a value of FOS is more noticeable for slopes which contain bedrock. For sand slopes, vegetation contribute to the significant increase of the FOS, but the rock layer has in this case smaller influence.

Scenarios without a rock layer, where slip surfaces are deeper, more circular and where forces which destabilize a slope are greater, have lower values of FOS than scenarios with a rock layer. Differences are especially evident in clay slopes (Figure 5.1a) where the cohesion provides significant strength, and consequently requires more mass to create unstable conditions.

Because of lower shear strength of sand slopes, slip surfaces are planar and they are more superficial than failure surfaces of clay slopes (Figure 5.1b). Consequently, influence of a rock layer in sandy slopes is less apparent, since the rock layer affects more the shape of the slip surface in clay.

In case of clay slopes, slip surfaces are deeper than the root zone, therefore the presence or absence of vegetation has little influence on slope stability. However for sand slopes, it is evident, slip surfaces that ought to cross the root zone, where the soil is stronger. Thus slip surfaces are slightly deeper and stability significantly higher than in case of the reference slope.

In sandy soils, the FOS has the highest value for the cylindrical root architecture. This root architecture, not being a continuous soil layer, is near the shear zone. Thus the cohesion of the roots have a greater impact. The uniform root architecture is shallow and does not influence significantly stability. In case of semi-spherical root architecture, the failure surface cross just some parts of the root zones, which is insufficient to noticeably increase the slope stability. Generally, presence of vegetation, and its different root architectures, do not affect the shape of slip surfaces, only its depth.

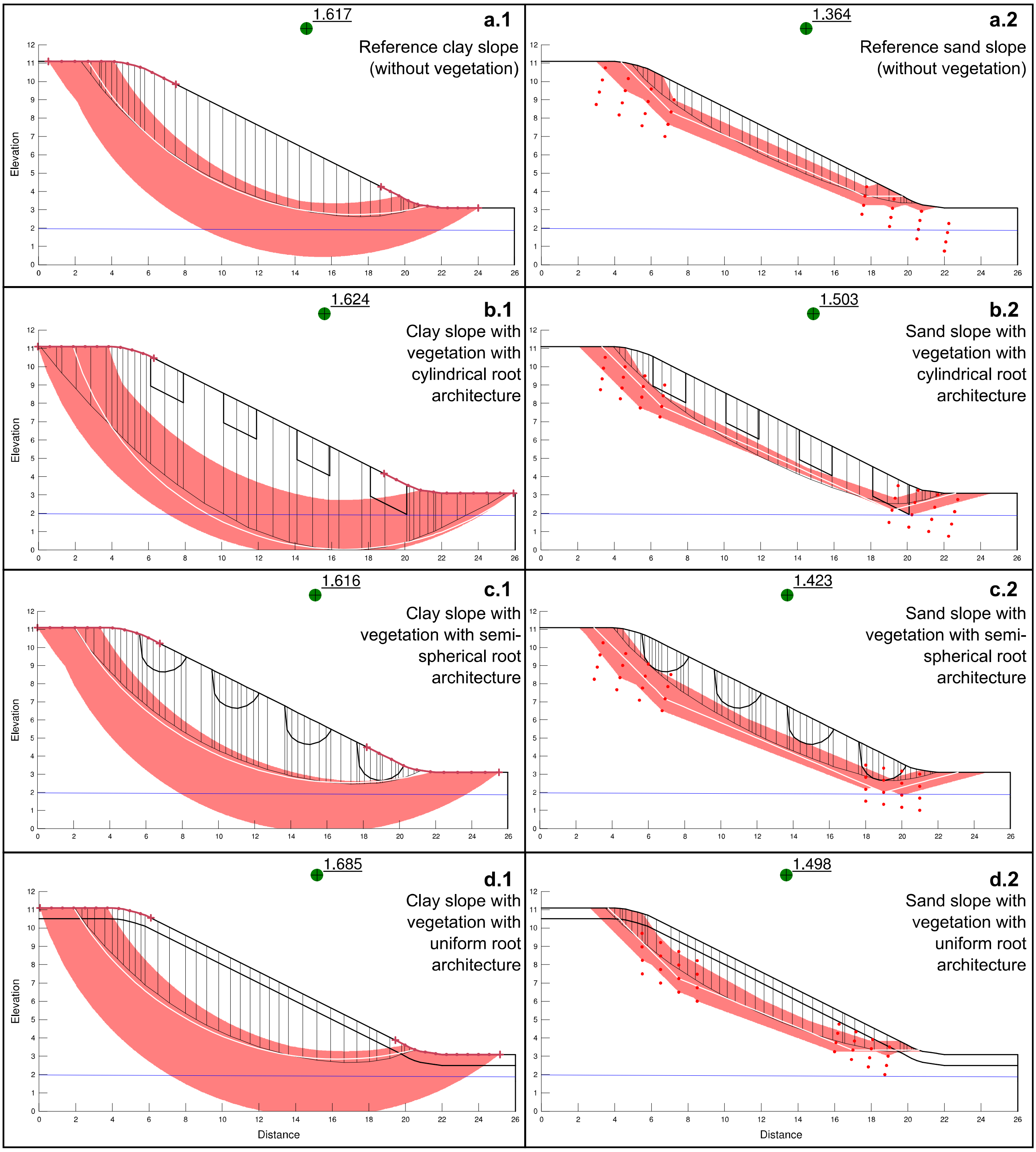

Figure 5.1. Slip surfaces with FOS excluding suctions in the scenario without impermeable layer.

The red shaded area in Figure 5.1 represents the location of slip surfaces for the range of the FOS values within an increment in FOS of 0,05 with respect to the minimum calculated and the dot is the center of rotation of the optimized critical slip surface. The vertical thin black lines, represent the slices of the sliding mass used to calculate the FOS.

A presence of a rock layer, forces slip surfaces to cross the root zones (Figure 5.2), therefore, when there is an underlying rock layer, influence of vegetation is stronger, and FOS is higher than in case of the reference slope, regardless the material of the slope.

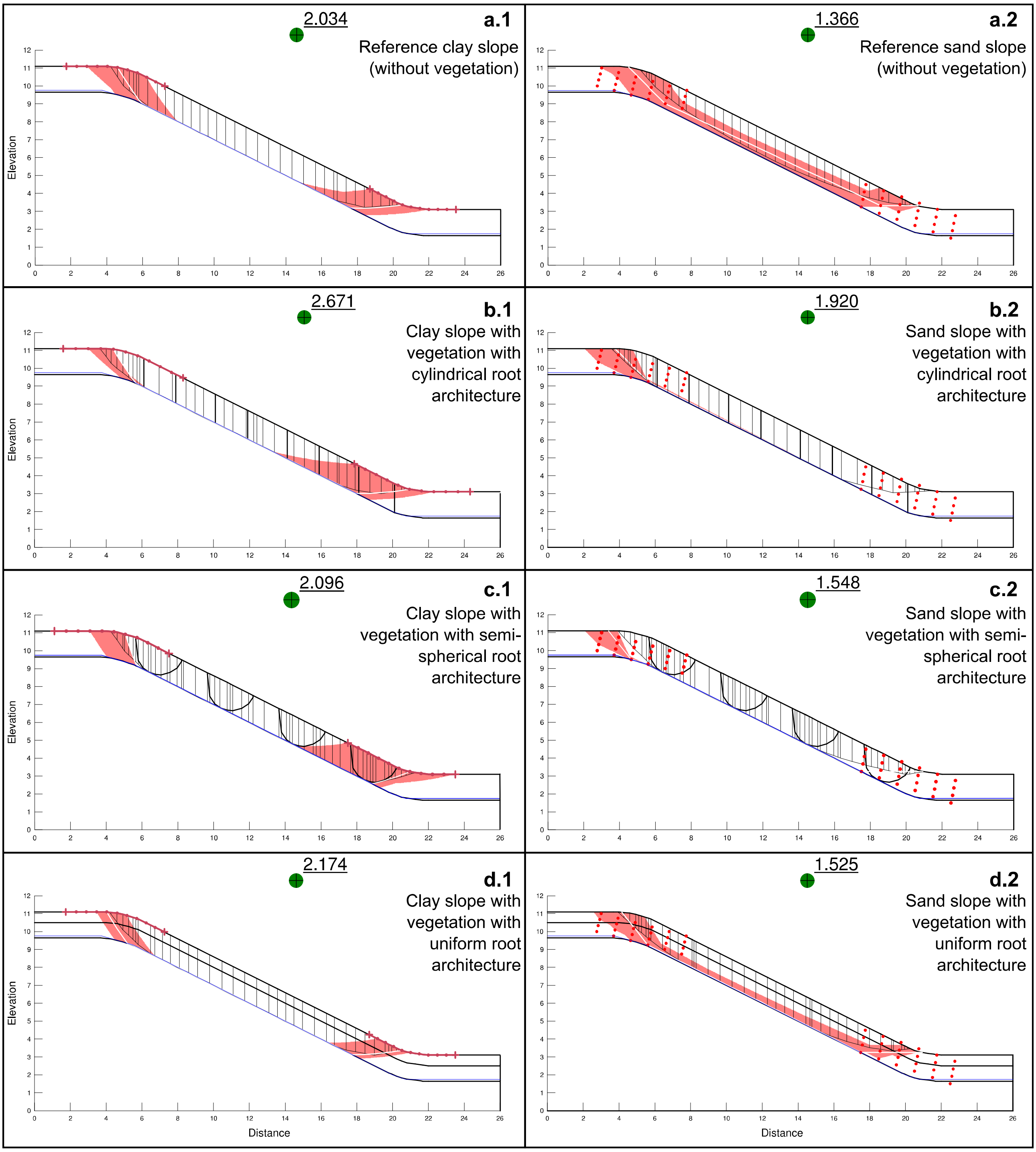

Figure 5.2. Slip surfaces and FOS for the scenario with a rock layer and excluding suctions.

It is important to notice that even though a slope with a rock layer has higher values for FOS, it is very susceptible to the changes in friction of the interface between soil and rock (not included in this project). Moreover, if the rock is impermeable, positive pore water pressures can build up rapidly during the rainfall event, thus destabilizing the slope. This case is studied in the slope analyses where impact of the suctions developed in the soil is taken into account.

In conclusion, clay slopes have deep and circular slip surfaces and their stability is heavily influenced by the presence of an underlying rock layer. Failure surfaces in sand slopes are shallow, planar and affected by presence of vegetation. When vegetation is taken into consideration, cylindrical root architecture increases the most slope stability, followed by uniform root architecture. Root zones of a semi-spherical shape have the smallest impact on the stability of the slope. Lastly, vegetation can stabilize slopes more effectively when there is a rock layer or the potential slip surfaces are shallow.

5.2 Soil water flow simulations in vadose zone

All water flow simulations are done for scenarios where an impermeable rock layer is present. Two climatic conditions are tested: a mid term simulation for regular climatic conditions in Paris, and a short term simulation of an extreme rainfall event in Vienna.

5.2.1 Simulations with climatic conditions of Paris

Average evapotranspiration rates are equal to 0,25 m^3/day of water loss for the whole slope (assuming that the slope is 1 m wide in the direction perpendicular to the drawn section). Total rates do not vary significantly for different soils (clay or sand, Figure 5.3). This is due to a constant flux of water from the lateral hydraulic boundary conditions (see “Hydraulic boundary conditions“ section) enabling global rates close to potential evapotranspiration values. These values depend mostly on climatic conditions, although in specific points of the slope, rates can vary greatly between cases.

The reference slope, due to the absence of vegetation, has the highest rates of evaporation. Contrarily uniformly distributed vegetation cover, has the highest transpiration rates. This last one, has no meaningful rates of evaporation at any time, because the soil does not dry enough to raise any kind of water stress to which plants would restrict transpiration and surface evaporation would increase.

It is important to notice that evapotranspiration rates are assumed to be the same for all the vegetation types. In reality, different root architectures correspond to different plant species and root water uptake can be significantly different. Cylindrical and semi-spherical root architectures are generally associated to trees and extract more water from the soil, thus the transpiration rates would also be higher. Biomass or size of the plant above the ground should be taken into account for more accurate estimations.

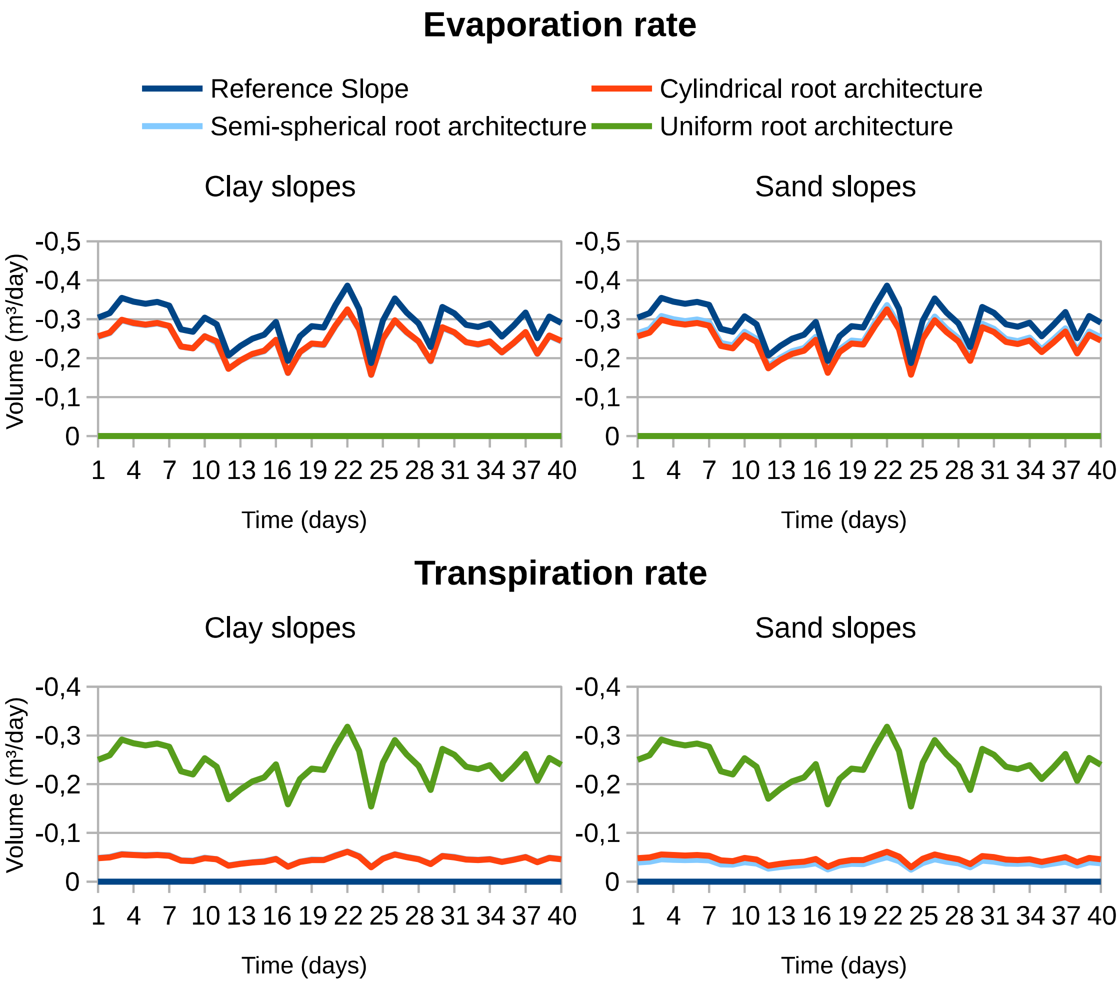

Figure 5.3. Daily evapotranspiration rates for climatic data of Paris.

In the other hand, because vegetation covers completely the soil surface, the uniform layer of vegetation provides the lowest total evapotranspiration rates. Rates for spherical and cylindrical root models, are almost identical, since their surface coverage is similar. Only transpiration is slightly higher in case of the cylindrical root architecture due to the higher density of roots in deep areas, where water suctions are lower.

Water conductivity is much lower in clay and so is the infiltration rate, making it fairly easy for clay soils to generate runoff. Precipitation intensities do not reach high enough values to cause runoff from sand slopes (Figure 5.4). Evaporation rates are the lowest from the uniform vegetation layer, therefore soil at the surface is more humid and the infiltration values are in this case lower than for the rest of the cases.

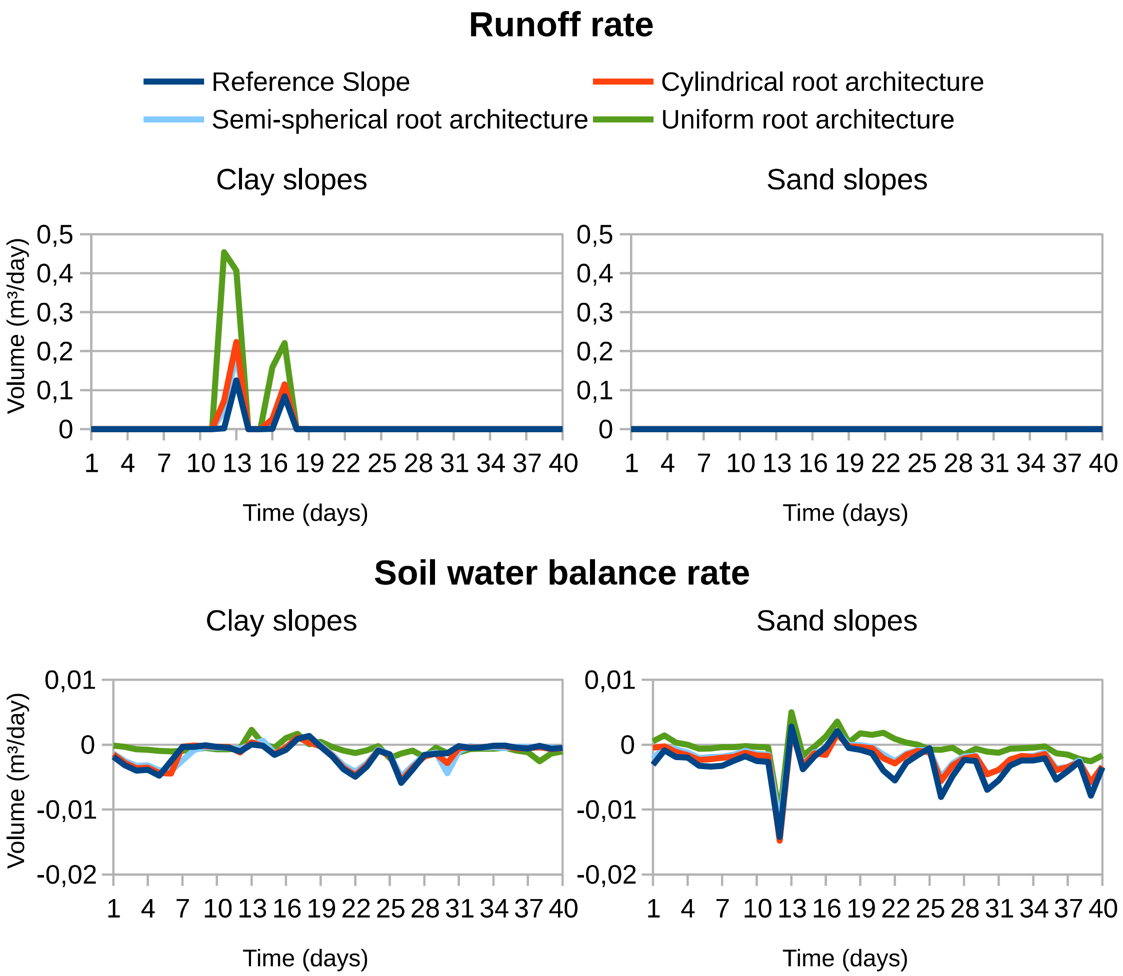

Figure 5.4. Surface runoff during precipitation events and total soil water balance for climatic conditions of Paris.

Soil water balance (Figure 5.4) remains roughly constant over time, with an exception of a peak of water loss of approximately -0,013 m³/day. This peak, occurs in sand slopes 12 days after the simulation started. This day has a peak of precipitation intensity of 23 mm/day. Water moves fast in sandy soil, and significant amount of it is lost through boundaries, causing a negative water balance.

Water balance is only sightly less negative in case of the uniform vegetation layer, since evapotranspiration rates are also lower than for the other cases. It is important to point out that in this model, hydraulic properties of soil are homogeneous in vegetated and non-vegetated zones. However, the superficial 10 cm layer has higher conductivity than the rest of the soil. This allows accounting for superficial soil weathering, making it even harder to generate runoff.

Comparing pore water pressures distribution in clay slopes there is a clear differentiation between the reference slope and vegetated slopes (Figure 5.5). In the reference slope, suctions, after a dry period, reach high values in the surface regions, while the rest of the soil remains humid. This is an evidence for the slow movement of water in clay soils.

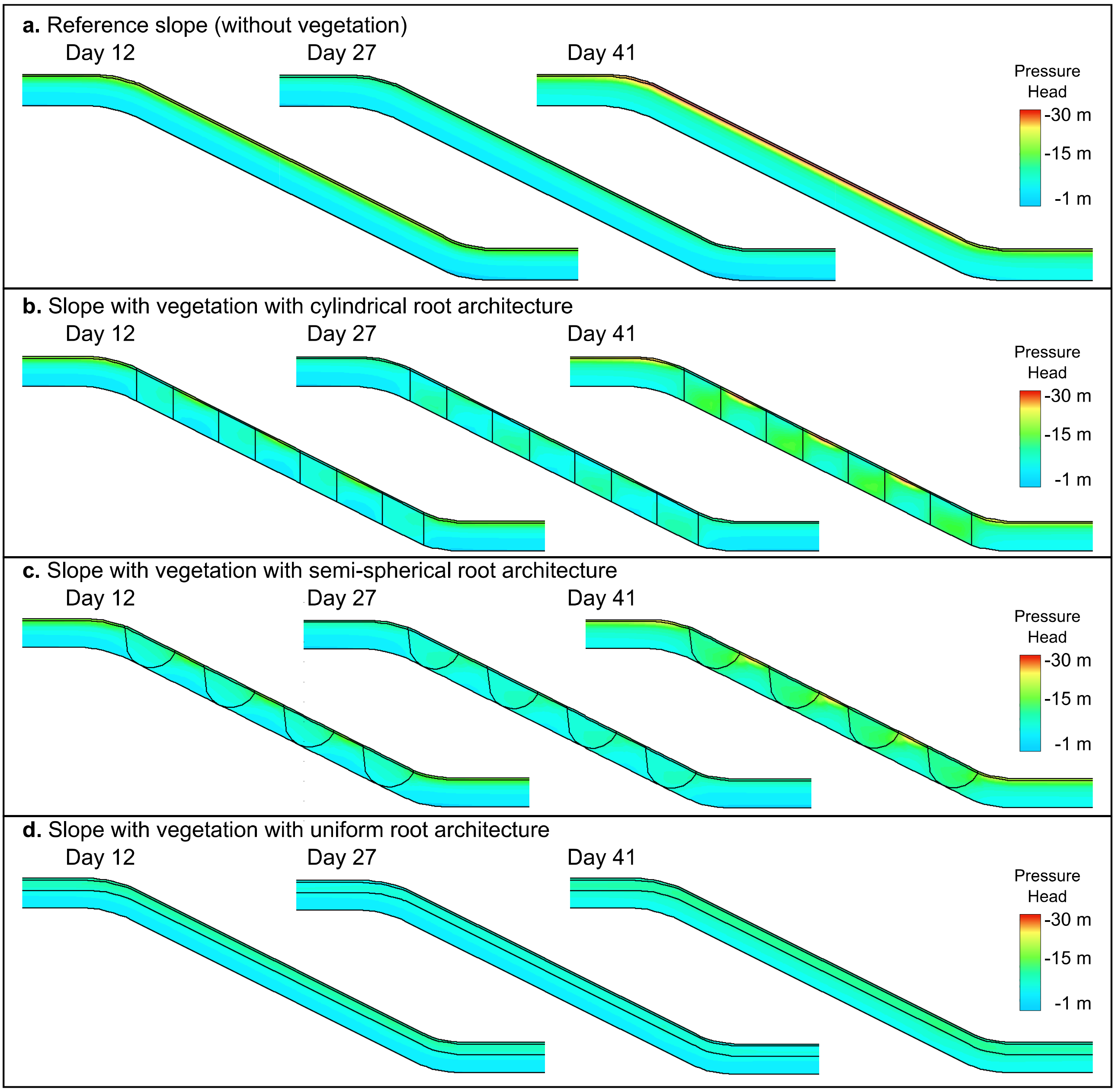

Figure 5.5. Pore water pressures distribution in clay slopes.

Due to the root water uptake, there is less available energy for surface evaporation, therefore in vegetated slopes, surface suctions are lower, but the deeper parts of the soil profile are drier. In case of the vegetated slopes, with cylindrical and semi-spherical root architectures, between the roots, the surface is dry, but in root zones, high suctions develop in the subsoil. In the uniform root architecture, suctions distribute homogeneously in the root zone.

Cylindrical root architecture have the highest values of suctions deeper than in case of the semi-spherical root model. In the cylindrical model, density of roots is considered to be uniform through the depth, so root water uptake is the same. But in the semi-spherical model, root density has a triangular distribution and is higher towards the surface, and so are the suctions.

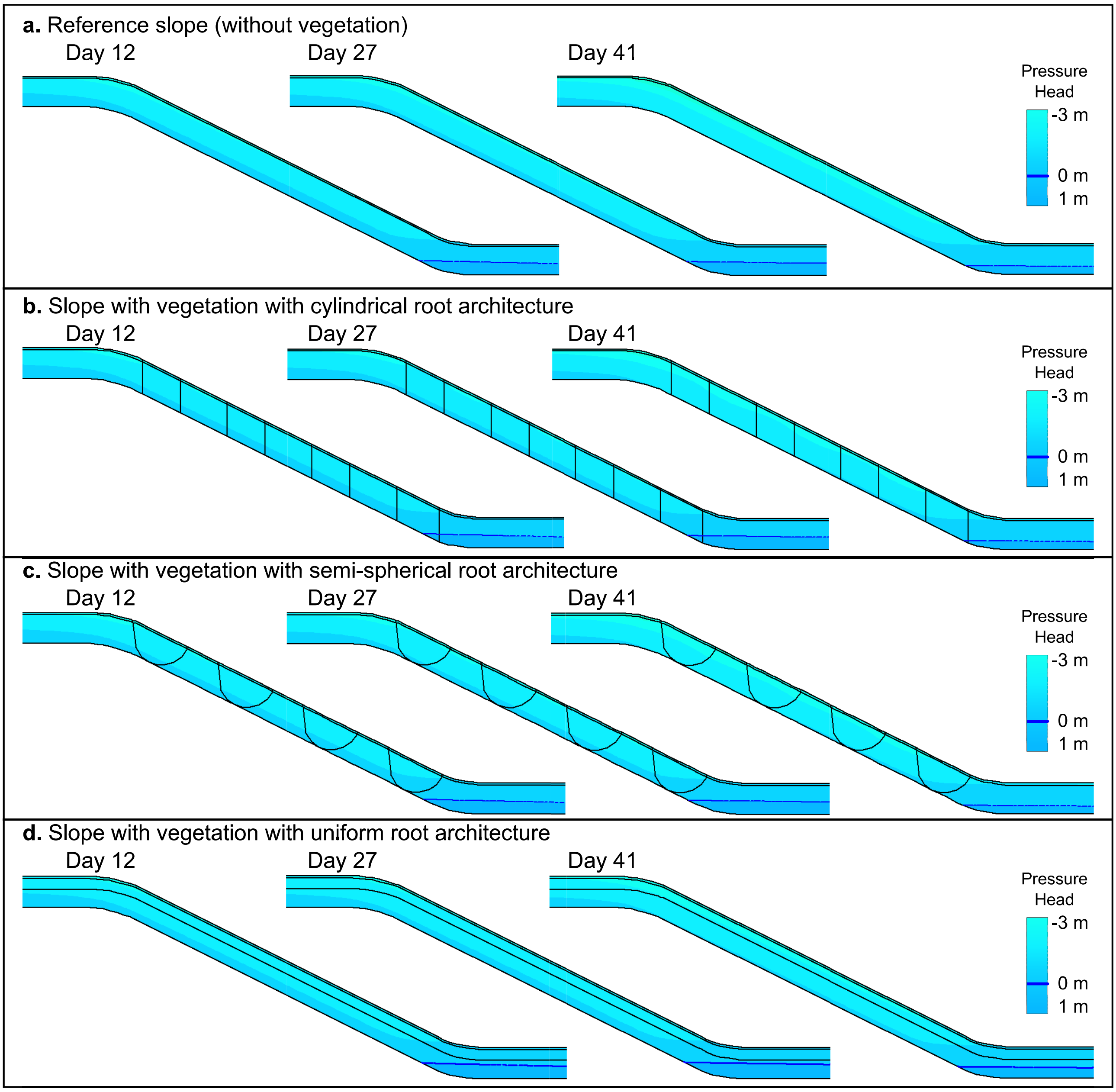

Figure 5.6. Pore water pressures distributions in sand slopes.

Hydraulic conductivity in sand is much higher than in clay. Therefore, if there is a constant water source (see “Hydraulic boundary conditions“), soil remains humid and water flow is driven by gravity. Consequently suctions are very low, and differences between all the cases are minimal. In Figure 5.6, each contour color represent a difference of 1 m in the pressure head, and all cases have the same profile. Over time the water table decreases due to evapotranspiration, but it lowers at the same rate regardless of presence or absence of vegetation.

Water flow from underground sources in sand slopes, is fast enough to compensate water loses due to evapotranspiration. The hydraulic influence of vegetation on sand slopes are not as evident as in clay slopes, where suctions values are much higher.

If there was no water source form the hydraulic boundaries, sand would dry rapidly, reaching high suctions values, decreasing soil permeability and finally cause the fade of vegetation. In case of numerical simulations, such situation would lead to unrealistic results.

5.2.2 Extreme event simulation in Vienna

The first 5 days of the event is a period with no precipitation, followed by other 5 days of extreme precipitation and other 5 days with no precipitation. For evapotranspiration rates, there are no significant differences between clay and sand soils (Figure 5.7). An average rate of 0,3 m³/day for the whole event, is a similar rate to the obtained in the case of Paris. This is an evidence that the atmospheric conditions are similar, just rainfall intensities are different.

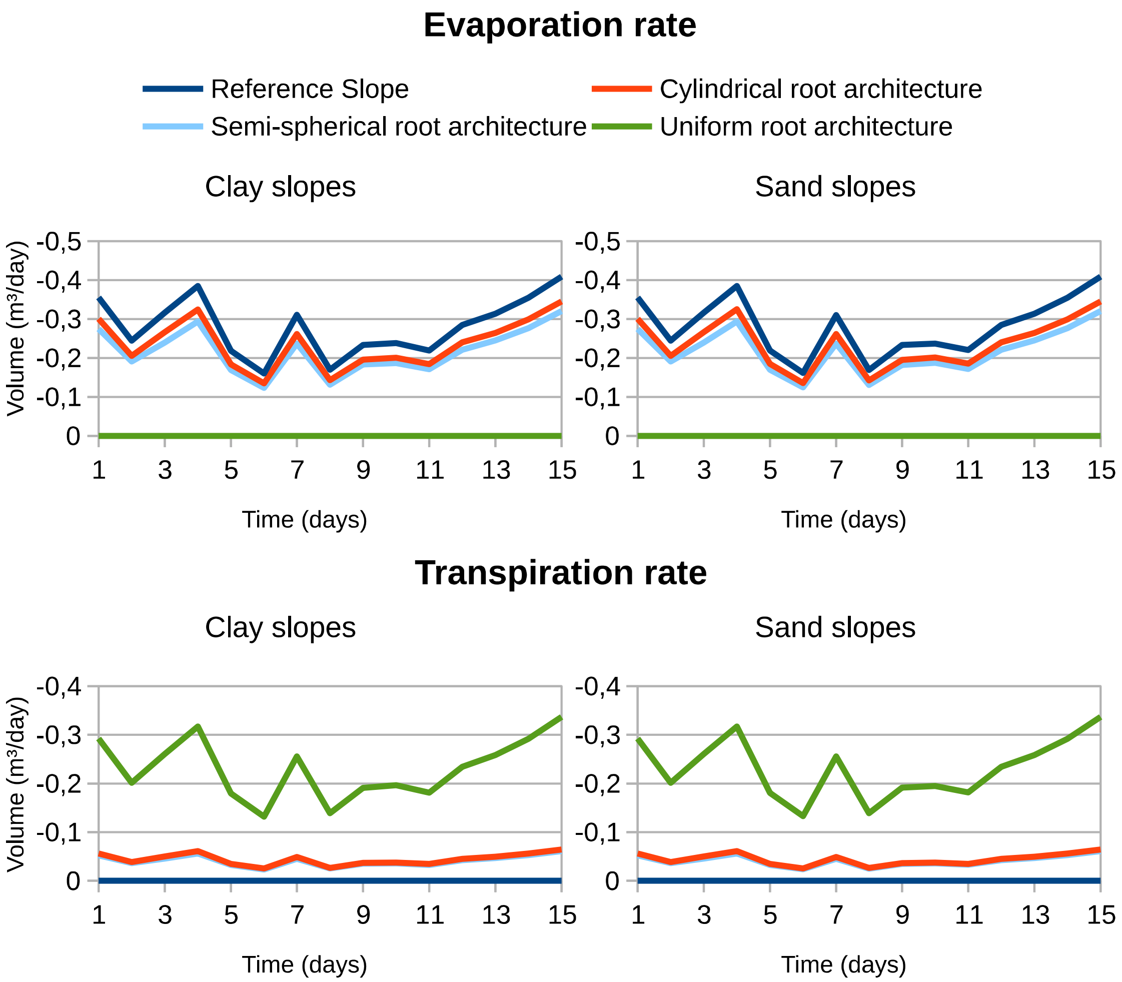

Figure 5.7. Daily evapotranspiration rates during the event simulation of Vienna.

Likewise in the Paris case, vegetation plays an important role in evapotranspiration rates, and conclusions are the same: reference slope has higher values of evaporation and slopes with uniform vegetation layer, have the highest transpiration rates.

Precipitation intensities during the event are high enough to generate runoff in clay and sand slopes. In this last one the amount generated is much lower (Figure 5.8). Since the soil water contents in the reference slope and the vegetated slopes are very similar before the precipitation begins, there are no differences in runoff rates.

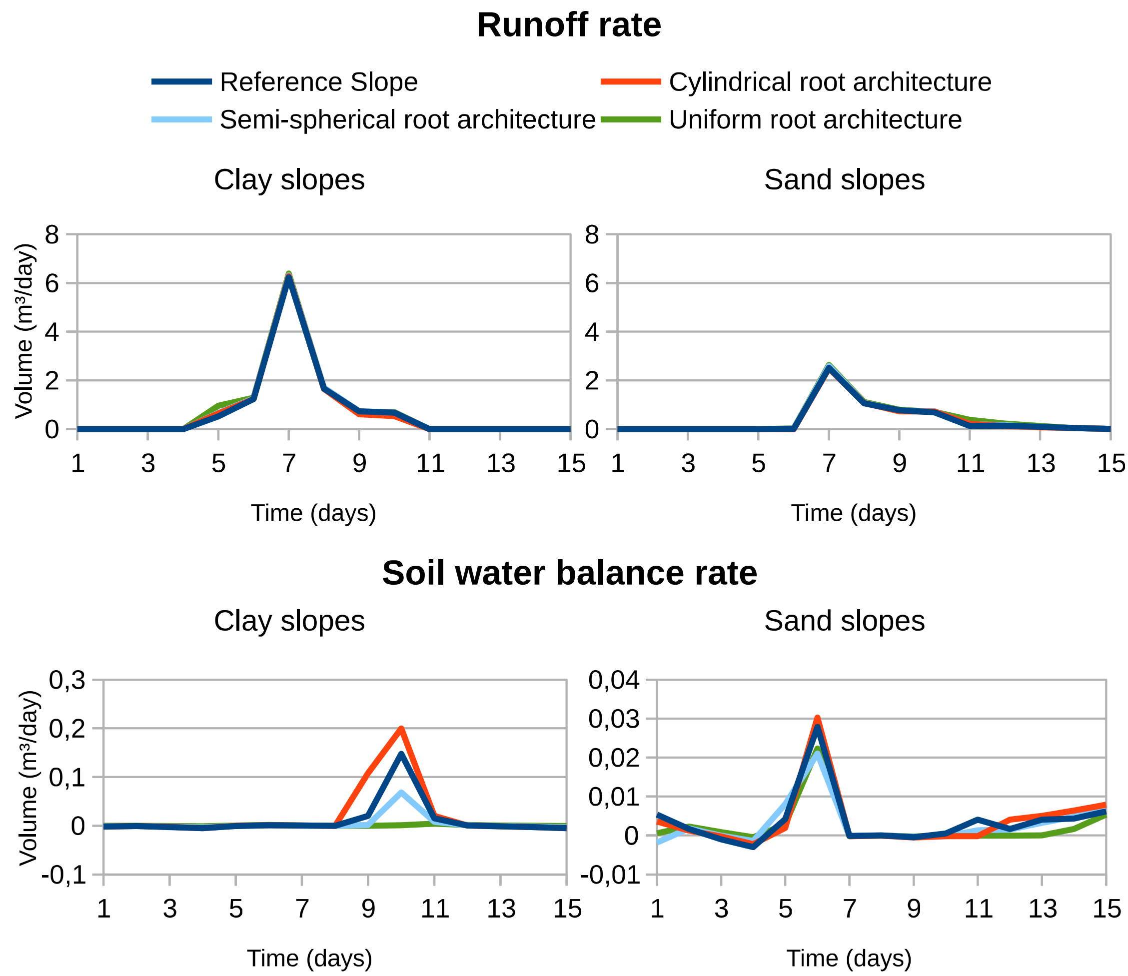

Figure 5.8. Surface runoff and total soil water balance during the extreme event in Vienna.

Water balances have positive rates. Due to the different hydraulic conductivities, water storage in the soil is different, and peak values occur earlier in sand than in clay: in sand slopes peak positive water balance rates are after 6 days of simulation, while in clay after 10 days. Peaks are higher in clay slopes, since water does not move out through boundaries, as it happens in sand, where high amounts of water leave the model due to the lateral outflow.

As it happens in the case of Paris climatic conditions, pore water pressure distribution is more meaningful in clay soils than in sand. In Figure 5.9 pore water pressures, at the day in which slope stability is the lowest, are shown. In the reference slope, this moment occurs in the same day for both soils, after 10 days of simulation. In vegetated slopes, instability can be noticed earlier in sand slopes than in clay.

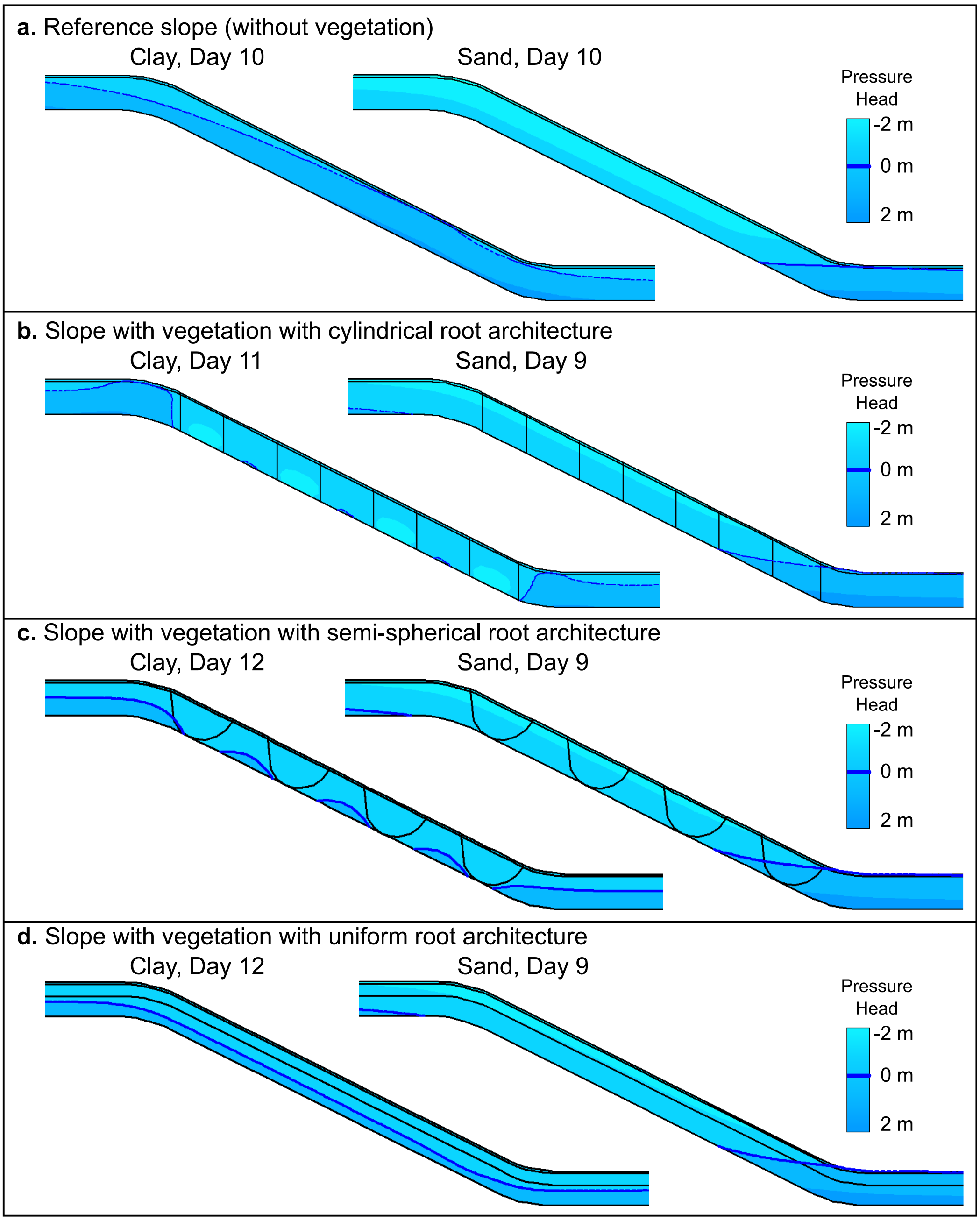

Figure 5.9. Pore water pressures distributions during the extreme event when slope stability is lowest.

In sand slopes, despite of heavy rainfall, water moves fast enough to accumulate at the bottom of the slope, where positive pore pressures are present in the entire soil profile and water seeps out to the surface. The rest of the slope maintains constantly the value between 0 and 2 m of negative pore water pressures. There is no significant differentiation between vegetated and reference slope in pore water pressures.

Clay reference slope, after 10 days of simulation, under heavy rainfall, is almost entirely saturated. However in vegetated slopes, root water uptake is high enough during the previous 5 days before precipitation, so that soil does not saturate entirely.

In the clay cylindrical root zones, suctions are present in the entire slope, having highest values at the bottom of the root zones. In the semi-spherical model, suctions are lower, and are present in all root zones, but in areas without roots, positive pore-pressures start to develop at the bottom of the profile. Finally, for the uniform vegetation layer, water table develops just under the root zone.

From slope stability point of view, the cylindrical root architecture is the most efficient, since it has the highest suctions in the shear zone, thus suctions have more effect on stability than in other models. In sand slopes, suctions also develop, but in top of the soil profile, where it has smaller effect on the stability of the slope.

The different days at which the worst case scenario happens, reflects the difference in hydraulic conductivity. In sand, lateral flow is much faster, independent of vegetation type. Therefore the weakest point comes in all vegetated slopes about the same time. In clay slopes, the worst case scenario in vegetated slopes, occurs later than in case of the reference slope, since water takes more time to compensate root water uptake.

5.3 Slope stability analyses with accounting for negative pore water pressures

Once pore water pressures are calculated for each day, slope stability analysis is conducted, accounting for an extra strength that suctions add to the soil, which is called "apparent cohesion". By adding this term, slope stability is expected to be higher than for cases where suctions are ignored.

5.3.1 Simulations with climatic conditions of Paris

In Table 5.2, values of FOS at the beginning and at the end of the simulation period are shown. As expected, FOS is higher just by accounting for the suctions in calculations. This difference is much more noticeable in clay slopes than in sand. Moreover, differences between the reference and vegetated slopes are more evident. Vegetation increases significantly slope stability, especially that with cylindrical root architecture.

Table 5.2. Factors of Safety of slopes calculated with suctions and climatic conditions of Paris.

Material	**After 1 day of simulation**		**End of simulation (40 days)**	
	Clay	Sand	Clay	Sand
Reference slope	2,22	1,63	3,65	1,60
Cylindrical root architecture	2,89	2,16	5,34	2,20
Semi-spherical root architecture	2,31	1,75	4,45	1,86
Uniform root architecture	2,36	1,76	3,62	1,77

In sand slopes, stability does not vary significantly from the beginning to the end of the simulation. But in the clay slopes, stability increases over time, due to the loss of water in the model. As a result, suctions get higher and so the FOS values (Figure 5.10).

Semi-spherical root architecture, has slightly higher FOS. Sand slopes, during the whole analysis reach similar values of FOS to the reference slope (Figure 5.10). In case of clay slopes, differences increase due to the root water uptake, which starts to be more noticeable deeper in the soil and thus shear strength of the soil in these regions and stability of the slope increases. The stability of slopes with cylindrical root architecture, differ the most comparing to the case of the reference slope.

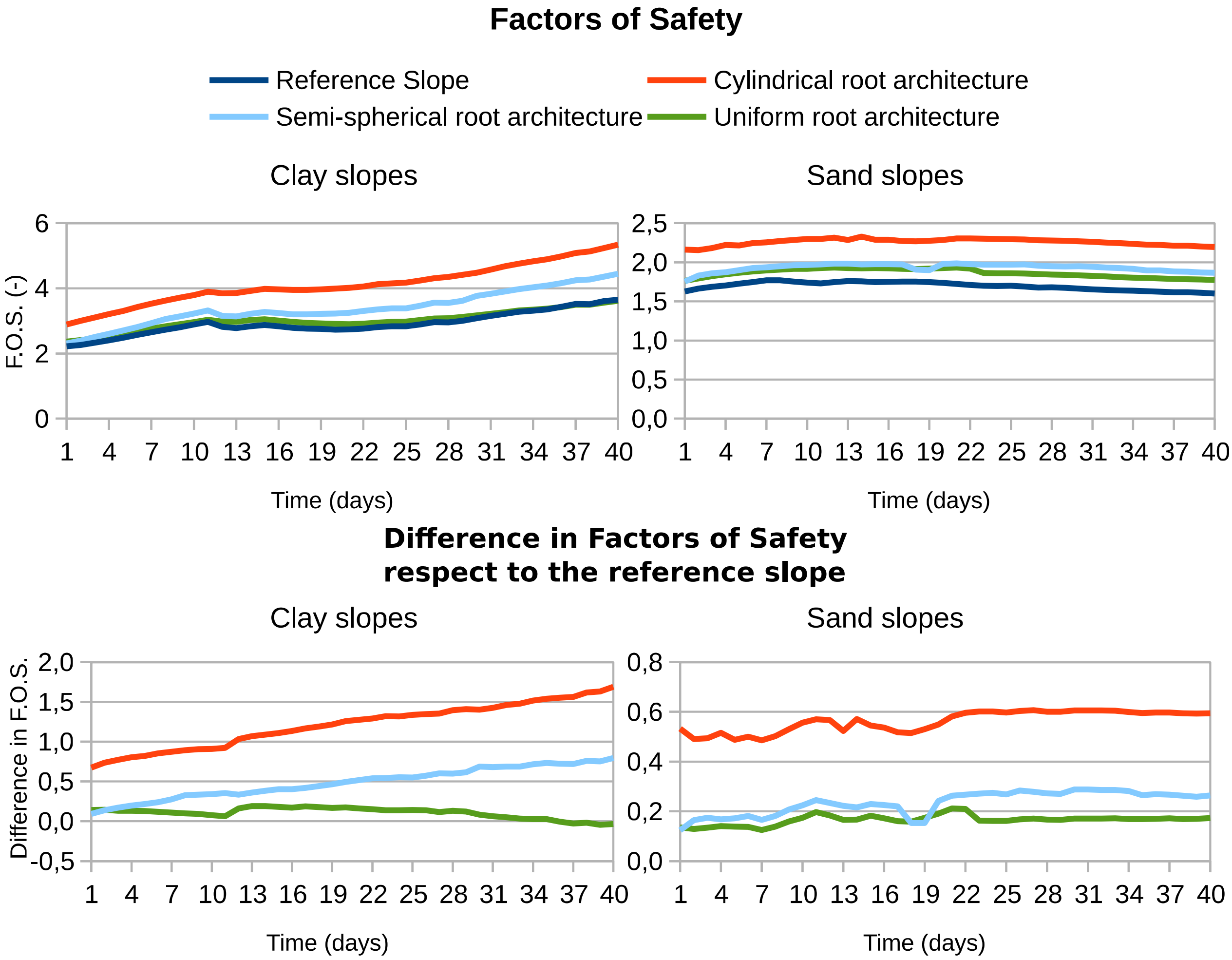

Figure 5.10. FOS evolution over time, and its differences respect to the reference slope for climatic conditions in Paris.

Uniform root architecture has very little differences with respect to the reference slope and follows the same evolution over time. For sand slopes, root reinforcement effect is the most significant, since slip surfaces are affected by the presence of the root zone (Figure 5.11).

Shapes of the slip surfaces do not change significantly over time and they are similar to those calculated in the case without suctions (Figure 5.11).

In conclusion, it is important to take into account negative pore water pressures when possible during slope stability analysis. It is relevant factor that stabilizes slopes, especially when vegetation is present and root water uptake cause the development of suctions close to the slip surfaces. Slope stability differences are more noticeable in clay slopes since water flow is slow and negative pore water pressures higher. In sand slopes, suctions are less important, still the mechanical effect of root cohesion is significant.

Sand slopes have lower FOS than clay slopes and these values do not vary significantly over time. This is a result of the higher permeability of sand and thus ability to transport water into and out of the slope easier than in case of clay slopes. In regular climatic conditions, clay slopes tend to retain water longer, but also water percolation and wetting is slow. Stability of these slopes is higher than corresponding sand slopes and FOS vary more, since it depends significantly on pore water pressures.

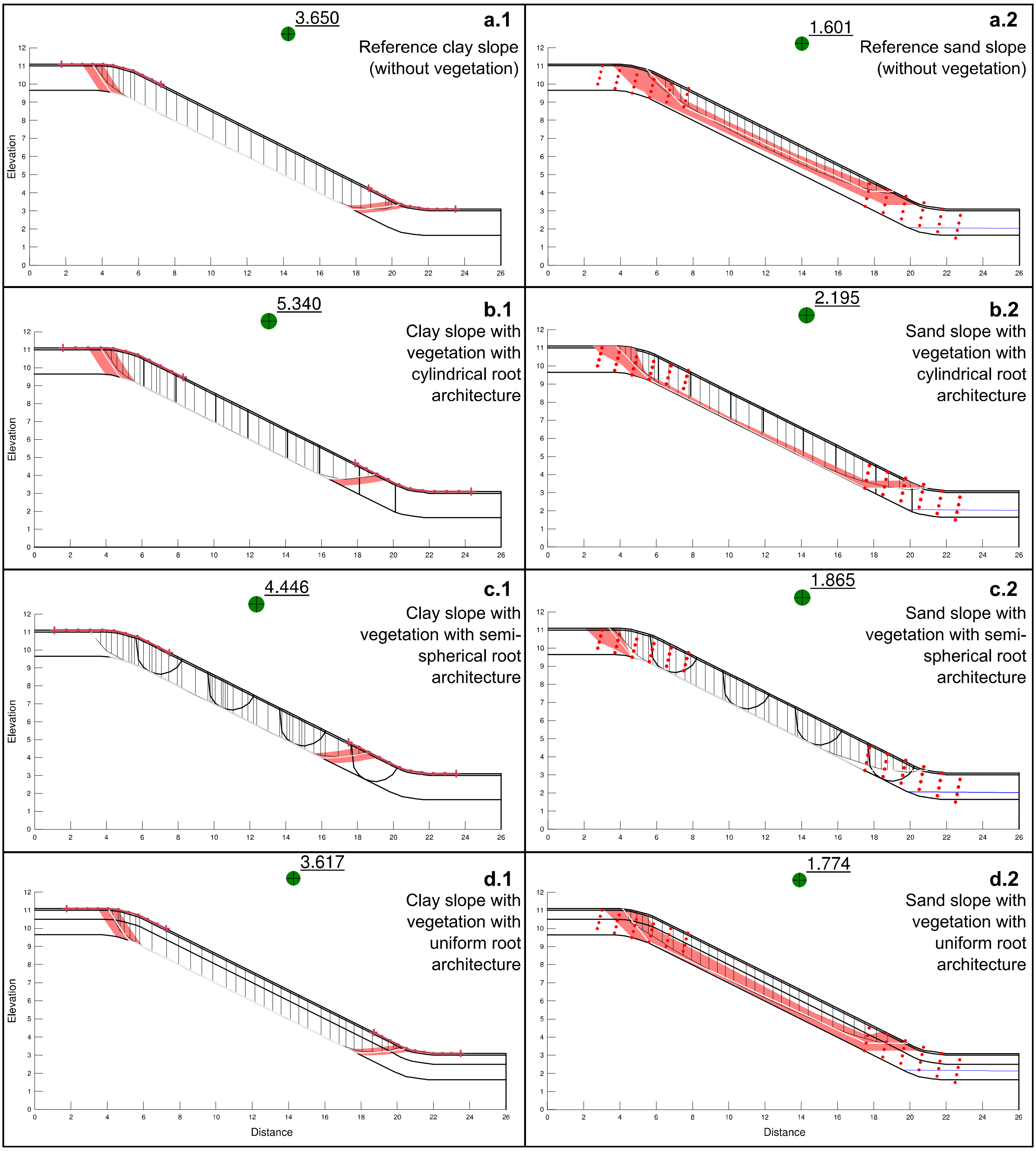

Figure 5.11. Slip surfaces and values of FOS including suctions, for climatic conditions in Paris, at the end of the simulation (after 40 days).

Vegetation with cylindrical root architecture, stabilizes slopes more efficiently, because its deep root distribution extracts water close to the slip surface. Uniform root architecture, although forms a continued root zone, it is not deep enough, and semi-spherical root architectures are only deep in a very limited point, so root water uptake is less efficient.

Root distribution depends largely on water and nutrients availability (besides other soil characteristics). Usually cylindrical architectures correspond to small and medium sized plants of well irrigated areas, so they usually do not develop deep roots. Heart-like roots usually are deeper and are considered more suitable for stabilizing slopes. In this case, dimensions of root zones are exaggerated, with the same area occupied with roots for both modelled shapes of root architecture, to see effects more clearly and to be able to compare results (see the Discussion section for more details).

5.3.2 Extreme event simulation in Vienna

In the extreme event simulation, in all cases the slope remains stable with FOS greater than 1,0. FOS decreases when precipitation starts, and then it increases slowly again. The clay reference slope, is the case where this behavior is the most evident (Figure 5.12). Slopes reinforced with cylindrical root architecture show the highest values of FOS, regardless of the soil. In case of the stabilization with the other vegetation types, obtained results are comparable.

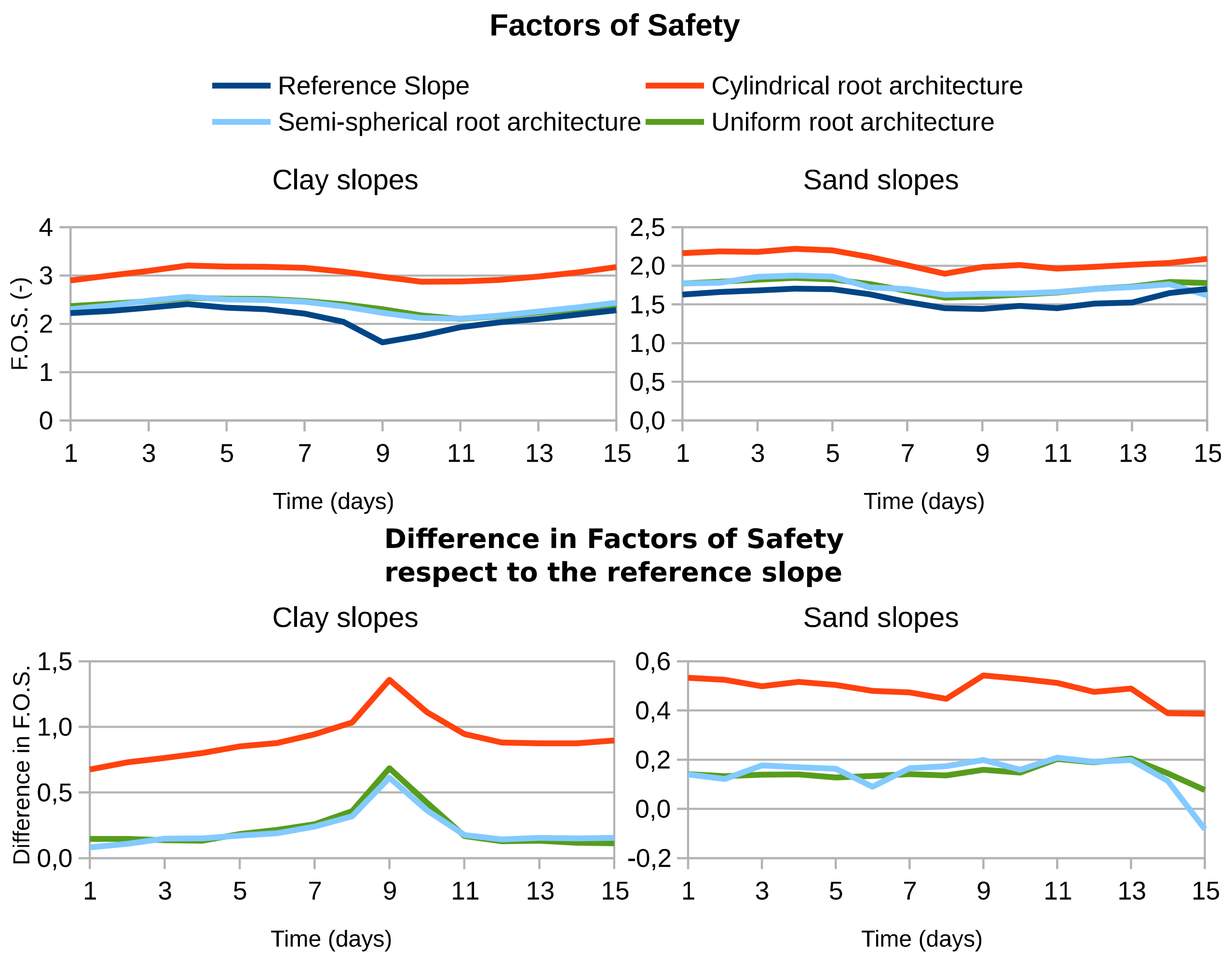

Figure 5.12. FOS evolution over time, and its differences in respect to the reference slope for the simulation in Vienna.

Differences in FOS, remain more or less constant, except a peak in clay soils, where FOS of the reference slope drops suddenly, which does not happen when considering the vegetated cases. The tolerance of the FOS during calculation is 0,01 so differences lower than this can be ignored.

In Table 5.3 the values of FOS in the worst case scenario are shown. Except of the reference slope, the worst day happens earlier in sand slopes than in clay. The lowest FOS occur in case of the reference slope, and the vegetated slopes have significantly higher FOS. Slopes reinforced with plants with cylindrical root architecture are the most stable.

Table 5.3. Factors of Safety of slopes in the worst case scenario of the extreme event simulation.

Material	**Clay**		**Sand**	
	Day	F.O.S.	Day	F.O.S.
Reference slope	10	1,61	10	1,44
Cylindrical root architecture	11	2,87	9	1,90
Semi-spherical root architecture	12	2,11	9	1,62
Uniform root architecture	12	2,10	9	1,59

The clay reference slope has a very low value of FOS comparing to other cases with clay. This is because in this case, due to the slow movement of water, almost the entire slope is saturated, and all the slip surfaces cross the zone of positive pore water pressures (Figure 5.13 a.1). For the sand reference slope, water is accumulated at the bottom, and some seepage causes water accumulation at the surface (Figure 5.13 a.2), which can be very dangerous considering erosion processes.

The root water uptake from the cylindrical root system causes the development of negative pore pressures during the simulation (Figure 5.13 b.1 and b.2), which provides additional stability of the vegetated slopes. This proves the effectiveness of extracting water from deep parts of the soil profile where these effects are most significant in terms of slope stability.

Uniform and semi-spherical root systems, having a positive effect with respect to the reference slope, behave similarly to each other and are not as effective as the cylindrical root architecture (Figure 5.13 c.1, c.2, d.1 and d.2).

Slip surfaces in clay slopes tend to be more shallow during the event than during the regular climatic conditions. In sand slopes the shape and depth of failure surfaces remain more or less constant. During the event, the shapes are constant in all cases once precipitation started. The most important factor is that during the event, suctions are reduced drastically, positive pore water pressures start to develop and thus the slope looses its stability.

In sand slopes, the effect is not so visible, since water moves fast enough through the soil, and accumulates only at the bottom. Effects like surface erosion and "piping" effect are not considered in this work. However, it is well known that vegetation is a natural cover for the slope and protects the soil surface from drying and other forms of erosion.

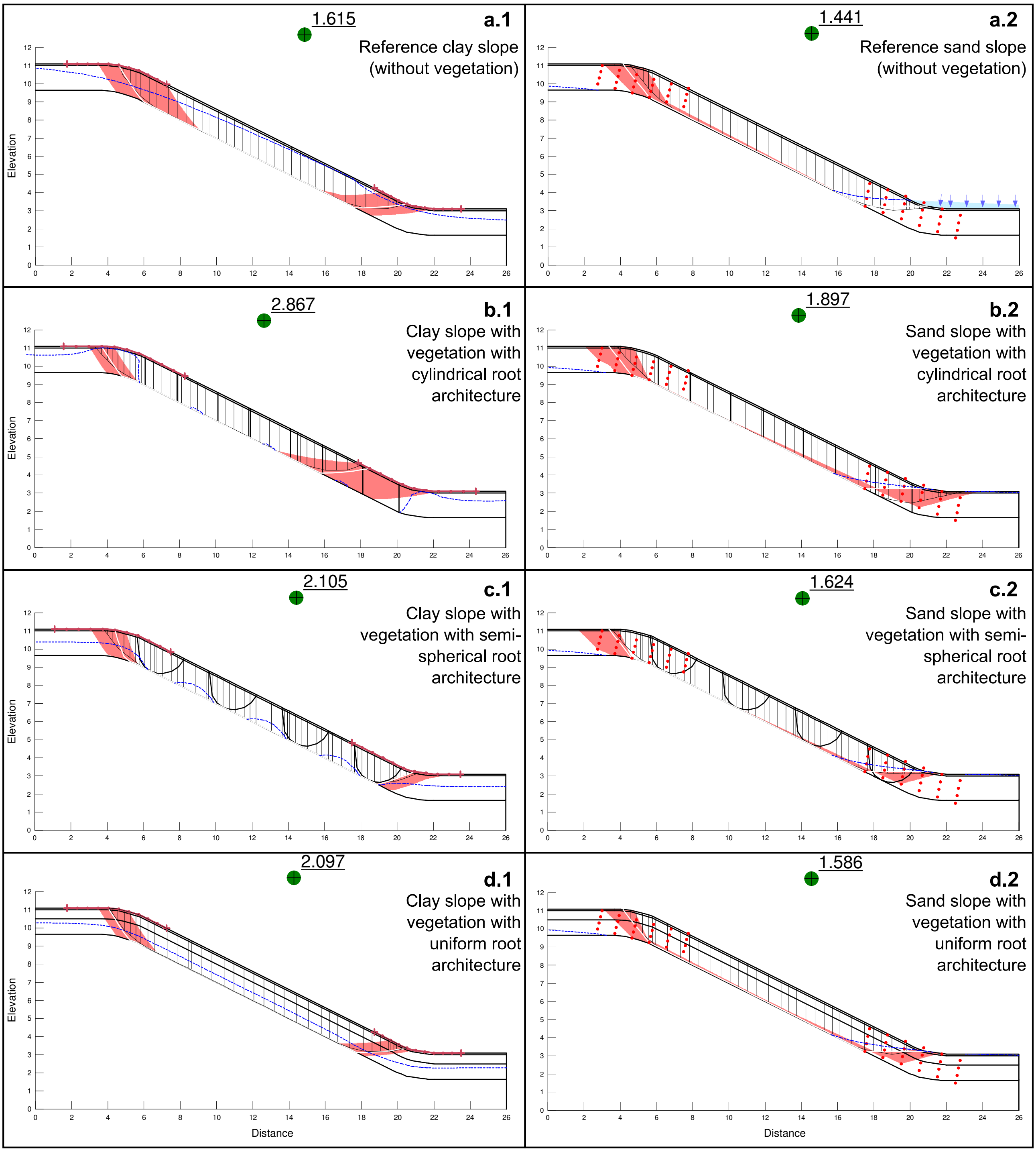

Figure 5.13. Slip surfaces and FOS in the worst case scenario during the event simulation in Vienna.

In conclusion, even during short extreme events, vegetation plays a very important role. The presence of plant roots provides additional cohesion which compensate the loss of strength due to a decrease in soil suction. Moreover, vegetation helps to drain soil before and after the event via root water uptake, which increases water storage capacity during the event, avoiding development of positive pore pressures that dangerously destabilize the slope. These effects are more visible in clay soils stabilized with vegetation with cylindrical root architecture. In sand slopes, although the rapid movement of water in the soils helps to avoid the development of high positive pore pressures in the major part of the slope, vegetation still plays an important role in providing additional cohesion.

6 Discussion

Slope stability depends on numerous factors:

1. Slope material. Recent volcanic material can be very unstable in contrast to very stable, hard and compacted rock, like in case of intact gneiss slopes.
2. The layout of the material. Layers of rocks dipping toward slope are particularly unstable. The slope angle is another important variable.
3. Weight distribution along a slope. Loading applied on the top surface or cutting the slope at its base may have great influence, promoting sliding conditions.
4. Water is one of the most important instability factors. It decreases apparent cohesion in soils and increases weight and pore water pressure in soil. The rate at which water seeps into to the slope may also be critical. Some slopes may become unstable if even small amounts of water penetrate fast into the soil; others are more sensitive to the amount of water which reaches the slope surface during a long time.
5. External impulsive forces or cyclic loading such as earthquakes, waves, and volcanic eruptions.

Vegetation influences the slope material by increasing the cohesion and also removes water from the slope via transpiration. However, vegetation may also have a negative impact on stability. Some species of bushes increase instability by promoting the catchment of superficial water. In addition, trees add weight to the slope and this effect may be significant for superficial soils (Sidle and Ochiai, 2006, De Blasio, 2011). In all cases presented in this thesis, vegetation has increased stability significantly. It should be however highlighted that many variables are simplified: friction between rock and soil is the same as the soil's strength, or the effect of the weight of trees is ignored.

6.1 Weight of trees

External loads on the slope are not included in this analysis. When dealing with grass or shrub like vegetation, their weight can be neglected. With mature trees, weight is important enough to affect slope stability. Depending on the location of the tree, it can stabilize or destabilize the slope (Rees and Ali, 2012, Greenwood et al, 2004).

It is not yet clear how to include weight of vegetation in local slope stability analysis. Some authors consider a point load on the surface and other a localized distributed load (Greenwood et al, 2004, Hammond et al, 1992, Kim et al, 2013 and Simon and Collison, 2002). More research in this area it is needed so it can be applied in regular basis.

This thesis presents cases in which trees are distributed regularly on the slope. Assuming that they have the same size and age, it is expected that trees at the top of the slope (which may have destabilizing effect), are compensated by trees at the toe. In this case, mechanical and hydrological effects of roots are more important than effects of tree weight (see “External forces“).

This assumption is supported by the fact that many field inventories show landslides within the forested areas occur on steeper slopes than in open land, most likely due to the reinforcing effect of the diverse root systems of the trees and the associated forest vegetation. Also it is found that shallow landslides are less frequent in forests than in an open land (Rickli and Graf, 2009).

6.2 Root characteristics

Forested areas provide stability performance comparable to that provided by open land vegetation on gentler slopes. Generally, when the slope is vegetated, it can be safely assumed that the reinforcement contributes significantly to the stability an overcomes destabilizing effects (De Blasio, 2011). This thesis does not take into account plant growth. Root length and density are considered to be constant over time.

The most important characteristic of roots, related to slope stability, is rooting depth, which is dependent on the type of vegetation species, when soil conditions are not a limiting factor. In water-limited environments, root depth is strongly correlated with infiltration depth and with the root distribution.

Root distributions are generalized as root architecture types, and main differences are those which can be highlighted by comparing woody with non woody species, determinating root angle, relative horizontal versus vertical root spread and root density.

As discussed in the literature review, different plants have different root distributions, which are approximated to geometrical shapes. A uniform root architecture represents grass-like vegetation, where the root depth is limited. The cylindrical root architecture, represents tree species with shallow root systems that grow in humid conditions. The semi-spherical model, represent trees in arid areas, which develop deep roots to reach water and anchor the tree.

Geometric approximations, however, do not take into account other factors such as inclination of the root with respect to the shape of the slip surface. Roots normal to the potential slip surface will act at full tension, whereas those parallel to the slip surface will be more likely to slip before failure in tension occurs. Therefore, greater number and diversity of roots increases the thickness of the shear zone.

To correct an overestimation that is inherent in simple perpendicular root models, recent work allows accounting for progressive root breakage using a fiber-bundle model (FBM). Executing a FBM within a Monte Carlo framework, allows to include diversity of root angles (Pollen-Bankhead et al, 2010). The results from FBMs can then be coupled with limit equilibrium slope stability algorithms to provide estimates of FOS.

Within spatial distribution of roots there is a variability in root sizes. It is known that thin and thick roots have different tensile strengths (due to differences in cellulose content) and it can also vary between species. However, it is suggested that differences in tensile strength have little influence on the overall FOS and that root distribution within the soil is much more significant (Genet et al, 2010 and Mao et al, 2012). Generic equation for root tensile strength is therefore justified when studying the stability of temperate forested slopes with mixed species.

Distribution of thick root is the most important since it affects directly the fine roots distribution, basic element for soil fixation. Development stage and position within the branched hierarchy of the root system are all elements that determinate root type and consequently, root distribution (Eissenstat et al, 2000).

In many cases, root distribution is expressed as root area ratio (RAR, root area with respect to corresponding soil area). But not always increase of the RAR cause increase in the slope strength. The stability factor initially increases with the RAR, after attaining a certain stability factor, however, further increase of the RAR does not impart stability and continuous increase of the RAR can even reduce it. There is an optimal amount of roots for slope stabilization (Tiwari et al, 2013).

In this thesis, geometric approximations are used to represent root distribution, and the classical method of additional cohesion is used for calculating root reinforcement (Wu, 1976). This method is simple, but does not take into account directly the above mentioned factors, such as angle of root or root diameter. All effects are averaged in one single cohesion value, that is assigned to the soil in a root zone. It is assumed that all vegetation types provides the same cohesion, but in reality, different species and soil types should be accounted for.

Root distribution changes over time, and how fast a plant grows is of particular importance to quantify the effects of a gap after an alteration in the vegetation cover, e.g. tree fall or a clear cut. When a fast, shallow reinforcement of soil is required, fast-growing herbs can be an alternative for slower growing shrubs and trees (De Blasio, 2011).

Nonetheless, in humid conditions, homogeneously distributed fibrous roots can easily tear away from the subsoil (Tasser, Mader and Tappeiner, 2003). Although such shallow root systems may provide protection against shallow surface erosion, they exert little to no protection against shallow or deep-seated landslides (Rice and Foggin, 1971 and Gabet and Dunne, 2002). This is consistent with results obtained from this thesis where the considered cases of slopes with vegetation of uniform root architecture, have little influence on FOS.

Woody vegetation, and more particularly trees, tend to develop large conical-shaped woody central roots. Tree root systems have traditionally been classified into three types, depending on their overall shape (Stokes et al, 2009). However, this classification is simplified, as many species have a mixture of root system types. In the other hand, it is important to remember that a slope is stabilized by the whole community of plants, and not individual root system in isolation. Nevertheless, the type of root system could be important in species choice, with deep tap rooted systems planted in the middle and bottom of a slope and plate rooted uniform systems at the top of the slope (Danjon et al, 2008).

6.3 Influence of roots on soil water flow

Evidence of root water uptake as a soil stabilizing factor is seen clearly for example in Malaysia, where evapotranspiration is high throughout the year and stable slopes were associated with large root densities and relatively low water contents, whereas unstable slopes tended to be relatively wet and without roots (Osman and Barakbah, 2006).

However, other researchers found that tropical forest removal would only moderately and temporally decrease FOS and have little effect on landslides in shallow soils (Sidle and Ochiai, 2006). Generally the larger the biomass, the larger the potential evapotranspiration rate, but differences can arise due to root distributions and soil types.

Root water uptake is governed mostly by the type of a plant root system, the transpiration rate, the permeability of the soil and its suction at the wilting point. These should be measured or estimated accurately for an acceptable prediction of ground conditions in the vicinity of trees (Fatahi et al, 2010).

In relative strong soils, root growth is limited to channels and weak planes, where clustering of roots may occur. When agglomerated within cracks, water uptake may take longer time since water has to move larger distances to reach roots (Passioura, 1991), When calculating hydraulic conductivity in root zones and root water uptake, this phenomena should be accounted for.

Results of this thesis are consistent with those obtained by other authors, whereas evapotranspiration of plants increase the FOS. Although total evapotranspiration rates are very similar, results differ between different root architectures. Hence the importance of the use of a correct model of root distribution.

Transpiration rates depend on the leaf area index of the vegetation. Although here it is assumed to be uniform for all cases, in reality, trees with higher LAI extract from the soil more water than grass or shrubs, therefore can be considered to be more effective in stabilizing slopes.

6.4 Root development and its influence on soil properties

The interactions between the root system and soil type influences the nature of structure formation, which has an impact on soil characteristics and thus slope stability. Roots play a major role in the formation of soil structure by providing a source of carbon, via root decomposition and exudation, and by wet-dry cycles that bind particles together with mucilage (De Blasio, 2011).

This gives the typical crumb-like soil structure, which can be found under grass where the presence of roots and their associated fungal and bacterial communities, binds soil together and decreases erosion. The effect is confined to the surface horizons where most of the roots are located and has little effect on landslides' development.

In the other hand, the infiltration rate of water is not only characterized by the soil unsaturated hydraulic conductivity, but also by preferential flow paths in cracks of the soil structure or old root channels. In steep topography, these preferred flow networks can rapidly transport water down slope increasing pore water pressures in impermeable layers or in hydrological discontinuities, inducing landslides.

In a nutshell, soil characteristics depend on root distribution and root distribution depends on soil characteristics, with areas favorable for root growth and areas where it is constrained. In these areas, asymmetrical root systems develop, frequent on mountain slopes. Plants within a same species, can encounter different root morphologies, depending on the soil in which the plant grows. Tap rooted or heart rooted systems can be transformed into a plate root system when influenced by local soil conditions, such as the presence of a hard pan or a seasonal water table.

As a result, soil-root composites have different characteristics than soil without roots. Accounting for these is complex and is not included in this thesis. It is assumed that all cases affect soil in the same manner, they only differ in their root distribution.

Some plant species, develop roots that seek cracks in the bedrock and are able to better tolerate water and nutrient stress, but with higher energy costs for constructing deeper roots, and problems related to oxygen deficiency and lower water and nutrient availability (Schenk, 2008). These plants are able to grow through the soil and anchor the plant to the underlying bedrock, and thus additionally stabilize the topsoil.

However, roots of many species, e.g. *Pinus pinaster*, are not able to penetrate through the bedrock and grow along its surface, resulting in an unstable shallow root plate. Plants where roots are anchored to the bedrock, often continue the root growth through cracks and may enlarge them over time, thus destabilizing the rock, which may lead in turn to a slope failure (Sati and Sundriyal, 2007).

Roots are living systems and interact with the environment. Adaptations of the roots is a key for the survival of plants and lead to the development of very complex and unique structures. Soil environment affect root water uptake, root growth, distribution and strength. In order to fully describe the interactions between plant and soil it is not only necessary to understand root water and nutrients uptake, but also to consider the existence and influence of microbial communities.

Root interaction with the soil and modifications in root traits can therefore be highly diverse, and when added to their complexity, responses may be quite different depending on whether a plant is grown individually, as a mono-culture, or with a mixture of species. Also, plant roots' traits change over time, depending on nutrient availability and rainfall regime.

When trees die, roots remain in the soil and for a period of time their reinforcement effect will slowly decrease as the roots decay, if vegetation is not replaced. Slope becomes unstable as the forest deteriorate or after a wooden area dies off. Within a decade after tree death the root system of protection forests looses most of its soil-stabilizing function (Preti, 2012).

Due to its complexity, distribution of trees, and hence their root systems, forested slopes prone to landslides have been studied little (Schmidt et al, 2001, Sakals and Sidle, 2004, Danjon et al, 2008, Genet et al, 2008, 2010). Trees need a certain amount of time to fully develop their root structure and thus efficiently reinforce the soil. This is the most significant disadvantage of soil-bioengineering slope stabilization.

Genet et al (2008) found that in older plantations, where trees had been thinned and large gaps occurred between trees, the smaller the average distance between groups of trees, the higher the FOS. But no relationships between FOS and stand structure were observed in young plantations, due to the high stand density and homogeneous structure.

Model simulations of root cohesion over time and space can allow foresters to determine how gap formation between trees would affect slope stability (Sakals and Sidle, 2004) in order to establish appropriate types of planting depending on the FOS of the slope.

The development of a simple slope stability model which takes into account the impact of vegetation it is still needed (De Blasio, 2011). However it is unlikely that a simple model can take into account the complexity of root architecture. Moreover, a majority of existing slope stability models which consider vegetation are static. Coupling growth models (Fourcaud et al, 2008), with soil, climate and hydrological models is an exciting challenge and may allow answering the question of the consequences of climate change on substrate mass movement. Such models should take into account the temporal nature of root dynamics and trait expression.

Root development is also not included in this study. It is very complex, but its understanding is a key to model root distributions. To include them in calculations of slope stability, biologists and landslide engineers need to work together to develop long-term strategies for the ecological management of slopes without destabilizing them.

The results obtained, simulated under simplistic conditions, are consistent with other studies, in which evidence on the increase of slope stability in areas prone to shallow landslides is gained by including vegetation, especially trees with deep roots, forming a cylindrical or semi-spherical root system.

6.5 Other considerations

Mechanically, plant roots reinforce a slope soil by providing additional cohesion, what is usually estimated using either a Wu approach or a Fiber Bundle Model (FBM). The first one assumes that all roots break simultaneously, whereas the second assumes progressive breakage of these roots. For both models root density is the most significant parameter.

Cohesion calculated by Wu's model is higher than that calculated by the FBM (Mickovski et al, 2009, Pollen-Bankhead et al, 2010, Mao et al, 2012). In recent years, many different versions of the FBM have been developed, with significant differences in obtained results. More research which allows development of a consistent model is needed before it can be implemented in a commercial software.

The easiest and most often used methods for calculating slope stability are limit-equilibrium models. However, they only evaluate if a slope will fail or not. But for long term studies, strain and displacement of slopes has to be included. The presence of roots strongly modifies the local stiffness of the soil, thus under similar stress conditions, a local slope may respond differently to lateral shearing, compression, or tension (Schwarz et al, 2012). New numerical models should have the ability to quantify the dynamics of root reinforcement, allowing a realistic implementation in slope stability models, including transient calculations.

Development and more detailed research that take into account all factors mentioned above is necessary for a correct understanding of vegetated slope dynamics. But this requires more complex numerical models, with very detailed information, which is not always available. Simple models are very useful as first approximations, large scale simulations, or in situations where data is inaccurate or insufficient.

Accurate information about the quantitative effects of roots on soil strength is necessary to guide the design and management of stabilization systems that incorporate a vegetative element, and data from species suitable for field applications is essential (Mickovski et al, 2011).

7 Conclusions

1. Vegetation increases slope stability significantly, by providing additional cohesion in the root zone and increasing soil suctions via root water uptake. Root depth, distribution and density, represented by generic root architecture models, are extremely important in order to quantify correctly the effect of vegetation.

   Plants with cylindrical root architecture increase the most significantly slope stability. Uniform root architectures are not deep enough and semi-spherical root architectures have very few deep roots.

   Mechanical effects of vegetation are more evident in sand slopes, where potential slip surfaces are shallow and planar. In clay slopes mechanical effects of vegetation are not so noticeable. In the other hand, hydrological impact on slope stability is much more important in clay slopes than in sand since hydraulic conductivity is lower in clay and suctions are higher.

2. From the mechanical point of view, clay slopes have deep and circular potential slip surfaces, making the presence of a rock layer very influential. Slopes with a rock layer, are much more stable, assuming that the friction rock-clay is as strong as clay shear strength. Sand slopes have shallow and planar failure surfaces and the presence of bedrock does not influence the stability significantly, since it lays deeper than the slip surface.

   Positive pore water pressures accumulate in clay slopes above the bedrock, and vegetation has more influence than in cases where no impermeable layer is present. In sand slopes, water moves fast and only accumulates at the toe of the slope and hydrological effects of vegetation are minimized.

3. In temperate climate conditions, similar to Paris, slopes tend to desaturate over time, which positively contribute to stability. Even if positive pore pressures develop, they dissipate very fast. In clay soils, runoff forms easily during a rainfall event, and high suctions develop in shallow zones in slope soil during prolonged dry periods. In sand slopes, there is rather no runoff, and suctions depend on water flow within the slope. Therefore variations in soil moisture as result of variations in atmospheric conditions are less noticeable.

4. During an extreme rainfall event, slopes without vegetation saturate completely. However, vegetation in clay slopes extract enough water during the previous dry period, to avoid full saturation. Slope stability decreases during the event, with a certain time lag due to the slow movement of soil water. In sand slopes water moves fast enough to avoid development of significant positive pore pressures in most of the slope, and stability only decreases slightly during the event..

5. Commercial software still relies on classical simple methods for calculating effects of vegetation. For first approximations, or situations without enough information, this is good enough. However for a better assessment of stability of bioengineered slopes, or for accurate long term studies, more detailed models, now available in scientific research, are still needed. Different approaches should be used depending on the scale of the study and the overall objectives.

8 Summary

Slope instability is a major threat, as it often affect infrastructure, buildings and even cause fatalities. Landslides are of a concern for the protection of human lives and infrastructure from natural hazards. Thus a deep understanding of the mechanisms of slope instability is fundamental for risk prevention and management.

A vast majority of slopes are covered by vegetation, yet contribution of vegetation to slope stability is very rarely included in safety calculations nor in development of engineering solutions. This project identifies the mechanical and hydrological effects of various types of vegetation on the stability of clay and sand slopes, during fluctuating atmospheric conditions and extreme rainfall events.

Slope stability is tested under different scenarios and factors such as soil type, presence of bedrock, different root architectures and atmospheric conditions. Three types of root morphology are considered in respect to a reference slope and the chosen soil properties are typical for clay and sand soils. Moreover, it is assumed that presence of the roots enriches the actual value of cohesion in the root zones of 10 kPa.

Clay slopes, with deep circular failure surfaces, are heavily influenced by the presence of a bedrock and mechanical effects of vegetation are only noticeable when the impermeable layer is present. In sand slopes, with shallow planar slip surfaces, the bedrock has little influence on factor of safety values, but the mechanical effect of vegetation due to the additional cohesion in the root zone is more significant than in clay slopes.

During unsaturated water flow simulations, it is shown that vegetation with cylindrical root architecture reach the highest values of suctions close to the shear zone compared to other shapes of root architecture. In the other hand, suction values are significantly higher in clay slopes than in sand slopes. As a result, pore water pressure distribution is more meaning full in clay soils, but in sand slopes the mechanical effect of root cohesion is more significant.

In clay slopes, vegetation helps to drain soil before and after a rainfall event via root water uptake, which increases water storage capacity during the event, avoiding development of positive pore pressures that dangerously destabilize the slope. In sand slopes, the fact that water moves fast in the soil keeps most of the slope unsaturated and vegetation presence of less significant in this matter.

Results show that the cylindrical root architecture is more effective in slope stabilization than other geometries of the root zones, especially on clay slopes. Evapotranspiration from the vegetated surface increase slope stability and its intensity may differ between different vegetation types. Hence, a correct model of root distribution is of a great importance. Concluding, it is evident, that an increase in slope stability in areas prone to shallow landslides is gained by including vegetation. Trees, shrubs or plants with deep roots are the most efficient in slope stabilization, as they provide additional cohesion in the root zone and increase soil suctions via root water uptake.

Commercial software include vegetation effects using classical simple models. However, for long-term studies, deformation of slopes as well as dynamic root reinforcement and distribution models are still necessary for a better understanding and sufficient accuracy. However, this requires complex numerical models and detailed information, which is not always available. Simple models are very useful as first approximations, in large scale simulations, or in situations where data is inaccurate or insufficient.

References

Allen, R. G.; Pereira, L. S.; Raes, D.; Smith, M., 1998. "Crop evapotranspiration - Guidelines for computing crop water requirements ". FAO Irrigation and drainage paper 56.

Allen, R. G.; Pruitt, W. O., 1996. "Evaporation and transpiration". *ASCE Handbook of Hydrology*. New York, American Society of Civil Engineers . 125-252

Aubertin, M. M.; Bussiere, B.; Chapuis, R. P., A, 2003. "Physically-based model to predict the Water Retention Curve from basic geotechnical properties". Canadian Geotechnical J .

Avanzi, G.D.; Giannecchini, R.; Puccinelli, A., 2004. "The influence of geological and geomorphological settings on shallow landslides. An example in temperate climate environment: the June 19, 1996 event in northwestern Tuscany (Italy)". Eng. Geol 73. 215-228

Bagi, K., 1996. "Stress and strain in granular assemblies". Mechanics of Materials. 22 (3). 165-177

Bear, J., 1972. "Dynamics of fluids in porous media". Dover Publications Inc..

Bear, J., 1979. "Hydraulics of Groundwater". McGraw-Hill.

Bishop, A. W., 1959. "The principle of effective stress". Teknisk Ukeblad 106. I Samarbeide Med Teknikk. Oslo, Norway. 859-863

Bishop, A. W., 1955. "The use of slip circle in the stability analysis of slopes". Geotechnique 5 (1). 7-17

Blöschl, G.; Nester, T.; Komma, J.; Parajka, J.; Perdigão, R. A. P., 2013. "The June 2013 flood in the Upper Danube basin, and comparisons with the 2002, 1954 and 1899 floods". Hydrol. Earth Syst. Sci. Discuss. 10. 9533–9573

Burroughs, E. P.; Thomas, R. R., 1976. "Root strength of Douglas Fir as a factor in slope stability". USDA Forest Service Review, INT 1600-1612 .

Ceriani, M.; Lauzi, S.; Padovan, N., 1992. "Rainfalls and landslides in the Alpine area of Lombardia region, central Alps Italy". Int. Symp. Interpraevent 1992. Bern. 9-20

Cheng, Y. M.; Lansivaara, T.; Wei, W.B., 2007. "Two-dimensional slope stability analysis by limit equilibrium and strength reduction methods". Computers and Geotechnics 34. 137-150

Crosta, G., 1998. "Regionalization of rainfall thresholds: an aid to landslide hazard evaluation". Environ. Geol. 35 (2). 131-145

Danjon, F.; Barker, D. H.; Drexhage, M.; Stokes A., 2008. "Using 3D plant root architecture in models of shallow-slope stability". Ann Bot 101. 1281-1293

De Blasio, F. V., 2011. "Introduction to the Physics of Landslides: Lecture Notes on the Dynamics of Mass Wasting". Springer Science+Business Media B.V.. 23-52

Edlefsen, N. E.; Anderson, A. B. C., 1943. "Thermodynamics of soil moisture". Hilgardia 15 (2). 31-298

Eissenstat, D. M.; Wells, C. E.; Yanai, R. D.; Whitbeck J. L., 2000. "Building roots in a changing environment: implications for root longevity". New Phytol 147. 33-42

Fatahi, B., 2007. "Modelling of influence of matric suction induced by native vegetation on sub-soil improvement". PhD Thesis, School of Civil, Mining and Environmental Engineering, University of Wollongong.

Fatahi, B.; Khabbaz, H.; Indraratna, B., 2010. "Bioengineering ground improvement considering root water uptake model". Ecological Engineering 36. 222-229

Fellenius, W. , 1936. "Calculation of the stability of earth dams". Transactions of the 2nd Congress on Large Dams, Vol. 4. Int. Comm. on Large Dams, Washington, D.C. 445–463

Fourcaud, T.; Zhang, X.; Stokes, A.; Lambers, H.; Körner, C., 2008. "Plant growth modelling and applications: the increasing importance of plant architecture in growth models". Ann Bot 101. 1053-1063

Fredlund, D. G.; Anqing Xing, 1994. "Equations for the soil-water characteristic curve". Canadian Geotechnical J. 31. 521-532

Fredlund, D. G.; Morgenstern, N. R.; Widger, R. A., 1978. "The shear strength of unsaturated soils". Canadian Geotechnical J. 15 (3). 313-321

Fredlund, D. G.; Rahardjo, H., 1993a. "Soil Mechanics for Unsaturated Soils". John Wiley & Sons Inc.

Fredlund, D. G.; Rahardjo, H., 1993b. "An overview of unsaturated soil behaviour". *Unsaturated Soils*. Houston, S. L. and Wray, W. K., ASCE Geotechnical Special Publication 39. 1-31

Gabet, E. J.; Dunne, T., 2002. "Landslides on coastal sage-scruband grassland hillslopes in a severe El Niño winter: the effects of vegetation conversion on sediment delivery". Geol Soc Am Bull 114. 983-990

Gardner, W. R., 1961. "Soil suction and water movement". *Pore pressure and suction in soil*. London, Butterworths. 137-140

Gardner, W. R. , 1960. "Dynamic Aspects of Water Availability to Plants.". Soil Science 89 (2). 11

Genet, M.; Kokutse, N.; Stokes, A.; Fourcaud, T.; Cai, X.; Ji, J.; Mickovski, S. B., 2008. "Root reinforcement in plantations of *Cryptomeria japonica* D. Don: effect of tree age and stand structure on slope stability". For Ecol Manag 256. 1517-1526

Genet, M.; Stokes, A.; Fourcaud, T.; Norris, J., 2010. "The influence of plant diversity on slope stability in moist evergreen deciduous forest". Ecological Engineering 36 (3). 265-275

Geo-slope international Ltd, 2008a. "Stability modeling with SLOPE/W 2007 version". GEO-SLOPE International Ltd.

Geo-slope international Ltd, 2008b. "Vadose zone modeling with VADOSE/W 2007 version". GEO-SLOPE International Ltd.

Graf, F.; Frei, M.; Böll, A., 2009. "Effects of vegetation on the angle of internal friction of a moraine". For. Snow Landsc. Res. 82 (1). 61-77

Gray, D. H., 1978. "Role of woody vegetation in reinforcing soils and stabilizing slopes". Symposium on Soil Reinforcing and Stabilizing Techniques. Sydney, Australia. 253-306

Green, R. E.; Corey, J. C., 1971. "Calculation of Hydraulic Conductivity: A Further Evaluation of Some Predictive Methods". Soil Science Society of America Proceedings 35. 3-8

Greenwood, J. R.; Norris, J. E.; Wint, J., 2004. "Assessing the contribution of vegetation to slope stability". Geotechnical Engineering 157. 199-207

Hammond, C.; Hall, D.; Miller, S.; Swetik, P., 1992. "Level I stability analysis (LISA) documentation for version 2.0". USDA Forest Service Intermountain Research Station, Ogden, UT, General Technical Report INT-285. .

Hausmann, M. R., 1978. "Behavior and analysis of reinforced soil". Ph.D. Thesis. University of South Wales, Sydney, Australia.

Jordan, C. A., 2011. "Combined hydrology and slope stability assessment of the Olympic region of Washington state". M.Sc. Thesis, Department of Civil and Environmental Engineering, Washington State University.

Kasim, F.; Fredlund, D. G.; Gan, J. K.-M., 1998. "The effect of steady state rainfall on long term matric suction conditions". Slope engineering in Hong Kong. K.S. Li, J.N. Kay and K.K.S., Ho. Balkema . 75-85

Kim, D.; Im, S.; Lee, C.; Woo, C., 2013. "Modelling the contribution of trees to shallow landslide development in a steep, forested watershed". Ecological Engineering.

Kirschbaum, D.; Adler; R., Adler, D.; Peters-Lidard, C.; Huffman, G., 2012. "Global distribution of extreme precipitation and high-impact landslides in 2010 relative to previous years". Journal of Hydrometeorology 13 (5). 1536-1551

Kokutse, N.; Fourcaud, T.;Kokou, K.; Neglo, K.; Lac, P., 2006. "3D Numerical modelling and analysis of the influence of forest structure on hill slopes stability". *Disaster Mitigation of Debris Flows, Slope Failures and Landslides*. Universal Academy Press, Inc. . 561–567

Köstler, J. N.; Brückner, E.; Bibelriether, H., 1968. "Die Wurzeln der Waldbaüme". Verlag Paul Parey .

Lu, N.; Şener-Kaya, B.; Wayllace, A.; Godt, J. W., 2012. "Analysis of rainfall-induced slope instability using a field of local factor of safety". Water Resources Research 48.

Lumb, P., 1975. "Slope failures in Hong Kong". Quarterly Journal of Engineering Geology 8. 31-65

Lumb, P. , 1962. "Effect of rain storms on slope stability". Symposium on Hong Kong soils; May 1962. Hong Kong Joint Group of the Institution of Civil, Mechanical and Electrical Engineers.

Mao, Z.; Saint-André, L.; Genet, M.; Mine, F. X.; Jourdan, C.; Rey, H.; Courbaud, B.; Stokes, A., 2012. "Engineering ecological protection against landslides in diverse mountain forests: Choosing cohesion models". Ecological Engineering 45. 55-69

Mickovski a, S. B.; Stokes, A.; van Beek, R.; Ghestem, M.; Fourcaud, T., 2011. "Simulation of direct shear tests on rooted and non-rooted soil using finite element analysis". Ecological Engineering 37. 1523-1532

Mickovski, S. B.; Hallett, P. D.; Bransby, M. F.; Davies, M. C. R.; Sonnenberg, R.; Bengough, A. G., 2009. "Mechanical reinforcement of soil by willow roots: impacts of root properties and root failure mechanism". Soil Sci. Soc. Am. J. 73. 1276-1285

Milly, P. C. D., 1982. "Moisture and heat transport in hysteretic, in homogeneous porous media: A matric head based formulation and a numerical model". Water Resources Research 18 (3). 489-498

Morgenstern, N. R.; Price, V. E., 1965. "The analysis of the stability of general slip surface". Geotechnique 15 (4). 289-290

National Research Council, 1990. "Groundwater models: Scientific and regulatory applications". Water Science and Technology Board, Committee on Ground Water Modelling Assessment. Commission on Physical Sciences, Mathematics and Resources. National Research Council, National Academy Press, Washington, D.C.

Nyvall, J., 2002. "Soil Water Storage Capacity and Available Soil Moisture". F. a. F. Ministry of Agriculture. Abbotsford, BC.

Osman, N.; Barakbah, S. S., 2006. "Parameters to predict slope stability—soil water and root profiles". Ecol Eng 28. 90-95

Passioura, J. B., 1991. "Soil structure and plant-growth". Aust J Soil Res 29. 717-728

Penman, H. L., 1948. "Natural evapotranspiration from open water, bare soil and grass". Proc. R. Soc. London Ser. A. 193. 120-145

Philip, J. R. , 1957. "The theory of infiltration 1: The infiltration equation and its solution ". Soil Science 83.

Pollen-Bankhead, N.; Simon, A.; Thomas R. E., 2010. "Modelling root-reinforcement with a fiber-bundle model and monte carlo simulation". Ecological Engineering 36. 47-61

Preti, F., 2012. "Forest protection and protection forest: Tree root degradation over hydrological shallow landslides triggering". Ecological Engineering .

Priestly, C. H. B.; Taylor, R. J., 1972. "On the assessment of surface heat flux andevaporation using large scale parameters". Monthly Weather Review 100. 81-92

Rees, S. W.; Ali, N., 2006. "Seasonal water uptake near trees: a numerical and experimental study". Geomechanics and Geoengineering: An International Journal 1 (2). 129-138

Rees, S. W.; Ali, N., 2012. "Tree induced soil suction and slope stability". Geomechanics and Geoengineering: An International Journal 7 (2). 103-113

Reubens, B.; Poesen, J.; Danjon, F.; Geudens, G.; Muys, B., 2007. "The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review". Trees 21. 385-402

Rice, R. M.; Foggin, G. T., 1971. "Effect of high intensity storms on soil slippage on mountainous watersheds in southern California". Water Resour Res 7. 1485-1496

Richards, B. G., 1967. "Moisture flow and equilibria in unsaturated soils for shallow foundations". American Society for Testing of Materials. 4-33

Richards, L.A., 1931. "Capillary Conduction of Liquids Through Porous Mediums". Physics (1).

Rickli, C.; Graf, F., 2009. "Effects of forests on shallow landslides - case studies in Switzerland". For. Snow Landsc. Res. 82 (1). 33-44

Rickli, C.; Zimmerli, P.; Böll, A., 2001. "Effects of vegetation on shallow landslides: an analysis of the events of August 1997 in Sachseln, Switzerland ". Proceedings International Conference on Landslides Davos 2001 .

Rubin, J.; Steinhardt, R., 1963. "Soil water relations during rain infiltration: I. Theory". Soil Science Society of America Proceedings 27. 246-251

Rubin, J.; Steinhardt, R.; Reiniger, P., 1964. "Soil water relations during rain infiltration: II. Moisture content profiles during rain of low intensities". Soil Science Society of America Proceedings 28. 1-5

Sakals, M. E.; Sidle, R. C., 2004. "A spatial and temporal model of root cohesion in forest soils". Can J For Res 34. 950-958

Sati, S. P.; Sundriyal, Y. P., 2007. "Role of some species in slope instability". Himalayan Geol 28. 75-78

Saxton, K. E., 1982. "Mathematical modelling of evapotranspiration on agricultural watersheds". *Modeling Components of the Hydrologic Cycle*. Singh, H. 183-203

Schenk, H. J., 2008. "Soil depth, plant rooting strategies and species' niches". New Phytol 178. 223-225

Schmidt, K. M.; Roering, J. J.; Stock, J. D.; Dietrich, W. E.; Montgomery, D. R.; Schaub T., 2001. "Root cohesion variability and shallow landslide susceptibility in the Oregon Coast Range". Canadian Geotechnical J. 38. 995–1024

Schwarz, M.; Cohen, D.; Or, D., 2012. "Spatial characterization of root reinforcement at stand scale: Theory and case study". Geomorphology 171-172. 190-200

Schwarz, M.; Lehmann, P.; Or, D., 2010. "Quantifying lateral root reinforcement in steep slopes from a bundle of roots to tree stands". Earth Surface Processes and Landforms 35. 354-367

Sidle, R. C.; Ochiai, H., 2006. "Landslides : processes, prediction, and land use". American Geophysical Union.

Simon, A.; Collison, A. J. C., 2002. "Quantifiying the mechanical and hydrologic effects of riparian vegetation on streambank stability". Earth Surface Processes and Landforms 27. 527-546

Smith, P. G. C., 2003. "Numerical analysis of infiltration into partially saturated soil slopes". PhD Thesis, Imperial College of Science, Technology and Medicine, University of London.

Stokes, A.; Atger, C.; Bengough, A. G.; Fourcaud, T.; Sidle, R. C., 2009. "Desirable plant root traits for protecting natural and engineered slopes against landslides". Plant Soil 324. 1-30

Sun, H. W.; Wong, H. N.; Ho, K. K. S., 1998. "Analysis of infiltration in unsaturated ground". Slope engineering in Hong Kong. K.S. Li, J.N. Kay and K.K.S., Ho. Balkema . 101-109

Tasser, E.; Mader, M.; Tappeiner, U., 2003. "Effects of land use in alpine grasslands on the probability of landslides". Basic Appl Ecol 4. 271-280

Terzaghi, K., 1943. "Theoretical soil mechanics". Wiley, New York.

Thornthwaite, C.W., 1948. "An approach toward a rational classification of climate". Geographical Review 38. 55-94

Tiwari, R. C.; Bhandary, N. P.; Yatabe, R.; Bhat, D. R., 2013. "New numerical scheme in the finite-element method for evaluating the root-reinforcement effect on soil slope stability". Geotechnique 63 (2). 129-139

Tratch, D., 1996. "Moisture uptake within the root zone". M.Sc. Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

Turmanina, V. I., 1965. "The strength of tree roots". Bulletin of the Moscow Society of Naturalists Biological Section 70. 36-45

Van Genuchten, M. Th., 1980. "A closed-form equation for predicting the hydraulic conductivity of unsaturated soils". Soil Science Society of America Journal 44. 892-898

Vanapalli, S. K.; Fredlund, D. G.; Pufahl, D. E.; Clifton, A. W., 1996. "Model for the prediction of shear strength with respect to soil suction". Canadian Geotechnical J. 33. 379-392

Waldron, L. J., 1977. "Shear resistance of root-permeated homogeneous and stratified soil". Soil Science Society of America Journal 41. 843-849

White, W.N., 1932. "A method of estimating ground water supplies based on discharge by plants and evaporation from soil: Results of investigation in Escalante Valley, Utah". Washington, D.C.: U.S. Department of the Interior. Water-Supply Paper 659-A. .

Willigen, P.; van Dam, J. C.; Javaux, M.; Heinen, M., 2012. "Root water uptake as simulated by three soil water flow models". Vadose Zone J. 18.

Wilson, G. W., 1990. "Soil evaporative fluxes for geotechnical engineering problems". Ph.D. Thesis. University of Saskatchewan, Saskatoon, Canada.

Wu, T. H., 1976. "Investigation of landslides on Prince of Wales Island, Alaska". Geotechnical Engineering Report (5). Ohio State University, Department of Civil Engineering.

Wu, T. H., 1984. "Effect of vegetation on slope stability". Soil Reinforcement and Moisture Effects on Slope Stability. Transportation Research Record 965. 37-46

Yeh, H. F.; Lee, C. H., 2013. "Soil water balance model for precipitation-induced shallow landslides". Environ. Earth Sci.

Ziemer, R. R., 1981. "The role of vegetation in the stability of forested slopes". Proceedings of the International Union of Forestry Research Organizations, XVII World Congress. Japan. 297-308

Affirmation

I certify, that the master thesis was written by me, not using sources and tools other than quoted and without use of any other illegitimate support.

Furthermore, I confirm that I have not submitted this master thesis either nationally or internationally in any form.

Vienna, Decemberer 2014. Lorenzo Holsworth