Chapter 10
Use of Vegetation for Landslide Risk Mitigation

Bjørn Kalsnes and Vittoria Capobianco

Abstract Landslide risk management involves several activities, modelling being a required premise for most of them. Modelling of climate-induced landslides include both the analysis of the triggering process, i.e. static slope stability analysis and dynamic propagation (run-out) analysis. These analyses are vital for mapping purposes, as well as for selection of effective means to reduce the landslide risk when this exceeds a certain value of tolerance. With the prospect of increasing rainfall duration and intensity in parts of Europe, the need for further development of modelling tools is evident. In recent years, the use of Nature-Based Solutions (NBS) for mitigation of natural hazards has further demonstrated the need for developing the modelling tools. The use of vegetation as NBS is increasingly being used for erosion protection and shallow landslide mitigation. For slope stability analyses, the use of vegetation makes the modelling more complex for a number of reasons, mostly linked to the influence of vegetation on both the soil–atmosphere interaction (i.e. rainfall interception, evapotranspiration) and the soil hydro-mechanical properties. All effects that are difficult to model due to lack of knowledge and to large variations in time and space. Even though there is an increasing activity in the geotechnical environment to incorporate the effects of vegetation in the modelling for quantifying the change in slope stability (i.e. calculate slope safety factor), the status is far from being at the level of traditional landslide modelling tools. More efforts are therefore needed in the years to come to demonstrate that the use of vegetation as a viable and effective measure in landslide risk mitigation management can be verified in a more quantifiable manner.

Keywords Landslides · Nature-based solutions · Mitigation · Vegetation · Slope stability modelling

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Introduction

Landslide risk management in the context of climate change has been a profiled study for more than a decade. Many studies have shown that a change in rainfall duration and intensity will cause an increase in natural water-induced phenomena, such as floods, soil erosion and landslides in large parts of Europe, with damaging effects on people, infrastructure, housings and the environment. The need for a proper landslide risk management strategy is therefore significant at all scales, namely, national, regional and local. A premise for sound landslide risk management is modelling of triggering and run-out phenomena, to determine location and extent of potential landslides and thus the selection of appropriate risk reduction measures.

In recent years, there has been an increasing focus on the use of Nature-Based Solutions (NBS), both with regard to urban and rural development, and for disaster risk reduction. This paper presents the challenges related to the use of NBS for landslide mitigation purposes. The question is simply: how can we verify that the use of NBS is an effective measure for mitigating a landslide problem for a detailed case, and simultaneously being not harmful to the environment? The focus of the paper will be on modelling of slope stability with the use of vegetation. What are the effects of vegetation in reducing the probability of landslide occurrence, and how do we model these effects?

Climate-Induced Landslides

Landslides Risk in View of Climatic Changes: Relevant Past and On-Going Projects

The effects of climate change on the landslide risk have been a major concern for many years. The need to protect people and property with a changing pattern of landslide hazard and risk caused by climate change and changes in demography was the main motivation for the FP7 research project 'SafeLand' (2009–2012) on landslide risk in Europe (Nadim and Kalsnes 2014). In the SafeLand project, considerable effort was done on developing models for the prediction of precipitation-induced landslides. One of the conclusions was that the thresholds for landslide triggering are affected by long-term precipitations in areas that are covered by deep deposits of fine-grained soils, while they are controlled by short-term precipitations in areas with shallower deposits with coarse-grained soils. For shallow landslides, the soil–atmosphere interaction is a major factor influencing the slope stability. Various geotechnical stability programmes are able to model these effects as slope top boundary conditions, taking into account the pore pressure development and general soil behaviour characteristics.

The main aim of any management strategy is to reduce the landslide risk to acceptable levels when found necessary. This can be done using structural and/or non-structural measures (for instance, early warning systems). Structural means may include measures to hinder the landslide to develop, thus stopping the triggering phase, or measures to reduce the run-out effects of a landslide already taking place. As a follow-up of an activity in SafeLand, the Norwegian Research Center Klima 2050 has developed a web-based tool LaRiMiT (Landslide Risk Mitigation Toolbox, https://www.larimit.com) aimed at assisting decision-makers to select an appropriate mitigation measure for a given landslide problem (Uzielli et al. 2017). More than 80 various measures are identified in LaRiMiT, most of them relevant for rainfall-induced landslides. Out of a total of 11 categories of landslide mitigation measures, 2 categories and a total of approximately 15 measures imply NBS measures or hybrid measures (combination of NBS and traditional 'grey' measures). Most of the measures are relevant for erosion control and shallow landslides.

Slope Stability Modelling

The landslide modelling normally implies two phases, one is the geotechnical static slope stability analysis and the other is the dynamic propagation analysis (run-out). The first serves for the hazard analysis and the latter serves for both hazard analysis and the identification of hazard scenarios, as input for estimating the consequences of a certain landslide event. The use of vegetation is not yet sufficiently addressed in neither of them. In this paper, the focus is on the geotechnical modelling of static slope stability, i.e. hazard analysis.

Two main modelling principles are used for geotechnical static slope stability analyses: (i) the limit equilibrium methods (LEM) and (ii) the finite element methods (FEM). The principal difference between these two methods is that LEM is based on static equilibrium, while the FEM uses the stress–strain relationships or the constitutive law, to simulate the mechanical behaviour of the soil. The LEM method identifies potential failure mechanisms and derives factors of safety. Among the various LEM methods available, those most used satisfy both force and moment equilibriums. FEM requires the definition and the use of complex constitutive models for all materials, especially for describing the soil behaviour. Different constitutive laws may be used, for example, linear elastic–perfectly plastic, linear elastic-hardening plastic laws. In both cases, the modelling of the soil behaviour is the key to reliable results, thus detailed field and laboratory tests are required for defining input parameters.

Nature-Based Solutions (NBS)

Nature-Based Solutions for Climate-Related Challenges: European Strategy

Nature-Based Solutions (NBS) is a collective term for solutions that are based on natural processes and ecosystems to solve different types of societal challenges. Of particular interest is mitigation and adaptation strategies to address climate-related challenges. The use of NBS has several advantages beyond their primary goals, such as preventing natural hazards. IUCN (2017) points out the breadth of benefits the use of NBS can include: (a) increasing biodiversity; (b) long-term stability; (c) ecological management both 'upstream and downstream'; (d) direct societal benefits; (e) local governance.

A first milestone in the establishment of NBS was the World Bank's report *Biodiversity, Climate Change and Adaptation: Nature-Based Solutions from the World Bank Portfolio* (World Bank 2008). In recent years, NBS has received increased attention, not least as a result of the European Commission (EC) investing considerable resources in building up European competitive advantage in this field. The EC has, indeed, established a clear strategy of Europe being a main actor in the development and use of NBS for various climate-related societal challenges. A large number of research programmes have been launched since 2014; one of them is related to use of NBS for hydrometeorological risk reduction (EC 2017). These studies incorporate the use of NBS for landslide risk mitigation, which also includes the need for proper modelling tools. However, the latter are far from being at the level of traditional landslide modelling tools, even though the interest is increasing internationally. More efforts are needed in the years to come to be able to handle in a quantitative manner the use of NBS for landslide mitigation.

Climate change will cause a change of rainfall patterns and intensity in large parts of Europe. This will lead to an increased probability for rainfall-induced landslides with high destructive potential for exposed infrastructure. In order to reduce the societal risk associated with climate change and enhanced precipitation, NBS can represent a sustainable, efficient and cost-effective approach. NBS have been increasingly applied to design new resilient landscapes and cities with beneficial outcomes for the environment, the society and human well-being.

Use of NBS in Landslide Risk Mitigation

In the recent years, a large variation of NBS measures were proposed for mitigating natural hazards. Some of them are grounded in the Ecosystem-Disaster Risk Reduction (Eco-DRR) with the aim to achieve sustainable and resilient development (Estrella and Saalismaa 2013). Sutherland et al. (2014) identified almost 300 NBS-specific measures for natural hazards mitigation and for agricultural problems. For landslide and erosion protection, most of these measures involved the use of vegetation. Arce-Mojica et al. (2019) made a similar study, focussing on the NBS measures for reducing the risk of shallow landslides. They performed a systematic literature review to ascertain the extent to which vegetation is identified as a controlling factor and the targeting of NBS for landslide risk reduction. They concluded that despite there has been an important increase in the number of articles dealing with NBS approaches for shallow landslides mitigation; science appears to be lagging behind compared to the promotion of NBS in international and policy arenas. There is a need for further research, both related to a most suitable selection of vegetation species in different forest ecosystems and biogeographical regions, which is essential for a successful mitigation, and to the potential negative effects of vegetation as a shallow landslide triggering factor.

Modelling of Slope Stability Using Vegetation

Effects of Vegetation on Landslide Protection

Several studies have identified both positive and negative effects of using vegetation for landslide protection (Stokes et al. 2014; NVE/NGI 2015; Krzeminska et al. 2019). The major findings are that the use of vegetation for landslide protection have two positive effects and one potential negative effect: (i) the strength of the soil increases due to roots and binding of soil layers, (ii) the pore water pressure is reduced due to plant's uptake and canopy cover, (iii) vegetation may destabilize slopes in connection with strong winds (this is valid only for trees). These are all effects that may be modelled, but as the studies show there are a lot of uncertainties related to this aspect. Examples of challenges with regard to modelling include the following:

- The undrained shear strength depends on the type of roots, the position of the main roots network and the season of the year.
- The effect of reduced soil water content and induced soil suction is highly uncertain and can vary considerably from case to case, also in relation to the distribution and vegetation density along the slope.

Expected Development Within Landslide Modelling Using Vegetation

Landslide modelling when including the vegetation contribution in slope stability analyses will be more complex, due to the coupled effect that they provide to the soil: (i) hydrological, through the soil–vegetation–atmosphere interaction and (ii) mechanical, through the root–soil interaction.

Figure 10.1 shows a methodological approach which takes into account the vegetation contribution in the slope stability modelling. The approach consists of two main parts: (i) hydrological modelling, to assess the pore water pressure regime and (ii) slope stability modelling, to assess the safety factor. As input data, hydrometeorological analysis implies the collection of current meteorological data (e.g. rainfall intensity, wind, temperature, relative humidity), or the analysis of potential future climate scenarios, to be used to feed the hydrological model. It is important to stress that precipitation events are often linked to the triggering of landslides, but it is the change in pore water pressures that leads a slope to fail (Toll et al. 2011). As it concerns, the input data related to the soil, many soil parameters as well as hydraulic processes (water fluxes) are function of the vegetation. A tentative to categorize the effects of vegetation on the input data has been done on the base of whether they are function of the root features (mostly density, architecture and depth) or the canopy (type of aboveground vegetation).

For the hydrological modelling and the evaluation of the pore water pressure regime in the ground, the hourly rainfall is an essential input to the water flux, while both the roots and the aboveground vegetation features influence the processes and the soil parameters. Some challenges related to the definition of these relationships are as follows:

Soil hydraulic properties: The hydraulic conductivity of the soil strongly depends on the type of roots (coarse or fine) and their age (i.e. young roots or decaying roots). Some preliminary functions were proposed to model the effect of roots on the change of soil hydraulic conductivity, but they have been included so far only in analytical analyses (Ni et al. 2018). However, recent studies have found that

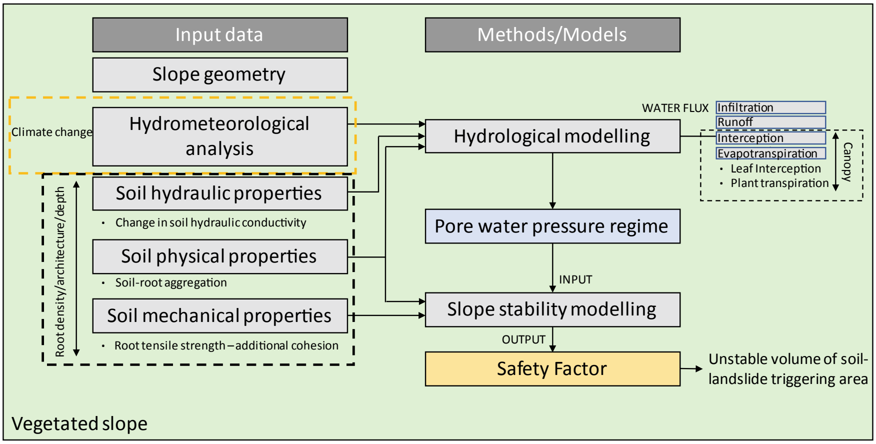

Fig. 10.1 Methodological approach for slope stability modelling including vegetation—soil parameters and processes influenced by the presence of vegetation (root density/architecture/depth and canopy area)

hydraulic conductivity of the soil can change also with time as the roots develop and grow (Capobianco et al. 2020).

Soil physical properties: As roots occupy the pores, they tend to change also the soil void ratio. How much they change the soil unit weight needs additional studies.

Interception: This accounts the rainwater intercepted by the vegetation that does not infiltrate into the soil. Such factor is strongly affected by the canopy area and the parameters such as the Leaf Area Index (LAI).

Evapotranspiration: Most of the hydrological models calculate the potential evapotranspiration with the equation proposed by Penman-Monteith (Allen et al. 1998), in which the potential transpiration given by the vegetation is usually function of the LAI and the soil cover fraction.

Once the pore water pressure regime is assessed, this is used as input for the slope stability modelling, where only the root features are considered to influence the mechanical properties of the soil. The effect of roots on the soil mechanical properties has been extensively studied and understood from the perspective of geotechnical engineering: the root tensile strength provides additional cohesion to the soil with a magnitude depending on the tensile strength and the root density. It is evident that the soil–vegetation–atmosphere interaction is complex and requires both the knowledge of the root features and how the vegetation is developed aboveground.

Challenges Related to Legislation

Vegetation has traditionally been used for erosion protection in many areas of Europe. The positive effects of use of vegetation for shallow landslides have also been widely recognized. However, due to challenges with regard to quantifying these positive effects, use of vegetation is often overseen as a practical measure for landslide protection. When it comes to building and construction, Eurocode standards need to be followed in many European countries. This implies that a minimum safety factor of 1.4 (ratio between stabilizing forces and driving forces) needs to be demonstrated for local slope stability analyses. In such cases, the need for better modelling is needed as the tools available at present is not sufficient for demonstrating properly in quantitative manner the positive effects of use of vegetation for landslide protection.

Conclusions and Recommendations

Use of vegetation as a viable and effective measure in landslide risk mitigation management needs to be documented in a more quantifiable manner. The effect of vegetation is complex and varies with time, type of soil and atmospheric conditions. A methodological approach to include the vegetation in slope stability modelling in hazard prone areas is herein proposed, where the hydrological and mechanical reinforcement provided by the vegetation on the soil properties are classified whether they are root-related or canopy-related. Some key challenges in this respect are as follows:

Modelling the vegetation effects on slope stability needs many parameters related to the vegetation features which are strongly time-dependent. Moreover, vegetation features differ from species to species. There is a need to understand how to consider the vegetation growth effects.

Only one safety factor is calculated as average. Small-scale effects of vegetation on slope stability are not calculated. However, vegetation may not be distributed homogeneously, thus there is a need to consider time-spatial variation of vegetation effects on a slope (Stokes et al. 2014).

Climate change may alter the precipitation scheme dramatically in many areas, with more intense rainfall combined with more dry periods. The need for combined efforts in local instrumentation and modelling development is pronounced.

This study on landslide modelling is focussed on addressing the effects of vegetation on rainfall-induced landslides. However, climate change may also increase the frequency of droughts, which lead to tree mortality and forest fires. Possible extreme events like these, which still imply the vegetation, need to be studied with regard to the initiation of extreme surface runoff and flash floods due to heavy rainfall.

References

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome 300(9):D05109

Arce-Mojica T, Nehren U, Sudmeier-Rieux K, Miranda P, Anhuf D (2019) Nature-based solutions (NbS) for reducing the risk of shallow landslides; where do we stand? Int J Disaster Risk Reduct 41 (2019). https://doi.org/10.1016/j.ijdrr.2019.101293

Capobianco V, Cascini L, Cuomo S, Foresta V (2020) Wetting-drying response of an unsaturated pyroclastic soil vegetated with long-root grass. Environ Geotech 1–18

EC (2017) Large-scale demonstrators on nature-based solutions for hydro-meteorological risk reduction. SC5-08

Estrella M, Saalismaa N (2013) Ecosystem-based disaster risk reduction (Eco-DRR): an overview. The role of ecosystems in disaster risk reduction. United Nations University Press, Tokyo, 332

International union for conservation of nature, IUCN, 2017. The IUCN Global Programme 2013–16, adopted by the IUCN World Conservation Congress, September 2012

Krzeminska D, Kerkhof T, Skaalsveen K, Stolte J (2019) Effect of riparian vegetation on stream bank stability in small agricultural catchments. CATENA 172:87–96

Nadim F, Kalsnes B (2014) Progress of living with landslide risk in Europe. In: Sassa K et al (ed) Keynote paper to 3rd World Landslide Forum, Beijing, June 2014. Landslide science for a Safer Geoenvironment, vol 1. Springer International Publishing, Switzerland. https://doi.org/10.1007/9783-319-04999-1-1

Ni JJ, Leung AK, Ng CWW, Shao W (2018) Modelling hydro-mechanical reinforcements of plants to slope stability. Comput Geotech 95:99–109

NVE/NGI (2015) Oppsummeringsrapport for skog og skredprosjektet. Samanstilling av rapportar frå prosjektet. Rapport 92/2015 (In Norwegian)

Sutherland WJ, Gardner T, Bogich TL, Bradbury RB, Clothier B, Jonsson M, Kapos…and Dicks, L.V. V (2014) Solution scanning as a key policy tool: identifying management interventions to help maintain and enhance regulating ecosystem services. Ecol Soc 19(2):3. https://doi.org/10.5751/ES-06082-190203

Stokes A, Douglas GB, Fourcaud T, Giadrossich F, Gillies C, Hubble T, Kim JH, Loades, Walker LR, et al (2014) Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. Plant Soil 377:1–23. https://doi.org/10.1007/s11104-014-2044-6

Toll DG, Lourenco SDN, Mendes J, Gallipoli D, Evans FD, Augarde CE, Mancuso C (2011) February. Geological society of London, Soil suction monitoring for landslides and slopes

Uzielli M, Kalsnes B, Choi JC (2017) A web-based landslide risk mitigation portal. In: Proceedings, 4th World Landslide Forum, Ljubljana, Slovenia, June 2017

World Bank (2008) Biodiversity, climate change and adaptation: nature-based solutions from the world bank portfolio. Washington, DC