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Simulating the stabilization effect of soil bioengineering interventions in Mediterranean environments using limit equilibrium stability models and combinations of plant species

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Dedicated to the memory of Prof. Wolfram Pflug (1923–2013), co-founder and 1st President of the Gesellschaft für Ingenieurbiologie (Society for Soil Bioengineering) predecessor of the European Federation of Soil Bioengineering. Dear Master and friend.

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ABSTRACT

One of the critical problems in projecting soil bioengineering interventions is the difficulty in developing precise calculations of the evolution of the structures and the type and combination of vegetation plantations that are planned for the particular site and problem. This is mainly due to the uncertainties in the plant development in each type of soil, the long and short term weather patterns and other edapho-climatic factors that determine limited calculation possibilities causing considerable degrees of uncertainty. This leads to a reduced level of reliability of bioengineering projects in terms of predetermined factors of safety. In Mediterranean conditions this problem is even stronger due to the high seasonal and year-to-year climatic variability, and high degree of uncertainty in the vegetation installment and growth patterns.

To evaluate the comparative short and long term (up to 20 years) efficacy of the most used slope stabilization techniques, common calculation models were used to assess the factor of safety of those techniques. SLIP4EX was used to evaluate the factor of safety, while the normal Coulomb model was used to assess the resistance to sliding and overturning. Considering the average Mediterranean climatic conditions, the considered environmental conditions were the least favorable, in order to assess the reliability of the "worst case scenario". Two common tree species in the western Mediterranean region (*Pinus halepensis* and *Quercus faginea*) were selected for the simulation and three common soil types were considered (stony clay, loose sandstone and sandy marl).

The results of the simulations for different types of substrates, plant combinations and designs, show that, according to the modeling approaches, the use of soil bioengineering techniques, present a reliable effectiveness, confirmed by the experience gathered in interventions in Mediterranean sites with similar edapho-climatic conditions.

Additionally, because bioengineering is about the factor of safety of the target vegetation after the decay of the combined structure, the efficiency as a slope support structure of a vegetated log cribwall was compared with the expected developed vegetation. It was concluded that an adequate development of the vegetation ensures all safety requirements even in the worst considered scenarios.

Our results also illustrate that there is a generalized lack of data on the geotechnical characteristics of the Mediterranean vegetation, which is particularly critical in a geo-ecological context where bioengineering techniques face important limitations (very few species able of vegetative development of roots and shoots from live cuttings).

1. Introduction

Soil and water bioengineering are old techniques that embodied the need of men to use the natural systems and elements to ensure the safety and functionality of land use. Recently, "*soil bioengineering has set itself the aim of designing our environment in a "living" way by applying construction methods which are close to nature (. . .)*

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based on materials which are found in nature and which are combined with technical building materials" (Studer and Zeh, 2014, pp. 36). Typically, plants and parts of plants are used as living building materials, in such a way that, through their development in combination with soil and rock, they ensure a significant contribution to the long-term protection against all forms of erosion and several forms of soil instability. In the initial phase, they often have to be combined with non-living building materials, which may, in some cases, ensure more or less temporarily, most of the supporting functions (Styczen and Morgan, 1995; Gray and Sotir, 1996; Li and Eddleman, 2002; Norris et al., 2008; Evette et al., 2009; Bischetti et al., 2012; Hacker, 2015).

Soil bioengineering techniques have been extensively used all over the world, and applied in different contexts including slope stabilization (e.g. Lammeranner et al., 2005; Rey et al., 2005; Burri et al., 2009; Rey, 2009; Moscatelli et al., 2009; Stokes et al., 2010; Prasad et al., 2012), wetland restoration and streambank protection (e.g. Li et al., 2006; Evette et al., 2009; Anstead and Boar, 2010; Buchanan et al., 2012; Krymer and Robert, 2014), and to minimize soil erosion after ecological disturbances such as fire (e.g. Wagenbrenner et al., 2006; Robichaud et al., 2008; Myronidis and Arabatzis, 2009; Vallejo and Alloza, 2012; Aristeidis and Vasiliki, 2015), among others. In short, the planning and construction objectives are the protection and stabilization of land uses and infrastructures as well as the development of landscape elements in predominantly humanized landscapes. The use of organic materials as auxiliaries in the first development stages of the vegetation is preferred, because, along with the vegetation development and its increasing stabilization ability, these materials will rot and be reincorporated in the natural biogeochemical cycles (Hacker and Johannsen, 2012; Florineth, 2012; Studer and Zeh, 2014; Hacker, 2015).

In bioengineering, the main construction materials are living plants or parts of plants. Therefore, two main difficulties present themselves to the planner, engineer and designer. The first issue is related to the selection of plants, and to determine if they fulfill the bio-geotechnical characteristics demanded by the projects and can be successfully installed in the intervention site (Stokes, 2006; de Baets et al., 2009; Evette et al., 2012; Gastón and García-Viñas, 2013; Ghestem et al., 2014). The second concerns the need to ensure that the development of the plants (installed and naturally post colonizing the site) fulfill the long term technical demands of the intervention (Hubble et al., 2010; Krymer and Robert, 2014; Pander and Geist, 2013; Preti, 2013). In any case, indigenous (autochthonous) and site-specific plants are preferred because of their adaptation to the local ecological conditions and to avoid the risk of introduction of invasive species or alien varieties and the related risk of biogenetical contamination (Krautzer and Hacker, 2006). The first difficulty is critical when compared with the manifold information existing in relation to traditional construction material (e.g. wood, steel, stone and concrete) because each plant is a living organism that responds differently to its environment and responds also differently to different environments. Therefore, information gathered on a given set of environmental conditions is not necessarily suitable for being generalized to other environments.

One of the objections presented relatively too many combined bioengineering interventions is that, when the supporting structure decays, there is no evidence that the vegetation will be able, on itself, to ensure the stabilization functions. There are multiple field researches where such bioengineering interventions were analyzed on the long term, and its efficiency evaluated (e.g. Böll et al., 2009; Stangl, 2007). However the problem remains on how to perform the evaluation of the safety of the resulting vegetation stand after the structure decay, according to standard procedures.

One critical aspect of plants when working in slope stabilization, are roots and their tensile and shear strength (Gray and Sotir, 1996; Vergani et al., 2012), as well as their development pattern (plate-roots, heart roots, taproots) and their response to different types of soil or substrate (Jackson et al., 2000; Fattet et al., 2011; Hacker and Johannsen, 2012). Roots, described by Krudner (1952, 1985) as the "subterranean forest", play a critical role in soil bioengineering, because of the diversified actions they ensure and that constitute a comparable, if not greater contribution to the balances of nature, as the visible part of the forest or vegetation stand (e.g. Pflug, 1979, 1985; Baluška et al., 1995; Kutschera et al., 1997; Stokes, 2000; Gregory, 2006; Bourrier et al., 2013; Eshel and Beeckman, 2013; Fernandes, 2013; Tardío and Mickovski, 2015). Information on the architecture of plant roots is still mostly lacking, with the exception of Central Europe due to the lifelong work of Lore Kutschera and her collaborators, that were able to publish the 7 extensive root-atlases of grasses, shrubs and trees of central Europe and other temperate life zones (Kutschera, 1960; Kutschera and Lichtenegger, 2002; Kutschera et al., 1982, 1992a,b, 1997, 2009). Other systematization efforts, although at a different level and scope, must be referred to, for example, Schenk and Jackson (2002). Regarding the geotechnical characteristics of roots, there are several researches, but all very limited and without a systematization effort (e.g. Reubens et al., 2007). Coppin and Richards (1990) present an extensive sample of existing research up to the publication of their work and, following the three International Conferences on Eco-Engineering (the proceedings of the 1st are published in Stokes et al. (2007b), several papers from the 2nd conference were published in Plant and Soil and Ecological Engineering journals (see Stokes et al. (2009) and references therein, and finally the proceedings of the 3rd, that took place in Vancouver (Canada) in July 2012 and partly published in Special Editions of Plant and Soil, 2013 and Ecological Engineering, 2014, important research in this field is being conducted throughout the world, with a stronger effort on the development of systematic criteria and methodologies for sampling, measuring and classification (e.g. Mokany et al., 2006; Stokes et al., 2007a; Reubens et al., 2007; Danjon et al., 2008; Fan and Su, 2008; Stokes et al., 2009; Mao et al., 2014a,b; Stokes et al., 2014), and with more (but not exclusively) attention to the Mediterranean region (Silva et al., 2003; Mattia et al., 2005; Cornelini et al., 2008; de Baets et al., 2007; Schwarz et al., 2010; Bifulco and Rego, 2012).

In the domain of the integration of the vegetation effect on slope stability, one must again refer to the pioneering work of Coppin and Richards (1990) and later Gray and Sotir (1996) whom presented the first systematic analysis of the different models that tried to incorporate the influences of vegetation in slope stability models. This work was further strongly improved with the development of models such as the SLIP4EX (Greenwood et al., 2004, 2006; Greenwood, 2006), by including all influences of the vegetation in the consolidated slope stability model. However, these and other researches (e.g. Osman and Barakbah, 2011), are still unable to adequately cover the basic needs for a sound engineering project, due to the above mentioned natural uncertainty associated with plant establishment and development, and the lack of much associated technical data. Nevertheless it is already possible to use the available information and models to analyze the efficiency of some bioengineering approaches to slope stabilization.

Root reinforcement models are used to determine the contribution of vegetation to the factor of safety (FOS) of a particular slope (e.g. Bischetti et al., 2010; Genet et al., 2010). This factor is defined as the ratio between the actual soil strength and the minimum shear strength required for equilibrium. Many models are available to calculate the FOS of a vegetated slope (Stokes et al., 2008), such as limit equilibrium (Greenwood, 2006), finite difference (Wilkinson et al., 2002; van Beek et al., 2005) and finite element (Kokutse et al., 2006) models. Vegetation must be taken into account as reinforcement