TESIS DOCTORAL

NEW TOOLS AND ROUTINES FOR ECOTECHNOLOGICAL SLOPE STABILITY ANALYSIS

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Espero que las nuevas herramientas desarrolladas en este trabajo tengan una buena acogida y, sobre todo, resulten útiles a investigadores y profesionales del sector de la restauración ecológica.

Para todos ellos es este trabajo.

Resumen

El uso de material vegetal vivo y materiales biodegradables en las obras de estabilización, control de erosión y, en general, restauración ecológica, incluyen en la fase diseño una serie de particularidades a las que la ingeniería civil tradicional no tiene que enfrentarse. Es precisamente esta característica la que está ralentizando la adopción de las técnicas de bioingeniería en el mundo de la obra civil y la geotecnia. La utilización de un lenguaje común entre el mundo de la restauración ecológica y la ingeniería tradicional permitirá tender puentes entre ambas disciplinas y mejorar tanto su colaboración como sus sinergias.

Por otro lado, la anterior situación también limita las posibilidades de estandarización e inclusión en pliegos de condiciones de las técnicas de bioingeniería.

El objetivo general principal de este trabajo consiste, pues, en aportar nuevas herramientas de calculo y diseño para apoyar el proceso de especialización del sector de la eco-ingeniería y facilitar la transición de los técnicos de la ingeniería civil y la geotecnia al mundo de las obras de restauración ecológica.

Para dar respuesta a esta empresa, este trabajo se ha estructurado en cuatro bloques. Un primer bloque aportando un nuevo método para mejorar la simulación del comportamiento mecánico de un suelo con raíces. Un segundo bloque, aportando nuevas metodologías de diseño que incluyan las particularidades de las obras de eco-ingeniería. Un tercer bloque donde se desarrolla una metodología no invasiva para facilitar la toma de datos necesaria para simular los efectos de la vegetación en los análisis de estabilidad. Finalmente, en el cuarto bloque se analiza la evolución de una obra de eco-

ingeniería para mostrar la gran importancia que tiene la fase de seguimiento en este tipo de obras.

Palabras clave: Suelo reforzado, restauración ecológica, estabilidad de taludes, bioingeniería del suelo, eco-ingeniería, técnicas de estabilización.

Abstract

The use of both living plant material and biodegradable materials in slope stabilization and erosion control works, include several particularities at the design level stage that traditional civil and geotechnical engineering do not need to face. This situation is slowing down the incorporation of eco-engineering techniques in traditional engineering sectors. The use of a common language between ecological restoration and traditional engineering will permit building bridges between them as well as improving their collaboration possibilities and synergies.

On the other hand, the preceding situation also limits the necessary standardisation process of the eco-engineering works and their inclusion at the procurement stage.

The main aim of this work consists in contributing with new design tools to both support the specialisation process of the eco-engineering sector and offer an easier transition for civil and geotechnical engineers to the ecological restoration world.

In order to give a suitable answer to the preceding objectives this work has been organised into four blocks. A first block where a new methodology, allowing for a more realistic rooted soil mechanical behaviour simulation, is offered. A second block introducing new design methodologies including the eco-engineering work particularities. A third block, where a non-invasive field work scheme for determining, in a cost effective way, useful information for incorporating the plant effects into soil stability analyses. Finally, a fourth block where an eco-engineering work evolution is analysed in an attempt to highlight the great importance of the monitoring stage in this type of works.

Key words: reinforced soil, ecological restoration, slope stability, soil bioengineering, eco-engineering, stabilization techniques.

The following oral communications and papers have been generated throughout the PhD development:

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García Rodriguez, J. L., Tardío, G., 2015. Monitoring a bioengineering technique applied to combat impacts of forest fires: the technique of mixture dykes of masonry and forestry residues. Proceedings of the international conference Frontiers In Environmental and Water Management. Kavala, Greece. Pp. 94-99. ISBN: 978-960-363-062-3.

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GENERAL INTRODUCTION

Ecotechnology is the use of technological means for ecosystem management, based on deep ecological understanding, to minimize the costs of measures and their harm to the environment” (Straskraba, 1993). As pointed out by Stokes et al (2008), the science of ecotechnology is similar to that called ecological engineering, which in turn has been described as “the proactive design of sustainable ecosystems which integrate human society with its natural environment, for the benefit of both” (Mitsch, 1996). The use of eco- and ground bioengineering techniques falls within the science of ecotechnology. Eco-engineering has also been defined as the long term, ecological strategy to manage a site with regard to natural or man-made hazards (Stokes et al., 2004). For natural slopes, these hazards are well represented by mass movements and soil erosion.

Eco-engineering is a technical and scientific discipline that combines technology and biology, making use of plants and plant communities to help protect land uses and infrastructure, and contribute to landscape development. It matches technical (erosion control protection and slope stabilisation), ecological (eco-systemic restoration), landscape (improvement and landscape integration) and socioeconomic (more efficient and source of employment). Typically, plants and parts of plants are used as living building materials in such a way that, through their development in combination with inert materials, they ensure a significant contribution to the long-term protection against slope instabilities and all forms of erosion (Schiechtl, 1980; Coppin and Richards, 1990; Gray and Sotir, 1996; Mitsch and Jørgensen, 2004; Stokes et al., 2004). It represents a movement to more flexible and sustainable treatments offering a fulfilment of broader functions aiming at integrating human society with its natural environment (Mitsch, 1996; Painter, 2003).

To support this present trend, several challenges must be faced since the use of vegetation as a reinforcement element requires new methodologies to incorporate and asses its effects in engineering projects because of its natural variability (Wu et al., 1979; Waldron, 1977; Pollen and Simon, 2005; Mickovski et al., 2008). Furthermore, soil and fluvial eco-engineering are sustainable tools to improve resilience against soil loss and soil degradation.

In eco-engineering design schemes, the initial stabilization effects are due to the inert material while, as time progresses, the stabilising effects are progressively taken over by the living material (plants and roots). Before plant roots grow and settle, any reinforcing effect is mainly due to the inert materials included in the bioengineering techniques. In this case, differences with traditional stabilization techniques are minimal (USDA, 1992).

Once the plants are able to improve the soil mechanical properties, the need for the incorporation of their effects makes the crucial change. This includes having tools for realistically simulate the soil-root complex mechanical behaviour which must involve a strain synchronisation process between the different elements involved (soil and plant roots). This is essential for a correct design of soil bioengineering or eco-engineering techniques.

On the other hand, the mechanical integrity of the wooden/timber materials used in bioengineering works, depending on both the tree species and the service class, ensures a minimum number of years of service life during the wood natural durability (Ranta-Maunus, 1999). Within that time span, all the plant species used in these actions are able to develop their root systems.

The design methodologies must make allowance for all these eco-engineering work particularities and, hence, the lack of adapted routines and procedures for the soil and water bioengineering works is one of the issues addressed in this PhD. The definition and calibration of those existing traditional soil stabilization design procedures to the soil bioengineering case will be developed and presented.

The hydromechanical adverse and beneficial effects of trees in slope stability have been thoroughly studied during the past decades (Pollen and Simon, 2005; Norris et al., 2008; Stokes et al., 2009; Preti and Giadrossich, 2009; Schwarz and Lehman, 2010; Fan, 2012; Bourrier et al., 2013). All existing models to estimate root effects need a relatively detailed root morphology data. Since direct methods (Böhm, 1979; Van Noordwijk et al., 2000) are both labour intensive and expensive, the need for methodologies integrating indirect methods is an important point in order to assess both the vegetation contribution and root distribution characterisation in a cost-effective manner.

The use of non-invasive sub-surface ground analysis along with theoretical root distribution models are the kind of indirect methods able to give good predictions about tree root morphology. Ground-penetrating radar (GPR) is a candidate technology for noninvasively establishing subsurface structural roots layout and, hence, it has been included in a non-invasive field work methodology for assessing root distribution patterns.

Finally, giving both the semi-empirical nature of eco-engineering design and the behaviour of the materials used in this type of interventions, a monitoring stage for collecting data and analysing the work performance becomes essential. To highlight this feature, the monitoring outcomes of an eco-engineering work are shown to reflect the work design, approach and effectiveness. The objectives pursued at the presented monitoring stage will be:

- To check the design and effectiveness of the strategy followed within the project

- To better translate the results to different scenarios and conditions and, hence, to improve the replication potential of the eco-engineering intervention.

According to the preceding approach and PhD objectives, a structure in chapters has been followed. The chapters´ titles and abstracts of the PhD section contents are shown in the following paragraphs:

CHAPTER 1. Method for synchronisation of soil and root behaviour for assessment of stability of vegetated slopes.

Abstract: In this chapter a new methodology to incorporate the mechanical root anchorage effects in both short- and long-term slope stability analysis is proposed based on observed and assumed behaviour of rooted soil during shear failure.

The main focus of this section of the PhD is the stress-strain range comparison for both soil and roots and development of a stability model that would incorporate relevant root and soil characteristics based on the fact that available soil-root composite shear resistance depends on the magnitude of the shear strain. This new approach, combining stress-strain analysis, continuum mechanics, and limit equilibrium stability assessment, allows for a more realistic simulation of the rooted soil composite whereby the stabilising effect of the rooted soil is incorporated in the slope stability calculations by means of the synchronisation of root and soil mechanical behaviour during failure.

The stability of vegetated terraces in a study area in Spain is used as a case study to demonstrate the proposed methodology and to compare the results with the traditional use of the perpendicular root reinforcement model. The results of the study show that as the shear displacement (strain) increases, the stress is transferred from the soil that provides most of the resistance at low strains onto the roots that provide the most of the resistance to shear at high strains. Including this behaviour in the overall resistance to failure of the root-soil continuum resulted in a more conservative and realistic assessment of the stability of a vegetated slope immediately after a precipitation event when a progressive failure is most likely to be triggered.

CHAPTER 2. New methodologies adapting existing civil engineering routines and protocols to the eco-engineering case.

Abstract: Eco-engineering techniques involve the use of both plants and inert materials where, in the latter, non-treated wood is usually present. The two different

elements will both evolve with time and change their mechanical properties differently. On one hand, the wood will degrade decreasing its effective cross sectional area with time. On the other hand, the live plant material will grow and propagate new roots as time progresses. Both root development and inert material changes must be accounted for in order to realistically simulate a bioengineered slope evolution and design effective eco-engineering solutions.

The dynamic nature of a bioengineered work sets different scenarios throughout the slope design life. All these different stages must be taken into account in the work design process. In this work, we propose an adaptation of the existing routines and procedures of both geotechnical practice and civil engineering design scheme in order to closely reflect the inclusion of bioengineering methods in the classic geotechnical engineering problems. A design methodology covering different critical points within the lifecycle of a bioengineered slope is proposed and put into practice into the design stage for a case study in Scotland. By detecting critical points at the design stage the proposed methodology was proven to offer an improved eco-engineering work design scheme. With the use of the proposed method both external and internal stability checks with their corresponding safety factor values increase with time and there are no conflicts between the two evolving processes involved in this kind of works.

CHAPTER 3. New non-invasive methodology to retrieve root system information from a slope stability point of view.

Abstract: Asymmetric root distribution pattern on steep terrain is analysed by combining GPR (Ground Penetrating Radar) image analysis with a theoretical root distribution model and is verified with field investigation data. Root distribution and morphology of a mature deciduous tree were analysed in terms of the plant's anchorage needs in an asymmetric loading condition scenario. The GPR method was combined with trench profile and root excavation techniques for both the structural and non-structural root data collection.

Good correlations between the field analysis, the theoretical model outcome and the GPR output imagery were found. GPR was proven to be an efficient tool for both root lateral distribution characterisation and vertical root cluster distribution. The combination of the GPR output with a theoretical root distribution model seemed to be a viable non-invasive methodology for assessing root system vertical and horizontal distribution.

CHAPTER 4. Monitoring of erosion preventive structures based on eco-engineering approaches: The case of the mixed check dams of masonry and forest residues.

Abstract: The mixed check dams were conceived in late 2007, during actions to control the onset of erosion processes in Teide National Park subsequent to a forest fire. A simplified scheme of these mixed check dams consists of a structure of horizontal and vertical wooden elements creating a core that is filled with fine branches and forest residues. Besides this, rocks are placed on both sides of the check dam. The mixed check dam technique follows an eco-engineering design approach. These check dams are temporary structures because their cores will decompose in a few years (from 5-10 years depending on the size of the forest residues used). After our last visit to Tenerife (August 2012), it could be checked that the mixed check dams are providing the predicted results. The sedimentation processes achieved are satisfactory. Based on the collected data during the monitoring stage, the performance of this technique can be already characterised as successful.

It is worth noting that the general aim of the new tools and methodologies developed throughout this thesis is to increase the confidence of practitioners about the use of eco-technological solutions.

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CHAPTER 1. METHOD FOR SYNCHRONISATION OF SOIL AND ROOT BEHAVIOUR FOR ASSESSMENT OF STABILITY OF VEGETATED SLOPES

Method for synchronisation of soil and root behaviour for assessment of stability of vegetated slopes

1. Introduction

The development and use of plant root reinforcement models to assess the effects of vegetation in slope stability analysis has become a prominent research area all over the world in the last 10 years with research developments in root anchorage models (Pollen and Simon, 2005; Norris et al., 2008; Stokes et al., 2009; Preti and Giadrossich, 2009; Schwarz et al., 2010; Fan, 2012; Bourrier et al., 2013) and their application in practical stability problems such as shallow landslides or soil erosion (Coppin and Richards, 2007; Danjon et al., 2007; Schwarz et al., 2010; Comino and Druetta, 2009; Mickovski and van Beek, 2009; Thomas and Pollen-Bankhead, 2010).

From a mechanical point, rooted soil behaviour can be simulated by using different root reinforcement models. Some of them are based on traditional limit equilibrium (LE) approaches (e.g. Greenwood, 2006), other are based on more advanced numerical analysis (e.g. Dupuy et al., 2007; Bourrier et al., 2013). The most common mechanical root reinforcement models are the perpendicular and inclined root reinforcement model (Wu et al., 1979; Gray and Leiser, 1982), the fibre bundle model (Pollen and Simon, 2005; Schwarz et al., 2010), the energy approach model (Ekanayake et al., 1997) and a number of LE, Finite Element (FE), and Finite Difference (FD) numerical methods integrating the above models (Gray and Sotir, 1996; Chok et al., 2004; Fourcaud et al., 2007; Briggs, 2010; Mickovski et al., 2011; Bourrier et al., 2013).

All of the above approaches consider a composite material comprising soil matrix and roots and, therefore, must include two different mechanical behaviours in the analysis. Although attempts have been made in the past to account for this (Dupuy et al., 2007; Lin et al., 2010; Bourrier et al., 2013), the modelled root system and soil properties were either assumed or simplified to suit the particular model which made it difficult for practical application. The existing strain based rooting models (e.g. Fiber Bundle Model, Root Bundle Model) have simulated the failure mechanisms of a group of roots without accounting for varying strength of the materials at different strains which are important in both the rooted soil simulation and the stability analyses at a slope scale. To exceed these limitations, there is a need for a methodology that would combine the simplicity of the LE approach while incorporating continuum mechanics concepts and strain compatibility within the realistically modelled soil-root composite in order to provide the basis for wider, practical application.

Similar to the geosynthetic reinforcements used in geo-environmental engineering, plant roots enhance the soil strength by transferring shear stresses from the soil onto the roots that, due to different elastic properties, are better suited to resist it (Mickovski et al., 2009). It is conceivable that, as with other reinforcement elements, in the case of rooted soil the strain level corresponding to the root peak strength is higher than the one for soil peak strength due to differences in elastic properties of the roots and the soil. Although this premise has been investigated in the past for other composite materials (Jewell and Milligan, 1989; Prisco and Nova, 1993; Morel and Gourc, 1997; Zornberg, 2002; Hatami and Bathurst, 2006; Michalowski, 2008; Jonathan et al., 2013), it has never been explored in the context of sustainable use of vegetation for soil reinforcement.

Based on this concept, in this paper we propose a methodology that takes advantage of both the design for stability and the strain compatibility methodologies incorporating roots as reinforcing elements. We illustrate our approach through application in a case study of terraced slopes in Spain exhibiting instability and compare the results of this analysis with the results from other existing models.

The aim of this paper is to propose a practical framework for realistically accounting for the mechanical effect of roots on soil reinforcement in the design for slope stability. The objectives are to explore the behaviour of the soil-root continuum at failure comparing it to the behaviour of a reinforced soil, and apply it into the existing rooting models as an input into a LE slope stability analysis. Linking the soil and roots strain in an iso-strain state (equality of strain of both soil and roots) of the root-soil continuum and demonstrating its application in a representative case study not only provides a more realistic representation of the root-soil interaction in terms of stress transfer processes and soil reinforcement, but also provides a mode of application of relatively easily measured and analysed parameters into stability assessment of vegetated slopes which, in turn, could increase the confidence of practitioners about the use of eco-technological solutions.

2. Material and methods

2.1 Background

In traditional slope safety factor (SF) calculation (Eq.1; Zheng et al., 2006) for a slope to be safe, the SF has to be greater than unity (SF>1), i.e. the available strength (e.g. by the root-soil continuum) has to be greater than the required strength. At the same time, all terms included in the numerator are assumed to have compatible stress-strain behaviour (similar development of stresses in all elements at any strain level), while the effects included in the denominator do not depend on the strain level (Leshchinsky, 1997).

$$Safety\_Factor\_(SF) = \frac{Available\_Strength}{\mathrm{Re}quired\_strength} \qquad \text{Eq. 1}$$

To realistically model the behaviour of a composite material such as the soil permeated with roots, the different contributions to the strength of the root-soil continuum by the elements of the continuum (roots and soil) that have differing elastic properties have to be made compatible before including them in Eq.1.

In the case of Mohr-Coulomb failure criterion (Smith and Smith, 1998), the soil shear strength τ [kN/m^2] is expressed in terms of its cohesion c [kN/m^2] and its internal friction angle ϕ [°] for different normal stress σ [kN/m^2].

$$\tau = c + \sigma \cdot tg(\phi) \qquad \text{Eq. 2}$$

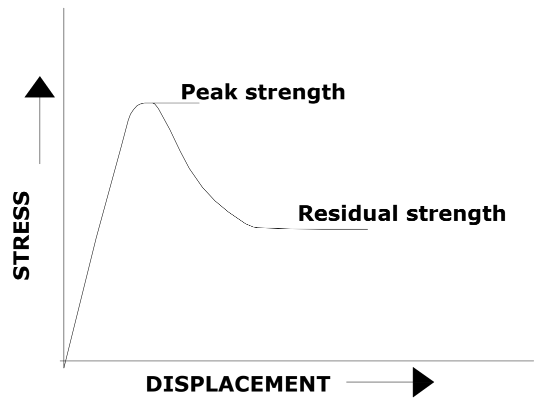

Figure 1 Typical behaviour of soil under shear. The stress-displacement curve of a non-reinforced soil shows that as the displacement increases, the soil stress increases up to the soil peak shear strength value before decreasing and levelling off to the residual soil shear strength value at very large displacements

The values of both cohesion and internal friction angle shown in Eq.2 can be either peak or residual depending on the level of strain (Figure 1), but in the case of reinforced soils, the strain level at which extensible reinforcements may develop their peak values will usually be higher than the strain when the soil develops its peak value (Leshchinsky, 2002; Schwarz et al., 2010). This is particularly true for small diameter roots which can be considered as flexible reinforcements (Wu et al., 1979; Mickovski et al., 2007), and which provide ductility for the root–soil continuum , reaching the peak strength at high strains (e.g. Mickovski et al., 2007; Mickovski and van Beek, 2009). This suggests that at high strain (displacement) level the soil may be developing its residual strength value while, at the same time, the roots (reinforcements) are developing their peak strength - a concept which has to be taken into account in the analysis of slope stability and factor of safety calculation for vegetated soil.

The reinforcement effect due to the plant roots (excluding the major structural roots) can be expressed in terms of an “added cohesion” ΔS which is added on to the strength of the non-rooted soil (Eq.2) and can be calculated, for example, for a known root tensile strength t_R [KN/m^2] and Root Area Ratio (RAR; the ratio of area of roots crossing the shear plane and shear plane area; Waldron (1977) and Wu et al. (1979); Eq.3) as:

$$\Delta S = 1.2 t_R \qquad \text{Eq. 3}$$

To make the soil and root mechanical behaviour compatible, the displacement at which the soil reaches its peak strength can be linked to the corresponding root elongation (Shewbridge and Sitar, 1985; Abe and Ziemer, 1991) as:

$$\varepsilon = (1 + B^2 b^2 e^{-2bx})^{1/2} - 1 \qquad \text{Eq. 4}$$

Where: ε = root strain [mm/mm]; x = shear displacement [mm]; B = Half of the shear displacement [mm]; b = coefficient depending on root diameter D [mm] and RAR (Abe and Ziemer, 1991) expressed as:

$$b = 0.2262 - 0.0715\ RAR - 0.0016D \qquad \text{Eq. 5}$$

With known strain and elastic modulus of the roots, the tensile strength can be calculated from Hooke´s law for known RAR at the shear surface (Eq.6) which will ultimately help to calculate the synchronised additional cohesion due to roots (Eq.3):

$$t_R = \varepsilon\ E\ RAR = \sigma\ RAR \qquad \text{Eq. 6}$$

Where σ is the mobilised root tensile strength corresponding to ε.

2.2 Approach / Methodology

In traditional reinforced soil engineering, long-term (peak) strength design value for the reinforcement is chosen in such a way that it will be mobilised at a strain value corresponding to the soil peak strength (Berardi and Pinzani, 2008). The strength values of the composite material elements are synchronized within the limited strains (or displacements). This situation justifies the use of soil strength peak values in safety factor calculations for newly designed reinforced soil slopes.

In natural vegetated slope cases, strains are not limited and failures occur gradually over a large range of strains in the long-term. Therefore, it is recommended to use soil residual strength values in slope stability analysis (Jewell, 1990) while ensuring that the long term design strength of the reinforcement (root strength) is to be achieved at a strain level corresponding to the residual soil strength. This is a necessary step for achieving strain compatibility in slope stability formulae and a requirement of the methodology proposed in the following sections. With this approach, a situation with the entire shear surface working at soil peak strength (traditional geotechnical engineering approach which is unrealistic due to lack of compatibility between mobilising and resisting strength) will become a situation where a number of zones progressively develop along the shear surface. In these zones, the soil will resist failure with its residual strength due to large displacements/strains. At the same time, the critical sliding surface locally around the roots will be determined using soil peak strength values due to the small displacements of the soil around the roots that now provide the major resistance to the shear load/stress.

2.3 Proposed methodology for stability assessment of a vegetated slope

To capture the processes of initiation of a slope instability event, development of a sliding surface and its progressive expansion through to the failure of the root-slope continuum, first the stress state local to the rooted soil should be analysed for a 'local' safety factor (Krahn, 2004) in order to confirm the progressive failure in a particular section of the rooted soil. The proposed methodology is shown on Figure 2 and described below.

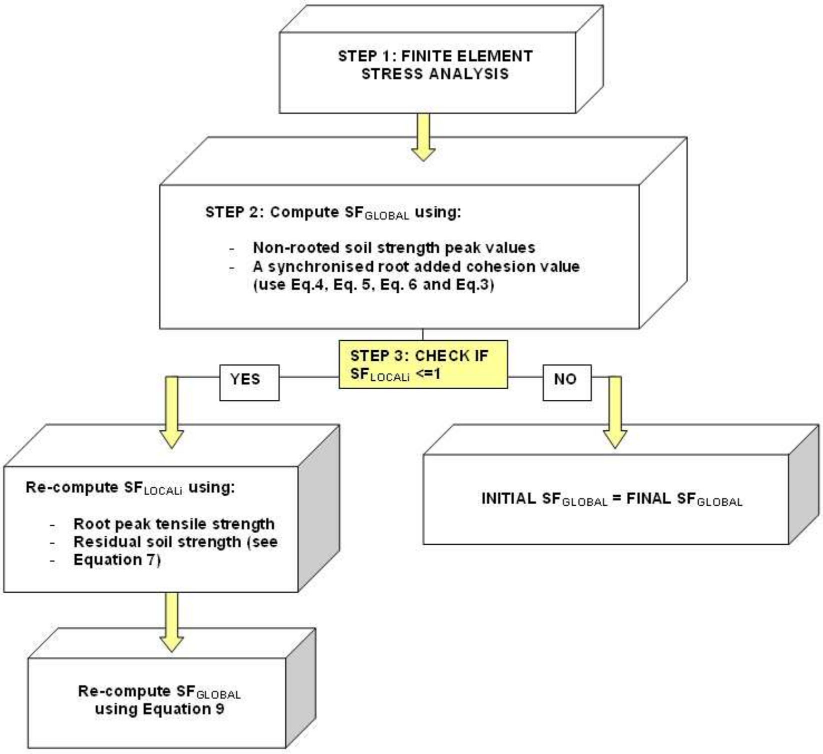

Figure 2 Flowchart of the proposed methodology. SFGLOBAL = Global safety factor. SFLOCAL = Local safety factor

STEP 1. Establishing the stress distribution and values necessary for local safety factors calculation using Finite Element (FE) stress analysis.

STEP 2: Application of a LE method for global slope stability assessment, using:

- The non-rooted soil peak shear strength value obtained from laboratory or in situ shear tests;
- Root strength value corresponding to the strain level at which the soil reaches its strength peak value (Equations 4, 6, and 3), i.e. linking soil displacement to root elongation (e.g. Abe and Ziemer, 1991; van Beek et al., 2005; Wu, 2006) to synchronise soil and reinforcement stress-strain behaviour.

STEP 3: Inspection along the critical slip surface derived from the above analysis to identify any local safety factors indicating failure (SF_L<1; Krahn, 2004) i.e. zones where a failure had occurred locally. If none of the local SF is lower than one, the global SF calculated in Step 2 can be taken as definitive. If there are local SF_L<1 along the critical slip surface, a progressive failure is likely to have occurred at least in part of the slip surface and, as failure progresses, the strength developed will be at or close to the soil residual strength value (Figure 3). The local safety factor can then be re-calculated as:

$$SF_i residual\_zone = \frac{ROOT\_PEAK\_STRENGTH}{(\sum F_{DESTABILIZING}) - SOIL\_RESIDUAL\_STRENGTH} \qquad \text{Eq. 7}$$

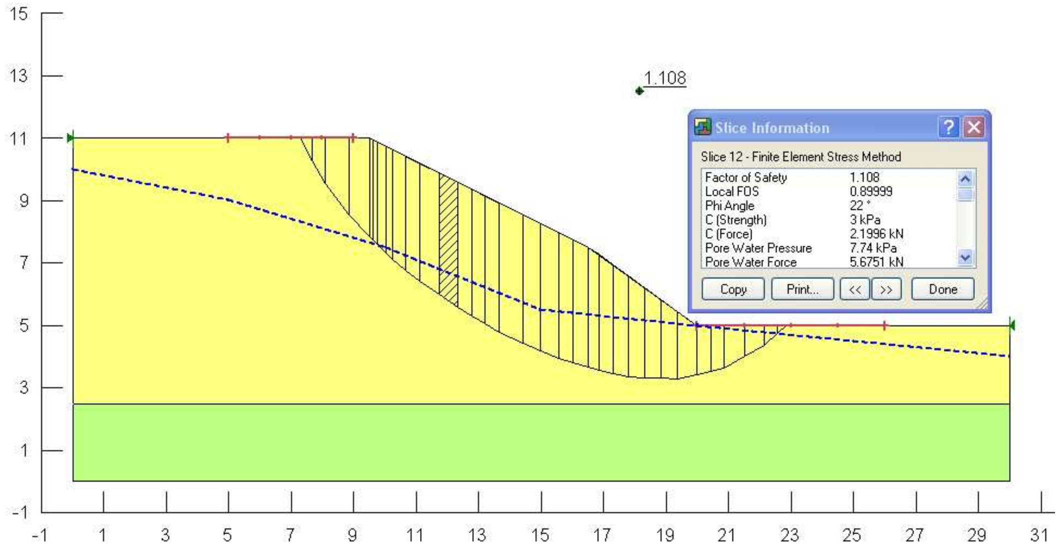

Figure 3 An example of Finite Element stability analysis using commercially available software (Geoslope, 2014). Although the slope global safety factor is 1.108, a local safety factor lower than one is shown to occur at the bottom of the shaded slice (SFL = 0.89) indicating that progressive failure phenomenon is likely to have occurred. Local safety factors are checked throughout the critical sliding surface (Step 3 of the proposed methodology)

In this expression, it is assumed that the roots develop their peak tensile strength value while the soil is mobilizing its residual shear strength value due to large displacements/strains. Because the soil residual strength has a constant value and it does not vary with the strain level, Eq.7 can be rearranged as:

$$\sum F_{DESTABILIZING} = S_{required} = \frac{ROOT\_PEAK\_STRENGTH}{SF} + SOIL\_RESIDUAL\_STRENGTH$$

Eq. 8

The above shows that, at large displacements, the necessary strength to achieve equilibrium is equal to the mobilized root strength plus the residual strength of the soil (which operates fully mobilized). The safety factor does not apply to the residual soil strength because the soil strength is at its minimum (constant) value after the phenomenon of progressive failure has occurred and any extra stress would be transferred to the adjacent zones of the shear surface.

The global safety factor (SF_{GLOBAL}) for the slope in the zones where SF_L<1 (i.e. the soil is resisting shear with its residual strength value), and the SF_L calculated using Eq.7, can be calculated as a weighted average using the slice lengths as the weighting factor (Eq.9).

$$SF_{GLOBAL} = \frac{(\sum SF\_local \cdot l_i)_{RESIDUAL\_ZONE} + (\sum SF\_local \cdot l_i)_{PEAK\_ZONE}}{\sum l_i} \qquad \text{Eq. 9}$$

Where l_i is the length of the i^{th} slice.

The first term of the SF_{GLOBAL} expression (Eq.9) is the sum of local safety factors in the residual zone calculated according to Eq.7. The second term in the numerator refers to the peak zone of the failure surface (Figure 4). For cases where safety factor values are very different (e.g. one of the safety factors is much higher than the rest), a geometric mean would be suitable to use in order to avoid bias in Eq.9.

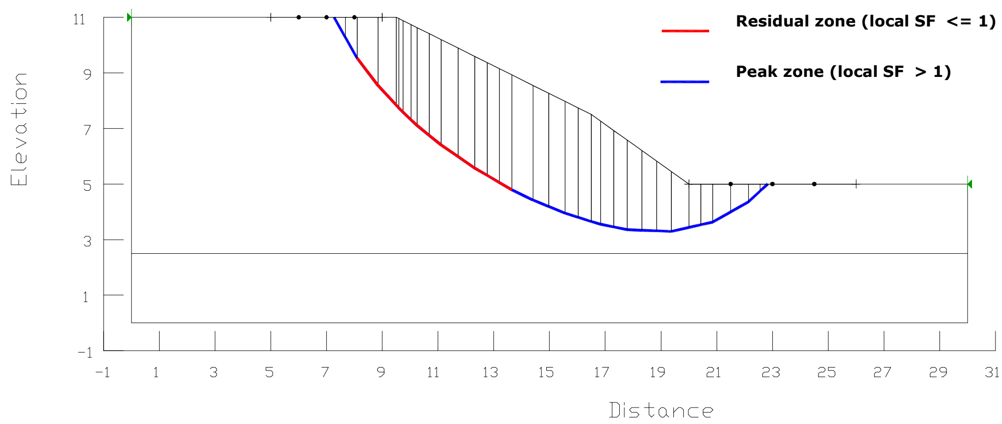

Figure 4 An example of a failure surface divided into the residual zone (failure in soil occurred locally, soil resisting with residual shear strength) and the peak zone (no failure occurred locally, soil resisting with peak shear strength) delineated using commercially available software (Geoslope, 2014)

2.4 CASE STUDY (model validation)

We applied the proposed methodology to calculate the stability of a series of terraced slopes exhibiting instability. The study site is located near Almudaina, Spain (X=729275 Y=4293850 and Z=480 m on UTM 30 s) and comprises approximately 2.0 m high slopes with overall slope angles ranging between 45° and 70°. The slope length was approximately 60 m, and long term monitoring recorded potential instability connected to runoff and soil slippage after intense rainfall events (Mickovski and van Beek, 2009). The runoff from the slope contributed to the undermining of the slope toe where the progressive failure initiated before migrating up the slope and resulting in bulging mid-slope and soil mass depositing at the toe (Figure 5).

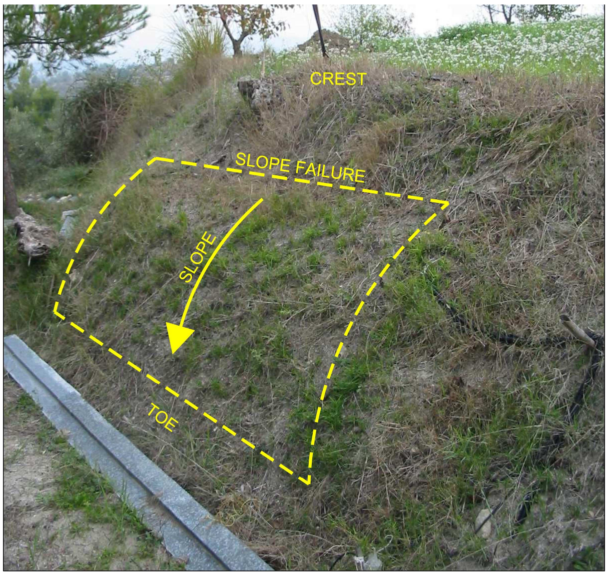

Figure 5 Observed slope failure at the study site (Mickovski and van Beek, 2009). Runoff over the slope contributed towards the loss of toe support, resulting in bulging mid-slope and deposition of soil material at the toe of the slope

The slopes, comprising soil with Young's modulus Es = 50 MPa and Poisson's ratio v = 0.33 measured in the laboratory, were planted with rows of vetiver grass (*Vetiveria zizanioides*) in order to mitigate the effects of slope instability. The spacing between the rows of vetiver was approximately 0.3 m and their length between 3 m and 4 m. Root distribution with depth as well as root morphological and physical properties (diameter and root tensile strength) were recorded using block excavations and investigation trenches. The vetiver roots had a root mean diameter of 0.75 mm, permeated the soil vertically down to 0.3 m depth. The strength of the rooted soil was measured using in situ direct shear tests (Mickovski and van Beek, 2009) while the strength of the non-rooted soil was measured in the laboratory using standard shearbox apparatus (BSI, 1990). At the shear surface developing during the shear tests, the RAR was recorded as 0.04 %. Roots were sampled from site and tested in tension, yielding an average value of the root tensile strength of t_R = 4.91 MPa (Mickovski et al., 2005; Mickovski and van Beek, 2009) and an average Young's modulus of elasticity of E = 1.0 GPa.

These parameters measured in situ or in the laboratory were used as an input into a Limit Equilibrium analysis for slope stability and the perpendicular root model (Wu et al., 1979) for root reinforcement.

The software used to implement the proposed methodology was SIGMA/W (Step 1) and SLOPE/W (Step 2 and 3) (Geoslope, 2014). For comparability, the critical slip surfaces obtained and reported in a previous analysis of the same slope (Mickovski and van Beek, 2009) were analysed.

3. RESULTS

STEP 1

FE stress analysis using Sigma/W was carried out using the elastic properties of the soil as shown on Figure 6.

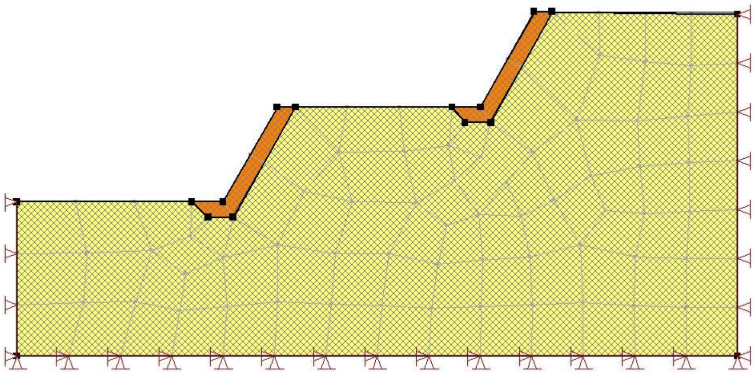

Figure 6 Finite element stress analysis of the terraces using Sigma/W. Stresses are calculated in each node of the FE mesh based on soil elastic properties. Shaded areas show vegetated terraces where roots contribute towards the strength with added cohesion

STEP 2

Using Bishop´s LE method and stresses calculated in the previous step, the critical slip surfaces for both long- and short-term conditions of non-rooted soil (Table 1) were established, yielding SF=1.01 and SF<1 for the short- and long-term analysis, respectively, as in the work of Mickovski and van Beek (2009).

Table 1 Non-rooted soil peak properties used in determination of critical slip surface

Short term analysis (undrained)		Long term analysis (drained)		
Cohesion (kPa)	Angle of internal friction (º)	Cohesion (kPa)	Angle of internal friction (º)	Soil unit weight (kN/m^3)
4.5	0	0	34.5	18

The elongation of an average diameter root for a 5 mm shear displacement was calculated as 9.85×10^{-4} [mm/mm] from Eq.4. The mobilised root tensile strength at 5 mm displacement (i.e. shear displacement at which the non-rooted soil strength reaches its peak value) was calculated as 0.99 MPa (σ in Table 2) which is the synchronised root strength value. By using both this value and the RAR at the shear surface in Eq.6, the tensile strength of roots per unit area of soil (t_R) was obtained.

Finally, the calculated value of the synchronised added cohesion due to roots (Eq.3) was 0.47 kPa (Table 2). For the rooted soil simulation, this value was added to the non-rooted soil cohesion shown in Table 1 for both short- and long-term LE analysis of the slope stability.

Table 2 Input parameters and synchronised added cohesion (c_r) value corresponding to non-rooted soil peak shear displacement (x=5 mm)

x (shear displacement) (mm)	B (mm)	b (mm^{-1})	ε (mm/mm)	E (GPa)	σ (MPa)	RAR (%)	t_R (kPa)	c_r (kPa)
5.0	2.5	0.0222	9.8519×10^{-4}	1.00	0.99	0.04	0.39	0.47

Using Bishop´s LE method and the values in Table 2 showed a global slope safety factor of 1.02 and 0.916 for the short- and long-term analysis, respectively, (Figure 7) i.e. a slight increase when compared to the stability of the non-vegetated slope. The associated critical slip surfaces were investigated in Step 3 (local safety factor check) of the proposed methodology.

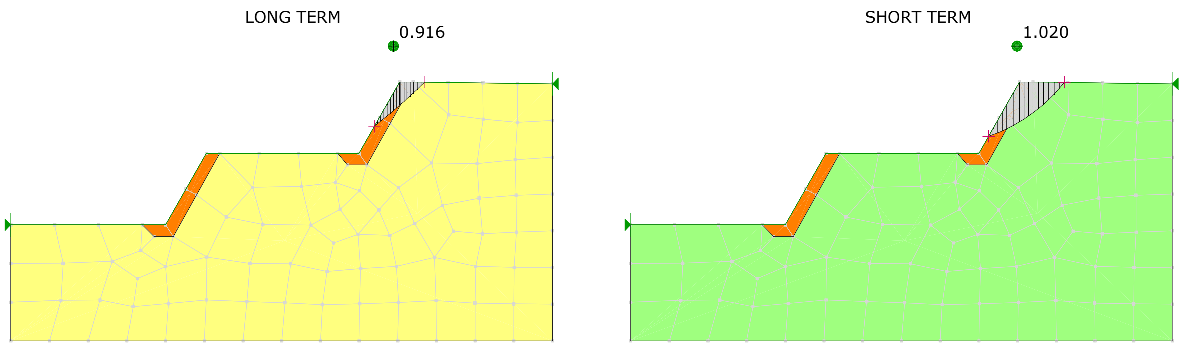

Figure 7 Step 2 long- and short-term stability analyses including vetiver root effects (added cohesion = 0.47 kPa)

STEP 3

After the inspection, the critical slip surfaces were divided into peak and residual zones based on the SFs calculated locally for each slice. In the residual zone the roots were considered to be deforming and mobilising their tensile strength until reaching their ultimate tensile strength t_R, which would yield the peak value of the root reinforcement of as $\Delta S = 2.3$ kPa (Eq.3). This value is the total available strength value which is used in the numerator of Eq.7.

For the slices with $FS_L<1$ and without any root reinforcement, the difference between the actual applied stress and the soil residual stress was considered to be transferred to the adjacent slices (i.e. re-calculation of FS_L for the affected slices using Eq.7) yielding the results shown in Table 3.

Table 3 Initial local safety factors (Step 2), recalculated local safety factors (Step 3 – Eq.7) and the recalculated global safety factor (Step 3 – Eq.9). Long-term slope stability analysis case

SLICE	LOCAL SF	NEW SF (Eq.7)	SLICE LENGTH [m]	SLICE LENGTH/TOTAL LENGTH	(SLICE LENGTH/TOTAL LENGTH)*LOCAL SF
1	1.1		0.14	0.08	0.09
2	1		0.14	0.08	0.08
3	1		0.12	0.07	0.07
4	1		0.12	0.07	0.07
5	1		0.12	0.07	0.07
6	1		0.13	0.08	0.08
7	0.98	1.51	0.11	0.07	0.10
8	0.93	1.7	0.11	0.07	0.11
9	0.89	1.65	0.11	0.07	0.11
10	0.85	1.36	0.11	0.07	0.09
11	0.82	1.25	0.11	0.07	0.08
12	0.78	1.16	0.11	0.07	0.08
13	0.77	1.16	0.11	0.07	0.08
14	0.75	1.16	0.11	0.07	0.08
		Total length	1.65	New global safety factor	**1.19**

The comparison between the SFs obtained using the traditional soil only approach (Mickovski and van Beek, 2009) and the new proposed methodology are shown in Table 4.

Table 4 Comparisons between the safety factor (SF) values of the studied slope calculated with different approaches

Slope stability (SF)	*Mickovski and van Beek (2009)*		*Proposed methodology*		
	Fallow soil	Rooted soil	Fallow soil	Rooted soil (Step 2)	Rooted soil (Step 3)
Short-term	1.01	1.13	1.01	1.02	1.11
Long-term	<1	1.06	<1	0.91	1.19

4. DISCUSSION

The comparison between the slope safety factor values calculated using traditional geotechnical and eco-technological engineering approaches shows that the effect of vegetation is very important in the cases where the fallow slope is at risk of failure. Relatively small RARs can contribute to minimal increase in the resistance of the rooted soil which, in turn, can result in an increase in safety factor. It is important to note that the traditional application of global increase in soil cohesion due to the presence of roots can lead to an overestimation of the stability of the slope in the short-term (Table 4), i.e. at the time when the pore-water pressures are built-up in the soil, there is no sufficient time for drainage, and the resistance to shear failure mainly depends on the mechanical effects of the roots (Mickovski et al., 2009; Schwarz et al., 2010). For this case, the proposed methodology provides a more conservative estimate of the slope stability which is also more realistic and applicable wherever progressive failure dominates the instability mechanism (Liu, 2009). For both short-term (undrained) and long-term (drained) cases, the magnitude of differences between the two approaches is offset by the fact that the soil encountered on the case study site was normally consolidated (natural slope) and, therefore, its peak and residual values coincide (Smith and Smith, 1998). An analysis of a slope comprising overconsolidated soil would have yielded results with bigger differences between the approaches.

The SF value obtained for long-term analysis (drained conditions) in the proposed methodology is higher than the one obtained by Mickovski and van Beek (2009). This is partially due to the fact that the critical slip surface analysed in this case is relatively shallow due to the nature of the soil on site and, thus, intercepts a larger number of roots with higher RAR. Furthermore, in the case study the effects of the pore-water pressures were negligible which, again, showed that the mechanical effects of the roots on slope stability become predominant during the dry periods.

The safety factors obtained in Steps 2 and 3 of the proposed methodology account for the stress transfer between the soil and the roots which is not the case in the traditional stability analyses. As the slope progressively fails and roots gain relevance in the slope global stability, the safety factor increases its value (Table 4) which is in contrast to the traditional analyses (Wu et al., 1979) where the role of the roots is the same throughout the process. The slope stability analyses in Step 2 of the proposed methodology give a lower SF values because the tensile stress used in the added cohesion formula is not the ultimate root tensile strength but the root strength value corresponding to the strain level at which the soil reaches its peak strength value.

In our model, in the residual zones of the failure surface the role of the flexible roots is very important as the available strength mainly depends on the roots' mechanical capacities due to their lower rigidity when compared to the soil. This effect is intuitive and coincides with the results obtained by Bourrier et al. (2013) who found that the reinforcement effect of flexible roots was the highest when the soil had developed its residual strength as in the assumptions of our approach.

In this study we used the perpendicular root model for soil reinforcement (Wu et al., 1979) based on the observed root morphology and root failure mechanism during the in situ tests. The use of this model, subject of criticisms due to potential overestimation of root reinforcement (Preti and Giadrossich, 2009; Mickovski et al., 2009), was justified by the comparable results of the measured *vs* calculated shear resistance of the soil rooted with vetiver roots (Mickovski and van Beek, 2009).

The main advantage of the proposed method is that it is generic and allows the incorporation of different rooting models in the stability assessment process. Root models such as Fibre Bundle (FBM; e.g. Pollen and Simon, 2005) or Root Bundle (RBM; e.g. Schwarz et al., 2010) and the phenomena such as lateral root cohesion (Schwarz et al., 2010) can be incorporated in Step 2 of the proposed methodology for a known force-displacement behaviour and used as an input into the LE methods for slope stability assessment. In these cases, the root bundle force corresponding to non-rooted soil peak displacement must be included in the numerator of the SF formula along with the soil peak strength values (Step 2). At high displacement (strain) level, the peak root bundle force must be included in the SF formula numerator and the soil residual strength must be included in the SF denominator (Step 3).

On the same lines, our method allows for stability assessment in accordance with Eurocode 7 (EN ISO 1997) where partial factors specified within the code can be applied to both peak and residual soil strength values in Steps 2 and 3 to verify the GEO limit state. From this perspective, the calculations shown within this article could be considered as calculations with the characteristic values of both material and actions which, in the case of natural slopes, is usually the first step in the assessment of stability.

Another advantage of the proposed methodology is the incorporation of simulation of the stress transfer process and the heterogeneous existing stress-strain state within the root-soil continuum in the LE stability assessment (Steps 2 and 3) based on the mode of the observed slope failure in situ. The value of the calculated stress mobilised by the roots (0.99 kPa) shows the proportion (approx. 20%) of the total root tensile strength (4.91 MPa) mobilised at the moment when the soil reaches its peak shear strength value. This implies that for flexible roots, during the first stages of shear, the soil strength dominates the behaviour of the root soil composite. The value obtained compares well with the shear test results on the rooted soil block (Mickovski and van Beek, 2009) where there is a negligible difference in the behaviour of rooted and unrooted soil up to the stage when the soil reaches its peak value. At this point, the roots have been straightened up (Schwarz et al., 2010) and the tensile strength within them starts to be mobilised. However, in the calculations this effect has been neglected due to the observed verticality of the vetiver root system (Mickovski et al., 2005) and therefore the results may be considered conservative.

The proposed methodology offers, through Step 3, a chance to investigate the potential critical zones where the sliding soil mass would be the weakest and could be targeted for stabilisation with other, potentially structural measures. The implementation of the proposed methodology in existing slope stability software is relatively straightforward and it offers insight into which parts of the soil are contributing with their residual strength and in which parts of the slope the vegetation is playing a major role in terms of slope stability. The analysis of local safety factors also allows for a deeper insight into stress transfer phenomenon and therefore improves the safety factor calculation process.

The validation of the proposed methodology was limited to particular soil conditions and fibrous root system. While this was carried out due to practical reasons, i.e. availability of comparable data, it also contributed towards confirmation of the benefits of the fibrous root systems in providing reinforcement. The flexible nature of the vetiver roots helped in preventing soil mass wasting after a slip was initiated unlike, say, more rigid, structural roots that would prevent slip initiation but would not necessarily prevent mass wasting after the slip initiation (Duckett, 2014). The potential analysis of more complex root architectures would require incorporating both flexible and rigid root behaviour and their respective contribution to reinforcement. Furthermore, more simulations on different soil types with different overconsolidation ratios and other environmental settings will have to be carried out in order to increase the confidence of the use of the proposed methodology in eco-engineering applications.

5. CONCLUSIONS

The incorporation of root mechanical effects into the stability assessment of vegetated slopes should take into account the different pace at which soil and root strength is mobilised. Plant root reinforcement effects cannot be only quantified as a constant additional shear resistance of the soil as the available soil-root composite shear resistance depends on the shear strain.

A methodology to harmonize these different mechanical behaviours is proposed in order to achieve a more realistic simulation of rooted soil composite materials. The methodology combines stress-strain analysis, continuum mechanics and LE stability assessment. For this methodology, the stress-strain behaviour for both soil and reinforcement (roots) must be known and compatibility sought in order to incorporate a realistic value of the root reinforcement into a LE method for calculation of slope stability.

The proposed methodology is validated by the findings of a field study incorporating measurements and observations on soil as well as the plant root morphology and physical characteristic (Mickovski and van Beek, 2009). In both approaches, as the shear displacements (strain) increase, the stress transfer processes between the soil and vetiver roots is well represented by the obtained numerical results. The results of the simulation show more conservative and realistic results for the stability of a vegetated slope immediately after a precipitation event when progressive failure is most likely to be triggered.

With the proposed methodology, a better simulation of the progressive failure phenomenon is included in traditional slope stability analysis showing that the safety factor calculation is not stress-strain independent. Furthermore, the proposed methodology gives an insight into the root reinforcement effect distribution along the slip surfaces, failure mechanism, and synchronised behaviour of both root and soil.

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CHAPTER 2. IMPLEMENTATION OF ECO-ENGINEERING DESIGN INTO EXISTING SLOPE STABILTY DESIGN PRACTICES

Implementation of eco-engineering design into existing slope stability design practices

1. Introduction

Ground bio-engineering, also termed eco-engineering, is the use of living plants or cut plant material, either alone or in combination with inert structures, to control soil erosion and the mass movement of land in order to fulfil engineering functions (Schiechtl, 1988). The self-repairing characteristics of the vegetation used, and the resilience capacity of the bioengineered area (Mickovski, 2014) are very important allies in the eco-engineering design philosophy.

The eco-engineering solutions have inherent advantages over classic civil engineering solutions with respect to economy, ease of construction, low landscape impact and opportunities for incorporation of vegetation or plantings within the structure (Gray and Sotir, 1996). One of the main design disadvantages are related to this latter issue since the use of both living and inert biological materials (e.g. wood) involves incorporating temporary variable elements in terms of design and performance reliability of the eco-engineering works (Stokes et al., 2014). The eco-engineering philosophy follows the sustainability idea of design with readily available materials on or adjacent to the site which involves the use of materials such as wood or rocks. The use of wood coming from nearby silvicultural treatments (Coppin and Richards, 1990) entails the use of materials with a wide variety of properties (young and mature wood) from different species.

The eco-engineering solutions provide a combination of the benefits of immediate protection against soil instability and the long-term stabilisation due to the reinforcement effect of the roots on the soil. As with any stabilization technique, there is a stress (or load) transfer between the soil and the structure but, in contrast to other solutions, this initial response is substituted by an evolving role of the living material used in the eco-engineering work as the time progresses. Once the plants become established, the subsequent vegetation gradually takes on more of the structural function of the inert members (Gray and Sotir, 1996). The way roots reinforce soil can be explained by both mechanical and hydrological effects. From the former perspective, roots can bind the soil together and contribute to both a higher soil bearing capacity and shear strength (Willatt and Sulistyaningsih, 1990) whereas, from the latter, they can decrease the soil pore water pressures and, therefore, soil effective stresses (Terzaghi´s principle; Lambe and Whitman, 1979) thus improving the slope stability.

Over the past eighty years, extensive engineering and research studies have provided a sound set of soil mechanical principles and analytical procedures for slope stabilization (Terzaghi, 1936; Sowers, 1979; Duncan and Wright, 2005). An improved understanding of the changes in soil properties that can occur over time is one of the most important developments of slope stability design schemes. The presence of other material in the soil (including plant roots) changes the properties of the continuum and, if these changes can be predicted, the engineers can choose the best additions for stability. The recognition of the requirements and limitations for the use of non-inert (live) material in slope stability design standards would usher in a more mature phase of the use of ecotechnological solutions for soil stabilisation purposes.

With bioengineered slopes, the nature of the materials used generates a natural evolving dynamic into the slope design life. One of the most important changes in the soil conditions takes place when plants, the live components, begin to grow and propagate new roots (Bischetti et al., 2009). Besides, the wood, one of the inert components used in eco-engineering techniques, is generally not treated and, as a consequence of this, its mechanical properties deteriorate as time progresses (Leicester et al., 2003). Therefore, for bioengineering slope design the time and elements durability must be considered more explicitly throughout the design life of the slope.

The existing structural timber design standards (e.g. EN 1995-1-1:2004/A1:2008 Eurocode 5) provide a regulatory framework for eco-engineering work design. Similarly, the existing structural/geotechnical design procedures for slope stabilisation solutions (e.g. manufacturers standard designs, trade associations standard designs, state and federal agencies, Eurocode 7, etc.) do not accommodate the particularities derived from the dynamic and changing nature of the eco-engineering solutions. However, the eco-engineering design is more complex due to both the presence of different materials and the need to take into account the combination and integration of the particularities of the wooden elements used for specific eco-engineering works (e.g. wood decay rate, wood natural durability and the use of small diameter round wood) with the live materials used. Furthermore, the ground bioengineering techniques are designed according to soil stabilization or geotechnical design general methodologies (Coppin and Richards, 1990; Menegazzi and Palmeri, 2013) and they do not have a standardised specific approach as it is the case with other traditional stabilisation techniques. To the best of our knowledge, the engineering approach comprising a sequence of stages reflecting the design life stages and associated changes in the eco-engineering structure has not yet been applied to eco-engineering design.

To cover the apparent gap in the design with vegetation for stability (Stokes et al., 2014), there is a need for a clear methodology, based on existing structural/geotechnical design procedures, to put the eco-engineering solution design into practice and justify its application from sustainability, resilience and stability point of view (Mickovski, 2014). The aim of this paper is to use the existing engineering approach and attempt incorporating both wood deterioration and live plant processes and effects within a temporal framework. To achieve this, our objectives are to integrate the stress transfer process between the inert elements and the vegetation, as well to incorporate both the typical dynamic nature and the evolution of an eco-engineering work into eco-engineering design methodologies, demonstrated on a real life case study.

2. Materials and methods

2.1. Background

In designing and constructing new earthwork slopes, it is important to attempt to anticipate the relevant changes in properties and conditions that may affect them during the design, ensuring that the stability is not compromised by any foreseeable change (Duncan and Wright, 2005). In the case of bio-engineered slopes, one of the major changes in the long term is the growth and development of the plants used in conjunction with inert materials. Additionally, the changes in the loads or stresses acting on the slope will result in changes in the stability of the slopes. Therefore, it is often necessary to perform stability analyses corresponding to several different scenarios, reflecting different stages in the life of a slope. This is a well established principle in the standard slope stability design (Duncan and Wright, 2005; EN 1997 Eurocode 7), and it should be applied to bioengineered slopes because a changing scenario during the slope design life is in the very core of the ecotechnological solution design and philosophy. The two main elements involving changes in an eco-engineering technique stability checks during the slope design life are the wooden elements and the plants. While wooden elements will degrade with time, the plants´ roots will develop and grow.

2.1.1. Wood durability

The inherent ability of wood species to resist biological deterioration is referred to as natural durability or decay resistance (Eaton and Hale, 1993; Johnson et al., 2006). Natural durability varies between wood species (e.g. State Forests of New South Wales, 1995) and is explained mainly by the composition and amount of wood extractives (Eaton and Hale, 1993). Generally, sapwood is the least durable wood part

(Figure 1), while heartwood cannot be treated and therefore its durability is dictated by its natural durability class (State Forests of New South Wales, 1995). Knowledge about natural durability is obtained by field and laboratory tests (e.g. Princes Risborough Laboratory, 1976; Leicester et al., 2003) as well as by practical experience of the end users (Willeitner and Peek, 1997).

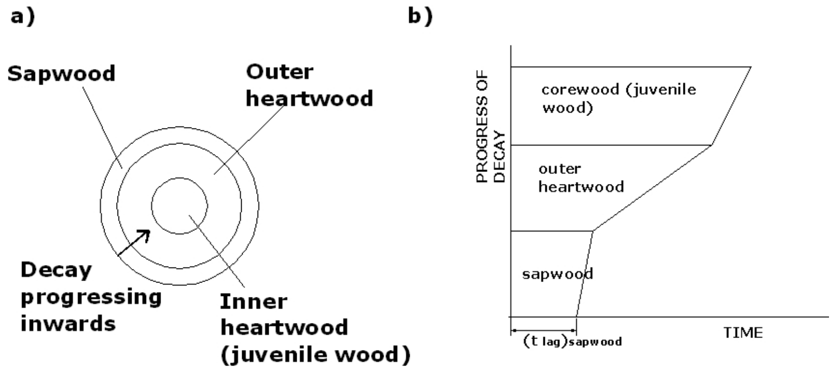

Figure 1 a) Wood parts, b) deterioration rates for the different wood parts (adapted from Leicester et al. (2003)

The existing models for simulating wood deterioration processes (e.g. Scheffer, 1971; Leicester et al., 2003), idealise the process to be bi-linear (Leicester et al., 2003) (Figure 2) where the untreated wood in the ground would steadily decay along the perimeter after a time lag of decay. The rate of decay (mm/year) can be calculated as:

$$r = k_{wood} \cdot k_{climate} \qquad \text{Eq. 1}$$

While $K_{climate}$ depends on mean precipitation value, mean annual temperature and the number of dry months on the site (see Leicester et al., 2003), K_{wood} depends on the type of wood (Leicester et al., 2003).

The lag time (years) for the sapwood (which is the wood with the least durability and would decay first; Fig. 1) can be estimated in terms of the sapwood decay rate ($r_{sapwood}$) as shown in Eq. 2 (Wang et al., 2007):

$$t_{lag\_sapwood} = 5.5 \cdot r_{sapwood}{}^{-0.95} \qquad \text{Eq. 2}$$

According to the preceding model the decay progresses inwards while the remaining wood keeps the initial mechanical properties. Therefore, if at a time t the decay depth is d_t (mm) (Fig. 2), the bending strength can be calculated as (Wang et al., 2007):

$$R = \frac{\pi}{32}(D - 2d_t)^3 f_d \qquad \text{Eq. 3}$$

Where D is the initial diameter (mm) and f_d is the design strength value which is calculated by using both characteristic strength values and structural design standards (e.g. EN 1995-1-1:2004/A1:2008 Eurocode 5). Characteristic strength values of undecayed wood can be found in the literature or measured in the laboratory (de Vries, 1998; Ranta-Maunus et al., 1998).

In a wooden element, the service life is assumed to be the time at which its residual strength decreases to 70% of its original strength (Wang et al., 2007). For the case of a circular wooden element of initial diameter D (mm) subjected to bending, the decay depth (mm) at service life, d_L(years), is (Leicester et al., 2003):

$$d_L = \frac{1}{2}(1 - 0.7^{1/3}) \cdot D \qquad \text{Eq. 4}$$

Then, the service life L (years) (see Fig. 2) is estimated taking into account either the decay lag (t_{lag}, Eq. 2) or the decay rate (r, Eq. 1) as shown in Eq. 5.

$$L = t_{lag} + \frac{d_L}{r} \qquad \text{Eq. 5}$$

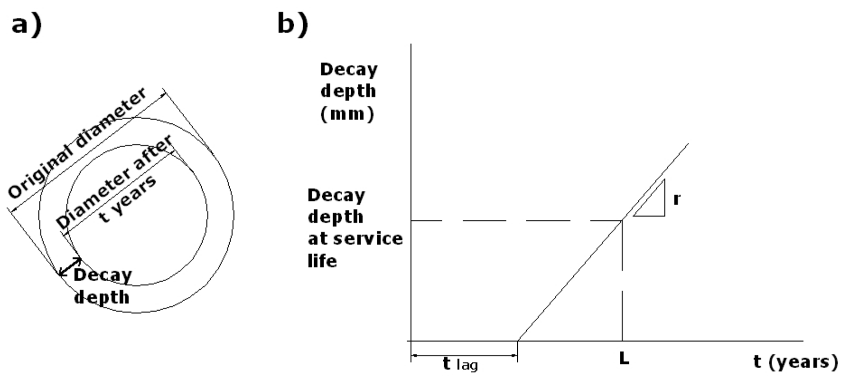

Figure 2 a) Diameter variation and decay depth (d_t), b) idealised progress of decay depth with time (adapted from Leicester et al., 2003). t_{lag} (lag time) and L (service life) are shown.

Apart from the decay effects, the physical and mechanical properties (density, strength, elasticity; Simpson and Wang, 2001) of wood are affected by its moisture content (MC) because of its hygroscopic nature. The wood exchanges its moisture content (MC) with the outer atmosphere until equilibrium moisture content (EMC) is achieved. Generally, this occurs in the course of the first year of exposure (Forest Products Laboratory, 1999). EMC values vary with both relative atmospheric humidity and temperature (Forest Products Laboratory, 1999). In wood structure calculation standards both physical and mechanical properties refer to 12% moisture content (MC). As the in situ wood would have different MC, in order to calculate the density of such wood at EMC, a 0.5% adjustment is made for every percentage point difference in moisture content between EMC and MC (EN 384:2010).

2.1.2. Plants

Plants have both beneficial and adverse effects on slope stability and are the most variable element in an eco-engineering intervention. The way in which vegetation enhances mass stability is both via root reinforcement and via soil moisture depletion. Mechanical effects of vegetation on slope stability have been extensively documented overtime (e.g. Wu et al., 1979; Norris et al., 2008; Stokes et al., 2014). Among the main adverse effects of vegetation are the windthrow and the surcharge because of the vegetation weight. Models related to either plant growth or root distribution with depth are very useful for incorporating new effects in eco-engineering techniques design because roots take the loads and distribute into soil. Small vegetation roots reinforce the soil providing and added cohesion value (Waldron, 1977) which can be included in the Mohr-Coulomb constitutive equation (Wu et al., 1979; Ekanayake and Phillips, 2002; Stokes et al., 2008) for soil strength.

Under field conditions, roots occur in different sizes and lengths and can have different tensile strengths and degrees of fixity. Accordingly, two failure mechanisms are predominant in a deforming rooted soil: root tensile break mode and root pull-out mode (Waldron and Dakessian, 1981). For preliminary assessment of vegetation reinforcement, a simple breakage model (perpendicular reinforcement model; Wu et al., 1979) can be used assuming all roots break in tension under load. This should be used with caution because of its simplicity, reduced amount of input parameters (Root Area Ratio at depth z – RAR(z) and root tensile strength Tr; Eq. 6) and observed realistic application (Mickovski et al., 2008). It must be borne in mind that only small roots (diameter < 10 mm) are considered in this model to compute the added cohesion value (c_r), since big roots only contribute to slope stability as structural anchorage (Mickovski et al., 2009).

$$c_r = 1.2 \cdot RAR(z) \cdot T_r \qquad \text{Eq. 6}$$

Root pullout mechanism depends on the root anchorage length, soil type, root physical properties and root system architecture. When a root is not long enough it will tend to slip or pull-out when the soil-root composite is sheared. Assessing the pull-out resistance for quantification of root reinforcement has been analysed by several authors (Norris, 2005; Mickovski et al., 2005). Vertical uprooting of whole plants has been also used to determine the contribution of a root system to soil fixation (Norris, 2005). Lateral plant uprooting (or overturning) has been investigated by winch experiments (e.g. Crook and Ennos, 1996; Coutts et al., 1998; Mickovski and Ennos, 2002; Mickovski and Ennos, 2003; Cucchi et al., 2004; Stokes et al., 2007).

Root system morphology and properties can be studied by field techniques (e.g. Böhm, 1979; Van Noordwijk et al., 2000) or indirectly estimated from theoretical root distribution models (Laio et al., 2006; Preti et al., 2010) that only need readily available long-term climatic and pedological parameters and a species–specific scaling factor. Published literature (e.g. Francis et al., 2005; Schenk and Jackson, 2002; Waisel et al., 2002) includes data of root systems of the most common living material used in ecotechnological solutions.

2.1.3. External and internal stability

As with any stabilization structure, eco-engineering solutions must be checked from a structural point of view to ensure that the external (sliding, overturning, bearing capacity and slope failure; Fig. 3) and internal stability are satisfactory and these checks must include both decay and plant effects in order to reflect the changes during the lifetime of the eco-engineered solution. In the case of wooden elements, the internal stability calculation is based on the governing timber structural design (EN 1995-1-1:2004/A1:2008 Eurocode 5). On the other hand, the external stability checks are usually performed in line with existing geotechnical engineering design standards and the stability is expressed in terms of a Factor of Safety (FoS; e.g. Tardio and Mickovski, 2015). In this study, we have adopted the FoS expressions for bare and vegetated soil (Gray and Sotir, 1996) and use lumped global FoS for the sliding and overturning checks since the purpose on this paper is to show how the different stability checks vary with time. The resistance to sliding (FoS_s) will be affected by evolution of the RAR value with time across the sliding plane (Preti and Cantini, 2002) while the resistance to overturning (FoS_o) will be affected by the pull out force evolution with time due to root growth (Figure 3). The global stability of eco-engineered slope can then be assessed using existing slope stability analysis methods (Duncan and Wright, 2005) taking into account both long term (drained) and short term (undrained) scenarios.

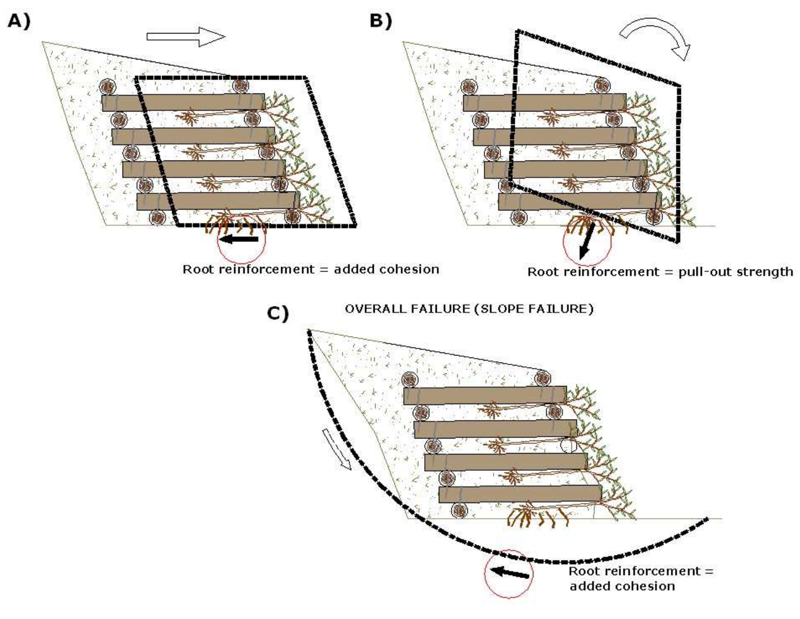

Figure 3 A) Sliding check, B) overturning check, C) slope failure check. The roots effect (if applicable) is highlighted in a circle

2.2. Approach and methodology

In order to include the variation of strength in both living and inert components of the eco-engineering solution and assess its effect on the stability of the system with time (Gray and Sotir, 1996), monitoring and adaptation of the stability check methodology are required. Based on durability considerations, the eco-engineered slope design must include at least two stages: before the plants have propagated roots (traditional/standard design of stabilization projects) and after the propagation of new roots which affect the soil mechanical properties (newly proposed methodology). Within the latter, intermediate scenarios making allowance for the stress transfer phenomena between the wood or inert material and the plants should be considered before the last scenario where living plants are considered to be the major source of the overall system stability. In this latter case, the wooden materials accompanying the plants would have already fully decayed or are considered ineffective for stabilization purposes. This new proposed methodology fits well within the generic geotechnical design framework where several stages or design situations must be analysed over time (EN 1997 – Eurocode 7: Geotechnical design) and the analysis of the structure at different time stages incorporates different values of the variables involved (e.g. decay depth, mechanical strengths, root evolution/reinforcement, etc.).

When using untreated wood elements, the decay process evolution can be introduced in the design stages through the service life concept (L, Eq. 5) used as a basis for the definition of design stages. The service life of the inert materials used must ensure a suitable development of the living material in order to make feasible the stabilising effect transfer process. Therefore, the effective role of the inert material used must provide a service life in terms of their stabilising effects of at least several years, because all elements interact to affect the overall safety factor of the system over time (Gray and Leiser, 1982). On the other hand, small and medium sized (100-250 mm diameter) round wood used in eco-engineering works (e.g. log crib walls or live slope grating; Zeh, 2007) is the main structural material with known properties (de Vries, 1998; Ranta-Maunus et al., 1998; Boren, 1999) but has higher decay rate values because of the high proportion of sapwood (Zobel and Sprague, 1998).

In the methodological approach proposed in this paper (Figure 4) the service life of the structural wooden elements is assumed to set the threshold after which there is no interaction/synergy between the living plants and the wooden elements as stabilising factors. From this threshold on, the vegetation will play the major role in keeping the system stable and the structural effects of the wooden elements should be neglected in stability checks in line with the main philosophy of the ecotechnological approach which should take advantage of the dynamic of the living systems (Gray and Sotir, 1996).

A set of different scenarios (stages) is defined in order to cover the eco-engineering work evolution with time (Figure 4). For the short term (undrained, end of construction stage) check the plant effects will be not be included due to a lack of time for plant establishment after construction. For the drained (long term) checks, different scenarios will be taken into consideration. First, a scenario representing the stage throughout the first growth season of the eco-engineering work in which the plant effects are not included yet. After this stage, depending on whether wooden elements are present in the work or not, more design scenarios are defined. Without wooden elements being used, an additional stage that includes full plant effects will be necessary to depict the overall evolution of the eco-engineering work from a design point of view. Where wooden elements are being used, several additional stages will be defined depending on the wood service life (L) value calculated according to Eq. 5.

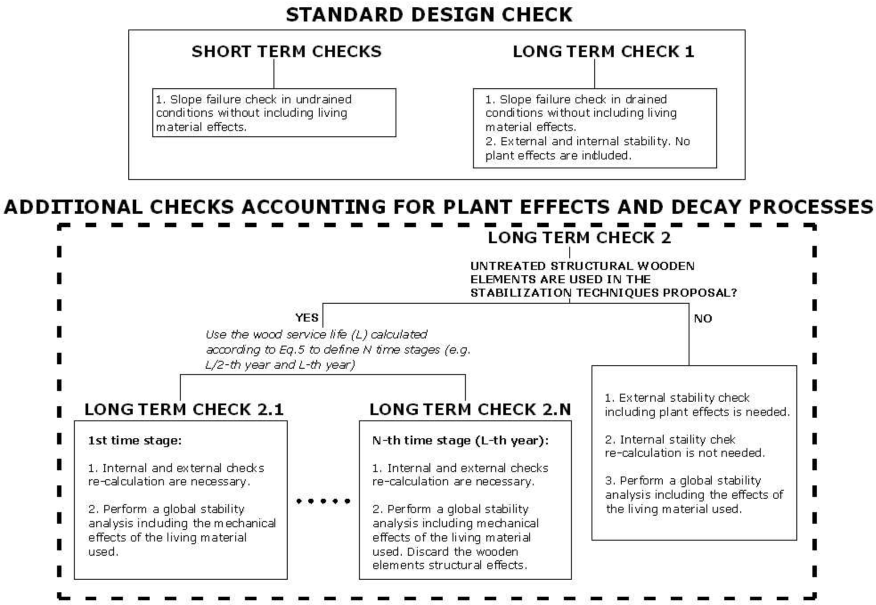

Figure 4 Flowchart of the methodology; adapted from FHWA-NHI-00-43 (2001). The novel approach stages are shown as additional checks within the dashed line area.

2.3. Methodology validation - case study

2.3.1. Site characteristics

The study site lies on Catterline Bay, Northeastern Scotland, UK (x: 387100 y:778350), located in a region with a mean annual temperature of 8.02ºC, a mean annual rainfall of 1232 mm, no (rainfall < 5 mm) dry months per year (UK Met Office) which constitutes a humid temperate climate (Cfc: subpolar oceanic climate: Köppen, 1884). The precipitation is characterised by frequent, low intensity rainfall events, seldom heavy storms, and Kclimate = 1.56 (Leicester et al., 2003).

The topography of the study site is dominated by sloped terrain (slope angle 25-50 degrees) and cliffs. Published geological maps (BGS, 2013) show the superficial soils at the site area to comprise Raised Beach Deposits (RBD) of sands and gravels of the Quaternary period on the slopes and Mill of Forest Till Formation (Glacial Till) at the crest of the slope. A more detailed geological characterisation of the site can be found in Mickovski et al (2015). Shallow and well drained soils are found within the study area resting on top of sedimentary bedrock (i.e. conglomerate and sandstone).

The soils comprise mainly silty sands with high organic matter content, soil porosity, and good drainage conditions (Mickovski et al., 2015).

Figure 5 Study site (Google Earth image © 2016 Getmapping plc)

The vegetation cover is dominated by herbaceous weeds and grasses, riparian tress and agricultural crops of wheat and barley. Typical perennial pioneer herbs that are well distributed over the site are *Erigeron acris* L., *Rumex obtusifolius* L. and *Silene dioica* Clariv. The main tree species in the area are *Fraxinus excelsior* L., *Acer pseudoplatanus* L., *Salix viminalis* L. and *Salix caprea* L. *Pinus sylvestris* L. is present in small stands within the site.

Different slope instability episodes have been reported in the past (e.g. Kincardineshire Observer 11/4/2013; Mickovski et al., 2015) mainly associated to heavy rainfall events (Fig. 6). A comprehensive analysis of the different slope failure types in the study site can be found in Mickovski et al (2015). Particularly, deep seated failures were detected at the toe of the coastal slope and, in order to mitigate against these instabilities, a log crib wall will be designed.

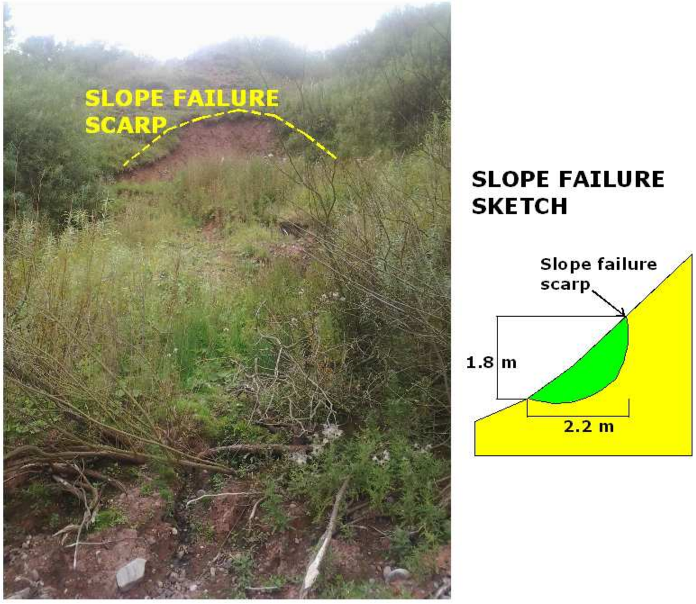

Figure 6 Slope failure in the study site

2.3.2. Material characteristics

Given the type and permeability of the soil, i.e. silty sands, only drained conditions will be taken into account. The soil strength properties obtained through a standard laboratory shearbox test (Gonzalez-Ollauri, unpublished data) showed an effective cohesion of 7 KPa, and effective angle of internal friction of 30º. The soil unit weight was 20.10 kN/m^3 (González-Ollauri and Mickovski, 2014).

It is assumed that the wood for the eco-engineering structure will come from the nearby Scots pine (*Pinus sylvestris* L.) stands following the sustainable design philosophy, with logs of approx. 200 mm diameter and characteristic bending strength of 20 N/mm^2 (C20 class; Moore et al., 2008) made available for the work. Scots pine corewood is moderately resistant (durability class 3; AS 5604-2005) which yields K_{wood} = 1.30 (Eq.1; Leicester et al., 2003). Scots pine sapwood has a K_{wood} equal to 5.44 (Eq.1; Leicester et al., 2003).

For a Service class 3 and permanent loads the modification factor k_{mod} = 0.5 (EN 1995-1-1:2004/A1:2008 Eurocode 5). The material coefficient γ_m = 1.3 and, thus, the design bending strength will be equal to 7.69 N/mm^2. The wood density interpolation shows a density of 525.25 Kg/m^3 for the EMC=21% characteristic for Scots pine (EN 384:2010).

The living material will consist of 1.80 m length Goat willow (*Salix caprea* L.) living branches (approx. diameter 10 mm) harvested from the site. To investigate the rooting characteristics of goat willow, root pullout tests were performed on site in accordance with existing methodology (Mickovski et al., 2005) on five different plants of different age, matching the service life analysis (3x3-year-old plants, 2x6-year-old plants). Root characterisation and distribution with depth was performed both in situ and in the laboratory according to Böhm (1979). 50 root samples with diameters ranging between 0.64 mm and 4.63 mm were tested in tension using a universal testing machine while measuring the force at constant displacement rate of 5 mm/min which mimicked the potential failure velocity. Only specimens that fractured in the middle third of the sample were used in further analysis since rupture near the grips might be influenced by higher stress concentration or structural damage. The results of the root tensile tests were used to calculate the root tensile strength at the moment of maximum tensile force applied.

2.3.3. Proposed solution description and remarks

After analysing the topography on site it was decided to design a log crib wall with 1.8 m height, 1.8 m width and 5.0 m length (see Figure 6) – dimensions reflecting the size of the recent failure at the toe of the slope. The slope of the backfill was designed to be 30º and to match the surrounding terrain. Three goat willow living branches per meter will be used in every log row (see Figure 7; Schiechtl, 1988; Gray and Sotir, 1996).

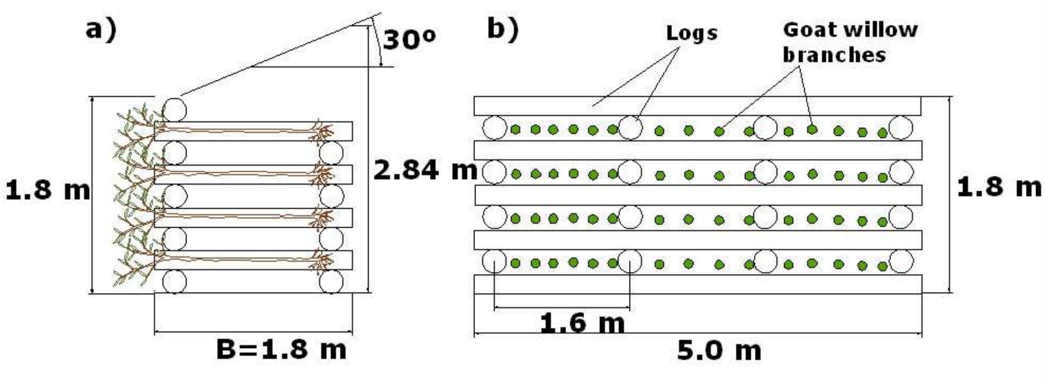

Figure 7 Log crib wall geometry a) cross-section, b) front-view

The internal stability check was performed for the ‘in-ground condition’ - critical situation where the wooden elements (logs) are buried (Figure 8). For the internal stability check, the bending strength analyses were performed according to Eurocode 5 (EN 1995-1-1:2004/A1:2008). The outer log row is considered the most critical from both durability and bending stress aspect (Stangl and Tesarz, 2003). The inner row of logs will be subjected to both a lower temperature and moisture variation throughout the year and at that depth the level of oxygen will be lower and therefore, the biotic activity will be lower (Stangl and Tesarz, 2003). Finally, from a bending analysis point of view, the outer row does not have soil in front counteracting the soil thrust unlike the inner row. The overall specific unit weight can be calculated by taking into account the volume occupied by the logs and the volume occupied by the soil (Preti and Cantini, 2002). By following this approach, the overall weight of the log crib wall was calculated as 61.96 kN/m.

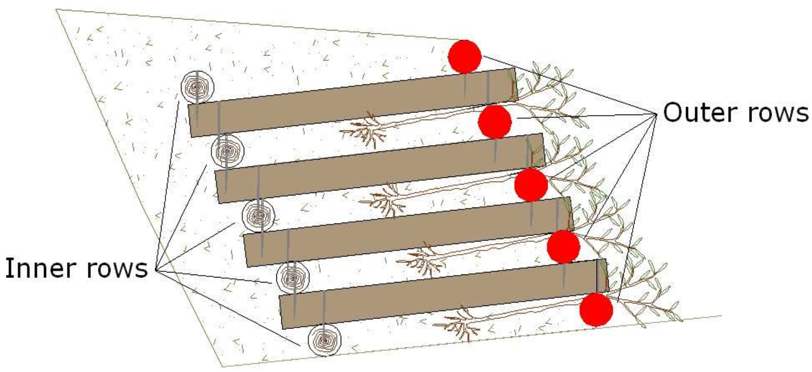

Figure 8 Log crib wall showing natural durability critical situation = in-ground condition (highlighted in red colour).

A minimum maintenance of the living material (willow branches) utilised in the work is assumed to be carried out throughout the work design time scale (i.e. wooden elements service life).

As it is shown in Figure 3, an added cohesion value calculated according to Eq. 6 was used in the sliding stability check. For the overturning stability check case, root pull out force was utilised.

The overall global stability was analysed using stability software (Slope/W 2012, GEO-SLOPE International Ltd, 2014) and spreadsheet (Slip4ex, Greenwood, 2006).

3. Results

3.1. Wood

The adopted decay model (Leicester et al., 2003) using the input parameters (Section 2.1) shows $r_{corewood}$=2.04 mm/year, $r_{sapwood}$=8.52 mm/yr, t_{lag}=0.72 yrs, and L (logs service life) of 6.22 years (Eq. 1, Eq. 2 and Eq. 5; Figure 9).

Based on the logs service life value (L=6.22 years), and for the purpose of this case study, two additional design stages were defined. One at t=3 years (stability check 2.1) and another at t=6 years (stability check 2.2).

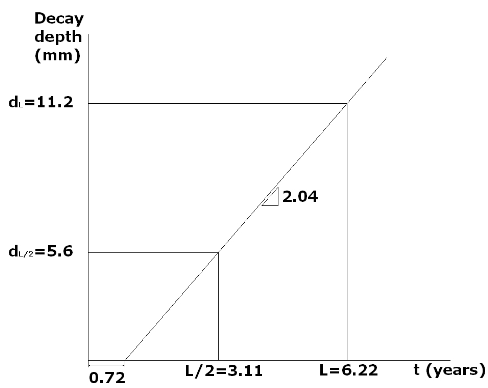

Figure 9 Scots pine idealised decay graph for the study area

3.2. Plants.

The five investigated plants showed that the plant resisting pull out force increased with plant age. The maximum pull out force ranged from 1.90 to 3.87 kN for

3 and 6 year old plants respectively. Given that three plants per meter are considered in the wall design (see figure 7), the root pull out values to be used in the overturning stability check will be 5.7kN and 11.61kN for t-3 years and t-6 years, respectively.

Since the roots are better developed within the outer half of the log crib wall (Stangl and Tesarz, 2003), the moment arm for the pull-out force is calculated as B/4 (where B is the length of the base of the log crib wall; Figure 7).

The exponential law obtained for the root tensile strength was $T_r=28.7981D^{-0.87155}$ [MPa] ($R^2=0.88$).

For the sliding check, the added cohesion values calculated from Eq. 6 for the selected time scenarios are 4.6 kPa and 5.93 kPa for t=3 years and t=6 years, respectively.

3.3. Stability

The external stability checks are shown in the following table

Table 1 external stability check in the selected time stages (t=0, t=3 years and t=6 years). Sliding and overturning safety factor formula adapted from Gray and Sotir (1996).

	T=0 (long term check 1; no plant effects)	**T=3 (long term check 2.1)**	**T=6 (long term check 2.2)**
FoS sliding	1.46	1.78	1.87
FoS overturning	2.15	2.25	2.36
FoS global (slope failure check)	1.47	1.49	1.53

The internal stability checks are shown in the Table 2.

Table 2 Internal stability check in the selected time stages (t= 0, t=3 years and t=6 years). Bending span length equal to 1.6 m. M=design bending moment. R=bending strength according to Eq. 3.

Check 1, t=0 years (end of construction stage)	**Check 2.1, t=3 years**	**Check 2.2, t=6 years**
M = 6.02 kNm No decay Diameter = 0.2 m R = 6.05 kNm Internal stability verified	M = 6.02 kNm Decay depth = 5.67 mm Diameter = 0.18 m R = 5.07 kNm Internal stability **NOT** verified	M = 6.02 kNm Decay depth = 11.21 mm Diameter = 0.17 m R = 4.23 kNm Internal stability **NOT** verified. Wooden elements are not developing a stabilising effect any longer.

4. Discussion

The proposed methodology is based on existing engineering standards and, therefore, engineer can become easily familiar with it. In the eco-engineering approach, the use of materials which change their properties with time (plants and wood) is very common, and a design methodology making allowance for the deterioration and change of the work will be a very useful tool for eco-engineers. Indeed, the proposed methodology allows the interconnection between the eco-engineering work evolution and the engineering work design stage.

From Table 2 it can be seen that the internal stability is not verified in the check 2.1 (t=3 years). This would mean that the structure could collapse before the plants had had enough time to develop their reinforcing effect. At this stage, there are two options available: either to increase the log diameter which would involve bringing wood from a different site or to lowering the span of the bending element which would increase the material requirement but will be more sustainable. Choosing the latter case, and a value of 1.45 m span, would give the values shown in Table 3:

Table 3 Internal stability check with a span of the bending elements equal to 1.45 m.

Check 1, t = 0 years (end of construction stage)	**Check 2.1, t = 3 years**	**Check 2.2, t = 6 years**
M = 4.95 kNm No decay Diameter = 0.2 mm R = 6.05 kNm Internal stability verified	M = 4.95 kNm Decay depth = 4.79 mm New diameter value = 0.19 m R = 5.07 kNm Internal stability **verified**	M = 4.95 kNm Decay depth = 11.21 mm New diameter value = 0.17 m R = 4.23 kNm Internal stability **NOT** verified

With this new design, the log crib wall would resist enough time so the vegetation would be able to perform adequately its stabilising role. Therefore, the proposed methodology detected a scenario where the structure would be unstable without giving enough time to the vegetation to properly settle down and reinforce the slope. Traditional design would not have detected this situation and therefore an improvement within the design stage of eco-engineering works has been proven.

Our analysis shows that the external stability of the bioengineered slope increases with time because of the living plant effects. The sliding safety factor shows the largest increase as also noted in the literature (e.g. Preti and Cantini, 2002). The global safety factor (slope failure check) does not vary much because of the typical shallow root system developed by the goat willow and because of this, the best practice would include basic maintenance (e.g. pruning) to encourage root growth rather than above-ground growth which would further destabilise the slope (Preti and Cantini, 2002). Indeed, with minimum maintenance and treatment tasks plant growth will develop within the wall vertical preventing the generation of eccentric loads which may, in turn, trigger overturning instabilities of the overall structure which is one of the main adverse threats that may ruin the eco-engineering intervention approach (Preti and Cantini, 2002).

The necessary input data for the proposed methodology is either readily available or easily measurable in the field (e.g. Böhm, 1979). The proposed methodology is compatible with theoretical root distribution models such as Laio et al. (2006) or Preti et al. (2010) and can accommodate prediction of the below ground biomass by analysing the above-ground biomass which makes the methodology even more accessible for preliminary design assessment. Similarly, the calculated values of root added cohesion compare well with the published values for willows tested in situ (Norris et al., 2008). However, in order to optimise the design, field data will be necessary and adequate investigations should be undertaken prior to the detailed design stage.

The use of readily available materials (e.g. plants and wood) adjacent to the works site is another feature of the eco-engineering philosophy. The case study presented here showed a very cost effective design when compared to traditional slope stabilisation works. The complexities generated because of both the prioritisation of using available materials and the use of living plants are well managed in the proposed methodology. Furthermore, the proposed methodology factors in the change in the material properties of the structural materials and the relative distribution of load transfer between the materials with time, reflecting the live, temporal dimension in the behaviour of the structure which is the novel aspect of the approach. Therefore, a good representation and simulation of eco-engineering works can be embraced within the proposed design method.

As time progresses, both the complete decay of the wooden structure and its collapse will be reached. At this stage, as pointed out by Fernandes and Guiomar (2016), the slope stability will have to be ensured by the autochthonous developed vegetation. The initial rigidity of the eco-engineering work will allow for the triggering of new natural processes such as an improved resilience, an improved ecological functioning, plant communities' succession processes, etc. Hence, the concept of work service life is not clearly applicable to the eco-engineering work case since the final stage of the eco-engineered slope would be represented by a natural ecological evolution of the slope which will include a natural restoration and succession of the indigenous plant communities. Indeed, reaching that natural succession process stage in one of the main aims of the eco-engineering work approach.

Fenandes and Guiomar (2016) analysed the stability of eco-engineering works 20 years after the end of construction stage (once the inert material effects were not present in the slope). Although their work is lacking real case study analyses, they showed for a variety of eco-engineering work types that the autochthonous vegetation stabilising effects were able to maintain and improve the general slope stability. More research is needed for an appropriate description of a complete eco-engineered slope evolution from a design point of view.

The decay values obtained by means of Leicester et al. (2003) model match well with both existing experimental data (Princes Risborough Laboratory, 1976) and the wood mass loss data prediction of the climate data-exposure conditions in Europe report (VTT working paper 181, 2011). Indeed, the mass loss predicted in the preceding document in the study area, for exterior above ground wood, is 20% in a 10 year time span. With Leicester et al. (2003) model, the mass loss obtained for a 10 year period of time is 30% which is higher than the 20 % predicted in the Climate conditions in Europe report (VTT working paper 181, 2011). This is due to the more critical service life conditions existing in an eco-engineering work (in-ground conditions) and the use of more precise climatic data. Therefore, Leicester et al. (2003) model is worst case and it can be used with more confidence as it will err on the side of safety.

As with other parts of soil mechanics, the methods proposed have to be improved and calibrated with experience because of their semi-empirical nature. The need for adapting and changing our methods according to the new experiences and the analysis of mistakes and failures will refine our accuracy to assess the short and long term behaviour of the eco-engineering techniques and its stabilising effects. This could be accomplished by means of eco-engineering work monitoring tasks. Besides, the collection of experiences of eco-engineering structures (e.g. Stangl, 2007; Böll et al., 2009) in common and shared databases constitutes another remarkable tool at the design stage level.

5. Conclusions

The dynamic nature of the eco-engineering works must be incorporated at the design stage in order to realistically simulate and estimate the evolution of the work. Parameters such as wood decay/deterioration processes and the changing living material roles as stabilising factors must be integrated into design methodologies for these types of interventions. A methodology making allowance for the eco-engineering particularities is presented. A time staged design scheme is proposed in order to cover the work evolution within a defined design time scale (the wooden elements service life). The proposed methodology is applied to a real case study incorporating measurements and observations on soil as well as the plant root morphology at different time stages. Besides, the methodology follows the sustainability principles such as the use of available materials on or adjacent to the site.

The stress transfer phenomena involved in the typical eco-engineering intervention is well shown in the proposed method. The methodology is able to detect critical design situations unlike traditional engineering design schemes. With the proposed method, the necessary time for the plant to grow and propagate new roots is ensured because, indeed, it is one of the objectives of the design philosophy. With the use of the proposed method both external and internal stability checks with their corresponding safety factor values increase with time and there are no conflicts between the two evolving processes involved in this kind of works which are: the wooden elements deterioration and the living plants evolution with time. An effective combination of these two phenomena is integrated into the design scheme.

The accumulation of eco-engineering monitoring data will be a remarkable source of useful information both to better define the suitable time stages and to gather data regarding wood decay, root morphology and plant evolution.

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CHAPTER 3. A NON-INVASIVE PREFERENTIAL ROOT DISTRIBUTION ANALYSIS METHODOLOGY FROM A SLOPE STABILITY APPROACH

A non-invasive preferential root distribution analysis methodology from a slope stability approach

1. Introduction

The importance of root system architecture for the stability of trees has received considerable attention in the past 30 years (Coutts, 1983; Crook and Ennos, 1996; Nicoll and Ray, 1996; Stokes et al., 1996; Stokes et al., 1997; Mickovski and Ennos, 2001; Chiatante et al., 2003). A number of studies (Chiatante et al., 2003; Coder, 2010; Mattheck, 2011) concluded that sloping terrain remarkably affects the tree root distribution in the soil. In flat areas, roots systems are usually symmetrical, following a so called “symmetrical bell-shape” pattern (Chiatante et al., 2003). In sloped areas, root distribution is no longer symmetrical and follows a so-called “bilateral fan-shape” pattern (Chiatante et al., 2003) as a morphological adaptation of the plant to inclined topographies.

To efficiently anchor themselves and prevent overturning or uprooting, the trees must transfer the loading forces into the ground via the roots (Stokes and Guitard, 1997). Specific anchorage patterns with respect to the slope plane may develop in plants growing on slopes in order to prevent overturning in a downslope direction (Chiatante et al., 2001). Different studies suggested that both large root surface area and asymmetric root architecture laterally around the trunk improve tree anchorage on a slope by increasing the resistance to overturning forces (Chiatante et al., 2001; Chiatante et al., 2003). These results connect with the idea that a bigger interbonding surface between roots and the surrounding soil is needed in the upslope area in order to mobilise friction between root and soil to counterbalance the tensile stresses generated due to the overturning driving forces the tree roots are subjected to when growing on slopes (Mattheck, 2011; Stokes and Guitard, 1997). This adaptation arrangement has been observed for a number of woody species (Chiatante et al., 2003), and similar traits have been observed in various plants subject to different, usually lateral, disturbing forces (e.g. wind; Mattheck, 2011).

The hydromechanical effects of trees on slope stability have been thoroughly studied during the past decade (Pollen and Simon, 2005; Norris et al., 2008; Stokes et al., 2009; Preti and Giadrossich, 2009; Schwarz and Lehman, 2010; Fan, 2012; Bourrier et al., 2013), leading to a number of models that include both the beneficial and unfavourable effects. Because of the variety and extent of these effects, all of the existing models to estimate the root contribution to slope stability need relatively detailed root morphology information. Direct methods (Böhm, 1979; Van Noordwijk et al., 2000) to obtain root spread information are both labour-intensive and destructive. Therefore, there is a need for cost-effective non-invasive methodologies for root system morphology investigation.

The most recent theoretical root distribution models are based on long term water mass balance in the soil (e.g. Laio et al., 2006) and developed for flat terrain. Additionally, these models do not consider mechanical variables that take into account root anchorage functions. Therefore, a complementary source of information may enhance the description of the root system spread for sloped topographies and lead to development of better hydrological-mechanical models of tree behaviour on slopes. To the authors' knowledge an approach that portrays the widely-observed root spread and its application to stability analysis on sloped terrain has not been proposed yet. Methodologies improving the description and modelling of root distribution laterally from the tree trunk are needed because of their direct impact in defining and estimating the distribution of lateral root reinforcement (Schwarz and Lehman, 2010). In the presence of significant lateral root reinforcement, the area that must be destabilized in order to trigger a landslide will increase (Reneau and Dietrich, 1987). This is particularly relevant in shallow failure prone slopes where the roots are most likely to have a major effect on the stability of the soil mass either by anchoring it (structural roots; Mickovski and Ennos, 2003) or binding the soil together and protecting it from erosion (non-structural and fibrous roots; Mickovski et al., 2005).

The use of non-invasive sub-surface ground analysis, along with the theoretical root distribution models, could provide valuable information about tree root system morphology. In this sense, Ground-penetrating radar (GPR) is a potentially suitable technology for detecting subsurface structural roots and creating root distribution maps. GPR is able to detect either large roots (diameter bigger than 10 mm; Stokes et al., 2002; Guo et al., 2013; Raz-Yaseef et al., 2013) or fine root clusters (Bassuk et al., 2011). Root system bulk properties, such as root density comparisons, could be performed with this technique as well (Butnor et al., 2003). GPR has been shown to successfully locate tree roots non-invasively and in three dimensions in forest soils (Hruska et al., 1997; Butnor et al., 2001; Stokes et al., 2002; Butnor et. al., 2003; Zenone et al., 2008). Despite the above lines of investigation, and to the best of the authors' knowledge, no applications of GPR investigations have been carried out with respect to slope stability analysis and root reinforcement models.

Without intention of generating a combined hydrological-mechanical simulation model for root system architecture predictions, in this paper the existing theoretical models are used in combination with a non-invasive technology (GPR) in order to derive a more realistic root system morphological description for sloped conditions. To achieve this aim, a field investigation campaign was carried out on a landslide-prone slope in northeast Scotland (UK). A GPR investigation of the root spread of a mature maple tree (*Acer pseudoplatanus* L.) growing on inclined terrain was carried out, before exposing relevant parts of the root system and recording the necessary tree metrics. The information obtained was used to validate the combined (GPR and theoretical root distribution model) methodology and to analyse the root system asymmetric shape from a mechanical point of view.

2. Materials and methods

a. Background

On an inclined plane, woody plant root systems usually develop a gravitropic taproot with a larger number of lateral roots growing preferentially upslope (Shrestha et al., 2000). The number of laterals growing upslope seems to increase with the slope angle, and the angle between the lateral roots growing downslope and the taproot is smaller than the angle between uphill lateral roots and the tap-root (Shrestha et al., 2000). The biomass' centre of gravity of the lateral roots is located upslope with respect to the trunk (Mattheck, 2011). The asymmetry in these "bilateral-fan shape" (Chiatante et al., 2003) systems observed in many tree species is a response to the different functions of the upslope/downslope portion of the root system. The functions governing the root development on the slope would include the tree stability (mechanical) and availability of water/nutrients (hydrological).

Theoretical root distribution models (Laio et al., 2006; Preti et al., 2010) assume symmetrical root systems. Although some attempts have been made to incorporate the slope influence on the root spread (Tron et al., 2014), these attempts have been set in hydrologic and pedoclimatic terms, not taking into account anchorage function and mechanics. Other authors (e.g. Tsutsumi et al., 2003; Tsutsumi et al., 2004) have incorporated the slope influence by means of hydrotropism (root elongation towards water), resulting in a clear asymmetric pattern. However, these models do not explain the occurrence of lateral roots with larger diameters in the upslope direction (Chiatante et al., 2003).

The optimisation of the root system development under different loading conditions has been investigated from a mechanistic aspect (e.g. Mattheck, 2011; Mattheck and Bethge, 2011) and can be visualised using a finite element method code (e.g. SKO-Soft Kill Option) (Baumgartner et al., 1992). The asymmetry in the root systems growing on slopes (more and bigger lateral roots growing upslope in comparison to the downslope direction; Fig. 1) is driven by the asymmetric loading; (Mattheck, 2001).

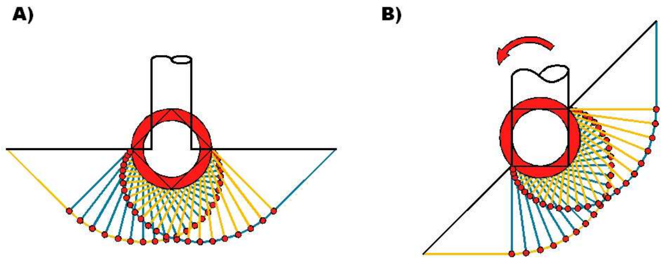


Figure 1 Compression (in blue) and tension (in yellow) force distributions in a safe root anchorage A) flat , B) sloped terrain conditions, the latter giving place to an asymmetric loading scenario (red arrow). Adapted from Mattheck and Bethge (2011).

The distribution of roots decreases with depth under the soil surface. This distribution, expressed as Root Area Ratio (RAR; ratio of cross section of roots and the soil cross section at depth z below ground) can be modelled using existing methods (e.g. Laio et al., 2006; Preti et al., 2010) as an exponentially decreasing function of soil depth and the average rooting depth (Preti et al., 2010; Eq. 2, Table 1) requiring readily available long-term climatic and pedological parameters and a species-specific scaling factor. In these models, the average rooting depth estimation is problematic for humid climate cases since, when using Laio et al (2006) model, the b_m value can become negative (Tron et al., 2014).

Table 1 Equations and parameters for the root reinforcement calculation (Laio et al., 2006; Preti et al., 2010)

$RAR(z) = \frac{Ar(z)}{Ars}$ Eq. 1 $Ar(z) = Ar_0 e^{\frac{-z}{b_m}}$ Eq. 2	RAR(z) = root area ratio at the depth z Ar(z) = roots cross sectional area with depth (m^2) z = soil depth (m) Ars = rooted soil area (m^2) Ar_0 =roots cross sectional area at z=0 (m^2) b_m = mean rooting depth (m)

Since the Laio et al (2006) model was developed from an hydrological point of view, it limits the possibilities to incorporate mechanical variables. Hence, if the model output is to be used and combined with other features (e.g. the slope condition, different loading scenarios, etc.), the model outputs need to be modified instead of attempting to include a set of virtual factors within the model in order to simulate the mechanical effects such as the slope of the terrain. The mechanical effects and the corresponding asymmetric root distribution pattern could be incorporated by both a root volume transformation coefficients obtained from in situ investigations. With this, the assumption of a conical shape of the root volume (Preti et al., 2010; Gonzalez-Ollauri and Mickovski, 2016), will be replaced with a realistic root distribution and the humid climate condition limitation (Laio et al., 2006; Preti et al., 2010; Tron et al., 2014) will be overcome.

Ground Penetrating Radar (GPR) is a pulsed electromagnetic technique that generates a two-dimensional section of the subsurface in a manner very similar to reflection seismics, originally developed as a tool for investigating geological structures (Annan and Davis, 1976; Olhoeft, 1984; Davis and Annan, 1989). As in geotechnical sub-surface surveys, the combination of GPR and intrusive investigation is a common strategy for the verification and confirmation of the obtained results (e.g. GPR and borehole campaign; Singh, 2006) and, we have used this approach in our study to analyse the preferential root distribution/growth on sloping ground which is one of the novel aspects of our investigation.

b. Approach/methodology

The mean rooting depth value (b_m) predicted by the existing models (e.g. Laio et al., 2006; Preti et al., 2010), which is a third of the total depth value (Laio et al., 2006; Gonzalez-Ollauri and Mickovski, 2016), is valid both at plant community level and for water controlled ecosystems and flat areas. When analysing a root system at an individual tree level and in sloping conditions, the value of b_m must be adjusted to account for the asymmetry in the root horizontal/vertical distribution. This new value of b_m which is site- specific, could be directly obtained by the use of the GPR readings regarding the detected root vertical and lateral distribution pattern (Butnor et al., 2003; Butnor et al., 2011; Bassuk et al., 2011). By analysing the detected vertical and lateral root distribution pattern around the tree trunk, a mean rooting depth value can be obtained at various distances from the tree trunk. In the case of taproot systems, as the GPR readings are taken at a certain distance from the tree trunk, measurements right below the tree stem will not be possible for trees growing on a flat terrain while, on inclined planes, the detection of the tap root depth will be more feasible (Figure 2). In the case of tap root detection, the depth readings away from the tree stem will be shallower than those of the actual tap root tip depth and, hence, erring on the side of safety. With the preceding methodology it will be ensured that all information related to specific slope conditions is implicitly taken into account in the root depth estimation both in a non-invasive and in a conservative manner.

The variation of root distribution with depth (Ar(z), Preti et al., 2010; Eq 2) is related to a depth both parallel to the ground surface and perpendicular to the cone height. For maintaining the conic shape of the root volumetric distribution (Preti et al., 2010; Gonzalez-Ollauri and Mickovski, 2016), on sloped terrain, the volume occupied by the roots is assumed to follow an asymmetric elliptic cone distribution. The base of this volume is an equivalent ellipse (Figure 2) whose area could be determined by either the root excavated patterns analysis or the use of GPR radargrams and existing image processing algorithms (Zhu et al., 2014). The total soil volume explored by the roots can then be expressed using Equation 3.

$$V = \pi * a * b * b_m * \cos\beta \qquad \text{Eq. 3}$$

Where:

a, b = major and minor axes of the equivalent ellipse, respectively (m)

β = slope angle (º)

b_m = average rooting depth in the vertical direction (m).

b'_m = average rooting depth in sloping conditions = b_m*cosβ, directly assessed by analysing GPR output images (m).

The Root Area Ratio at ground level (RAR_0) could be calculated by dividing the A_0 (Eq. 2) (obtained by directly measuring the root collar cross sectional area which is, in turn, the scaling factor used in Eq.2; Preti et al., 2010) by the elliptic area explored by the roots (=π*a*b) which, as explained before, can be determined by means of the GPR field work.

The soil area reinforced by the large structural lateral roots can be measured by processing the GPR radargrams with existing image processing algorithms (Zhu et al., 2014). Furthermore, the area explored by the lateral roots can then be calculated with reference to an axis perpendicular to the ground surface (**z´**; Figure 2) by using the same GPR readings. With this, the root distribution will be described according to planes parallel and perpendicular to the ground surface.

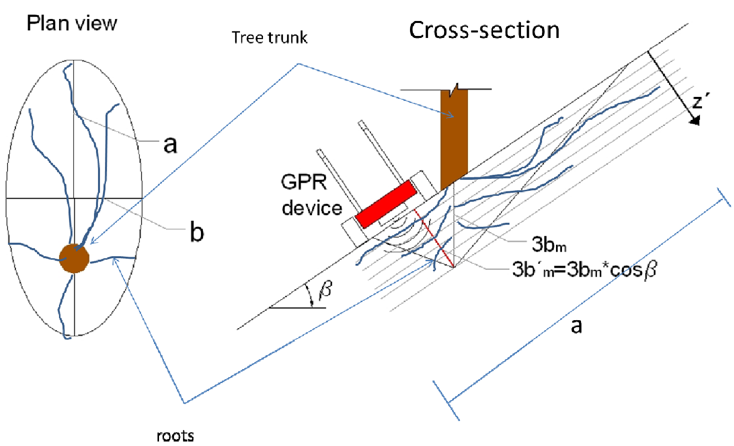


Figure 2 Root distribution laterally and in depth from the tree trunk shown in a) plan and b) cross-section of a slope as investigated using a GPR device. a and b are the major and minor axis of the elliptic surface indicating the lateral extent of soil explored by the roots, respectively. **b'_m** is the average rooting depth in sloping conditions used in the exponential root distribution model.

Finally, RAR (z´) (Eq. 1) values could be obtained from the GPR readings relative to z' axis for different depths and used in root reinforcement models (e.g. Wu et al., 1979).

To illustrate this approach, we identified a suitable site (see site general description section) and carried out the following steps:

1. Ar_0 was obtained by measuring the root collar area (Preti et al., 2010).

2. RAR_0 (Root Area Ratio near the ground level) was calculated as $Ar_0/(\pi*a*b)$.

3. $b´_m$ was obtained by analysing, from the GPR image processing (see GPR image processing section), the vertical root distribution information. By using $b´_m$ and the **z´** axis, Eq. 2 can be rewritten (Equation 4) where root area distribution according to planes parallel to the ground (Figure 2) can be calculated.

$$Ar(z´) = Ar_0 e^{\frac{-z´}{b´_m}} \qquad \text{Eq. 4}$$

4. For the RAR(z´) calculation, the area explored by the roots from Ars (at z´= 0) to 0 m^2 (at z´= 3*$b´_m$) was interpolated assuming a conical root volume distribution (Preti et al., 2010).

5. The model was compared and validated against the field data.

c. Case study and model validation

2.4.1 General site description

The study site lies in Catterline Bay, northeastern Scotland, UK (UTM 30V x: 547641 y: 6305896) (Figure 3). The site is within the maritime climate zone with warm summers and cool winters. The precipitation is relatively evenly dispersed throughout the year (McKnight & Hess, 2000).

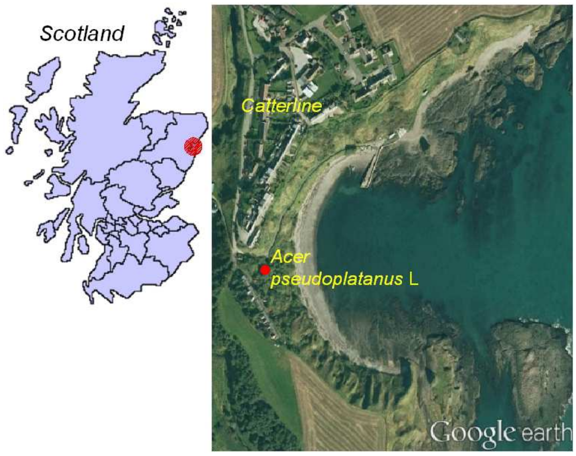


Figure 3 Analysed *Acer pseudoplatanus* L. location (Google Earth image © 2016 Getmapping plc)

From a geomorphologic point of view, the study area is dominated by sloped terrain (slope gradient=25º-50º) including near-vertical sea cliffs. Shallow and well drained soils, predominantly silty sands, can be found within the study area resting on top of sedimentary bedrock (Catterline Conglomerate Formation; BGS, 2013).

2.4.2 Non-intrusive field investigation of root distribution using GPR

The GPR system consisted of a RD1000^{TM} model (SPX Corporation) with a 125-375 MHz radar bandwidth and a scanning screen (Figure 4B). A bandwidth of 375 MHz was employed, which should suffice for the detection of coarse elements such as structural roots and root clusters (Barton and Montagu, 2004; Guo et al., 2013; Ferrara et al., 2014; Cui et al., 2016). Calibration of the GPR system was accomplished, in accordance with the manufacturer's specifications, by scanning a known object (cylindrical steel rod of diameter close to root diameters) buried at a known depth (0.24 m; mimicking expected root depth) into the soil on site. The soil was sampled after calibration and the volumetric moisture content was measured using standard laboratory procedure (42.4%; BS1377) in order to calibrate the readings and achieve better accuracy in GPR measurements.

Circular paths around a maple tree (*Acer pseudoplatanus* L.; Butnor et al., 2011) were followed to characterise tree root morphology and depth (Figure 4A). The circular path radii were limited by the presence of other trees around the selected maple but stretched as far as 2.5 m from the centre of the tree stem.

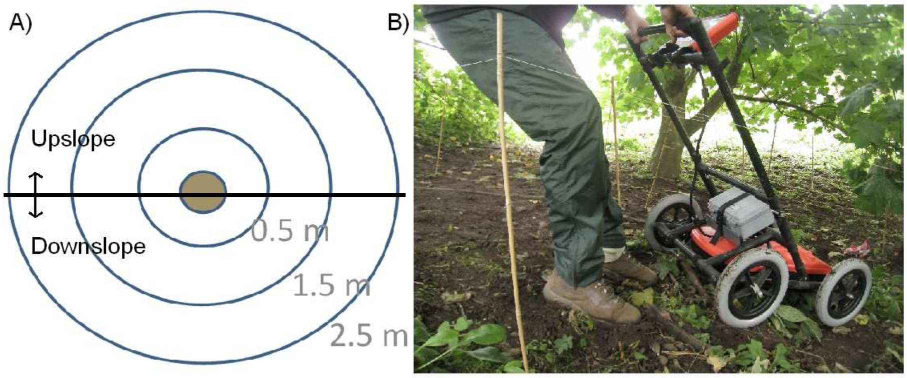


Figure 4 A) Circular paths around the maple stem, B) GPR set up marked on site with bamboo stakes.

GPR readings from the concentric paths were taken and the root distribution around the stem and at different depths below ground was determined by recording the images of each scanned path. These images were processed and analysed in order to detect horizontal and vertical distribution patterns and tree roots superficial distribution (see Results section). Each circumference was divided in two halves, an upslope half-path and a downslope half-path, respectively (Figure 4A). By means of this framework it was possible to differentiate where the roots were more abundant and to determine and compare the root depths in both halves (upslope/downslope) of the path.

2.4.3 Intrusive field investigation of root distribution

After completing the non-intrusive investigation, the soil around the roots maple tree was removed within the first 200-300 mm (Böhm, 1979) (Figure 5B) depth and 2.5 m radius form the centre of the tree stem. Root length and root diameter measurements along the length of each root were taken with digital callipers and, for data point localization, angular sectors around the tree were defined (Figure 5A). The root distribution around the stem and below ground was mapped and comparisons with GPR root detection were made.

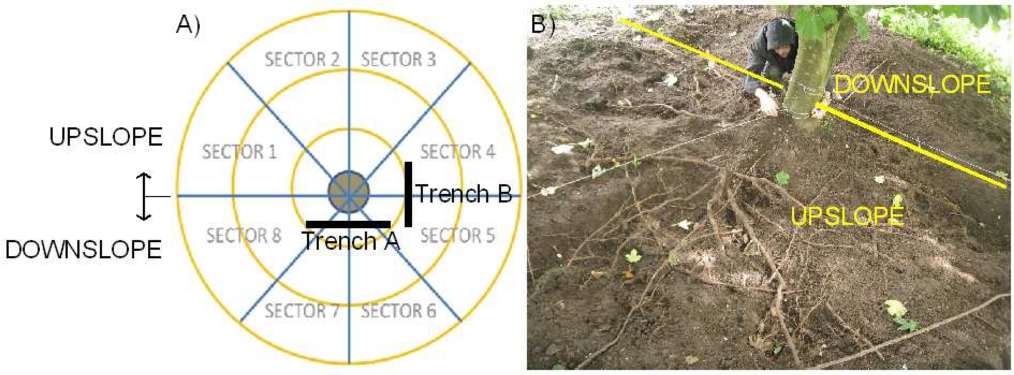


Figure 5 A) Sectors defined for root analysis, B) defining the sectors set up on site by means of ropes after root excavation works.

To calibrate the root vertical distribution model output, the profile wall technique (Böhm, 1979) was used (Figure 6**).** Two trenches were excavated, one perpendicular to the slope (trench A=downslope trench) and another along the slope (trench B=lateral trench) (Figures 5A and 6).

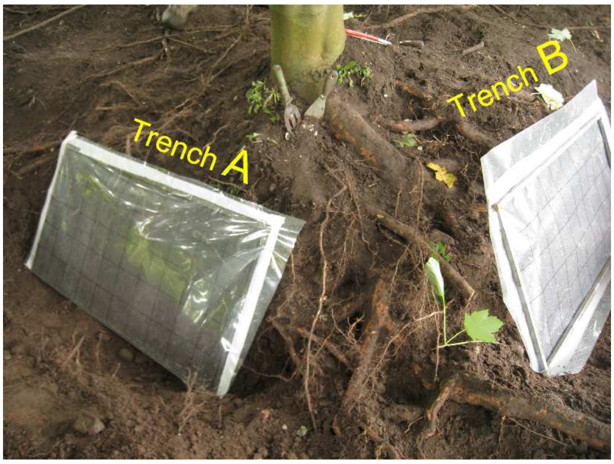


Figure 6 Profile trenches excavated during the field work campaign. Downslope trench (trench A). Lateral trench (trench B).

2.4.4 GPR image processing

The series of radargrams retrieved from the GPR system were imported into the statistical freeware R 3.2.1 (R Core Team, 2014) and converted to CImg format using the R package ‘imager’ (Barthelme, 2015). Each radargram was standardised (e.g. Guo et al., 2013) according to the distance covered by each GPR pass with respect to the captured depth (i.e. 1.15 m) and the number of pixels contained in the original image (i.e. vertical = 459 pixels; horizontal = 640 pixels) by the application of a rule of three; ensuring that the spatial scale in the X and Y directions was the same at the end of the standardisation process, and so the area of soil covered by a pixel known in order to appraise the root area from the images. As result of the standardisation process, the number of pixels in the X direction was extended. To extend the radargram a nearest-neighbour interpolation was implemented. Once standardised, the radargrams were de-noised by blurring the images anisotropically (e.g. Barthelme, 2015). Then, each standardised and de-noised radargram was split into its colour bands (i.e. red, green and blue) and converted into a raster format with the R package 'raster' (Hijmans, 2014). The three raster bands were combined to generate a false colour raster using a RGB algorithm (Heckbert, 1982) in order to identify zones likely to present a root by the pixel colour (Figure 8). Then, the number of pixels was counted by establishing different pixel value thresholds. Eventually, the potential root area was estimated by multiplying the number of pixels by their resolution at four different depth intervals (i.e. 0-100; 200-300; 400-500; 500-600 mm) and an exponential model was fitted between the calculated root area and the soil depth (Preti et al., 2010).

3. Results

3.1 Site and vegetation characteristics

The slope of the terrain was measured with a clinometer and showed a value of 22.5º. The above-ground tree biometrics recorded with a clinometer and measuring tape are shown in Table 2.

Table 2 Biometrics of the analysed individual of *Acer pseudoplatanus* L.

Variable	Value
Tree age (years)	17
Tree height (m)	7.17
Tree breast diameters (m)	0.14/0.21
Tree basal diameter (m)	0.23

Root collar cross sectional area Ar_0 (m2)	0.04

Because of the competition from the surrounding trees, the tree crown was very asymmetric (Figure 7) and this situation, along with the slope condition, generated an asymmetric loading scenario, similar to the one shown in Figure 1b, that will be analysed later in this paper.

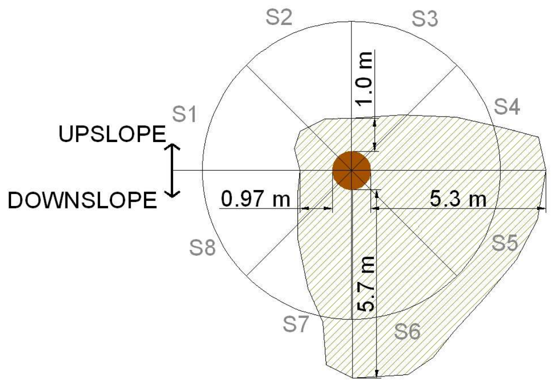


Figure 7 Sketch of the asymmetric crown of the analysed maple tree. The sectors (Si with i= 1 ….8) defined during the field work are shown as well.

3.2. Intrusive investigation of root distribution

The root area variation with depth according to the excavated trenches (Figure 6) is shown in Table 3.

Table 3 Root Area Ratio variation with depth corresponding to the different trenches excavated on site. Number of roots and diameter ranges with depth are also shown.

Depth (m)	Trench A			Trench B		
	Root cross-sectional area (mm^2)	Number of roots	Diameter range (mm)	Root cross-sectional area (mm^2)	Number of roots	Diameter range (mm)
0.0-0.1	28964.98	86	1.5-36.0	32091.82	13	2.3-35.5
0.1-0.2	35482.33	103	1.5-48.5	17310.47	19	2.0-38.7
0.2-0.3	21990.62	59	1.0-34.5	3727.37	11	2.0-35.4
0.3-0.4	2642.08	31	1.0-13.5	2673.15	7	2.0-21.2
0.4-0.5	1886.74	37	1.5-7.0	401.15	6	2.5-5.3

3.3 Non-intrusive investigation of root distribution (GPR)

The post-processing RGB algorithm (Heckbert, 1982) applied to the radargrams captured during the field work allowed for a better distinction between the rooted and the unrooted soil (Figure 8). Clear differences between upslope and downslope conditions were observed.

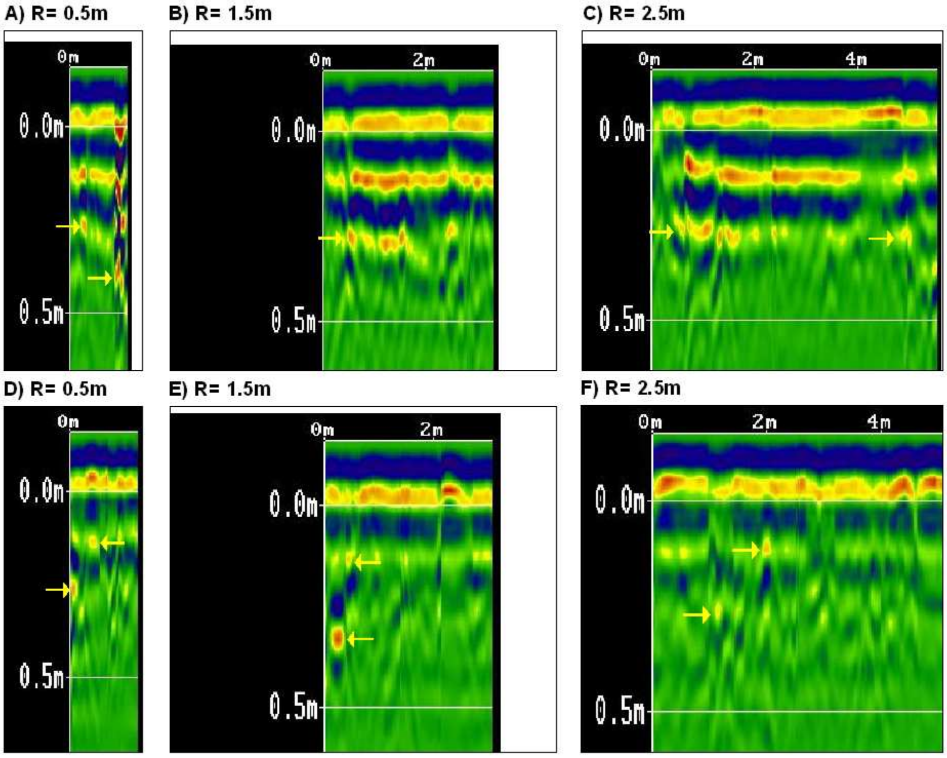


Figure 8 GPR images after applying post processing algorithms. Images A), B) and C) correspond to upslope areas. Images D), E) and F) correspond to downslope areas. Pixels showing root concentration and structural root detection are represented in red/orange/yellow colour (some examples annotated with arrows).

The number of pixels representing rooted soil was counted at different depths (Table 4) and was shown to vary significantly in the upslope and downslope directions. These results could indicate the characteristic root asymmetry present in sloped terrains. An indicator of the root distribution asymmetry index can be calculated as the ratio between the preceding pixel counts (total upslope pixels/total downslope pixels). According to this, the asymmetry index value was 1.97 for our case study.

Table 4 Number of rooted soil pixels and rooted soil area variation with depth for upslope and downslope conditions according to the GPR readings. Pixel area = 8.25125E-06 m^2.

Depth (m)	Number of rooted soil pixels		Rooted soil area (m^2)	
	Upslope	Downslope	Upslope	Downslope
0.0-0.1	46336	46869	0.38232992	0.38672784
0.2-0.3	38927	5762	0.32119641	0.0475437
0.4-0.5	18517	2797	0.1527884	0.02307875
0.5-0.6	2415	1362	0.01992677	0.0112382
TOTAL	**106195**	**56790**	**0.87624149**	**0.46858849**

The detected root system asymmetry is clearly shown in the pixel count variation with depth plot for both upslope and downslope conditions (Figure 9). As it can be seen, the asymmetry increases with the depth and the distance from the tree stem.

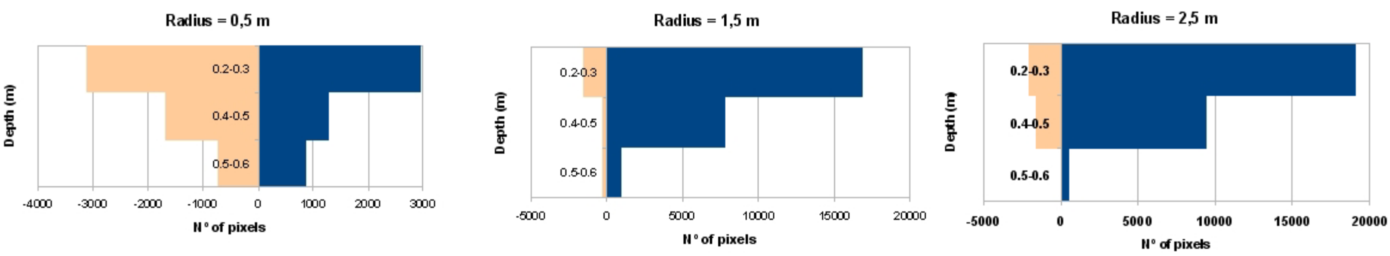


Figure 9 Root distribution with depth as interpreted from the GPR imagery. The plots show the number of pixels containing roots versus depth below ground level. The upslope area is represented in blue while the downslope area is represented in red colour. A clear asymmetry develops as distance from the tree stem increases from 0.5 m to 2.5 m.

3.4. Comparison between intrusive and non-intrusive investigations

The area explored by the roots according to the excavated root distribution pattern was 18.85 m^2 which could be assimilated to an equivalent elliptic surface with 6 m and 4 m of major and minor axis, respectively (Figure 10).

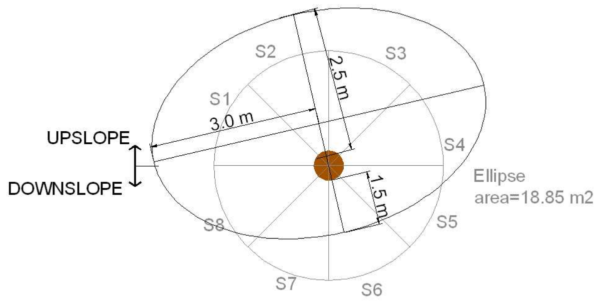


Figure 10 The area explored by the roots is represented as an elliptic surface with major radius equal to 3 m and minor radius equal to 2 m.

In addition, the downslope GPR scan for the 0.5 m radius path (Figure 8D) was compared to the downslope trench profile data (trench A; Figure 6) given the good correspondence between their extent, location and development (trench A is very similar to the semicircular path followed in the 0.5 m downslope path) (Figure 5A). A good correlation between the two sets of root cross-sectional area data was found (Figure 11). The other paths could not be compared to the trenches due to the differences in the position of soil volume explored.

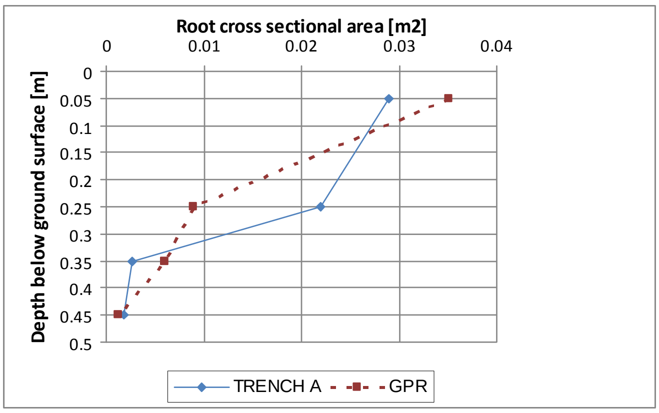


Figure 11 Comparison between the area of roots identified in downslope trench (trench A) and the area of roots inferred from GPR pixel count for the R=0.5 m downslope path.

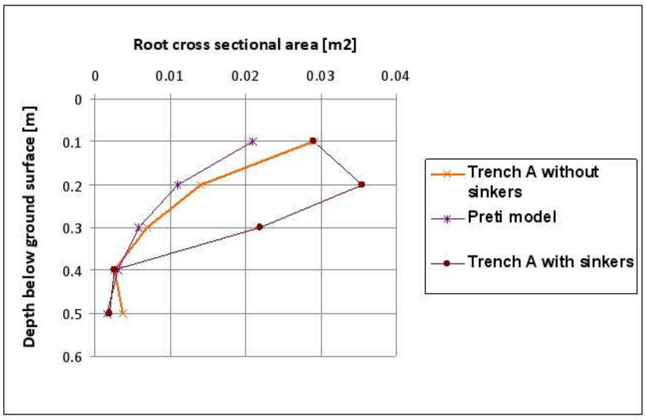
3.5. Combination of GPR results and theoretical root distribution model

Using the intrusive and non-intrusive investigations, the input parameters for the root spread model (Laio et al., 2006; Preti et al., 2010) are as follows:

- b'_m = 0.167 m according to a conservative root cluster vertical distribution analysis (average root total depth = 0.5 m and, therefore, b'_m = 0.5/3)
- Ar_0 = 0.04 m^2 (Table 3)
- *Ars* value will vary linearly from π*a*b* (= 18.85 m^2) at the ground surface to 0 m^2 at approximately 0.45 m depth.

Regarding the distribution of root cross-sectional area (Ar(z)) with soil depth, the model outputs and the trench profile data are compared (Figure 12). As it can be seen, when using the root depth value obtained from the GPR radargrams analyses (b'_m = 0.167 m), a good fit between the theoretical model output and the profile trenches field work data was found in the lateral zones (Figure 12B), while some discrepancies were noted in the downslope zone (Figure 12A).

A)



B)

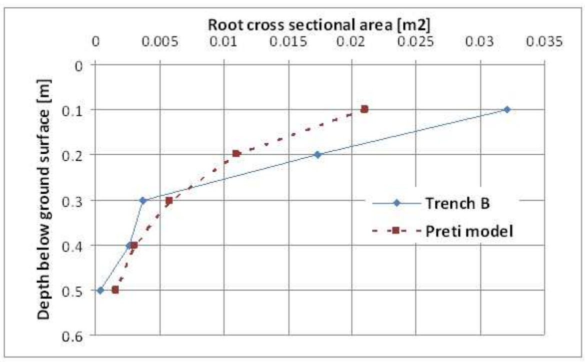


Figure 12 A) Comparison between the root cross sectional area measured in the downslope trench (trench A) with and without the detected sinker roots and root cross sectional area (CSA) predicted when using the theoretical model output, B) Comparison between the root cross

sectional area measured in the lateral trench (trench B) and root cross sectional area predicted when using the theoretical model output,.

4. Discussion

4.1 GPR and root distribution theoretical model

As shown by the GPR radargrams, most of the root cross sectional area was confined within the topmost 0.5 m of the soil and was mainly demonstrated as shallow lateral roots. Structural roots were detected with the GPR as shown in the radargrams (Fig. 8). However, the signal collected in the radargram showed an elongated linear reflection that could be produced by a non-perpendicular insertion of the roots in the ground (i.e. crossing angle of less than 45º with respect to the radar signal; Butnor et al., 2001; Barton and Montagu, 2004) or due to the presence of more than one root at a given location (i.e. non-discrete objects; Butnor et al., 2001; Barton and Montagu, 2004). Consequently, an accurate determination of the real root cross section area, in principle, could not be derived from this technique. However, based on the similarity of the root distribution curves from GPR and intrusive investigation (Fig 11), our protocol was shown to be effective for detecting both the location of the structural tree roots and the fine root clusters and it could constitute a good non-invasive technique to readily quantify the amount of root-reinforced soil. In this sense, our investigation detected a higher root density within the upslope scanned sections (Figures 8 and 9), confirming the preferential root growth due to the adaptation of the tree to the sloped terrain as postulated in the literature (e.g. Chiatante et al., 2003).

The GPR method has a limitation in that the profile direction should ideally be perpendicular to the strike of the root. However, the variable nature of tree roots caused distortions in signal reflection making the data interpretation more difficult. The GPR image processing method used in this work proved to be effective for improving the identification of the horizontal and vertical root distribution patterns. However, there is room for the refinement of the image processing protocols. For instance, by establishing different thresholds in terms of the root pixel value, a more realistic estimation of the total cross-sectional root area within a given soil horizon could have been obtained.

Differences between the upslope and downslope root distribution patterns were detected (Figure 8 and 9; Table 4). Thus, the differentiation between big, anchoring roots present in upslope areas and root clusters present in downslope areas was possible by using a GPR. These results coincide with the mechanically optimised root system shape postulated by Mattheck (2011) (Figure 1B).

The good correlations found between the GPR output and the profile wall data (Figure 11) can be explained because GPR scans mainly detect the rooted soil zone (not individual roots). Differences between GPR and the trench method (Figure 11) were mainly found near the 0.25 cm of depth. This could be due to the difference of distance between the central part of the downslope GPR circular path and trench A with respect to the tree stem (Figure 5B). Unlike the GPR readings (central part of Figure 8D), several big sinkers roots were detected near the tree stem in trench A (Table 3). Hence, in the CSA comparison, the general trend is well reflected but some differences because of the different explored planes are also reflected. Therefore, a proportional correlation between this rooted soil area values and the presence/absence of roots can be expected. This reasoning would be applicable to both the horizontal and the vertical root distribution analysis and, hence, it highlights the potential of the GPR as a non-invasive technique providing information to be used in the theoretical root distribution models.

Figure 12A also shows differences between the outcomes of trench A and Preti et al (2010) model at a depth of 0.25 m. As noted before, this could be due to the thick sinkers roots detected and measured in trench A. When the CSA (root cross sectional area) of these sinker roots is removed (Figure 12A) the resemblance between the two results is very satisfactory.

Figure 12B shows a good correlation between the theoretical model and the trench B measurements. This is due to the fact that, trench B is located further away from the tree stem, the influences in the CSA value of the aforementioned sinker roots in the downslope area are not present. This shows a good correlation between the two trends detected by both methods.

In both cases, if the output were to be used in a root reinforcement model (e.g. Wu et al., 1979), Preti et al (2010) model gives results erring on the side of safety. Hence, the use of GPR estimated b'_m value (mean rooting depth) in the theoretical model offers good possibilities for assessing the general root distribution pattern although influences by big sinker roots can introduce differences in the CSA comparisons. Nevertheless, these influences are less important in terms of root reinforcement models (e.g. Wu et al., 1979) since they are based on the role played by finer roots (added cohesion) and not by big structural roots (such as the sinker roots).

Differences between the theoretical model and GPR rooted soil measurements are mainly due to the big structural root presence and this situation is specially important for GPR readings close to the tree stem. The mean rooting depth value (b_m) used in Eq. 2 was obtained from the vertical root cluster distribution detected by the GPR field work. Therefore, the use of onsite information directly related to both the site conditions and a particular plant species, remarkably enhanced the model outcomes. If possible, in order to calibrate the GPR-theoretical model methodology it may be advisable to include a limited intrusive field work campaign which would allow for a validity confirmation of the methodology preliminary outcomes.

The proposed methodology offers a realistic way to characterise and analyse root systems in slope conditions at a tree scale. The results obtained can be readily used in root reinforcement models to estimate the stabilising role of tree roots in the overall slope stability (e.g. Wu et al., 1979). With the proposed approach, the sloped terrain scenarios will be more accurately analysed by means of non-invasive techniques.

4.2 Asymmetric loading scenarios and root system asymmetry analysis

The two loading scenarios present in the case study are: the sloping terrain and the tree crown asymmetric weight distribution. The slope direction falls within the 4th sector (Figure 13) and, given the slope inclination value (22.5º), the major factor defining the tree mechanical scenario is the asymmetric load due to the tree crown shape (Figures 7 and 13). According to the tension cone method approach (Mattheck, 2011), the loads exerted on a tree generate a stress state that can be reflected by means of compression and tension zones (Fig 1). Every load effectively pushes a 90º compression cone in front and pulls a 90º tension cone behind. This idea is based on the fact that, in the stress distribution of a single force, around 80% of the occurring radial stress will be included by a 90º cone symmetrically placed in front of the force and behind it (Mattheck, 2011). In the case study, sectors S1 and S2 would represent the tension cones derived from the tree crown asymmetry effect while sector S3 and S4 (including a part of S5) represents the tension cones derived from the slope conditions (Figure 13).

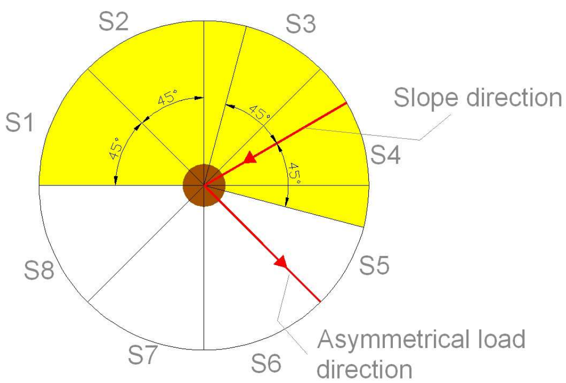


Figure 13 Loading scenarios in the study case (slope direction and asymmetric load due to tree crown shape. Tension cones (in yellow) are formed according to Mattheck (2011).

As a result, S1-S4 sectors correspond to the areas where the roots would be mainly loaded in tension and could be assimilated to a virtual general upslope condition. Contrariwise, S5-S8 sectors approximately correspond to the areas where the roots are loaded in compression (and bending) and could be assimilated to a virtual general downslope condition.

The lateral root distribution around the maple tree coincides with the conclusions reached by other authors (Chiatante et al., 2003; Mattheck, 2011) showing that under lateral loading conditions (e.g. wind, sloping terrain, etc.), the upslope roots grow thicker in an attempt to accumulate a bigger surface for developing friction strength within the soil. In this way the transfer of tension to the soil via friction is improved (Stokes et al., 1996) and the roots being under tension forces tend to be elongated unlike those under compression which tend to be shortened. In this sense, the tension zone included the major root area (Figure 13) and it is where the lateral roots were found to be larger. The yellow area in Figure 13 (tension area) matches very well with the root distribution encountered during the intrusive investigations (Figure 13; S1-S4 tension area and a S5-S8 compression area). Contact areas between S8-S1 and S4-S5 are also influenced by the tension conditions.

The former has implications related to tree stability and root morphology. The necessary tension for tree stability is achieved by means of extending lateral roots located opposite to the different loading scenarios (see Figure 14). In the middle of the tension area (S2-S3 bisector) some large tension roots were found. Secondary roots following 45º angles (Mattheck, 2011) with respect to primary roots (Figure 14) were also found, proving that the major loading in this zone (S1-S4 sectors) is tension.

Figure 14 Lateral and superficial tension roots in the upslope area. Secondary roots are formed at 45 º from primary roots.

As shown by published literature, trees on steep slopes develop fewer but larger lateral roots as the root plate mass is shifted more to the upslope side (DiIorio et al., 2005; Danjon et al., 2005). As it was observed (Figure 15), downslope areas presented deeper roots while upslope areas tended to have more superficial roots that covered a larger area (Figures 8, 9 and 10).

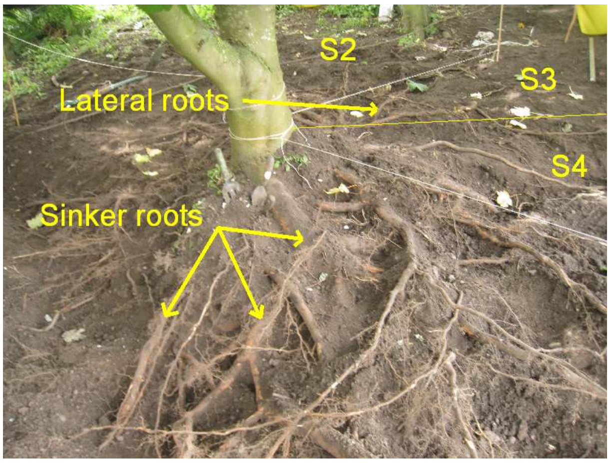


Figure 15 In sectors S1 to S4 superficial lateral roots are abundant unlike sectors S6 and S7 where sinker roots are the main root type

The diameters of the structural roots, which may be defined as those lateral roots having a diameter greater than 20 mm at a distance of 200 mm from the tree trunk (Mickovski and Ennos, 2001), were larger and longer in the upslope area (Figures 5B, 9 and 15; Table 3). These structural roots emerged from the first 200-300 mm of the taproot depth. As explained before, these results connect with the idea that a bigger interbonding surface is needed in the upslope zone in order to mobilise friction between root and soil and, this was well represented in the asymmetry detected with the GPR scans (Figures 8 and 9).

5. Conclusions

1) Ground penetrating radar can be used to identity root presence and to compare the soil-root reinforced area for upslope and downslope conditions. GPR can be considered as a useful, and cost-effective in-situ technique from a tree and slope stability analysis point of view because it permits the non-invasive exploration of natural slope profiles and its outcome presents a

great potential to be used in combination with theoretical root distribution models that can, in turn, be readily employed in combination with soil-root reinforcement models (e.g. Wu et al., 1979). In this sense, a mean rooting depth value was derived form the GPR information and was directly input into the root spread model, overcoming its limitations for humid climates and slope conditions. Additionally, the GPR scans were proven to be successful for inferring the asymmetric shape of root systems in sloped terrain. With the proposed approach the theoretical model was proven to be a useful tool for rooted soil vertical and horizontal distribution estimation although results close to the tree stem must be taken with caution given the sinker roots important influences.

2) The different loading conditions (e.g. slope conditions, asymmetric weights, etc.) analysed were directly related to the asymmetric root system distribution. Each loading scenario case explained part of the existing root distribution pattern and morphology. The aforementioned general virtual downslope/upslope conditions were shown to correspond with both lateral structural roots distribution (mainly concentrated in the general virtual upslope condition zone) and sinker roots (mainly located in the general virtual downslope condition zone). Particularly, the tension cone method (Mattheck, 2011) was proven to be very useful in depicting and explaining the lateral root distribution pattern.

Given that the GPR readings are affected by many factors such as root orientation, root moisture content, soil type, soil moisture content (soil conductivity), leaf litter thickness (Tanikawa et al., 2016), etc., more research is needed in order to test the proposed methodology in other field work conditions.

Improvement and enlargement of the proposed methodology could be accomplished by taking into account the following strategies:

- The use of GPR linear transects and their comparison with trench profiles in combination with the approach presented herein would enhance the methodology outcome.
- The use of different bandwidths for analysing different root diameters.
- The use of different root distribution theoretical models.
- The use of other GPR variables as model inputs.
- The analysis of different tree species and tree densities could contribute to shed light on the true potential of the proposed methodology.
- The analysis of how tree age and surrounding trees´ competition influence the root system spread on sloping terrain could aid to improve models´ predictions, in particular, and the use of vegetation on slope stability, in general.
- The analysis of slope value influence.

The authors would like to encourage further researchers and practitioners to employ the proposed non-invasive methodology for potential improvements of the approach and its validation in other field work scenarios.

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CHAPTER 4. MONITORING OF EROSION PREVENTIVE STRUCTURES BASED ON ECO-ENGINEERING APPROACHES: THE CASE OF THE MIXED CHECK DAMS OF MASONRY AND FOREST RESIDUES

Monitoring of erosion preventive structures based on eco-engineering approaches: The case of the mixed check dams of masonry and forest residues

1. Introduction

Eco-engineering is the use of living plants or cut plant material, either alone or in combination with inert structures, to control soil erosion and the mass movement of land in order to fulfil engineering functions [1]. The self-repairing characteristics of the vegetation used, and the resilience capacity of the bioengineered area [2] are very important allies in the eco-engineering design philosophy.

The eco-engineering philosophy follows the sustainability idea by using readily available material on or adjacent to the site such as wood or rocks. The use of wood material that originates from nearby silvicultural treatments [3] can lead to utilizing material with a wide variety of properties from different species.

The eco-engineering solutions have inherent advantages over classic civil engineering solutions with respect to economy, ease of construction, low landscape impact and opportunities for incorporation of vegetation or plantings within the structure [4]. In contrast, one of the main design disadvantages are related to this latter issue since the use of both living and inert biological materials (e.g. wood) involves incorporating temporary variable elements in terms of design and performance reliability of the eco-engineering works [5]. Because of this, a monitoring stage is essential in order to collect data and check the performance of the eco-engineering intervention as time progresses.

There are three different approaches regarding the way the living material (the plants) play a stabilizing role in this kind of interventions. One approach consists in establishing the plants during the construction stage. In another approach there are no plantation works initially, the inert material plays the initial stabilising role and the indigenous plants colonise the area as time progresses. After several years the main stabilising factor will be represented by the indigenous plant species. Finally, a third possibility consists of a combination of the two preceding approaches.

Another important feature of the eco-engineering design approach is the use of the material readily available in the area. Therefore, whenever possible, the wooden structures will be constructed by using the logs present in the surroundings of the construction site. Finally, the use of non treated wood in this type of structures involves that the wooden elements will degrade with time and, because of an inevitable stress transfer process, the logs will transfer their stabilising effect to the evolving indigenous plants that are colonising the stabilised soil.

During 30 and 31 July and 1 and 2 August 2007, the Canarian towns of Los Realejos, San Juan de la Rambla, La Guancha, Icod, Garachico, Los Silos, Buenavista del Norte, El Tanque, Santiago del Teide and Guía de Isora were affected by a huge forest fire that burned down a remarkable part of a *Pinus canariensis* forest. The total surface burned was over 18,000 ha.

The mixed check dam technique was conceived and designed by Guillermo Tardío in late 2007, during actions to protect and preserve the soil in Teide National Park. On one hand, the wood used in the structures came from the silvicultural treatments that were taking place after the forest fire. In this case, the inert elements fulfilled the initial stabilising needs and, as time progresses, the indigenous species colonised the area while the wooden elements progressively decayed.

Before the use of the mixed check dams there were no previous experiences with eco-engineering techniques in the Tenerife Island. The performance of these structures has triggered a change of the Tenerife local Administration attitude regarding the use of eco-engineering approaches in their interventions.

A visual monitoring plan was followed in order to check the eco-engineering structure evolution and its performance in terms of soil conservation and landscape restoration. The main aim of this article is showing the particularities of the mixed check dam technique from both a design stage and a visual monitoring stage.

2. Study area

The study area is near San Juan de la Rambla which is a municipality of Tenerife Island. It is located in a forested area dominated by *Pinus canariensis* and *Myrica faya*. The topography is very steep and gullies are very common in the area.

A forest trail were mixed check dams were constructed was selected. This trail is known as "Caño Chinque-La Tahona). The UTM coordinates of the beginning of this forest trail are 28R X:339977 , Y: 3137250. A location of the mixed check dams is shown in Fig.1.

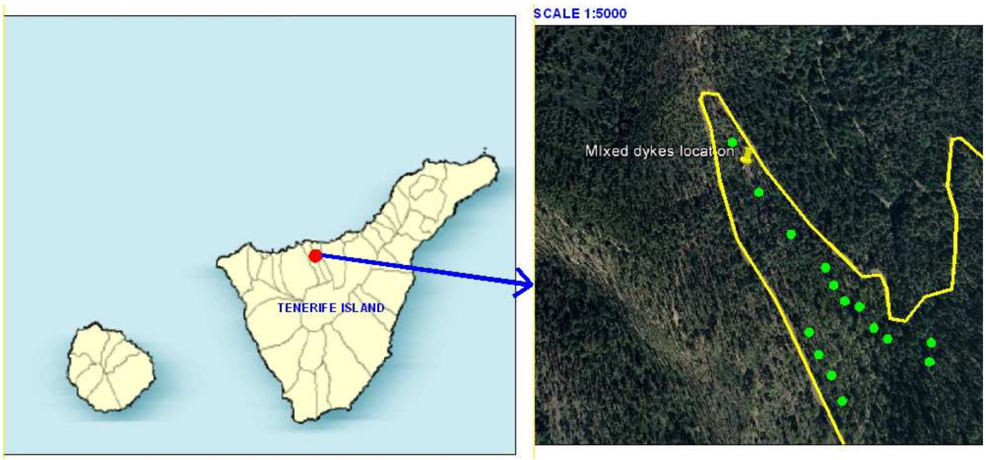

Fig. 1. Monitored mixed check dams location are represented as green circles (right figure with 1:5000 drawing scale)

3. Mixed check dam description

As shown in Fig.2, a simplified scheme of these mixed check dams consists of a structure of horizontal and vertical elements creating a core that is filled with fine branches and forest residues. Besides this, rocks are placed on both sides of the check dam. The vertical elements are tied to each other by means of a biodegradable rope and the end points of the check dam are anchored to the ground or to any adjacent tree, bush or stumps.

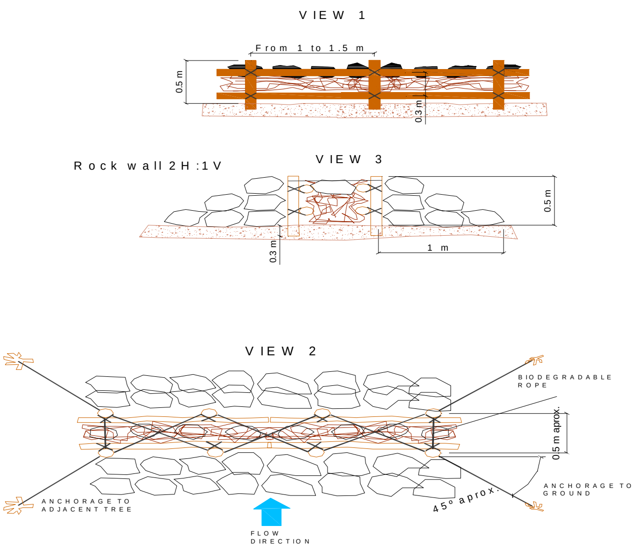

Fig. 2. Mixed check dam profile (view 1), cross sectional view (view 3) and plan view (view 2) (drawings elaborated by Guillermo Tardío)

One of the main features in the mixed check dam design was the use of the abundant forest biomass [6, 7] generated during the cuttings that were conducted. So far, the biggest size check dam built was 2.5 m high and 15 m wide. The main elements of a mixed check dam are shown in Fig.3.

A) B)

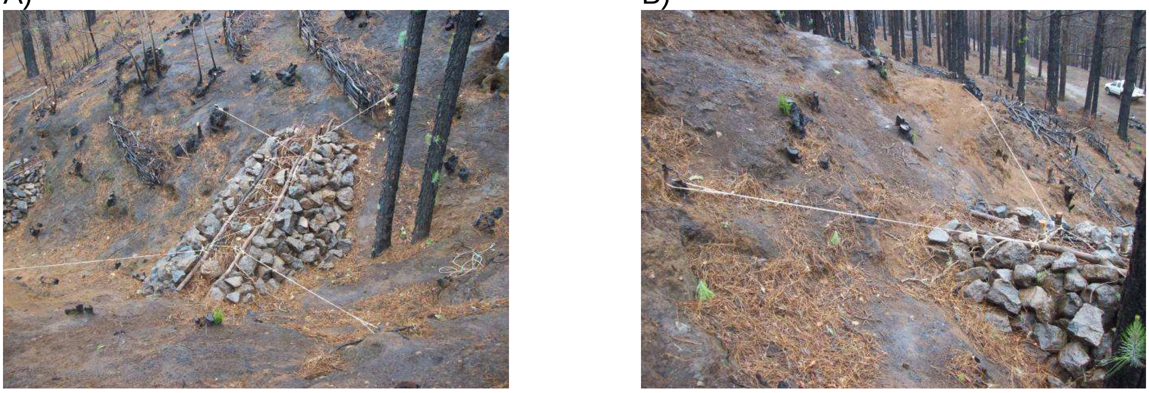

Fig. 3. A) Mixed check dam completely built. B) Detail of the anchoring of a mixed check dam to the ground (photographs taken by Guillermo Tardío)

Distances between the cross barriers (see Fig.4) depend on both the height of the check dam and the slope of the gully [8]. All the materials used in its construction are biodegradable, allowing for the creation of a new and fertilized substrate that will, as time progresses, be colonized by indigenous species.

Fig. 4. The series of mixed check dams will decrease the general slope within the gullies (drawing elaborated by the authors and photograph taken by Carlos Caballero)

This technique follows the ecological engineering philosophy because:

- The matrix formed by the fine residues creates a fertilized substrate that, as time progresses, is colonized by indigenous species. As time pass, the existing voids within the core of the check dam are filled with the materials carried by the runoff.

- All the materials used in its construction are biodegradable and the stabilised soil will be colonized by the indigenous species. Besides, the body of the check dam is permeable and, because of this, water flows through its body but in a controlled way.

- As time progresses, the effect of the mixed check dams inert elements will be replaced by the effects of the colonizing vegetation. Eventually, the mixed check dams will be decomposed and will disappear and the anchoring function to the ground will be played by the vegetation. The sediment mounds caused by the check dams will turn into a series of green islands throughout the gullies.

4. Dimensions of the vertical and horizontal elements

The calculation scheme at the design stage was as follows: once the height of the water level is determined in a certain cross section where a mixed check dam will de located [9, 10, 11], the next step is the calculation of the minimum diameter necessary to resist the forces involved. These forces are both water pressure and the rock walls that the check dam has on both sides. All the elements are calculated according to wood structure calculation principles [12].

As shown in Fig.5, both the vertical and the horizontal elements were calculated as a two pin support beam. The limit state condition in the internal stability check allowed the minimum diameter calculation for both type of elements. The horizontal elements were designed as beams subjected to a uniform pressure (Fig.5A) while the vertical elements were designed as beams subjected to pressures following a triangular distribution shape (Fig.5B).

A) B)

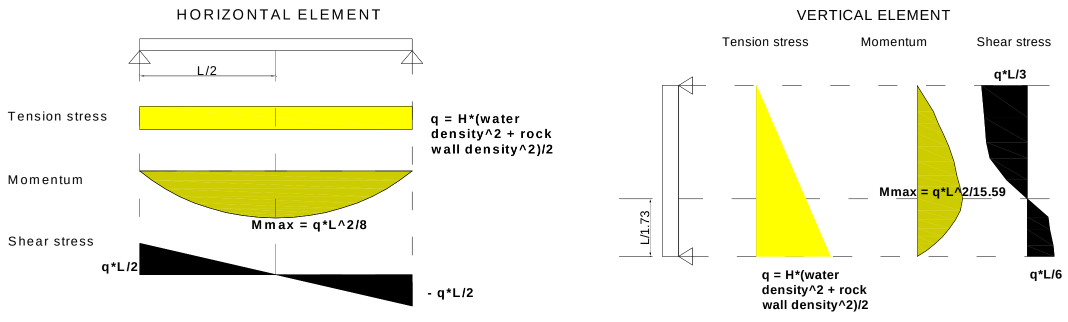

Fig. 5. Tension and shear stress diagrams. q is the total pressure exerted on the wooden element (drawings elaborated by the authors). A) Horizontal wooden elements, B) Vertical wooden elements

In order to calculate the necessary dimension of the circular cross sections, the maximum stress to be resisted by the wooden elements was calculated according to Eq.1 and Eq.2:

$$\sigma_{\max} = M_{\max} / W \qquad (1)$$

and

$$X_d = K_{\text{mod}} K_k / \gamma_m \qquad (2)$$

Where:

σ_{max}=maximum normal stress, M_{max}=maximum bending moment, W= bending stiffness for a circular cross section case, X_d=wooden element design strength, K_{mod} =modification factor (with this factor the moisture content effects and the load duration effects are included in the calculation), K_k=wooden element characteristic strength, γ_m=material partial safety factor.

As shown in Fig.5, to determine the maximum bending point both the rock wall pressure and the runoff water pressure were considered. The water level within the gully was calculated assuming a runoff corresponding to a 100 yr return period rainfall event. The values of the variables used in the calculations are shown in Tab.1.

Table 1. Values used in the wooden elements design

K_{mod}	γ_m	K_k	Runoff water density	Rock wall density
0.7	1.3	10 N/mm^2	1.2 t/m^3	1.8 t/m^3

Although it was not assessed, another important characteristic to be taken into account is the permeable nature of these structures. The first point to consider would be the assessment of the flow through its body. In this case, due to both the size of the porous medium and the runoff speed, the flow through the check dam is turbulent. The permeable nature of these check dams allows a controlled evacuation of the runoff through the check dam. This includes the control of runoff speed and the subsequent lowering of water erosion capacity.

5. Results

By following the preceding calculation scheme, the minimum diameters of both the vertical and the horizontal elements are shown in the Tab.2 and Tab.3.

Table 2. Minimum diameter of the vertical elements for different check dam heights

Minimum diameter for the vertical elements (cm)	Height of the check dam (m)
5.8	1.0
6.3	1.5
7.0	2.0

Table 3. Minimum diameter of the horizontal elements for different check dam heights

Minimum diameter of the horizontal element (cm)	Width of the check dam´s core (m)	Height of the check dam (m)
7.2	0.5	1.0
7.8	0.5	1.5
8.6	0.5	2.0

Despite the lack of data regarding the sedimentation rates, after our visits to the study site, we confirmed that these structures are performing well. In Fig.6 the first colonisation stages by the surrounding indigenous vegetation of the check dams sedimentation mounds can be observed.

A) B)

Fig. 6. A) Series of mixture check dams and B) creation of green islands throughout the gully. As it can be observed, the **very core** of the check dam was colonized by indigenous species. (Photographs taken by Guillermo Tardío)

Results based on the monitoring: the site was visited during 2008-2012 and the mixed check dam performance was checked. The wooden elements of smaller check dams were decomposed fulfilling their condition as temporary structures. Most of the check dams had formed stable sedimentation mounds allowing the indigenous plants to colonise the soil within the gullies.

Plant densities were higher in the gully compared to the surrounding areas (see Fig. 7A). In all cases, there is a clear transitional evolution from the initial structures to the local natural Canarian landscape since the different species are taking the stabilisation function over (see Fig.7).

A) B)

C)

D)

Fig. 7. A) Plant density is higher in the sedimentation mounds, B) indigenous species are taking over the stabilisation effects, C) small mixed check dam with its wooden elements in a clear decaying process and D) a series of mixed check dams is being replaced by the local natural landscape (Photographs taken by Carlos Caballero)

6. Discussion and Conclusion

The use of forest residues for erosion control works is a very useful strategy in forest management. As shown in Fig.8, the size of the minimum diameters needed to create a stable mixed check dam could be obtained in almost every forestry treatment (for instance, using cuttings, thinning and tree prunings products). The permeable nature of this type of check dam permits the evacuation of runoff flow in a controlled way.

Fig. 8. Pictures of the mixed check dams evolution, effects and main elements of the design. (Photographs taken by Guillermo Tardío)

The resistance transfer between the inert material and the plants was successfully accomplished. The wooden elements were fully decayed by the time the plants had already colonized the gullies.

The direct and indirect benefits of the use of this erosion control technique were acknowledged by both the Local and National Administrations. Indeed, this technique was included in the Spanish National list of techniques to fight against desertification processes.

After a five year visual monitoring plan, the following conclusions were reached:

- The design calculations were right.
- The sedimentation mounds caused by the check dams were turned into a series of green islands throughout the gullies.
- The very cores of the mixed check dams were colonized by indigenous species.
- This technique was effective at re-vegetating areas with erosion control problems.

The eco-engineering philosophy was fulfilled if the following terms:

- The use of the woody material of the nearby areas was effective.

- The utilized inert material (logs and rocks) effectively performed their initial necessary stabilizing role. Afterwards the indigenous species colonized the stabilized soil within the gullies.

The use of forestry residues for erosion control techniques is a very recommendable strategy in forestry management.

As with any stabilization technique, there is a stress (or load) transfer between the soil and the structure but, in contrast to other solutions, this initial response is substituted by an evolving role of the living material used in the eco-engineering structure as time progresses.

The decreasing slope within the gullies as well as the presence of stabilised sedimentation mounds allowed the indigenous species to colonise the area and, as time progressed, to perform the stabilising function by themselves. From this stage on, the very dynamic nature of vegetation will continuously increase the overall resilience of the ecosystem.

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CONCLUSIONS AND AREAS FOR FUTURE RESEARCH

After the development of the new tools, presented in this PhD, for the eco-engineering work design and approach, the following conclusions can be established:

1. The different mechanical behaviour of roots and soil was synchronised and strain development of the rooted soil composite was simulated in a more realistic way. The proposed methodology is readily applicable and more accurate safety factor values were achieved. Besides, the evolution of the safety factor values as strain develops could be reflected in a mechanically realistic fashion.

2. A methodology embracing the typical evolution of an eco-engineering work was presented. The existing stress transfer processes between the wooden elements and the living material was well reflected. Plant evolution with time was included at different time stages within the design stage scheme. Furthermore, the incorporation of the deterioration processes affecting the wooden element mechanical performance allowed the identification of design critical scenarios that were not detected with the traditional civil engineering design routines and protocols.

3. A non-invasive methodology for collecting field work information regarding root vertical and horizontal distributions was proven to be accurate and useful. The traditional labour intensive and expensive field work techniques for root exploration and characterisation can be replaced by the proposed methodology although a limited intrusive field campaign is always reckoned to be advisable for, at least, the calibration of the initial results. This proposed methodology offers the opportunity to include larger extension in the case studies as well as making more affordable the necessary field work data collection for both eco-engineering design and monitoring. Other theoretical tools such as the tension cone method were also proven to be very useful in explaining

root distribution and tree anchorage strategy. The field work data collected shows a promising performance for the methodology proposed but more fieldwork is needed in order to calibrate the proposed methodology in other field work scenarios.

Improvement and enlargement of the proposed methodology could be accomplished by taking into account the following strategies:

- The use of GPR linear transects and their comparison with trench profiles in combination with the approach presented herein would enhance the methodology outcome.
- The use of different bandwidths for analysing different root diameters.
- The use of different root distribution theoretical models.
- The use of other GPR variables as model inputs.
- The analysis of different tree species and tree densities could contribute to shed light on the true potential of the proposed methodology.
- The analysis of how tree age and surrounding trees´ competition influence the root system spread on sloping terrain could aid to improve models´ predictions, in particular, and the use of vegetation on slope stability, in general.
- The analysis of slope value influence.

Furthermore, given that the GPR readings are affected by many factors such as root orientation, root moisture content, soil type, soil moisture content (soil conductivity), leaf litter thickness, etc., more research is needed in order to test the proposed methodology in other field work conditions.

4. The eco-engineering long term approach was reflected throughout the monitoring stage of the mixed dykes work by showing the autochthonous plant natural colonisation and the wooden elements deterioration processes. The eco-engineering approach was

proven to be effective from both the ecological restoration and the soil conservation point of view.

5. New tools giving answer to the eco-engineering sector specialisation needs are offered embracing different work aspects such as the root effects simulation, the work design and the work monitoring and analysis.

The stress transfer phenomena existing between the end of construction stage (where the initial rigidity is allowing for the autochthonous plant communities establishment) and the final stage where the main processes defining the slope evolution are the natural restoration and natural succession dynamics, need to be further researched and analysed.

The implementation of the proposed design methodology will allow for its improvement and calibration in different pedoclimatic scenarios. A cross talk within practitioners and enterprises would speed up this process.

Furthermore, more data from eco-engineering works monitoring tasks are needed in order to better define the long term strategy to be followed in different pedoclimatic scenarios. Given the semiempirical nature of this type of works, case studies analyses and the experiences exchange will be crucial to improve the accuracy and the efficiency of this kind of interventions. Above all, with the detected climate change effects, the works long term strategies will have to take into account the new scenarios we will face soon.

A comprehensive plant database including the main plant traits regarding plant root evolution and plan biotechnical features in different climates and soils would represent a remarkable source of information for a proper eco-engineering work design and decision making process.

The incorporation of plant and fauna community natural succession and evolution is one major factor that should be included in eco-engineering projects.

Besides, the quantification of the direct and indirect benefits of this kind of works from an ecosystem services point of view will put eco-engineering works and projects in their real value and comparisons with other kind of traditional interventions will be more accurate, complete and fair.