Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly
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doi: 10.3850/978-981-18-5182-7_11-018-cd

Influence of the Evapo-Transpiration Contribution by Long-Stem Planting on the Stability Assessment of a Back-Filled Slope

Ilaria Bertolini[1], Carmine Gerardo Gragnano[1], Guido Gottardi[1]& Olivier Buzzi[2]

[1]DICAM Department, University of Bologna, viale del Risorgimento 2, Bologna, Italy
E-mail: ilaria.bertolini3@unibo.it
[2]Priority Research Centre for Geotechnical Science and Engineering, The University of Newcastle,
Callaghan Campus, NSW 2308, Australia.

Abstract: Evapotranspiration is a crucial phenomenon for the hydrological balance of the vadose zone; its evaluation is useful for those geotechnical problems in which climatic actions are impactful, as in the case of slope stability assessment. Yet, conventional engineering approaches ignore its impact on geotechnical design and assessment, due to the intrinsic complexity of the analysis required to achieve a rigorous solution to soil-vegetation-atmosphere interaction problems. An attempt in bridging the gap among researchers and practitioners in this field can be referred to a back-filled slope close to the traffic artery Inner City Bypass in Newcastle (Australia) that experienced in 2017 shallow landslides most likely due to heavy rains. To stabilise the slope, the use of drains at the toe of the slope together with long-stem planting have been proposed by Transport New South Wales (formerly Road and Maritime Services), the governmental agency responsible for building and maintaining road infrastructure. A native Australian plant, the Melaleuca Styphelioides, has been chosen for this purpose. A laboratory scale experiment has been carried out to evaluate the influence of a two years Melaleuca Styphelioides plant on the pore water pressure distribution in the site-specific soil when subjected to different hydraulic boundary conditions. The commercial Finite Element (FE) software Hydrus 2D by Pc-Progress has been used to reproduce the laboratory experiments and calibrate the root water uptake spatial distribution against experimental data. Subsequently, numerical models of the bank slope vegetated with an increasing number of plants (from 1 to 4) have been elaborated through the calibrated RWU model on a 50 days simulation period. Stability analyses, performed by means of the Limit Equilibrium method, were then performed on the different surface soil conditions and compared to a non-vegetated slope to highlight the influence of the soil-vegetation-atmosphere interaction on the stability assessment of the slope.

Keywords: Evapo-transpiration contribution; Slope stability; Long stem planting; Root water uptake.

1 Introduction

Soil bioengineering techniques make use of plants to solve or mitigate environmental and engineering problems. These techniques are becoming increasingly acknowledged and used to control surface erosion, riverbank and upland slope stabilization and revegetation. Their key features are the relative low cost, the improved aesthetics and the sustainability of the interventions but a major difficulty in deploying bio-engineering techniques is the complexity of modelling soil-plant interaction mechanisms in an unsaturated medium. Plants enhance the stability of soil slope both mechanically and hydraulically. With their high tensile strength, plant roots act as tensile reinforcement, providing an apparent cohesion to the soil (Wu et al, 1979). Furthermore, all the roots crossing the failure surface act as anchoring points, which further improve the stability of a soil slope. Plants also affect the pore water pressure in the soil and the weight of the soil mass by absorbing moisture during their transpiration activity. The suction generated within the slope mass is highly dependent on the root architecture and root length density, which are both difficult to quantify in practical applications. Some researchers neglect the hydrological contributions in slope stability models for their spatial and temporal variability (highly dependent on atmospheric conditions and plant growth) (Donat, 1995), whereas others claim the importance of considering evapo-transpiration given by the soil-plant system in the hydraulic balance (Simon et al, 2002). The present study aims at investigating the influence of the evapo-transpiration contribution of long-stem planting on the stability of a back-filled slope in close proximity to the traffic artery Inner City Bypass in Newcastle (Australia)(seeFigure1A and 1B right). The slope under investigation experienced a shallow instability in 2017, possibly after a period of intense rainfalls, despite the presence of drains. In order to improve the stability of the slope, a native western-Australian evergreen plant, Melaleuca Styphelioides, has been chosen to revegetate the slope (see Figure1C right). The Melaleuca Styphelioides is tolerant to drought, wet soil and smog and in its adult stage can reach 20m of height. Different inter-axis distances between Melaleuca Styphelioides plants have been hypothesized on the instable slope during a simplified 50 days simulation period and comparisons on the different pore water pressure (pwp) distributions and the associated obtained soil slope Safety Factorsare made.

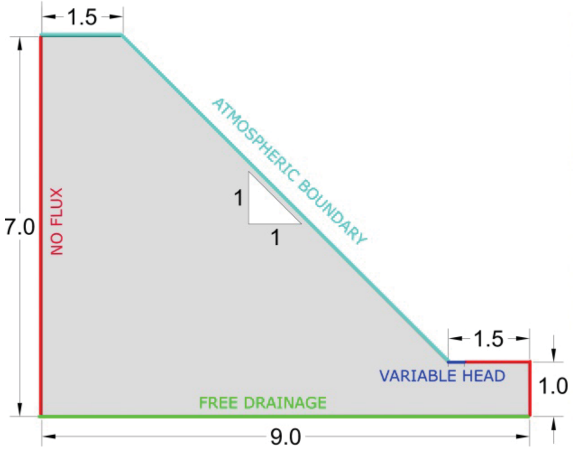


Figure 1(left). The simplified geometry of the unstable slope with indication of the boundary conditions adopted in the FE model. Note the slope modelled here is slightly steeper than the real slope (1H:1V against 1.5H:1V). **Figure 1A and 1B (right)** the traffic artery Inner City Bypass in Newcastle (Australia) overlooked by the backfilled slope under investigation. **Figure 1C (right)** an adult Melaleuca Styphelioides plant with its typical white flowers.

2 The numerical FE model

The commercial code Hydrus 2D by PC-Progress has been used for this study as it can simulate water flow through the unsaturated soil under steady state boundary conditions. The geometry of the slope (inclination 1:1) is presented in Figure 1 (left). Only the soil slope above the concrete retaining wall alongside the highway has been modelled, as this is the portionprone to shallow instabilities. Figure 1 (left) summarizes the boundary conditions adopted in numerical analysis. A no flux boundary condition (BC) along the left sideand the curb of the retaining wall, an atmospheric boundary for the top and inclined surface of the slope, a free drainage (i.e. zero pressure head gradient) for the lower boundary to represent the bottom outflow in case the water table is situated far below the spatial domain. The drain at the toe of the slope has been considered assuming a variable head BC set to zero when pore water pressures are positive and switched to a “No flux BC” when the specified nodal pressure head is negative. As initial conditions, a linear (and inclined as the slope 1:1) distribution with depth has been hypothesized: -10 m of water pressure head in the core of the soil slope which degrades to 0 m on the soil surface, as possibly typical for a rainy period.

The simulation period is characterized by spring typical daily conditions maintained constant for 50 days: an average temperature of 20°C, an average Relative Humidity of 70%, a low wind speed of 1m/s and a solar radiation of 30 MJ/m^2 day. Using the well-known Penman-Monteith method (Penman, 1949; Monteith, 1965) in the last revision by Allen et al. (1994), the Potential Daily Reference Evapo-transpiration (ETo), function uniquely of environmental conditions, has been computed (5.1 mm/day). The subdivision of ETo[L/T] into potential evaporation (E_{pot} [L/T]) and potential transpiration (T_{pot} [L/T]) contributions has been performed based on the Leaf Area Index (LAI [-]) and on the radiation extinction coefficient in plant canopy (k [-]= 0.463, Ritchie (1972)), according to Beer’s law.

Hydrus 2Dsolves Richard’s equation with a sink term S(x,z,t)that accounts for water uptake by plant roots. S(x,z,t) is defined as the volume of water absorbed by roots from a unit volume of soil as a result of plant water uptake. The 2D formulation of Richards’ equation is function of the soil permeability K[L/T], of the volumetric water content, θ[L^3/L^3] and of the sink term $S(x,z,t)$.Both K(h) and θ(h) functions are defined according to the van Genuchten-Mualem model (van Genuchten,1980; Mualem, 1976) which, in turn, depends on the effective saturation degree (S_r [%]),the current, maximum and residual water content (θ, θs, θr [L^3/L^3]), the inverse of the air-entry value(α [L^{-1}]), the saturated hydraulic conductivity (K_s [L/T]) and the dimensionless n and m parameters.

The fitting parameter n [-] is related to the pore-size distribution of the soil while the fitting parameter m [-] is related to the overall symmetry of the SWRC, here expressed as a function of n. The SWRC of the investigated soil has been obtained by laboratory tests using high-capacity tensiometers (to investigate the retention curve above the cavitation pressure) and the dewpoint potentiameter WP4 for the remaining part of the curve (Bertolini, 2021).The analysis allows computing the actual evaporation and transpiration contributions depending on soil moisture. The evaporation is maximum when the soil is close toits saturation state, then it decreases as the soil dries due to a reduction of its permeability. Similarly the actual root water uptake (RWU) is computed from the potential transpiration contribution according to a stress reduction function $\alpha(h,h_\Phi)$ which reflects the assumption that the water absorption by the roots decreases with increasing suction$h$and salinity,h_Φ. The sink term S(x,z,t) is formulated as:

$$S(x,z,t) = \alpha\left(h, h_\phi\right) S_p(x,z,t) \tag{1}$$

where $\alpha(h, h_\phi)$ is a dimensionless [-] stress response function equivalent to the ratio between actual root uptake (S[T^{-1}]) and potential root uptake ($S_p[T^{-1}]$) and it ranges between 0 and 1.The stress reduction function by Feddes et al.(1978)is implemented in the code and has been adopted for the present case study. This stress reduction function requires 7empirical parameters: $h_1$to h_4 are suction values (in L), T_{p1} and T_{p2} are transpiration rates (in L/T). More specifically:

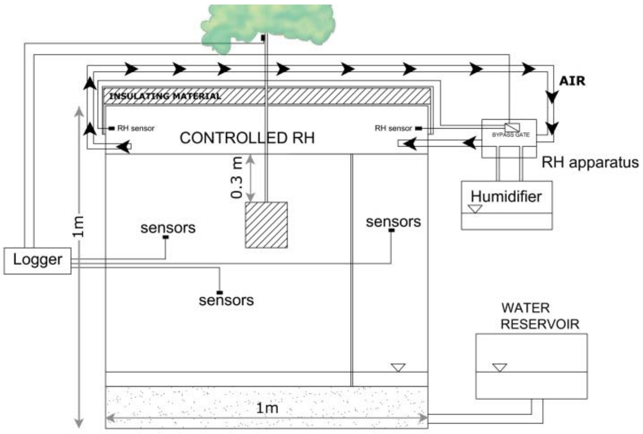
- $|h_1|$is an arbitrary anaerobiosis point (soil is close to saturation and for $h>h_1$ the transpiration is null due to oxygen lack)
- $|h_4|$ is the wilting point below which ($h<h_4$) transpiration is 0
- in the suction range$|h_1$-$h_2|$ and $|h_3$-$h_4|$, the water uptake increases/decreases linearly with |h| while in the interval $|h_2$-$h_3|$the potential RWU is equal to the actual RWU.
- For values of |h| below $|h_3|$, the potential uptake is reduced to the actual RWU.
- The value of $|h_3|$varies with the potential transpiration rate Tp: it can assume two values ($|h_{3low}|$ or $|h_{3high}|$) depending on the rate of transpiration (Tp_1 or Tp_2, where $Tp_1 > Tp_2$).The stomatal closure (and the simultaneous reduction from potential to actual RWU for values of $|h|>|h_3|$) is triggered at higher value of water pressure head ($|h_{3high}|$) if the transpiration rate is higher (Tp_1), at lower value ($|h_{3low}|$) if the transpiration rate is lower (Tp_2).

The potential transpiration is distributed over the root zone unevenly according to the root architecture and the root length density of a specific plant by means of the RWU spatial distribution function, b(x,z,t) [L^{-2}], defined in each point of the 2D domain (x,z) and at a time t. Thereby, the expression of the potential RWU, S_p [T^{-1}], for a spatial point of the domain and in a specific time instant tof the simulation, could be defined as follows:

$$S_p(x,z,t) = b(x,z,t) L_t T_p(t) \tag{2}$$

where L_t[L] is the width of the soil surface associated with the plant transpiration and T_p [LT^{-1}]the potential transpiration.To obtain the total actual RWU at time t,T_a [LT^{-1}], eq. (2) has to be substituted in eq. (1) then integrated over the whole root zone [L^2].

Despite the fact that the RWU spatial distribution, as previously stated, is time dependent due to the natural growth of the root bulb with time, Hydrus 2D version 2.05 has not implemented a Root Growth Module that could model root growth under different stress factors as simulation time passes. As such, the RWU spatial distribution is constant over the simulation period.The RWU spatial distribution *b(x,z)*has to be defined manually, in each point of the domain,or a 2D root spatial distribution function could be used.



water uptake function α(h) of Feddes et al (1978)

h_1 [m]	h_2 [m]	h_{3high} [m]	h_{3low} [m]	h_4 [m]	Tp_1 [m/day]	Tp_2 [m/day]
-0.1	-0.25	-4	-4	-160	0.005	0.001

hydraulic and retention parameters (VGM)

θr (-)	θs (-)	α (1/m)	n (-)	Ks (m/s)	l (-)
0.0001	0.45	4.26	1.422	$2.93\cdot10^{-7}$	0.5

Figure 2(left).A scheme of the large-scale apparatus developed to investigate the pwp distribution in soil in close proximity to a 2 years old Melaleuca Styphelioides plant and to calibrate properly the model parameters. **Figure 2 (right)** Table of calibrated parameters of the SWRC according to the Van Genuchten-Mualem modeland of the water uptake function α(h) of Feddes et al. (1978). All variables are defined in the text.

3 Model calibration through laboratory experiment

A specific apparatus has been developed to investigate the spatial and temporal evolution of suction in relation to the RWU of a 2year old Melaleuca Styphelioides (see Figure 2 left). The setup is composed of a 1m^3 container filled with 20cm of gravel under some soil collected from the site. The plant was positioned in the center of the container at a depth of ~30 cm from the soil surface and its growth was facilitated by a grow light placed 60 cm from the top of the plant.

The water level at the bottom of the container was governed by the position of a water reservoir connected to the base of the apparatus. Different piezometric head have been imposed in steps and, each analysis, enough time was given to achieve nearly stationary conditions.Teros 21 sensors by Meter group,monitoring soil suction (working range from -9 kPa to -100,000 kPa, with an accuracy of (+/- 10% of the reading +2kPa)) and temperature in time, were placed on the side and below the root bulb.The relative humidity was controlled on the top boundary by means of a humidifier, the air temperature was not controlled but the apparatus was positioned indoor and a combination of plastic cover and insulating material were used to reduce temperature fluctuations at the soil surface. The collected suction data was used to calibrate the Hydrus 2D FE model, which was found to accurately reproduce the spatial and temporal evolution of pore water pressure (pwp) inside the large-scale apparatus. The parameters of the van Genuchten-Mualemhydraulic and retention model were calibrated by means of Inverse Analysis technique implemented in Hydrus 2D package (Simunek and Hopmans, 2002), with the calibrated parameters reported in Figure2 (right). The user-definedRWU of Melaleuca Styphelioides plant specifically defined for the present application (see Figure 3A) was adopted together with the water uptake function α(h) of Feddes et al. (1978) whose parameters are reported in Figure2 (right).The parameters calibrated on the large-scale apparatus were then usedto investigate the effect of RWU on slope stability.

4 Hydraulic and stability analysis of the slope

The pwpevolution (from day 0 to 50) has been simulated in Hydrus 2D for different scenarios:

- bare soil (soil slope subjected only to evaporative phenomenon);
- from one (Figure 3A) to four plants (Figure 3B) equally spaced on the soil slope using the modeler-defined RWU distribution and a root bulb volume double (2x) and four times (4x) the one investigated in the large-scale apparatus.

The root bulb volume of the young 2 years old Melaleuca Styphelioides is, in fact, too small (a cylinder of diameter ~13 cm and a height of ~14 cm) and shallow to have a relevant influence on the stability of the slope under investigation; for this reason, more mature plants with root bulb volumes 2x and 4x and, accordingly, a RWU spatial distribution of 2x and 4x have been assumed in the models.

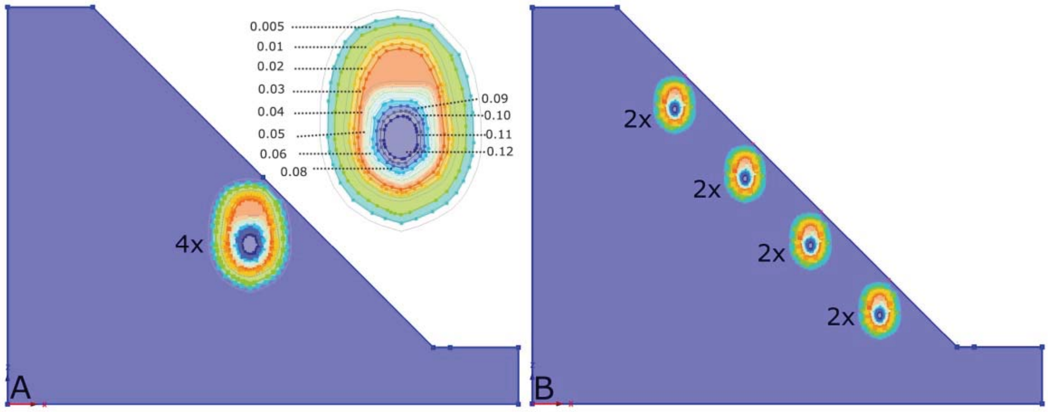


Figure 3A. Modeler-defined RWU spatial distribution with indication of the b(x,z) values and the configuration of the soil slope with one single plant, 4x root bulb volume. **Figure 3B**the configuration of the soil slope with 4 plants,2x volume.

A Leaf Area Index (LAI) of 1.8 has been used for the 2x root bulb volume (double of the LAI observed for the plant in the large-scale apparatus) and of 3.6 for the 4x volume,as an equal growth of the plant canopy and the below ground root bulb has been assumed.

The pwp distributions of each scenario, obtained from Hydrus 2D,have been subsequently imported in Geoslope (GeoStudio, 2012)for time steps corresponding to days 0,10,20,30,40,50 and stability analysis by Morgenstern and Price limit equilibrium method (Morgenstern and Price, 1965) were performed. Standard Mohr-Coulombfailure criterion was used for saturated soil conditions; when partial saturation arise, soil strengthis given by the Vanapalli et al. (1996) extended model, depending on the actual saturation degree and suction of the soil, through the saturated shear strength parameters. These latter have been estimated by means of saturated triaxial TxCU tests (coesion c'=7 kPa and soil friction angle φ'=27°). No cut-off to strength increment due to suction has been set for water content below a threshold value (usually defined as a percentage of the saturated water content θs), as no experimental information were available to support a conscious choice. The counterpart of this choice, however, is an eventual overestimation of the evapo-transpiration contribution on slope stability in correspondence of high suction values (i.e. very low water content close to the residual water content of the investigated soil) reached, as will be shown, within the plants root bulb between day 30 and 50.

The contribution of plant roots to the soil tensile strength has been disregarded in the present simulations since the paper focuses on the increment of the margins of safety towards slope instability due to evaporation and transpiration contributions, considered together and separately.

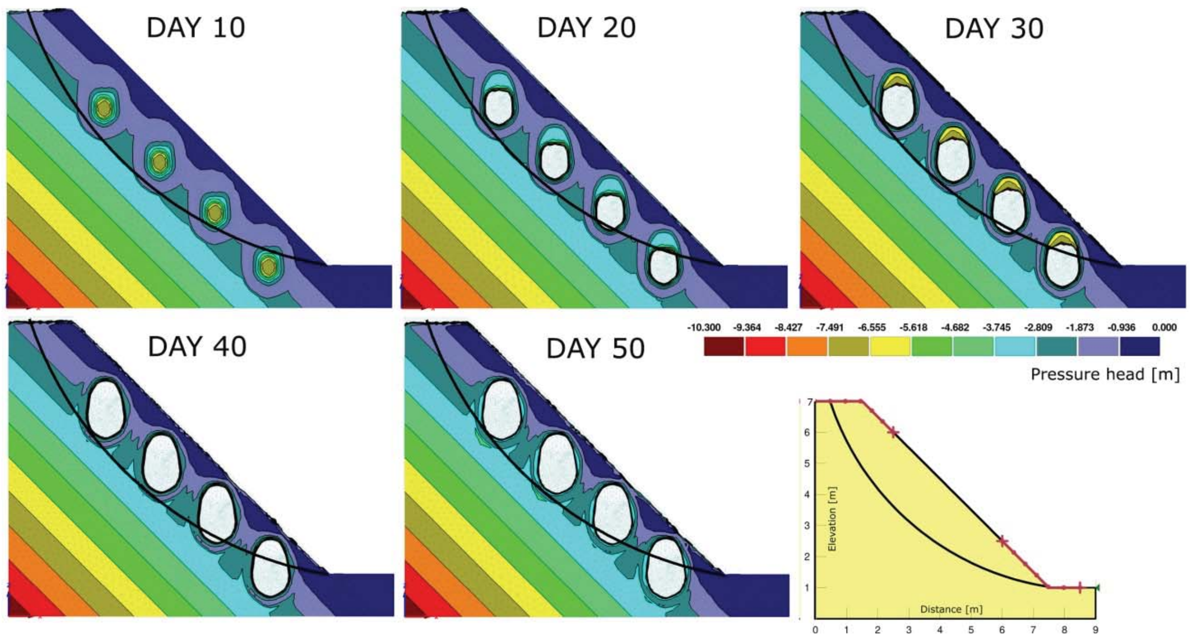


Figure 4. Time-lapse of the pwp distribution (range 0/-10m of water pressure head) in the soil slope for the 4 plants, 4x root bulb volume configuration and the user-defined RWU spatial distribution. The black line represents the most critical slip surface obtained in the configuration with only bare soil on the slope.

Figure 4 reports the time lapse of the pwp distribution in the range 0/-10.3 m of water pressure head for the 4x root bulb volume and in the case with 4 equally spaced plants.The white color observable in Figure 4 from day 20 in correspondence of the root bulbs suggest that pwp has reached values far below -10m of pressure head and the transpiration phenomena is continuing by depleting of water the nearby soil volume.

The pwp distributions show the superimposition of the most critical slip surface (black line) individuated for the configuration with only bare soil on the slope. The critical slip surface of the bare soil passes through the soil volume influenced by the presence of the root bulbs(see Figure4) while the one proper of the configurations with long-stem planting results deeper with respect to ground level and located in the soil volume where plants have minimal (or nul) influence on pwp distribution. However, in order to make a clear comparison among different cases, only the critical slip surface for the configuration with bare soil on the slope will be considered. The Factor of Safety (FoS) will be calculated for all the different considered configurations (FOS_i) of long-stem planting and for each of them a percentage increment in FoS(ΔFOS) with time will be computed as follows:

$$\Delta FOS = (FOS_i - FOS_{bare})/FOS_{bare} \tag{3}$$

Where $FOS_{bare}$is the Factor of Safety of the critical slip surface of the configuration with bare soil.

Figure 5 (left and center) reports the net and percentage increment of the FoS with respect to the bare soil, in other words the increment in FoS due exclusively to plant transpiration during the elapsed time. As we expect, for both 2x and 4x root bulb volumes, the configuration with 4 plants shows the greatest increment of the critical FoS(35% for 4x and 11% for 2x at day 50) with respect to the bare soil. The configuration with one single plant (as in Figure 3A) does not show any significant stability improvement with respect to the bare soil configuration, due to the fact that the root bulb (positioned halfway down the slope) affects only marginally the slip surface which, in this point, reaches the maximum depth from the soil surface. Configurations with 2 and 3 equally spaced plants show intermediate results between 1 plant and 4 plants, as expected. Moreover, it is relevant to highlight that the benefit in FoS increase passing from the 2x to 4x root bulb volume is more than double for all the different configurations (see Figure5 center).

Between 20 and 30 days, the maximum rate of water absorption is reached (potential water uptake coincides with actual water uptake) as per water uptake function α(h) of Feddes et al. (1978). Indeed, the slope of the curves in Figure 5 (4x root bulb) during this period (20-30 days) is steeper compared to the other ones. The 50 days of simulation were not sufficient to reach (or exceed) the wilting point in all the points of the soil volume interested by the root bulbs, which brings an end to the transpiration phenomena. Indeed, Figure 5 (right) reports an almost constant percentage increment in FoS after 30 days both for 2x and 4x root bulb volume.It has to be specified that this increment is due to the combination of evaporation and transpiration contributions; for this reason, comparing graphs in Figure 5(center) and Figure 5 (right) may give us an approximate estimation of the influence of evaporation contribution on the FoS increment (at 50 days, the 12.5% for 4x and 2% for 2x).

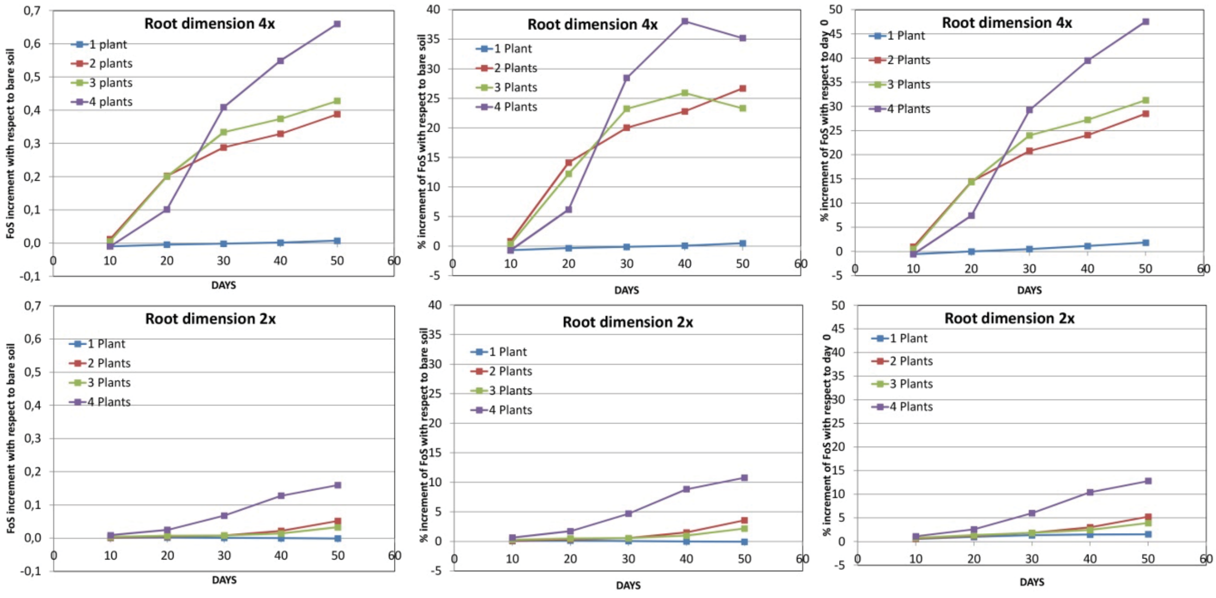


Figure 5(left). FoS increment with respect to the bare soil for the configuration with 1 to 4 plants and 2x or 4x root bulb volume. **Figure 5 (center)** Percentage of FoS increment with respect to the bare soil for the aforementioned configurations (influence of transpiration considered).**Figure 5 (right).** Percentage of FoS increment with respect to day 0 for the aforementioned configurations (influence of evaporation and transpiration considered).

5 Conclusions

The present study investigates the influence of evapo-transpiration processes on the stability of a potentially unstable slope, without considering the contribution of plants root to soil shear strength increment but only suction effects in soil. Native plants of Melaleuca Styphelioides, placed on the slope with different configurations (from 1 to 4 plants) and different root bulb volume (2x and 4x) have been considered and the pwp evolution has been simulated over a 50day period for each configuration. A clear influence of the transpiration contribution on theFoS increment with respect to the bare soil has been shown, especially as the number of the plant and root bulb dimension increase. Doubling the root volume, the percentage increment in FoS with respect to the bare soil is more than doubled, highlighting the impact on slope stabilization of a mature plant over a younger one. Evaporation and transpiration have different influence on FoS increment. The latter results the predominant phenomenon in fact at day 50 for a 2x root volume, evaporation causes a FoS percentage increase with respect to the bare soil of 2% and transpiration of 10.8% while for the 4x, an increase of 12.5% and 35.2% is observed, respectively. These results evidenced strong potentials in the use of this type of vegetation for improving slope stability of embankments.

Acknowldgements

The authors would like to acknowledge the Road and Maritime Services for the support received for this research.

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