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# A simplified analytical approach to the equivalent geotechnical multi-scale modelling of composite Soil and Water Bioengineering (SWBe) solutions

F. Preti[1,3], A. Dani[1], A. Geppetti[2], M. Uzielli[2]

[1]*Agricultural, Food, Environmental and Forestry Sciences and Technologies, University of Florence*
[2]*Department of Civil and Environmental Engineering, University of Florence*
[3]*AIPIN-Efib*

**ABSTRACT:** Soil Water Bioengineering (SWBe) solutions are significantly more complex than conventional “gray” solutions due to the heterogeneity of their elements and of the biological processes which intervene in their living components and which induce a significant spatial and temporal variability of their geohydromechanical properties. This paper proposes a simple but rational analytical approach to the parameterization of the aggregate contribution of soil, roots, and wood to the equivalent geomechanical cohesion of this composite continuum for geotechnical applications such as slope stability. The ease and breadth of applicability of the proposed model is demonstrated for a small-scale engineered retaining solution and a larger-scale rooted slope. Outputs are discussed critically.

**Keywords:** Soil Water Bioengineering (SWBe); rooted soils; structural wood; geotechnical modeling; slope stability; equivalent cohesion

## 1 INTRODUCTION

The term “Soil and Water Bioengineering (SWBe) interventions” encompasses a broad set of solutions in terms of typology, technological solutions, and scale (e.g., spanning from relatively small engineered structures such as live crib walls and live grids to large-scale rooted slopes). Notwithstanding the breadth of this general definition, all SWBe share the hybrid character of their components, which can be broadly categorized into: (1) geomaterials (soil, debris, rocks); (2) wooden elements that form the containment structure; and (3) vegetation as well as their expected synergy for improving engineering performance (e.g., slope stability) and mitigating other georisks such as erosion. SWBe solutions are significantly more complex due to the heterogeneity of their elements and of the biological processes which intervene in their vegetational components. This results in significant spatial and temporal variability of their geohydromechanical properties. In fact, while it is relatively legitimate to hypothesize the temporal invariance of the geomechanical strength of the geomaterials component, this assumption cannot be extended to the wood and roots components. Wood tends to degrade over time and, if not replaced, progressively loses its strength characteristics, thereby no longer contributing significantly to stability. Conversely, root systems tend to develop over time, increasing in density and size and occupying ever-larger volumes of soil, thereby contributing more and more to the geomechanical strength of the soil-root medium.

The geotechnical modeling of composite SWBe structures involving wooden structural elements and rooted soils requires the modeling of these components as “equivalent geomaterials” to allow their analysis using geotechnical approaches and analysis tools (e.g., limit equilibrium slope stability methods and software). These analyses require the definition of constitutive models and the declaration of failure criteria such as the Mohr-Coulomb and Tresca criteria. Given the para-natural evolution of SWBe solutions, which entails the occurrence of biological and chemical processes in their living components, the equivalent geotechnical modeling should also consider the temporal evolution of root development, the progressive degradation of wood strength (Chirico et al., 2013, Gonzalez -Ollauri et al., 2021, Preti et al., 2010, Preti et al., 2025a,b).

## 2 STATE OF THE ART AND RATIONALE

A conspicuous and steadily growing corpus of literature suggests that it is possible to estimate the effect of vegetation on slope stability using hydrological-hydraulic and geotechnical models (e.g., Arnone et al., 2016; Preti, 2013). Models for estimating root reinforcement have been developed since the 2000s, improving early pioneering work of Wu & Waldron to include the Fiber Bundle Model (Preti, 2006 in Mao, 2022; Schwarz et al. 2013; Murgia et al., 2022; Tongsan, 2024), also on an eco-hydrological basis (Preti et al., 2010; Tardio et al., 2016; Gonzalez-Ollauri et al., 2021) and with non-invasive indirect methods (Giambastiani et al. 2021; Giachi et al., 2024). With reference to the careful analysis by Mao (2022) of available methods for the evaluation of root reinforcement, reference will be made here to the Simplified Wu-Waldron Model modified by Preti (SWWM-Wu-Preti) scheme (Preti, 2006 in Mao, 2022) which has been extensively tested and validated and which in the design context is more usable than the Root Bundle Model (RBM) or Fiber Bundle Model (FBM) methods which require the knowledge of a large number of parameters (Schwarz et al. 2010; Gonzalez-Ollauri et al., 2021). Other studies have revised the SWWM-Wu (as defined in Mao, 2022) model by confirming the correction factors to account for the systematic overestimation in the SWWM-Wu model stemming from its approximate representation of root orientation, root failure mode, load-sharing law, and mechanical behavior of the mobilizing roots.

Among the models of varying complexity which have been contributed in the technical literature to parameterize the geomechanical contribution of SWBe structures, none are applicable to composite SWBe interventions including geomaterials, structural wooden elements, and root systems. Moreover, with few exceptions, the spatial and temporal evolution of the contribution to strength due to the simultaneous presence of wood and roots is not accounted for, assuming as the most conservative scenario the one immediately after the construction of the structure in which the contribution of the wood is at its peak and that of the roots is absent. This hypothesis could be misleading at least in cases of non-optimal survival or para-natural succession of vegetation, in which the contribution to resistance reduced by wood degradation may not be compensated by that which would be provided by correct root development.

This paper proposes a rationally reliable parameterization approach that can support geotechnical engineers in including SWBe-engineered solutions involving natural geomaterials, wooden elements, and root systems in well-established geotechnical analysis approaches such as limit equilibrium slope stability method. The main novel aspect of the paper lies in the parameterization of the soil-roots-wood complex as an "equivalent SWBe continuum" and in the quantitative modeling of the temporal variability of its geomechanical strength (more specifically, its cohesive component) resulting from the combined effect of the mutually contrasting degradation of the woody material and increasing strength provided to the soil by the presence of shrub and/or tree root systems. In this context, the paper also fills the knowledge gap regarding the rate of degradation of structural wooden elements.

## 3 PROPOSED COHESION MODEL

The proposed model for the equivalent cohesion of the SWBe continuum is

$$c_{eq}(z,t) = [1-\varepsilon_w(t)][c_s(z)+c_r(z,t)] + \varepsilon_w(t)\cdot c_{w0}[1-\lambda(t)\cdot t] \tag{1}$$

where $c_{eq}(z,t)$ is the equivalent cohesion (in kPa), in which

$$c_r(z,t) = k'\cdot k''\cdot T_R\cdot G_S(t)\cdot \exp(-z\cdot b) \tag{2}$$

is the root-induced cohesion (in kPa) and

$$\varepsilon_w(t) = \varepsilon_{wo}[1-\lambda(t)\cdot t] \tag{3}$$

is the time-depth-varying dimensionless ratio of the volume of the wood component to the total volume of the SWBe continuum (with $\varepsilon_{w0}$ being its value at the beginning of its service life, before the wooden components progressively turns into rooted soil); $\lambda(t)$ is the annual reduction ratio of the cohesion of the wooden component (in yr$^{-1}$); $c_{w0}$ is the initial cohesion of the wood component (in kPa); $c_s(z)$ is the cohesion of the non-rooted soil (in kPa); $k'$=1.2 and $k''$=0.4 are correction coefficients (Preti. 2006 in Mao, 2022); $T_R$ is the average root tensile strength (in MPa); $G_S(t)$ is the dimensionless basal area (ratio), given by the product of the average stem area and the number of stems per unit area; $z$ is the depth at which cohesion is estimated (in cm); and $b$ is a shape factor which accounts for average root distribution, and which depends from soil type and climatic conditions (Preti et al., 2010; Tron et al., 2014). The temporal evolution of the basal area is modeled using a hyperbolic trend:

$$G_S(t) = G_{S(asy)} - \frac{t_{asy}}{(t-t_0)+\frac{t_{asy}}{G_{S(asy)}}} \tag{4}$$

where $G_{S(asy)}$ is the asymptotic value of the basal area ratio, $t_0$ is the required time for minimum basal area and $t_{asy}$ is the time of quasi-attainment of the asymptotic value. Note that the proposed model is conservative with respect to geomechanical strength due to at least: (1) the neglection of a matric suction term; (2) the neglection of the temporal increase in $G_S$. The calculated equivalent cohesion can be used directly in geotechnical analyses referring to specific temporal scenarios and in geotechnical models accounting for the vertical spatial variability of geomechanical properties. Notably, the model given in Equation (1) is inherently multi-scale and multi-solution, i.e., it can be applied to engineered SWBe structures as well as to large slopes.

## 4 MULTI-SCALE APPLICATION

The wide applicability of the proposed model is exemplified for two scenarios; namely (1) a small-scale case study (SS) involving a combined stabilization intervention including minipiles, live crib walls, and live grids conducted on a slope located in Montisoni (Florence, Italy) that collapsed following heavy rainfall events and due to sub-optimal drainage of surface water from a public road above the slope; and (2) a large-scale (LS) rooted slope located at the Pomezzana landslide site in northwestern Tuscany (Italy). Details of the Montisoni site are reported in Uzielli et al. (2025) while the Pomezzana site is described in Preti et al. (2025). Details are omitted here due to space limitations. In both cases, the cohesion of the soil for the layer intercepted by the SWBe structures is 4.6 kPa. The value of the average tensile strength of the roots was set at $T_R$=36 MPa. The basal area ratio $G_S(t)$ was calculated using Equation (4) by setting $t_0$=0 yrs, $t_{asy}$=500 yrs, and $G_{S(asy)}$=30. For the plant species found at the site, the depth $z_{rm}$ at which the condition for the root area ratio $RAR$ <5% is satisfied is approximately 130.4 cm; consequently, the average rooting depth $z_{ra}$ ($\approx z_{rm}/3$ in case of exponentially decreasing $RAR$) is set at 43.5 cm, and the shape factor $b = 1/z_{ra}$ is set at 0.023. The initial cohesion of the structural wooden elements was set at $c_{w0}$=230 kPa. The above values were set on the basis of numerous tests carried out on plant species typical of the Tuscany region and should be understood as rationally conservative representative values. The linear strength reduction rate was set at $\lambda$=0.02/yr. This value refers specifically to a comprehensive analysis of Tuscan chestnut wood samples from 15 crib walls which were monitored over periods ranging from 2 to 31 years (Preti et al., 2025b), for which the linear degradation trend was found to fit experimental data with excellent adaptation. The main modeling distinction between the two cases is given by $\varepsilon_{w0}$, which is assigned as $\varepsilon_{w0}$=0.20 for the SS case on the basis of design geometry of the crib walls and live grids, and at $\varepsilon_{w0}$=0.03 for the LS case on the basis of site-specific calculations.

Figure 1 plots comparatively the outputs of the two example applications for a time interval of 25 years. More specifically, Figure 1a plots the temporal variability of $\varepsilon_w$ based on the respective initial values $\varepsilon_{w0}$. Figure 1b plots the temporal variability of $c_{eq}$ for the SS and SL cases for selected depths of 20,50,100, and 150 cm below ground level along with the root cohesion component $c_r$. which is common to both cases. The contour plot in Figure 1c allows the simultaneous assessment of the effects of depth and time on of $c_{eq}$. Observation of Figure 1 emphasizes the variability of the effects induced by SWBe and their intrinsic benefits even for comparable climatic and geotechnical scenarios. Among notable results, the SS case yields temporal decreases at all depths while the LS case indicates a temporally increasing benefit for relatively surficial depths. This inference confirms the well-known necessity to resort to combined solutions, involving the synergy between SWBe and conventional solutions, in cases on non-surficial failure kinematisms. It should be noted that these results are markedly case-specific and that temporal and spatial trends of equivalent cohesion may vary significantly based on local climatic and geotechnical scenarios, all of which can included in the proposed model.

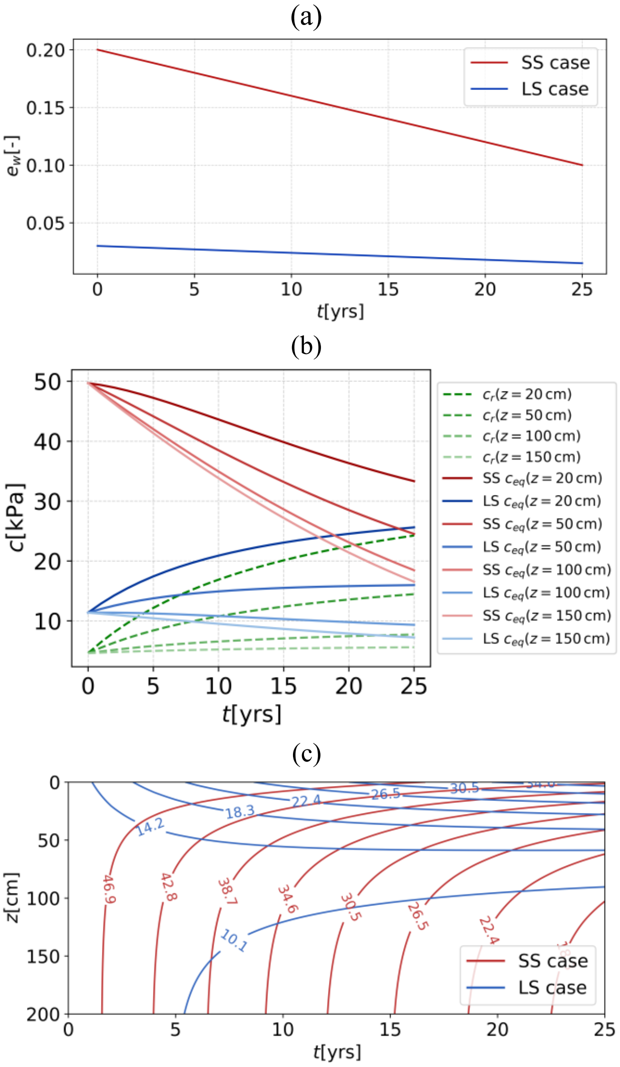

*Figure 1. Outputs of the comparative multi-scale application (predictions over 25 years): (a) temporal variability of the wood component ratio; (b) temporal variability of root and equivalent cohesion at selected depths; and (c) contour plots of equivalent cohesion*

## 5 CONCLUDING REMARKS

Through the proposed model, the calculation of the equivalent cohesion is deliberately simplified to ensure practical usability over a more complex and articulated modeling approach which may prove to have limited applicability in most real-world applications due to typical scenarios of data availability. Moreover, the linear modeling of wood strength degradation is a novel result which fills a scientific gap.

The proposed model aims to be rationally conservative in its deterministic formulation to adhere to fundamental engineering design principles. Current geotechnical design codes in many parts of the world (e.g., Eurocode 7) require an implicitly non-deterministic approach in the assignment of characteristic values. Additional research is required to transpose the proposed model into a non-deterministic formulation through the systematic modeling, processing, and reporting of uncertainties. Moreover, further investigations are warranted to (at least): (1) compile a catalog of reference values of model parameters (including the wood strength degradation rate) for different species; (2) improve the accuracy and precision of the ecology-based definition of the basal area ratio in the climax or subclimax phase for local conditions; and (3) identify potential improvement interventions in the modeling of the para-natural evolution of SWBe structures.

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