Proceedings RootS25
3rd International Workshop on Soil-Vegetation-Atmosphere Interaction
Boldrin D, Cecconi M, Cotecchia F, Leung A, Pedone G, Perrini P, Romero E, Tagarelli V, Zdravković L (eds)
ISSN: 3107-300X

doi: doi.org/10.53243/RootS2025-18

Thermo-Hydro-Mechanical model of vegetation based on an extended Barcelona Basic Model (BBM-VEG)

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ABSTRACT: The effects of vegetation in unsaturated soils are often simulated by modifying soil strength parameters, such as cohesion or friction angle. However, this simplification fails to represent the progressive nature of root-soil interaction during loading. To address this limitation, this study develops an extended Barcelona Basic Model (BBM-VEG) that incorporates vegetation effects into the thermo-hydro-mechanical (THM) framework for unsaturated soils. The model introduces a strain-dependent root reinforcement parameter (Rp_{veg}), linked to root mass fraction and activation strain, which dynamically alters the soil stiffness and strength. The yield surface evolves with suction and root effects, allowing for the simulation of strain hardening and softening in vegetated soils. It also integrates suction-dependent elastoplasticity and Bishop's effective stress for coupled hydromechanical behavior under both drained and undrained conditions. Compared to previous models, BBM-VEG captures the progressive mobilization and degradation of root reinforcement as a function of strain, allowing for a more realistic prediction of stress-strain behavior and strength enhancement in rooted soils. Validation against experimental triaxial tests on rooted soil demonstrates its capability to simulate both initial stiffness and peak strength under varying root densities, highlighting its robustness in modeling vegetated soils.

Keywords: Vegetation; Barcelona Basic Model; Coupled model

1 INTRODUCTION

Vegetation plays a significant role in modifying soil properties by influencing both the soil moisture content and the stress state through root penetration and water extraction processes. Characterizing the behaviour of vegetated soils under unsaturated and non-isothermal conditions is vital in the context of climate change. Few constitutive models address both hydro-mechanical and thermo-hydraulic responses (Świtała and Wu, 2018; Badakhshan et al., 2025a and 2024). While extensions of the Cam-clay model incorporate root reinforcement and desaturation (Świtała, 2021; Ng et al., 2024), they often assume instantaneous root strength or overlook strain-dependent mobilization, potentially misrepresenting reinforcement at small strains. Studies show that root–soil systems progressively strengthen under shear, a phenomenon known as root-induced hardening, which increases pre-consolidation pressure (Zhu et al., 2024; Badakhshan and Vaunat, 2025). Separate constitutive formulations for roots and soil (Meijer et al., 2022) reveal that shear-induced root strains are crucial for mobilizing composite strength, yet they do not account for thermal effects.

This study fills the gap by developing a THM framework for vegetated soils, extending the Barcelona Basic Model (Alonso et al., 1990) into the BBM-VEG formulation in a generalised stress space and implementing it in the finite element software Code_Bright (Olivella et al., 1996). The enhanced model includes factors related to the influence of vegetation, such as root-induced suction, the soil-plant-water relationship, and the alteration of the soil's mechanical properties due to the presence of roots. These improvements allow the model to more accurately simulate the impact of vegetation on soil mechanics, particularly in areas where vegetation plays a role in maintaining soil stability.

2 METHODOLOGY

2.1 *General root effect on soil behavior*

This section captures essential mechanical behaviors of unsaturated soils. These equations allow accurate modeling of unsaturated soil behavior, essential for geotechnical simulations. The parameter λ_s defines the compression behavior of the soil as

$$\lambda_s = \lambda_0\big((1-r)\exp(-\beta s) + r\big) \qquad (1)$$

where λ_0 is initial compression slope at zero suction, r is residual stiffness parameter, β controls stiffness increase with suction, and s is suction. As s increases, soil becomes stiffer, and its ability to compress decreases. Tensile strength of soil is modified as

$$p_t' = p_{t0_{veg}} + p_{t0} + k_s s \qquad (2)$$

where $p_{t0_{veg}}$ corresponds to the tensile effective strength of vegetation in saturated conditions, and suction-related parameter k_s governs the increase in stiffness with suction, vital for modeling unsaturated conditions.

Suction-dependent preconsolidation pressure (p_0') models the enhancement of cohesion due to suction, improving soil strength in unsaturated conditions, which defines how past loading history and suction influence preconsolidation pressure as

$$p_0' = p_{t0_{veg}} + p_r \left(\frac{p_0^*}{p_r}\right)^{\frac{(\lambda_0 - \kappa)}{(\lambda_s - \kappa)}} \quad (3)$$

where κ is initial (zero suction) elastic slope for specific volume-mean stress, and p_0^* is the apparent preconsolidation pressure, and p_r is reference pressure.

Yield function and transition to elasto-plasticity is defined by F. If F is greater than or equal to zero ($F \geq 0$), plastic deformation begins to take place, and the model switches to an elasto-plastic formulation. The yield function F is given by

$$F = q^2 - M^2(p' + p_t)(p_0' - p') \quad (4)$$

where q is deviatoric stress, M is critical state line slope, p' is effective mean stress, p_t is tensile strength influenced by suction. The preconsolidation pressure (p_0^*) is updated based on the plastic volumetric strain as

$$dp_0^* = \left(\frac{v}{(\lambda_0 - \kappa)}\right) p_0^* d\varepsilon_v^p \quad (5)$$

where $d\varepsilon_v^p$ is the plastic volumetric strain increment and v is soil specific volume.

2.2 *Strain-dependent root behavior*

This part defines the behavior of a variable Rp_{veg} based on the strain experienced by vegetation (ε_{veg}). The function describes how Rp_{veg} transitions from an initial value (Rp_{ini}) to a peak value (Rp_{peak}), then decreases to a residual value (Rp_{res}) as strain progresses. Finally, r is computed as a function of Rp_{veg} and m_{veg}. The effect of vegetation on soil-root interaction is incorporated by defining a root activation strain parameter as

$$\varepsilon_{veg} = \varepsilon_v + \varepsilon_q \quad (6)$$

This equation follows the approach proposed by Switała (2021), where root activation strain is the sum of deviatoric and volumetric strains. Then, the value of r is obtained as

$$r = r_0 - Rp_{veg} m_{veg} \quad (7)$$

where r_0 is the base reference value, and m_{veg} is multiplicative factor influencing r. This equation establishes a relationship between stiffness parameters and strain in the BBM-VEG model, incorporating vegetation effects (Figure 1). The approach defines how root reinforcement (Rp_{veg}) evolves with strain (ε_{veg}), adjusting soil stiffness dynamically.

If the strain experienced by vegetation is within the initial and peak strain limits, then Rp_{veg} increases linearly from Rp_{ini} to Rp_{peak} as

$$Rp_{veg} = Rp_{ini} + \left(Rp_{peak} - Rp_{ini}\right)\left(\frac{\varepsilon_{veg}}{\varepsilon_{v_{peak}}}\right) \quad (8)$$

where ε_{veg} is strain experienced by vegetation, $\varepsilon_{v_{peak}}$ is strain at which peak resistance is achieved, $\varepsilon_{v_{res}}$ is strain at which residual resistance is achieved, Rp_{ini} is initial value, Rp_{peak} is peak value, and Rp_{res} is residual value.

If the strain is beyond the peak value but has not yet reached the residual strain threshold, then Rp_{veg} decreases linearly from Rp_{peak} to Rp_{res} as

$$Rp_{veg} = Rp_{peak} - \left(Rp_{peak} - Rp_{res}\right)\left(\frac{\varepsilon_{veg} - \varepsilon_{v_{peak}}}{\varepsilon_{v_{res}} - \varepsilon_{v_{peak}}}\right) \quad (9)$$

If the strain exceeds the residual threshold, then Rp_{veg} remains at its residual value Rp_{res} as

$$Rp_{veg} = Rp_{res} \quad (10)$$

This formulation ensures a smooth transition of Rp_{veg}, capturing the mechanical response of vegetation to increasing strain, with an initial rise, peak, and gradual decline toward a residual value.

By integrating this strain-dependent reinforcement effect into the stiffness computations, the model captures how vegetation influences soil behavior under varying strain conditions.

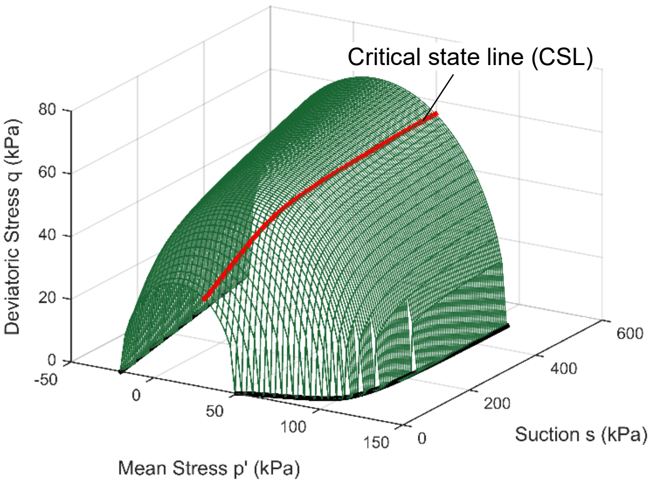


Figure 1. BBM-VEG model

3 VALIDATION FOR BBM-VEG MODEL

The BBM-VEG model in an associated flow rule was validated using experimental data from Liu et al. (2011), who conducted drained triaxial tests on silty clay with three layers of Manila grass roots under varying root contents and confining pressures. Two scenarios were simulated: bare soil and soils with 0.4 g of roots. Initial saturation was calculated from water content and void ratio, while the critical state line slope was derived from the friction angle.

Figure 2 presents the failure surface with an intersection curve in s-q-p' space. The three-dimensional plot illustrates the failure envelope for unsaturated soils, incorporating the BBM and its extension, BBM-VEG, which accounts for additional effects such as root reinforcement.

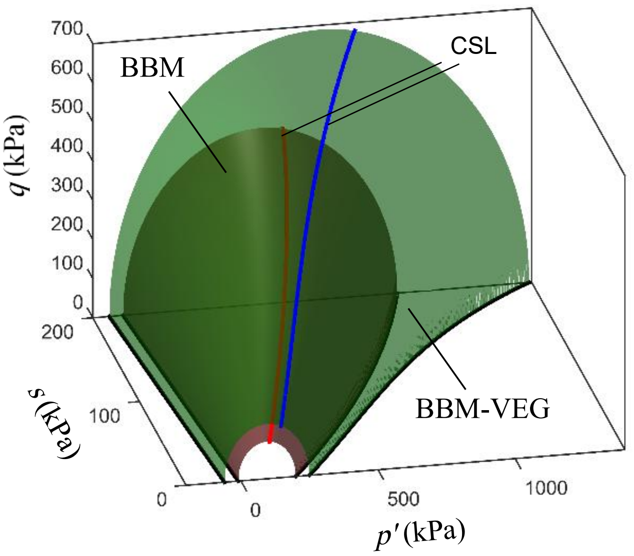


Figure 2. Comparison between BBM and BBM-VEG model

The model includes Van Genuchten (1980) parameters for soil-water retention. This equation models water retention changes with suction, affecting effective stress and stiffness. The degree of saturation is computed as

$$S_l = S_{res} + (S_{sat} - S_{res})(1 + (\alpha|\psi|)^n)^{-m} \quad (11)$$

where ψ is pressure head as $-p_w/\gamma_w$, γ_w is unit weight of water, α = 3.82 and n = 1.218, affecting soil water retention, and m (computed as $1-1/n$) impacting soil behavior under varying suction. The initial conditions include an initial effective mean stress (p'_0) of 21 kPa (Badakhshan et al., 2025b).

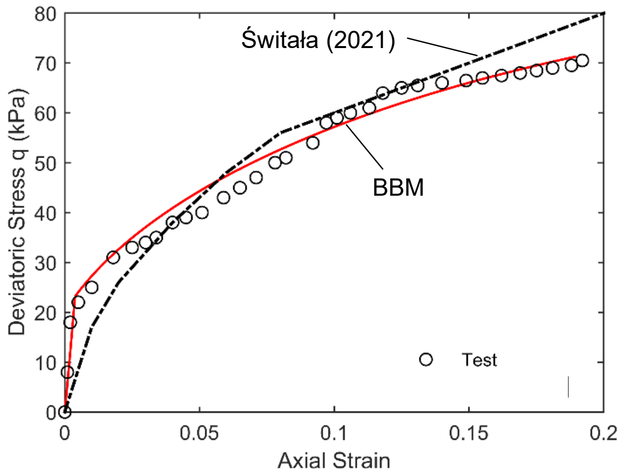
The parameters in Table 1 define mechanical, hydraulic, and root properties, allowing accurate predictions of stress-strain relationships. Using the known root mass, the initial root mass within the root zone, denoted as m_{veg}, can be determined as the ratio of root mass to the total mass of the root zone. Accordingly, m_{veg} is 3.3% for 0.4 g.

Table 1. Soil and vegetation parameters

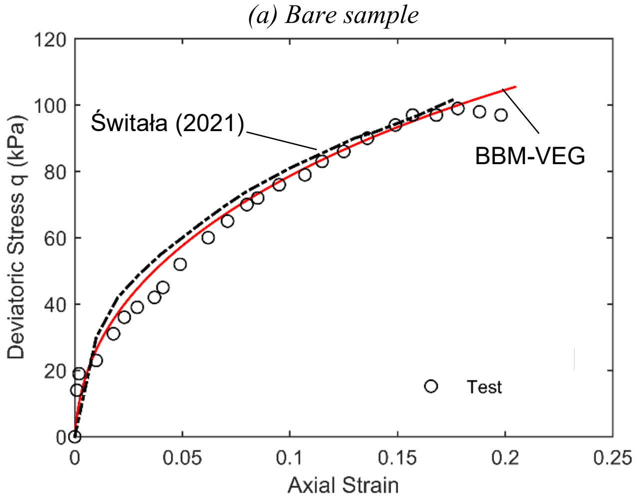
Parameter	Value
Elastic and Plastic Parameters	
λ_0	0.15
κ	0.02
κ_s	0.3
$p_{t0_{veg}}$	21 kPa
p_r	5 kPa
β	0.012 1/kPa
k_s	0.25
p_{t0}	10 kPa
p_0^*	140 kPa
N	2.2
r_0	0.73
M	0.85
Friction and Strength Properties	
Friction angle (φ')	28
M	6sin(φ')/(3 - sin(φ'))
OCR	1.0
Soil-Water-Retention Curve	
α	3.82
n	1.218
m	Computed as 1 - 1/n
S_{res}	0.02427
S_{sat}	1.0
Initial Conditions	
p'_0	21 kPa
s	220 kPa
Effective Stress and Yield Surface	
ψ	$-s/10$
p_{active}	$S_{eff}.s$
$p_{0(mean\text{-}eff)}$	$p' + p_{active}$
p_0_initial	$p_{0(mean\text{-}eff)}$.OCR
p_0*	140 kPa
Root Influence on Soil Strength	
m_{veg}	3.3%
Rp_{ini}	0.2
Rp_{peak}	0.4
Rp_{res}	0.1
ε_{veg}^{peak}	0.06
ε_{veg}^{res}	0.11

Figure 3 presents a comparative analysis of experimental and numerical modeling results (stress-strain curves) for soil behavior under bare and vegetation conditions. The results include BBM-VEG, experimental test results (Liu et al., 2011), and a previous numerical model by Świtała (2021).

In the bare case (Figure 3a), the BBM results exhibit a gradual increase in deviatoric stress as the axial strain increases, showing excellent agreement with the experimental data. The BBM-VEG model (Figure 3b) closely matches the experimental data, whereas Świtała (2021) model overpredicts the deviatoric stress at higher strains. The BBM-VEG model successfully follows this trend, whereas the Świtała model slightly overestimates the stress levels, indicating that it does not fully capture the progressive strengthening effects of vegetation.



(a) Bare sample



(b) Vegetated sample

Figure 3. Comparison of the stress-strain curves for model, experimental tests (Liu et al., 2011), and Świtała (2021)

Figure 4 presents the stress and strain contours within the specimens after analysis. The results clearly indicate that both stress and strain are concentrated in the root-zone layers, reflecting the mechanical reinforcement provided by the roots. This concentration suggests that root networks act as preferential load-bearing regions, modifying the stress distribution and enhancing soil resistance.

The localized strain patterns further highlight the progressive mobilization of root–soil interaction, which plays a critical role in the overall strength and deformation behavior of vegetated soils.

4 CONCLUSIONS

The BBM model has been improved to better account for the effects of vegetation on unsaturated soil behavior. With this extension, the model can be used to study more realistic scenarios where vegetation significantly affects the performance of unsaturated soils. Although THM behavior is mentioned, only hydro-mechanical responses are presented. In the BBM, temperature-dependent effects are also incorporated.

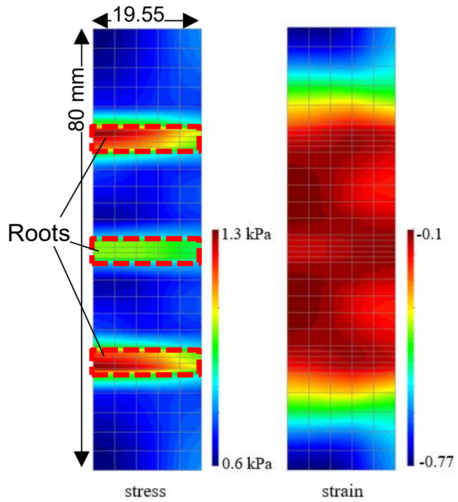


Figure 4. Vertical stress and volumetric strain in veg samples at a strain of 0.18

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