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The Influence of Soil Physico-Mechanical Properties on Plant Growth and Subsoil Water Movement

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Abstract: *Within the cutting-edge realm of Geotechnical Biology, the interplay between soil mechanics and biological systems has unveiled profound insights that align with the rural sustainability, forestry and agro-ecosystems. This inquiry, encompassing the role of soil characteristics and parameters in shaping plant behavior and root growth, creating a suction effect that draws water towards them and underscores the intricate relationships that govern soil-plant interactions. A numerical simulation was expertly dissected using Plaxis 2D software, particularly focused on understanding the complex behavior of root water uptake over time and the changing level of groundwater and its dynamics rhythm affected by the evolution of plants. The output results in our study have important implications for understanding the soil-plant system and the role of geotechnical processes in biological analyses. Our findings suggest that the stability and behavior of geotechnical systems can have a significant impact on plant growth and distribution, underscoring the importance of considering geotechnical processes in biological analyses*.

Keywords: Soil-Plant Dynamics, Root Growth, Suction, Water - Nutrient Uptake, Numerical Simulation. Bio-Geo Interfaces (BGi), Hypothesis

1. Introduction

Soils are a complex and dynamic medium (Figure 1) that play a crucial role in supporting life on the Earth [1-4], providing the essential foundation for species and supporting critical infrastructure and cities [5, 6]. Plants play a critical role in our environment and daily lives [7]. They provide us with food, oxygen, and play a key role in maintaining a healthy ecosystem. They also play a crucial role in mitigating climate change

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through carbon sequestration and provide habitat and food for wildlife [8-11]. The relationship between soil and plants is equally important, as the roots of plants help to aerate and enrich the soil, and in turn, the soil provides essential nutrients and water for the growth and survival of plants [12, 13]. This interdependence between plants and soil highlights the importance of understanding and preserving these vital relationships for the health of our planet [14-17]. Recent developments in related biological disciplines such as; botany, agriculture, soil sciences and entomology, have uncovered the intricate and dynamic interactions between soil and plants [18-24]. These findings highlight the need for a multi-disciplinary approach to studying these systems [25-27]. Despite the importance of soil-plant interactions, there are several gaps in the literature that need to be addressed, including a lack of integrated studies that consider both above- and below-ground components, unclear mechanisms, limited data, context dependence, simplistic approaches, and scaling issues. Plant roots can be considered as a critical component in the interface between the living biosphere and the Earth's subsurface [28-34]. By examining soil-plant interactions at different scales, from the cellular to the landscape level, researchers can gain a better understanding of how plants affect soil stability, erosion, and water flow, how they adapt to subsurface conditions, and how they can be utilized to improve soil quality and prevent erosion in construction projects. Additionally, to make meaningful progress in this field, it is essential to address these gaps and study soil-plant interactions in a comprehensive manner.

Figure 1. The vital role of soil as a foundation for both species and urban structures, Triq Setif St., Constantine, Algeria

Geotechnical biology is an interdisciplinary field that combines principles from biology and geotechnics to study the relationships between biological systems and geotechnical systems (Figure 2), such

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as soil, rock, and subsurface materials. By exploring the relationships between soil, plants, and insects, geotechnical biology is helping to advance our understanding of the complex and dynamic systems that support life on the Earth's subsurface. The goal is to develop sustainable solutions by considering the impact of interactions between plants, soil, and insects on both the stability, structure, and mechanical properties of geotechnical systems and the growth and function of biological systems. As research in this area continues to advance, we can expect to gain a deeper understanding of the complex interactions between plants and soils, and how this relationship influences the stability of natural and man-made structures.

2. Soil as a Nexus for Interdisciplinary Research in Biology, Geotechnics, and Entomology

Soil is a nexus for interdisciplinary research, where fields like biology, geotechnics, and entomology intersect and interact in intricate ways. By understanding the interrelationships between biological systems, geotechnical systems, and entomological systems in soil, researchers can develop innovative and sustainable solutions for a range of applications, from agriculture to construction and environmental management. In this partr, we explore the overlapping realms of biology, geotechnics, and entomology in soil and illustrate their interactions in a circle chart (Figure 2). This diagram provides a visual representation of the complex interplay between the three disciplines and highlights the importance of a multidisciplinary approach to soil research.

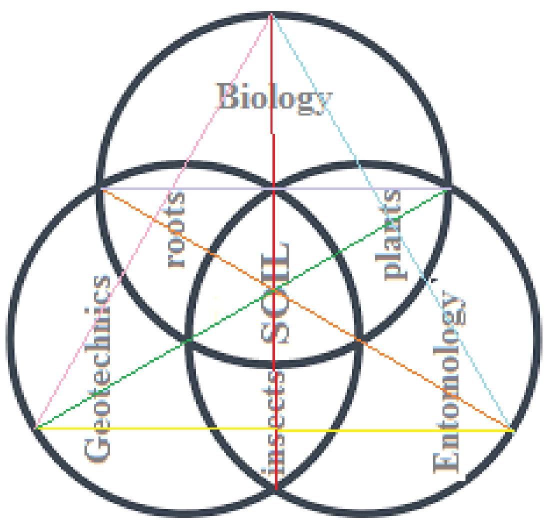

Figure 2. Mapping the Overlapping Realms of Biology, Geotechnics, and Entomology in Soil

The circle chart shows that soil acts as the intersection point between the three disciplines, where the roots of plants are the result of the intersection between biology and geotechnics, the plants themselves result from the intersection between biology and entomology, and insects result from the intersection between

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geotechnics and entomology. The interdependence of these disciplines is crucial in understanding the complexities of the soil ecosystem and developing sustainable solutions for agriculture, construction, and environmental management.

- The **plants-soil-geotechnics** intersection highlights the crucial role of plants in stabilizing the soil and improving its mechanical properties. This intersection is essential for developing sustainable solutions in industries like agriculture and forestry.
- The **entomology-soil-roots intersection** represents the relationship between insects and the soil, which is critical for understanding the impact of insects on soil health and plant growth. This intersection has many applications in areas like waste management and biohazards.
- The **entomology-insect-geotechnics** intersection represents the relationship between insects and subsurface materials, which has important applications in areas like pest control and geotechnical engineering.
- The **biology-soil-insects** intersection highlights the importance of understanding the interplay between biological systems and insects in maintaining healthy soil and ecosystem function.
- The **plants-soil-roots** intersection emphasizes the important role that roots play in improving soil structure and stability, which has important applications in areas like erosion control and soil conservation.
- The **biology-plants-entomology** intersection highlights the complex and dynamic relationships between plants, insects, and biological systems, which are critical for supporting life on the Earth's subsurface.
- Finally, the **biology-roots-geotechnics** intersection represents the important relationship between biological systems and the physical properties of soil. Roots play a critical role in maintaining soil stability and preventing erosion, while the physical properties of soil, such as porosity and permeability, affect root growth and nutrient uptake. This intersection is important in understanding how biological processes impact geotechnical systems and how geotechnical systems, in turn, affect biological processes. By studying the interactions between biology, roots, and geotechnics, we can develop sustainable solutions for managing soil erosion and optimizing plant growth in different environments.

Overall, the circle chart and its intersecting lines demonstrate the interdependence of biology, geotechnics, and entomology, and the importance of studying their relationships for developing sustainable solutions in many fields.

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3. The Interplay between Soil Mechanics and Plant Evolution

The evolution of plants is influenced by both geotechnical and biological factors. Geotechnical indices, such as soil strength, soil moisture content, and soil structure, affect root growth by influencing the plant's ability to penetrate the soil and obtain water and nutrients. On the other hand, biological indices, such as plant species, age, and nutrient status, also play a role in root evolution by affecting root growth and development. For example, some plant species have evolved specialized root structures, such as root hairs or lateral roots, that allow them to better adapt to specific geotechnical conditions. Additionally, the nutrient status of a plant can influences the development of its root system, as the plant will allocate more resources to root growth if it is deficient in certain nutrients [35]. Overall, the interplay between geotechnical and biological indices can lead to a complex and dynamic system, where the evolution of roots is shaped by the combined effects of these factors.

3.1. Soil-roots interaction

Soil-roots interaction (Figure 3) plays a crucial role in plant stability [36]. Strong and extensive root systems anchor plants in place, reducing their susceptibility to falling over due to wind or other environmental factors [37]. In addition, roots absorb water and nutrients from the soil, providing the plant with the necessary resources for growth and survival [38]. The presence of healthy roots also helps to increase soil stability and reduce soil erosion. On the other hand, if the soil lacks adequate nutrients or is otherwise compromised, it can negatively impact root growth and stability, potentially leading to plant stress or death. In conclusion, soil-plant roots interaction is a two-way interaction that affects both plant and soil stability. Furthermore; soil conditions can greatly influence the structure and growth of plants [39]. Soil properties such as fertility, pH, and water availability can impact a plant's root system, stem growth, leaf size, and overall health [35]. For example, plants grown in nutrient-rich soil may have larger and more extensive root systems, while plants grown in poor soil may have smaller root systems and may need to grow taller to reach light and nutrients. In addition, soil structure can also play a role in plant structure. Soils with good structure, such as those with high organic matter content and good aggregate stability, can provide good physical support to plant roots and promote healthy root development [40]. On the other hand, soils with poor structure, such as those that are compacted or prone to erosion, can limit root growth and overall plant health. So, it's evident that soil conditions can play a significant role in shaping the structure and growth of plants, and it's important for gardeners and farmers to understand and manage soil conditions to promote healthy and productive plant growth.

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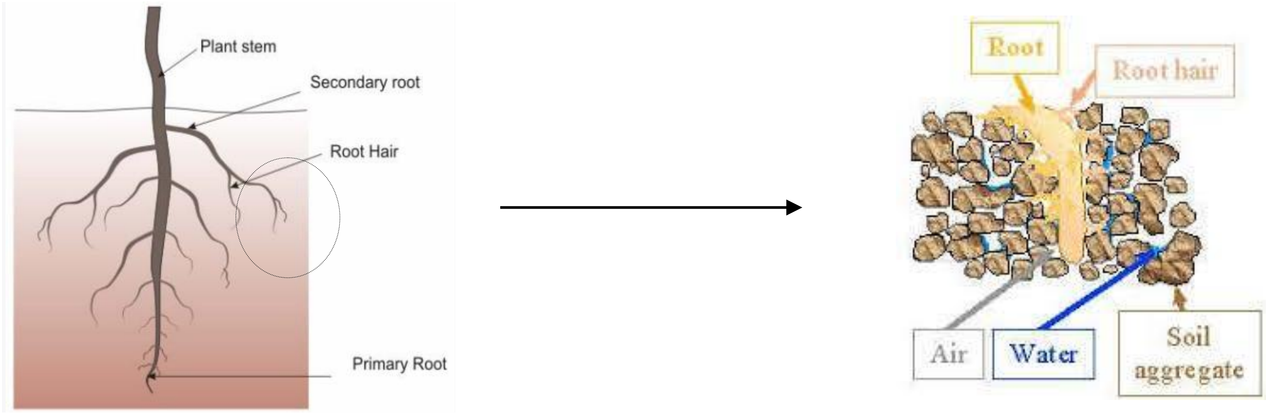

Figure 3. The left panel shows the interaction between the stem and roots of the plant with the surrounding soil layer. The right panel is a close-up of the interaction between the roots and soil aggregates, water, and air

3.2. Definition and Rheology of the Bio-Geo Interface (BGi)

The term "Bio-Geo Interface" could be used to describe the interface between the biological processes associated with plants and the geotechnical processes associated with soil. The Bio-Geo Interface represents a crucial component of the Earth's ecosystem, where soil, plants, and insects interact to support life and maintain the health and stability. Study of the Bio-Geo Interface have the potential to provide new insights into the complex and dynamic relationships between plants, soil, and the environment. This research could inform the development of new tools and technologies for improving the management and restoration of natural ecosystems, and for ensuring the sustainable use of soil and plant resources. So, the Bio-Geo Interface concept have the potential to fill some of the gaps in the field of root-soil interaction rheology. The Bio-Geo Interface approach considers the interactions between biological (root) and geotechnical (soil) systems and seeks to understand how these interactions affect soil structure and function (Figure 4). By incorporating biological processes into models of soil mechanics, the Bio-Geo Interface can provide a more comprehensive understanding of root-soil interactions, and it may be possible to develop more comprehensive and accurate models of root-soil interactions that consider both the biological and geotechnical aspects of the interactions.

The rheological model [41] of soil-plant interaction is a mathematical model that describes the mechanical interactions between soil and plants, including the roots, stem, and leaves. To create a soil-plant rheology (Figure 5), we could use; plastic flow element which could occur due to the growth and expansion of the root system, which can cause the soil to deform and move, viscous flow element which could occur due to the movement of water and nutrients through the soil towards the roots, also can cause the soil to temporarily deform, elasticity element to represents the ability of the soil to recover its original shape after deformation and change in volume element which could occur due to the expansion of the root system as the plant grows.

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Overall, the combination of these rheological elements can help to create a model of the soil-plant system that takes into account the complex interactions between the plant and the surrounding soil.

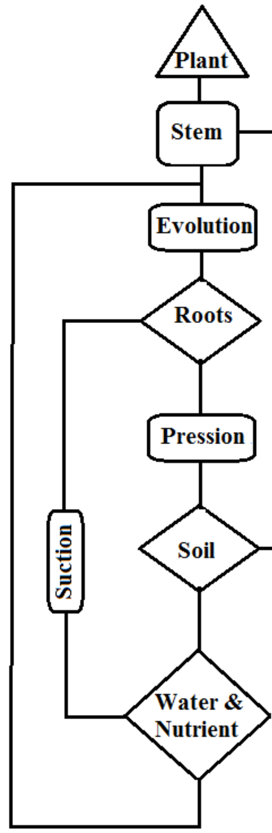

Figure 4. Flowchart of Soil-Plant Interaction and Water-Nutrient Uptake

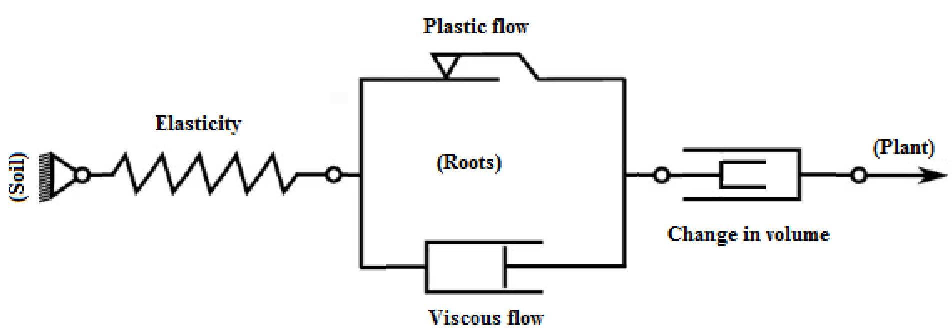

Figure 5. Rheological Modeling of Soil-Plant Interaction for Predicting Plant Growth and Soil Behavior

The rheological model takes into account the soil's mechanical properties, such as its elasticity, viscosity, and plasticity, as well as the plant's mechanical properties, such as its modulus of elasticity,

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modulus of rigidity, and stress-strain behavior. The model then uses these parameters to calculate the soil-plant interactions, including soil deformation, root growth, root-soil adhesion, and root-soil friction. The rheological model can help to understand the mechanical forces that act on the plant and soil system and can provide valuable insights into how these forces affect plant growth and development. This model can also help to predict the behavior of the soil-plant system under different loading conditions, such as changes in soil moisture, soil temperature, and soil structure, as well as changes in plant size, shape, and orientation. One of the main applications of the rheological model of soil-plant interaction is in the study of plant root growth and root-soil interactions. The model can help to understand how root growth is influenced by soil properties and how roots penetrate the soil and interact with the soil particles. This information can be useful for improving crop yields and for developing strategies for soil management and conservation. Overall, the rheological model of soil-plant interaction is a useful tool for understanding the mechanical interactions between soil and plants and for predicting how these interactions may affect plant growth and development.

4. Numerical Simulation of Soil-Plant System as BGi

Bio-Geo Interface modeling and simulation is an important tool for improving our understanding of the complex interactions between soil and roots, and for supporting sustainable land use and management practices. Bio-Geo Interface modeling and simulation (Figure 6) refers to the use of mathematical and computational models to study and understand the complex interactions between the soil and root systems, and how these interactions influence the functioning of terrestrial ecosystems. These models can help to provide insights into the behavior of the soil-root system under different conditions, such as changes in soil moisture and structure, and the impact of root growth and development on soil mechanics. The main components of soil-root interaction models are typically the root, soil, and water. Root growth and development are modeled based on various biophysical and environmental factors, such as light availability, soil texture, and water uptake. Soil mechanics, including soil compaction and deformation, are modeled based on the properties of the soil and the physical and biological processes that influence soil structure and porosity.

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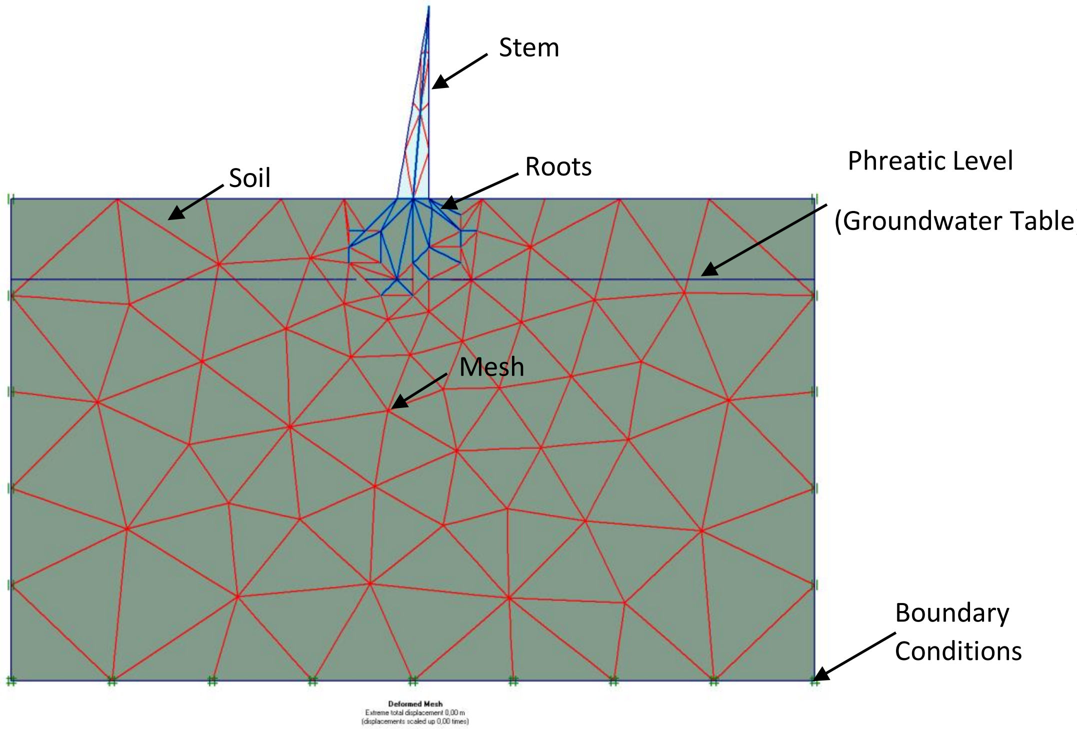

Figure 6. Bio-Geo Interface (BGi)

A numerical simulation in geotechnical biology has been used to investigate the interaction between plant roots and soil and their mechanical behavior. PLAXIS 2D software is chosen for modeling and simulating complex root-soil behavior. By incorporating drain elements for water absorption and suction and modeling plant shoots as plates, the software can provide valuable insights into soil deformation, stress distribution, and water flow under different loading conditions. To represent the volume evolution of roots, 2D cross sections of soil and roots are modeled, each representing a different time step in the evolution of the root system. Root diameter, density, and elastic modulus, along with the characteristics of the peat soil, should be included in the model (Table 1). The drain elements can model the seepage of pore water and negative pore-water pressure caused by root uptake of water. By incorporating the drain element, we can model the suction effect caused by the roots and its effect on soil deformation and stress. Also; simulating the plant shoot core with sand can be a useful approach to better understand the capillary properties of the upper part (stem) of the plant. Additionally, the effect of root growth and branching on soil structure and its properties should be considered. To ensure accurate representation, the model must be calibrated based on experimental data and actual root growth observations. Once set up, the software can simulate root growth, interaction with soil, interstitial pressure and suction, and deformation and stresses on the soil. Such simulations can provide insights into complex interactions and how different soil and root systems respond to environmental changes.

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Accurately representing physical and mechanical properties of soil and roots is crucial for simulation accuracy. Proper calibration of the parameters of the drain element and plate dimensions and placement are critical to accurately modeling the soil-plant interaction. This approach has the potential to provide useful insights into soil and root behavior under various conditions.

Table 1. BGi parameters

Material	Model	Type	γ_{unsat} (kN/m3)	γ_{sat} (kN/m3)	k_x (m/day)	k_y (m/day)	ν	E_{ref} (kN/m3)	E_i (kN/m3)	C_{ref} (kN/m3)	φ (°)	R_{inter}
Peat Soil	Mohr-Coulomb	Undrained	8	11,5	0,01	1*e-3	0,35	500	-	7	20	1
Stem Core	Mohr-Coulomb	Undrained	17	20	1	1	0,30	13000	-	1	31	1
Stem Crust	Elastoplastic	Plate	-	-	-	-	-	50000	10000	-	-	-

******: γ unsat: the dry unit weight of soil. γ sat: the saturated unit weight of soil. kx: the hydraulic conductivity of soil (m/day) in the x-direction. ky: the hydraulic conductivity of soil (m/day) in the y-direction. ν: Poisson's ratio, a dimensionless constant that relates the lateral and axial strains of a material. Eref: the reference Young's modulus of the soil. Ei: the initial Young's modulus. Cref: the reference cohesion (kN/m2) of the soil. φ: the angle of internal friction (°) of the soil. Rinter: the interface resistance (kN/m) between soil layers

The Figure 7 shows a clear interaction between the plant roots and soil over time. Initially, without any roots, the water level in the soil remains stable at the phreatic level. However, with the growth of the first small root after 30 days (Phase 1), there is no significant change in the water level. After 90 days (Phase 2), as the first root volume increases and the second one starts to grow, the water level starts to rise towards the roots at the top center of the plant. This indicates that the roots are absorbing water from the soil, creating a suction effect that draws water towards them. As the plant continues to grow, the water level in the soil increases in a more significant way. After 180 days (Phase 3), the third root on the left side of the plant begins to grow, resulting in a slight increase in water level on the right side above the phreatic level. After 270 days (Phase 4), the second root on the right side of the plant grows in volume, and the first half part of the stem is completed. This results in a substantial increase in the water level on the right side of the plant above the phreatic level. Finally, after 390 days (Phase 5), the two roots on the left side of the plant complete their growth, and the remaining half part of the stem is completed. This results in a significant increase in the water level in both the right and left sides of the plant above the phreatic level. Overall, this analysis demonstrates the importance of soil-plant interaction in regulating water movement in the soil. As the roots grow and develop, they create a suction effect that draws water towards them, leading to an increase in water level in the soil. This effect becomes more significant as the plant grows, highlighting the importance of considering the growth and development of the plant when studying soil-plant interactions.

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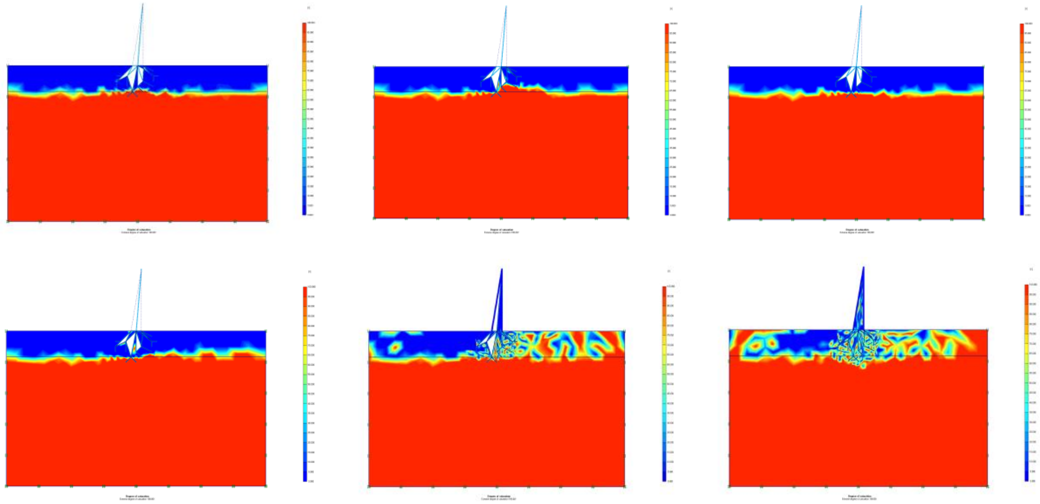

Figure 7. Degree of saturation: The percentage of void space in the soil that is filled with water over steps

The initial conditions (no roots) showed no displacement (Figure 8), but in the Phase 1, we observed a soil displacement of 8.9 mm around the first growing root on the right side of the plant in the downward direction. In the Phase 2, there was a slight displacement of 28.9 mm towards the left side of the plant. In the Phase 3, a cumulative displacement of 5,6 cm was observed on the roots towards the down-right direction. In the Phase 4, the stem's half part had a displacement of about 14.33 cm towards the left, with little soil displacement towards the right side. Finally, after plant growth completion, the stem had a total displacement of 45.56 cm towards the right side. This displacement behavior can be discussed in the soil-plant interaction system, where the growing roots cause the soil to displace around them, leading to deformation (Figure 9).

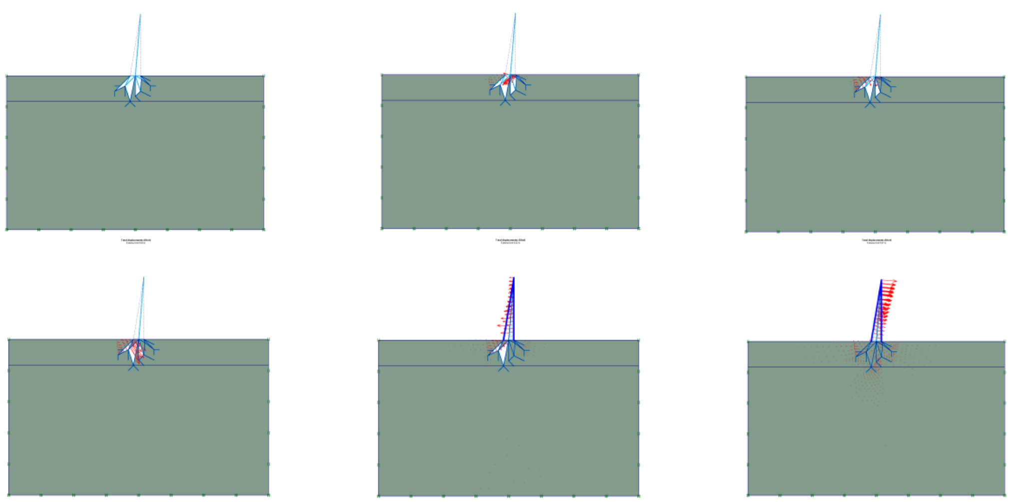

Figure 8. Total displacement: The total amount of movement of the soil-plant over steps

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As the roots grow and spread, they cause more significant displacement and deformation in the soil. The displacement of the stem can be explained by the bending stress induced by the weight of the plant, which also affects the soil around it. Therefore, the soil-plant interaction system is a complex process that involves the interplay of root growth, soil deformation, and bending stress induced by the plant's weight.

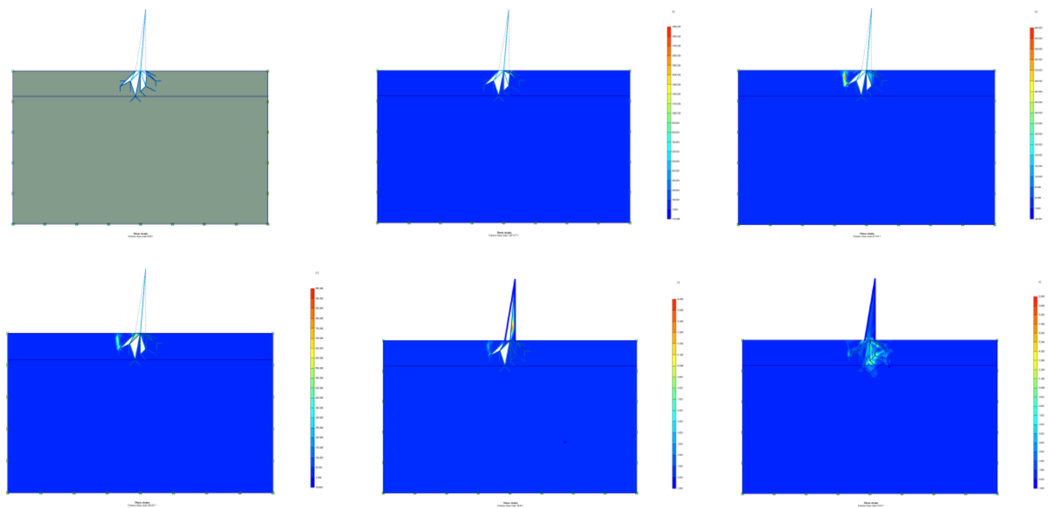

Figure 9. Shear strain: The amount of deformation due to shearing of the soil over steps. "The analysis shows that the shear strain increased gradually over the four phases until the plant and roots were fully grown in the fifth phase. However, the increase in shear strain was relatively small in the fifth phase, indicating that the soil was relatively stable and the plant did not have a significant impact on the soil deformation."

In the Figure 10, an increasing PPmax value (until 3,3* e4) over steps means that the maximum value of the multipliers applied to the soil properties or external loads is increasing over time. This could be useful in simulating the evolution of roots over time as the soil properties and external loads change. For example, if the roots are growing and exerting more pressure on the soil, the PPmax value could be increased over steps to simulate this increase in pressure. Similarly, if there are changes in the external loads acting on the soil, such as changes in groundwater levels or applied loads, the PPmax value could be increased over steps to simulate these changes. In the context of your root-soil system simulation, the PPmax curve increasing over steps indicates that the applied multipliers are becoming larger as the simulation progresses. This means that the influence of the roots on the soil properties and external loads is becoming more significant over time. On the other hand, the stable Sum-Mstage and Sum-Marea curves at 0, 2 and 0,9 respectively over steps (Red and Yellow Graphs) indicate that the accumulated effects of the multipliers on the soil properties and external loads are not increasing significantly. This suggests that the changes in the soil

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properties and external loads due to the root growth are not contributing significantly to the overall deformation behavior of the system. Therefore, while the PPmax curve shows an increasing influence of roots on the soil properties and external loads, the stable Sum-Mstage and Sum-Marea curves suggest that these effects are not contributing significantly to the deformation behavior of the system over time.

The output results can help to better understand the interaction between plants and soil. For example, the degree of saturation and flow field may be important if you are interested in understanding how water moves through the soil and affects the roots. Excess pore pressure and active pore pressure may be important if you are interested in how the soil responds to external loads or changes in water content. Plastic points and deviatoric stresses (q) may be important if you are interested in understanding the soil's strength and how it deforms under load. Mean stresses and effective mean stresses may be important if you are interested in how the soil's behavior changes over time or as a result of different loading conditions. Relative shear stresses may be important if you are interested in understanding the likelihood of failure or instability in the soil. Total displacement, total strain, shear strain, and volumetric strain may be important if you are interested in understanding how the soil and roots deform and how this affects the overall stability of the system.

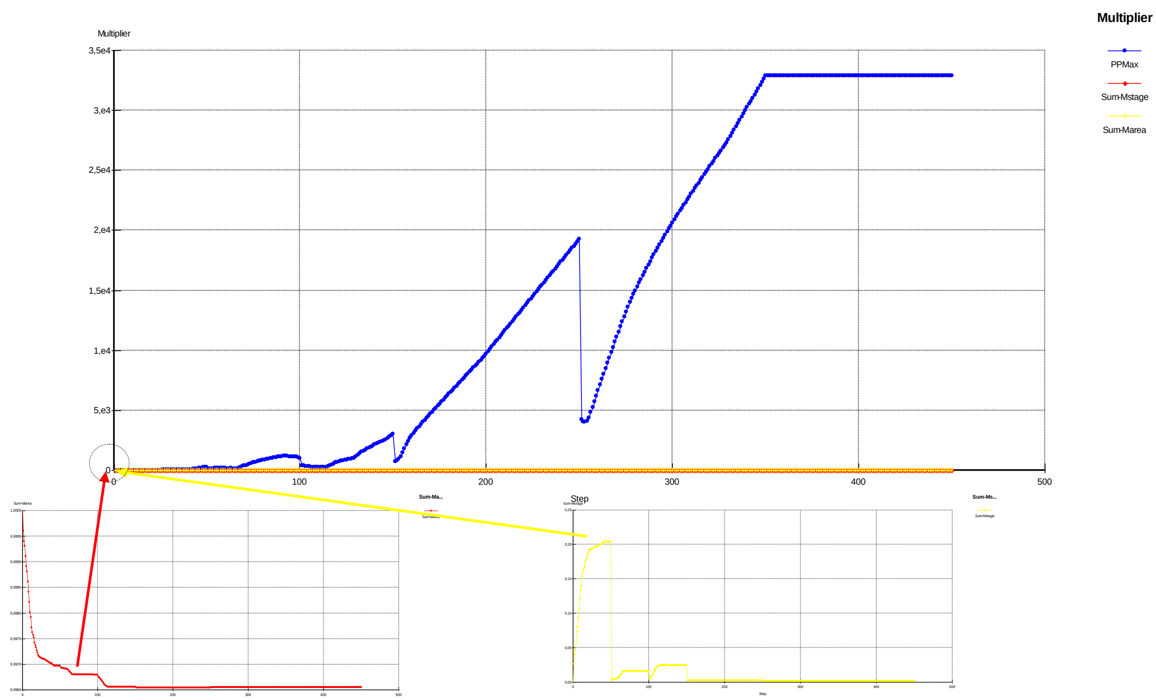

Figure 10. Simulation Multiplier of PPmax, Sum-Mstage and Sum-Marea curves Vs. Steps

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5. Results and Discussions

The results and discussion of our study centered around the concept of geotechnical biology and the integration of root-soil interactions. A new concept of geotechnical biology was introduced, which emphasized the role of plants in soil formation and stability. The concept of Bio-Geo Interface was defined as the volume where roots are integrated with the soil and the key factor in root-soil interactions. The soil-plant interface is a critical zone where biotic and abiotic processes interact. To understand the mechanisms that control water and nutrient uptake by plants, we need to investigate the rheological properties of the soil-plant system. In this article/review, we present a conceptual model of the soil-plant interface from a rheological perspective. We discuss the key components of the soil-plant system, including plant structure, root-soil interaction, and soil properties, and how they affect water and nutrient uptake. We also introduce the use of rheological models, such as dashpots and springs, to describe the mechanical behavior of the soil-plant interface. Finally, we highlight the potential applications of a rheological approach in improving plant productivity and soil health. This review provides a foundation for future studies that aim to understand the soil-plant interface and improve agricultural sustainability.

The numerical simulations conducted using Plaxis 2D in our study have important implications for understanding the soil-plant system and the role of geotechnical processes in biological analyses. Our findings suggest that the stability and behavior of geotechnical systems can have a significant impact on plant growth and distribution, underscoring the importance of considering geotechnical processes in biological analyses. These insights have important implications for the field of geotechnical biology, which seeks to better understand the interactions between geotechnical and biological processes in order to improve our understanding of ecosystem dynamics. By highlighting the importance of incorporating geotechnical data into biological analyses, our results have the potential to inform the development of new models and approaches for studying the soil-plant system and its critical role in supporting life on the Earth.

The future of Geotechnical Biology holds great potential for bridging the gap between soil mechanics and plant biology. By refining the Bio-Geo Interface as a tool for integrating biological and geotechnical parameters, it becomes possible to use specialized software for agricultural modeling. The Bio-Geo Interface can serve as a data transmitter for geographic information systems (GIS) [42], enabling the monitoring of agricultural land through drones or satellites and providing insights for preventive interventions. Additionally, the Bio-Geo Interface can be used to optimize plowing and watering patterns, determine the best type of fertilizer for soil conditions [43-45], and improve the efficiency of agricultural practices based on the geotechnical properties of the soil. By utilizing the Bio-Geo Interface, we can make significant advancements in optimizing agricultural production while preserving soil health.

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6. Conclusions and prospects for further research:

Geotechnical biology represents a novel and exciting area of study within the field of biology. This interdisciplinary field merges the principles of geotechnics and soil science with the study of biological processes and interactions in soil environments. Furthermore, geotechnical biology is providing new insights into the vital role that soil biodiversity plays in maintaining ecosystem health and functioning. As a new and rapidly growing field, geotechnical biology offers many opportunities for cutting-edge research and innovation, and is poised to make significant contributions to the advancement of biology and environmental science.

However, much work remains to be done in this field, and there are many challenges that need to be addressed. These include a need for more standardized methods for studying geotechnical biology, a better understanding of the complex and dynamic nature of the interactions between plants and soil, and the development of new models that can accurately predict the behavior of geotechnical systems over time. Despite these challenges, the future of Geotechnical Biology is bright, and we are confident that continued research in this field will lead to significant advancements in our understanding of geotechnical systems and their impact on the environment. The results of this research will have important implications for a wide range of applications, including the design and construction of infrastructure, the management of natural resources, and the conservation of biodiversity.

Authors' Contributions

All authors read and approved the final manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

Data availability

All data generated or analysed during this study are included in this published article.

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