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Plant-based sensing for monitoring soil matric suctions in vegetated slopes

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ABSTRACT: Wet and dry extremes induced by climate change are affecting soil mechanical behaviour, and consequent serviceability and stability of earthworks. Nature-based solutions using plants have been suggested as an environmentally friendly means to mitigate landslide hazards because of the hydrological and mechanical reinforcement provided by plants. This paper explores a new function of this nature-based solution named "plant-based sensing (PbS)", which utilises plant ecophysiological responses to monitor plant stress indicators that can be linked to soil matric suction. PbS aims to comprehend the fundamental understandings of plant ecophysiology, soil-plant hydraulics, and unsaturated soil mechanics under the influences of environmental stresses, to further exploit the engineering function of plants. PbS may be integrated into slope monitoring systems substituting the expensive needs for sensor installations on the slopes. Initial studies in geotechnical engineering have explored PbS by identifying plant morphological traits that are pertinent to soil matric suction; however, real-time monitoring remains a challenge. Therefore, this paper underscores the necessity for interdisciplinary collaboration to advance PbS technique in geotechnical discipline. By reviewing existing research, this paper identifies areas for future work and emphasizes the importance of integrating plant physiological and ecological insights into geotechnical engineering practices to enhance slope monitoring and management strategies.

Keywords: Vegetated slopes; Climate change; Slope monitoring; Plant-based sensing; Remote sensing

1 INTRODUCTION

Climate change is driving an alarming increase in extreme weather events, leading to more frequent and intense storms and droughts. In the case of Hong Kong, extreme rainfall events have become more frequent and rainfall records are being broken several times in the recent few decades. The mean temperature is also reported to be increasing at a rate of 0.37 °C per decade (Lee et al., 2021). Nature-based solutions using plants have been suggested to mitigate such climate change induced landslide hazards (Bordoloi and Ng, 2020). It is well-documented that plants contribute to slope stability by two mechanisms, i.e., mechanical and hydrological reinforcement. However, if the recent data on climate change is recognised, future climate will be typified by hotter, drier summers and wetter winters with more intense rainfall. Considering these future climate scenarios, it is expected that the stability of the vegetated slopes will not remain unaffected (Insana et al., 2011). During summers, the high demand for water by plants might threaten their survival. Conversely, in wetter periods, only the plants survived from summer could contribute to slope reinforcement.

Continuous monitoring and maintenance are thus essential to ascertain the performance of the vegetated slopes in the context of climate change. In general, slope monitoring guidelines suggest manual inspections of surface erosions, desiccation cracks and scars; blockage in surface drainage along the berms; decayed vegetation or excessive plant growth; and subsurface drainage. Additionally, tensiometers that are installed in designated areas of the slope can provide only spatially-limited information and cannot be deployed on large scale due to costs. Due to the difficulties of labour-intensive inspections and expensive monitoring tools, smart monitoring through remote-sensing technologies is rapidly progressing to improve the capability and efficiency of slope monitoring. Techniques like Light Detection and Ranging (LIDAR) and Synthetic Aperture Radar Interferometry (InSAR) are emerging in the recent years to detect ground movements in larger sites that are difficult to access (Necsoiu and Hooper, 2009). However, a key issue with these methods is that their data resolution is diminished by signals returned from vegetation, and they do not provide information on soil water conditions.

To address these challenges, we adapt the concept of "plant-based sensing (PbS)" from agricultural and ecophysiological disciplines, i.e., using remote sensing responses of plants to monitor soil matric suction in vegetated slopes (Fig. 1). Inspired by Faiz (1983), plants may be treated as biological tensiometers, where the plant roots act as a ceramic tip, water transport in the xylem as water level in the tensiometer shaft and leaf response as a measurement in vacuum gauge.

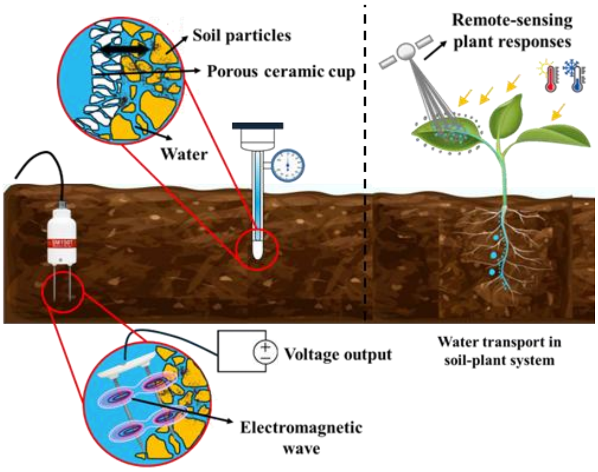

Figure 1. Plants as biological tensiometers to monitor soil suction in vegetated slopes

2 PLANT-BASED SENSING

PbS is an existing technique applied in agriculture and ecophysiology, which suggests that the changes in abiotic stressors (i.e., air temperature, water and nutrient conditions etc.) could be tracked by plant morpho-physiological responses at leaf, canopy and ecosystem scales. One approach to capture and quantify such plant-based feedback is by remote sensing. Across the solar spectrum, leaf spectral signatures in the visible and near-infrared spectral bands have been demonstrated to be effective at indicating the onset and development of plant biotic and abiotic stresses, including the changes in soil water conditions. Specifically, the near-infrared spectral band was found to be consistent with detecting plant water stress (Carter and Knapp, 2001). In addition to leaf reflectance, leaf surface temperature changes based on the endothermic process in plant transpiration (Jones and Leinonen, 2003) could indicate the soil water availability by thermal imagery. Such soil-plant feedback has been shown to be more sensitive in the recent 20 years to obtain more accurate PbS for even slight changes in soil water stress (Franks et al., 2013). In agriculture, thermal and hyperspectral imaging techniques have been used to detect crop health by monitoring the onset of water stresses (Zhang et al. 2019) and plant pathogens (Chaerle et al. 2004). At the ecosystem scale, vegetation indices are defined based on satellite infrared imagery and spectral reflectance to monitor the forest structures (Wu et al. 2020).

In geotechnical engineering, existing studies established correlations between soil matric suction and plant traits in varying soil types, plant species, and environmental conditions (Boldrin et al., 2017; Gadi et al., 2019; Ng et al., 2016). In general, these studies categorise plant traits into two: root-based and leaf-based traits (Fig. 2). Root-based traits often reflect how roots interact with soil, affecting their ability to access water, whilst leaf-based traits indicate how plants transpire to varying suction levels and environmental stresses. Existing studies identified a positive correlation between most plant traits and suction. Whilst these traits are crucial, they pose challenges for real-time monitoring due to their non-quantifiable nature in dynamic environments (e.g., leaf area or root length do not provide information on diurnal suction changes).

For any new sensor, it is vital to establish the sensing components, characterisation and calibration to assess the inherent performance limits and reliability. Similarly for PbS, following scientific challenges or research gaps need to addressed before its intended purpose in slope engineering: (1) ***real-time vegetation monitoring*** *(i.e. to establish the components of biological tensiometer)* - evaluation of remote sensing techniques or long-term seasonal monitoring of plant physiological responses has rarely been conducted mainly because of gaps in knowledge and technology; (2) ***diversity of plant species*** *(i.e. to characterise the biological tensiometer)* – unlike seasonal crops, different roadside landscape species may respond differently to soil suction changes, leading to variability in soil-plant feedback time. This results in opting for fewer selection of plant species that are suitable to slope applications of PbS; (3) ***modelling challenges*** *(i.e. to calibrate the biological tensiometer)* – existing soil-plant-atmospheric continuum models which often use the principles of energy and water balance, require complex parameters (such as hydraulic conductivity of leaves and roots) that are difficult to measure, and do not integrate any plant physiological or remote sensing measurements.

3 NEEDS FOR FUTURE WORK

(1) *To establish the components of a biological tensiometer*, it is essential to develop a comprehensive framework for collecting datasets that encompass both plant parameters and soil suction. By analogy, this would fine-tune the ceramic tip and vacuum gauge in tensiometer. Some of the important plant parameters that are currently being or need to be explored, are discussed in the following. Plant water status can be measured quantitatively in terms of water potential (ψ_w). Recently, Novick et al. (2022) mentioned that the dew-point potentiometer used in measuring soil suction, could be extended beyond its siloed application to measure ψ_w among plant samples. Ganesan et al. (2024a) recently explored the possibility of measuring root ψ_w of *C. zizanoides* using a dew-point potentiometer.

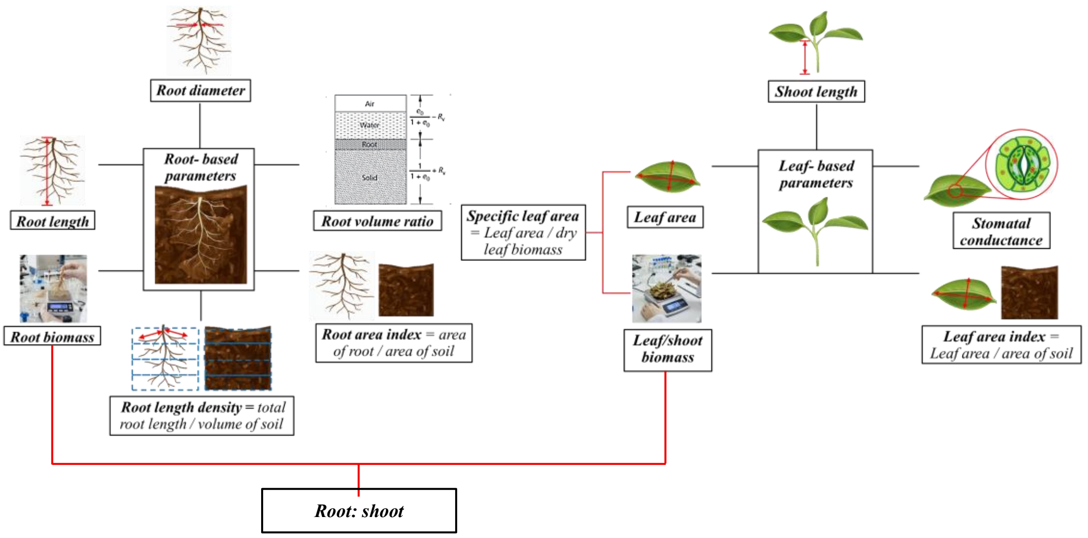

Figure 2. Existing plant traits that are associated with soil suction

Transpiration and photosynthesis can be measured using an infrared gas analysers (IRGA). Porometers, that are usually used to measure stomatal conductance, are deemed less accurate because of timing errors and their failure to establish uniform humidity gradients within the chamber. In addition, stomatal conductance estimates from porometers are subject to errors under low transpiration rates and low vapour pressure gradients. Due to the difficulty in controlling the environmental parameters in the field, the microclimatic control in IRGA provides a prominent advantage in fixing a desired value of the parameters.

In the contemporary landscape of environmental monitoring and geotechnical engineering, the integration of remote sensing technologies with plant physiological insights provides understanding on plant parameters and their relation to soil suction. Remote sensing technologies using aerial drones, have the capacity to collect vast amounts of data on plant spectral signatures. For instance, hyperspectral imaging allows for the detailed assessment of plant physiological traits by capturing reflectance data across a wide range of wavelengths. This technique can identify specific plant responses to varying soil suction, such as changes in chemical constituents in chloroplasts (Feret et al., 2008) and leaf senescence (Wu et al., 2020). Similarly, thermal imaging can be employed to monitor plant temperature variations, providing insights into transpiration rates and water deficit levels (Jones and Leinonen, 2003). Some geotechnical studies have made strides in addressing these challenges by employing thermal imaging (Boldrin et al., 2019) and chlorophyll fluorescence (Garg et al., 2020). Particularly, the chlorophyll fluorescence measurements have supplemented several geotechnical parameters including, proper estimation of the permanent wilting point (Garg et al., 2020) and critical soil suction parameters (Bordoloi et al., 2023; Ganesan et al., 2024b) that are helpful in identifying plant health and irrigation patterns (Figure 3).

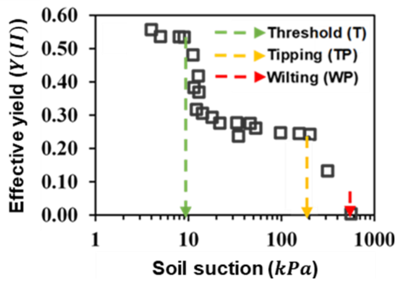

Figure 3. Chlorophyll fluorescence response (Y(II)) showcasing the amount of light used in photosynthesis, along with critical soil suction parameters in Axonopus compressus grown in sandy soil (Bordoloi et al., 2023). Threshold and tipping suctions indicate initial hampering and final Y(II) response before plant wilting, respectively

(2) *For sensor characterisation*, following recommendations and directives can be approached. It should be noted that most existing studies explored PbS from limited tree and grass species and limited suction values. This can easily be effectively addressed by performing iterative testing with different plant species (preferably that are native to the area) and different climate conditions. As data collection progresses, field studies should be conducted to correlate remote sensing measurements with direct soil suction readings, effectively linking remote data collection and in-situ conditions. By doing so, PbS can be characterised by optimising suitable plant species that are both beneficial in slope stability and in the sensing technique itself. Additionally, it becomes possible to enhance the predictive capabilities and improve our understanding of the soil-plant-atmosphere continuum.

(3) *For sensor calibration*, existing models, such as SCOPE (Soil-Canopy-Observation of Photosynthesis

and Energy; Van der Tol et al., 2009), can be adopted in simulating plant characteristics derived from remote sensing measurements. SCOPE integrates various bio-physical processes (radiative transfer and energy balance equations), allowing researchers to predict how plants respond to environmental stressors. By employing such models, it becomes feasible to develop a deeper understanding of the interactions between plant physiology and soil suction, paving the way for more effective monitoring strategies. Validation of datasets from different plant species and climate conditions using SCOPE like models should be conducted to ensure the applicability of PbS. Thereby leveraging PbS, engineers could establish a proactive approach to managing slope stability, allowing for timely interventions before potential failures occur.

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