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Application of Bioinspired Systems for Geotechnical Solutions- A Review

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Abstract. In the present era of the rapid growth of infrastructure, there has been a profound development in the engineered geotechnical systems. Engineered structures such as tunnels, foundation systems, and transport schemes have been constructed and implemented in large numbers to cater to the phenomenal changes. However, there have also been failures of these systems in a natural disaster or due to human mistakes. In contrast, the natural systems are comparatively more resilient and durable compared to the engineered structures. Human evolution and their survival have always known to coexist with nature. Many natural systems, such as the termite mounds with its numerous interconnected tunnels, flexible bamboo trees, palm trees in the coastal regions, are found to be failure resistant and tough due to its inherent ability to withstand the external stimuli. In the present study, an effort is made to explore the possibilities of incorporating bio-inspired processes and techniques to the geotechnical systems to make them more resilient and competent. The palm tree rooting system's mechanism is adopted in this study, and its mechanism of resisting severe winds in coastal zones is considered analogous to the lateral loading of tall structures, specifically in the coastal areas. The effective inclusion of these mechanisms in the foundation system could increase the system's bearing capacity and potential resilience against external forces. The incorporation of bio-inspired technologies in the geotechnical problems would add to the emerging field of bio-geotechnology and be an effective solution for nature-driven problems such as landslides and liquefaction.

Keywords: bio-geotechnology, bio-inspiration, palm tree, resilience, geotechnical systems.

1 Introduction

Most of the engineering problems and successful engineering marvels have found its solution based on an interdisciplinary approach. Specifically, several natural analogies have been adapted in the design solution for a multitude of problems. The natural systems or biological processes are multifunctional, and there is an incessant, inherent dynamic improvisation with complex connectivity. A detailed insight into these systems and abstraction of multifunctional processes can provide more sustainable and resilient solutions to present-day engineering problems

In the rapidly developing bio-engineering field, transfer processes such as biomimicry, bio-mediated processes, and bio-inspired engineering have been researched and gaining momentum in the past few decades. The Shinkansen bullet trains are directly bio-mimicked from the Kingfisher bird physiology; however, there could be a vast difference in material behavior and the dynamic properties of the two forms. Another example to quote for the bio-mediated process would be the microbially induced calcite precipitates to cement loose sands and clog pore spaces [1]. Alternatively, bio-inspired technology could take a slightly different turn. It uses biological parallels to develop solutions for engineering problems with either process-driven or solution-driven analogies from the more adaptable biological systems [2,3]. Most of the infrastructural systems demand higher performance and adaptability to natural hazards. Explicitly, the geophysical events (earthquakes, tsunamis), and events related to climate change (droughts, floods) can have catastrophic effects on the infrastructural competences of a structure. However, the natural systems, with its self-repairing adaptability, can preserve its multifunctionality without imperiling the ecosystem and thus be more resilient. Consequently, the adaptation methodology of the bioinspired mechanisms can be an effective solution in developing completely evolved systems with higher resilience and higher performing capabilities.

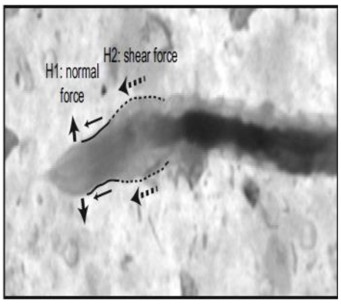
The level of abstraction could be from the anatomy of the natural forms, or from the behavioral response to an external stimulus. Nevertheless, the abstraction is mostly made on parallel contexts, but the performance and other constraints need to be perfected to meet the technological and environmental feasibility. The present study focusses on the review of the various natural analogies and their significance to engineering performance and also the feasibility of the abstraction of tree root anchorage system into the functional domain of the geotechnical foundation system. Furthermore, the functional augmentation of foundation system based on the tree-root biomechanical aspects are focused for application in coastal areas.

2 Geotechnology and Biological Analogies

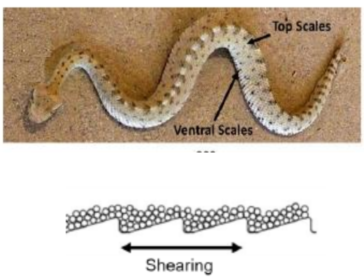
Certain biological processes are intriguing examples and inspiration to modern structural forms. Additionally, the fact of sustainability and resilience are visibly embedded in the natural forms in comparison to engineered structural forms. Most apparent analogy would be the termite mounds made of natural materials (Fig.1a). The natural cementation properties of the mound soil, unique air circulation system inside the mound without compromising the intactness of the mound are some of the unique features of the termite mound [4-6]. The mounds are resistant to climatic changes with a very good temperature control as well. The major composition of the soil type contributing the mound is the clay with a small percentage of sand. The strong cohesion and plasticity of the clay platelets prevents the deterioration of the mound from the extreme weather conditions [7,8]. Efficient system of ventilation and thermal regulation of the buildings and much lesser energy consumption are the key take away bioinspired features of the mounds and thus opens up new paradigms for an integrated structural form [8].

Field investigations in remote access sites are a frequent problem encountered in the construction sites. These issues mandate a well-developed, self-penetrating probe to provide access to isolated locations and better performance of the in-situ techniques such as the CPT (cone penetration test) or DMT (Dilatometer test). Bioinspiration technologies have been adopted in the development of self-penetrating site characterization probes. Many burrowing organisms have self-reaction propulsion mechanism, which allow them to burrow the soil (Fig.1b). The organisms progress the burrowing through penetration anchors and terminal anchors and soil fluidization due to water injection into the soil [9,10]. The generalized mechanism adopted by the organism includes radial expansion of the segment of the body to increase radial soil pressure, elongation of the tip of the body to progress penetration, radial contraction, radial pressure relaxation and retraction of the tip. These sequential motions help in furthering the penetration process. The mechanism differs with the type of soil; in cohesive soil, the radial expansion generates the tensile stresses [11], for cohesionless soils, there is radial expansions, decreasing the effective stresses [12]. This mechanism of movement could be adapted to perform mechanical analysis and development of self-burrowing probes. These bioinspired probes will be capable of generating enough reaction force within body to counter the soil pressure resisting tip advancement and mobilization of friction along the shaft [13].

(a)Termite Mound in Otjiwarango, Namibia. *(Image by Andrea Surovek.(Adapted Martinez,2019 [13])*



(b)Image of T. Mucronata burrowing *(Adapted Dorgan,2005,[11]).*



(c) Snake on sand and direction of shearing (*adopted from Martinez and Palumbo, 2018,[14])*

(c) Spreading roots of Mangrove trees [Adapted,Srikanth, 2015]

Fig 1. Depiction of various biological analogies in nature to geotechnical systems

The frictional interactions between the soils and the construction materials are a major influencing factor in the design of geotechnical structures, specifically for the geotechnical applications such as the deep foundations, soil anchors, landfill slopes etc. The interfacial frictional properties also govern the construction processes such as the pile driving, tunneling and reinforced soil structures [14]. The shear strength parameters of the interface are influenced by the surface roughness and hardness of the construction material [15,16]. Many studies have been carried out to understand bioinspired surface profiles that induce anisotropic soil-structure interactions ([14,17,18]. The anisotropy effects in the solid-solid interface frictions are greatly inspired from the snakeskin and its movement stimulating features [14]. The reptile uses its ventral scales, the transversely elongated scales to reduce the frictional resistances during their forward movement to reduce energy disbursement (Fig.1c). These scales also aid the reptiles in generating high frictional resistance to generate the reactions for movement, depicting a large degree of frictional anisotropy [14]. These adaptive technologies can aid in the reduction of energy consumption, in the way of less and more frictional resistance during the installation and service life of geostructures.

2.1 Role of tree roots in geotechnical Engineering

The analogy of the root system to the foundation system has been explored significantly and numerous approaches have been attempted to abstract the parallels in a broader perspective, the tree root system provides excellent anchorage to the substrata and also secures the strata in place, this helps in securing the slopes against failure in hilly terrains, man-made slopes and river banks. The root architecture governs the tree stability under severe horizontal loads (wind) apart from vertical loads and moments. Vegetative blanket stabilizes the soil against shallow landslides and hydraulic erosion. The plant roots traverse the potential slip planes and contributes for the slope stability. The plant root architectural traits and root strength are the major parameters which could be attributed to the slope stability. The binding network of roots provides stability of the aggregates [19,20].

The biomechanical adaptation of the root system of the specific species of trees such as the Pinus Pinaster or the Arecaceae family (Palm trees makes it highly adaptable to strong winds in the coastal regions. Wind firmness of a tree has a direct relationship with the root architecture and complete anchorage system of the roots [21]. Tree damages due to major storms have been commonly witnessed in many places. Studies carried out by Danjon et al on reportedly damaged and undamaged trees during a storm revealed the structural adaptation of the tree roots to the prevailing wind conditions and soil profile. The bio mechanics of the tree roots depends on many localized factors, however the root architecture developed by the trees are irregular and can develop T-beam, I- beam shaped diametrical reinforcements in the shallow roots in response to the wind movement [22].

The role of mangroves in protecting the coasts against storms, tsunamis and coastal erosions have been widely studied by many researchers [23,24]. The unique root system with its large spread plays a major role in flood control and promotes sedimentation [25] The dense fine root system helps to bind the soils and slows down the water inflow and thereby reducing erosion. The hydrodynamics of the tidal regions are modified by the mangrove roots, causing deceleration of the tidal waves. The bio inspiration of the mangrove root system adaptation through artificial mangrove banks can be a sustainable solution to seawalls and resilient coastline structures. Root morphology of the prop root is crucial in determining their rigidity under hydrodynamic loadings. The c/s of the prop root indicate a stiff woody annular section which contributes to the strength of the entire prop system. They are characterized by high modulus and tensile strength, contributing for the intactness even during Tsunamis [26].

3 Application of Tree Root System to Foundation Practices

The present study specifically focusses on the root architecture of the Palm trees and its engineering abstraction to foundation systems. The palm tree roots are wide spread with large number of short roots spread laterally at a shallow depth. This acts as an anchor system and helps in securing the soil. The stem structure and the heavy anchoring base of the tree helps the trees to bend to 40 to 50 degrees without snapping in the event of a storm [27]. Fig.2 and Fig. 3 represents the schematic of the typical root distribution in a Palm tree and also the root to bulb ratio of the Palm tree. The root to bulb ratio is measured as 2.5 to 4 as an average based on real measurements by the author.

3.1 Adaptation to foundations in loose sands

The foundation structures are susceptible to heavy winds in coastal areas. Slender structures like pylons, transmission towers, wind turbines in sandy deposits are often subjected to large overturning moments due to excessive cyclic lateral loads. Bridge foundations are often subjected to excessive scouring. The typical pile foundations or screw foundations could cater to the uplift of these foundations; however, a more efficient foundation system could be a better option and cost effective in all these cases. Fig.4 gives the schematic of the evolution and optimization of the adaptation of the root system to the foundation design. The main objective is to abstract the gripping effect of the root system into the foundation design. The grippers provided at the base of the foundation can simulate the root architecture and help in gripping the loose sandy soils. This can add additional resistance to the soil and thus augment the bearing capacity of the soil. The effectiveness of the additional grippers would be based on the material of the grippers, its way of attachment to the foundation base. On an experimental basis, a series of pullout tests on foundation would be able to quantify the efficiency of the technique. The failure mode of the gripper foundation could be evaluated through the tank-based tests. The Terzaghi's bearing capacity equation could be theoretically modified based on the addition of the friction derived at the foundation gripper base and the soil. However, this requires continuous fine tuning of the adaption of the techniques experimentally, evaluation of the mechanical properties and final upscaling to field implementation.

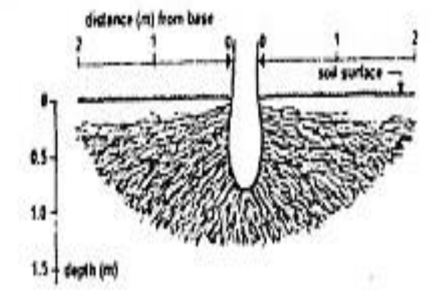


Fig.2. Schematic presentation of the rooting spread pattern of adult coconut palm (*http://agritech.tnau.ac.in/horticulture/horti_pcrops_coconut_botany.html)*

Fig.3. Root Bulb to stem ratio

4 Conclusion

The present study mainly focusses on the concept of bioinspired technology in the engineering system, specifically in the geotechnical design. The primary objective for these adaptations would be to have a more resilient structure in the event of geophysical and climatological events. The geotechnical infrastructural development always demands a higher performance and competence. Apart from outlining the bio-inspired analogies in the geotechnical domain, the main focus is on the abstraction of the tree root analogy to the foundation system. The foundation system in the coastal areas, erosion prone river beds requires further augmentation to provide a more efficient system to resist the external forces. The gripping effect of the roots of the palm trees and mangrove trees in securing the in-situ soil from lateral movement and erosion could be adapted to conventional foundation structures. This could also be theoretically developed based on Terzaghi's bearing capacity equation. The experimental evaluation of the abstraction technology, failure patterns could also be modelled adopting 3D finite element analyses which is the further scope of this literature review.

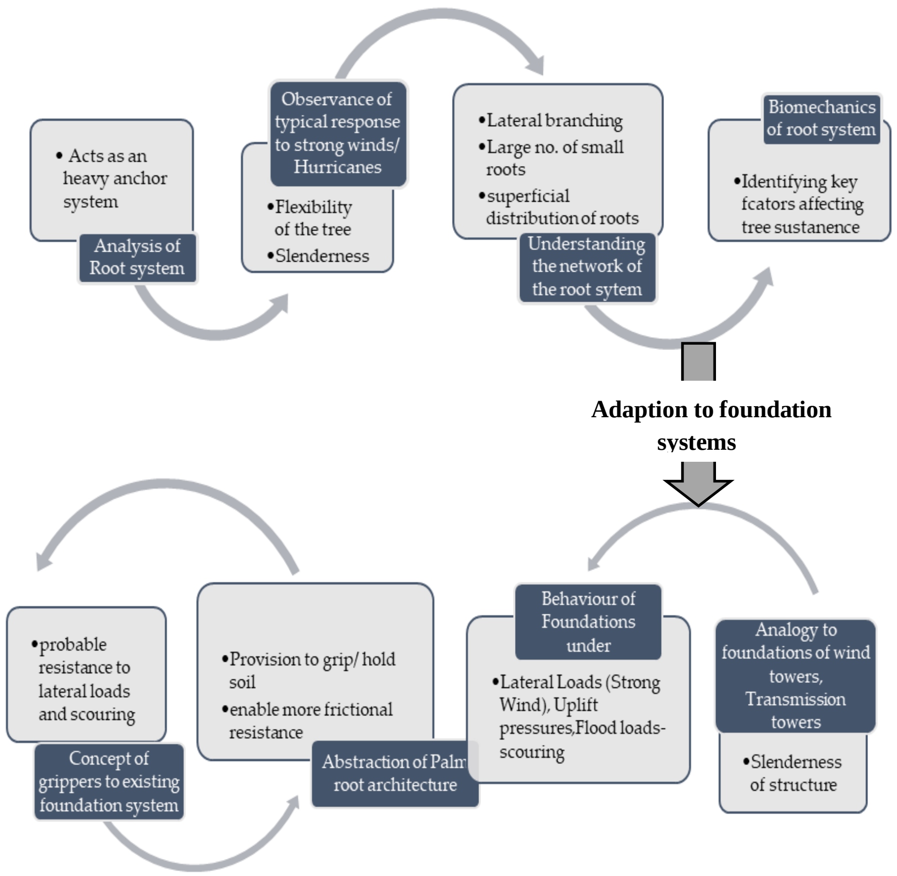


Fig.4. Evolution strategy of bio-inspired solution for foundation systems from palm tree roots

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