An examination of the foundations of mega-flora; implications for biomimetic geotechnics

Bret N. Lingwall

Assistant Professor, South Dakota School of Mines and Technology, 501 East St. Joseph Street, Rapid City SD 57701, 801-867-4249, bret.lingwall@sdsmt.edu;

ABSTRACT

The foundation systems of mega-flora (i.e. very tall or large trees), have long been used as an analogy for modern shallow and deep foundations. Terzaghi referenced trees as the model for footings and pilings. However, the topology, form, materials, distribution, and function of the natural foundation system have very little in common with the shallow and deep foundation systems that geotechnical engineers design and construct. These natural foundation systems are resilient, robust, and adaptable; ideal templates for a new generation of anthropogenic foundation systems and new understanding of soil-structure interaction. In an effort to further biomimetic geotechnics, this paper will present a review of the actual topology, form, materials, distribution, and function of mega-flora foundations, highlighting key differences with man-made foundation systems, materials and designs. This paper will dispel common myths about these natural structures, giving engineers insights into their performance under complex and extreme loads. Several key species will be highlighted, with unique aspects of each species' foundation system highlighted. Field measurements and observations of several natural foundation systems are included in the paper to highlight recent findings about these remarkable systems.

INTRODUCTION

While humans seek resiliency and sustainability through simplification and order, the diversity and complexity of natural systems is what makes them resilient and sustainable. This dichotomy has been noted in the past (NAE 1996, FHWA 2018) when examining natural organisms and systems to inspire engineered systems and materials. Nature has provided an avenue for developing analysis methods, materials, models and systems that provide resilience to extreme events and diverse load conditions at a minimum of resources to construct. Wordsworth once penned: "*let nature be your guide*." In Bio-inspired engineering and design, engineers study biological principles to develop new technologies (famous examples include microbial calcite precipitation and articulating roof structures in large modern stadiums). In biomimicry, engineers study biological behaviors, materials, and systems and mimic these behaviors, materials, and systems in anthropogenic materials and systems (famous examples are biomimetic robots). Lastly, if an Engineer is Engineering in Nature's Way, the engineer uses biological principles, systems, and organisms directly to accomplish modern outcomes to engineered systems (famous examples include shore restoration projects for storm surge protection).

Bio-inspired geotechnics and biomimetic geotechnics are new sub-fields within geotechnical engineering that use natural systems, materials, and organisms to develop new technologies and new ways at looking at traditional geotechnical problems and solutions. Most readers will be familiar with Microbially Induced Calcite Precipitation (MICP) as the most prominent of the bio-geotechnical technologies developed since 1990 (see Stocks-Fisher et al. 1999, Bang et al. 2001, and Anderson et al. 2014 for details on the technology).

One area of geotechnical engineering that is most in need of new materials, designs, methods, and concepts is foundation design and construction. Conventional foundation design focuses on conventional shallow and deep foundation systems (see Figure 1 for examples). This simplified cartoon shows examples of foundations that are being designed, analyzed, and constructed today in much the same way as they were when the pioneers of the profession were working (Tschebotarioff 1951, Sowers 1961, and Peck et al. 1973). Industry and academia have become extremely efficient in incremental advances in research, design, and construction of conventional foundations, but innovation has stagnated. Meanwhile infrastructure costs using conventional foundations continues to increase (Long 2017). Limitations to conventional foundations for specific hazards, site conditions, locations and areas of the US and world, resource availability, etc. are well known, while geotechnics is one of the riskiest of all engineering fields (Insurance Journal 2018, GBA 2018). Foundation failure is a prime cause of civil engineering industry litigation. In all industries, stagnation is a recipe for loss of economic value and power that leads to marginalization (Danning, 2018, Cho and Pucik 2005, and Jin et al. 2004). The solution to this lethargy may lay in the ubiquitous foundations of Mega-Flora, the very large and/or tall trees that were the original inspiration for piles and caissons. These foundation systems have been optimized by eons with a minimum of materials and disruption, while providing resistance to enormous vertical and lateral loads. Furthermore, as mega-florae are extremely adept at withstanding natural hazards (Stoffel et al. 2010), these foundation systems promise to deliver better extreme event resilience. A new generation of anthropogenic foundation systems can be inspired by these natural systems.

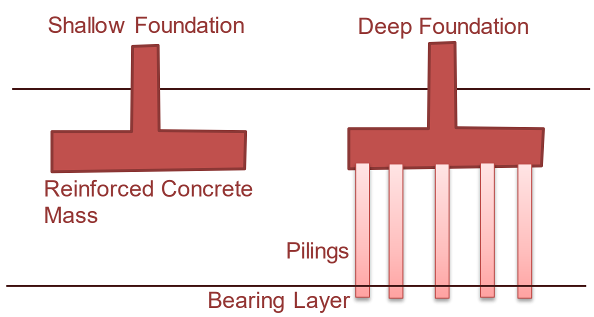

Figure 1. Examples of anthropogenic foundations

The western United States is home to some of the world's great mega-flora such as: giant Sequoia (*Sequoiadendron giganteum*), coast Redwood (*Sequoia sempervirens*) ancient Bristlecones (*Pinus longaeva*) in California; towering Douglas Fir (*Pseudotsuga menziesii*) of Cascadia; and the iconic pines (*Pinus ponderosa*), spruces (*Picea engelmannii*) and Aspen (*Populus tremuloides*) of the Rocky Mountains. These mega-florae are resilient to natural hazards while producing some of the largest and tallest organisms on earth (Flint 2002). The unique foundation systems of these species and organisms, are a vital component to the successes (Canadell et al. 1996). However, scientific information on the structure of the coarse roots systems (1^{st} and 2^{nd} order roots) that compose these foundations and their role in structural stability is sparse. Colloquial and parenthetical information on these natural structural foundation systems abound, but there is a paucity of scientific data pertaining to how the root systems contribute to the structural system of the massive organism.

FUNCTION AND PURPOSE; FORM AND SHAPE

Bio-inspired engineering research that carefully examines tree roots has tended to focus on the strength of a root reinforced soil (Liang et al. 2017), using root banks as an analogy for retaining walls (Pollen and Simon 2005), or in shallow slope stabilization (Gray ad Sotir 1996, Cohen and Schwartz 2017). Studies on these aspects show that root reinforcement strengthens soils and slopes, while reducing erosion. Recent work by Liang et al. is notable as they used 3D-printed fine root structures of herbaceous shrubs in geotechnical centrifuge modeling for understanding shallow slope reinforcement. Their experiments show that the root structures can be more efficient than typical anthropogenic slope stability mitigation techniques. Notable research is the work of Wu (Wu et al. 1988a, b, Wu et al. 2005) who performed excavations of small tree root systems. Exhumed roots were placed in a small chamber where pull-out tests were performed. However, the studies did not characterize the interaction of the soil along the root, nor did the study evaluate straining within the material. The work showed that pull-out resistance was impressive, giving credence to the hypothesis that roots can be a basis for improved foundation systems. Literature from the fields of forestry and ecology on coarse root structures is rich on some topics (such as how the root structure is involved in the physiology of the organism), while nearly void on others (the role of the roots on the structural stability). There are a few studies on the role of the roots on structural stability (Enos 2000, Hollis and Turner 2018) showing the effectiveness of the natural system under wind loads. Studies in these fields have paralleled those by engineers on reinforcement and erosion mitigation (Giadrossic et al. 2009, Hales et al. 2009, Eab et al. 2015, Fattet et al. 2011). Other studies have investigated anchorage against uplift (Crouzy et al. 2015, Jaes et al 2013, Spatz and Bruechert 2000).

However, misconceptions persist when using the course roots of a large tree for bioinspired foundation design. While it is true that the course roots of trees are intimately involved in extraction of water and nutrients and soil, this is not the sole function. Indeed, biologists know that trees have transferred much of that functionality to fungi that coat the roots (Ma et al. 2018). As trees have transferred more biological functions to microbes, the importance of the coarse roots for structural stability has enhanced. Indeed, there are many examples of cases where the coarse roots of a tree are functioning more for structure than solely for nutrient uptake. Figure 2 shows a photograph of one such tree in a lake in British Columbia, where water is ubiquitous and easily available to the tree at all times, while the roots are anchoring and providing structural support to the tree in addition to serving as part of the physiological system.

Ponderosa Pine, White Spruce and Douglas Fir are common trees found in the western US that provide ample opportunity for study of the root systems and their role in structural stability in the foundations of mega-florae. When studying the coarse root systems of mega-florae, especially the three species highlighted herein, it becomes apparent that the colloquial conceptions of coarse root systems do not align with the topology and morphology (shape and form) of the actual organisms. Figure 3 presents three common perceptions of the shape and form of tree foundations. However, Figure 4 presents the actual reality (at least for one specimen of one species). The shape and form shown in Figure 4 is typical of the species, as the author has studied dozens of individual specimens in 6 US states, over the last 5 years, and found them to be consistent with the shape and form show in in Figure 4. Figure 5 presents one such case history of an exhumed Ponderosa Pine that lay in a sediment filled valley with rock deeper than 3m.

Figure 2. Example of a tree with 1st-order roots being used for structure. Source Unknown.

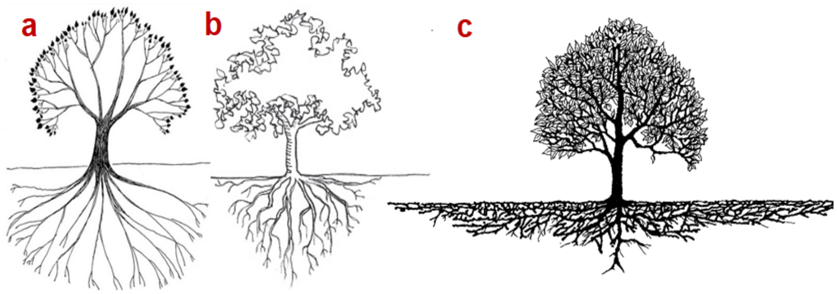

Figure 3. Three incorrect conceptual models of the mega-flora foundations. In (a) and (b), the roots are too deep. In (c), the roots may be too widespread, far beyond the dripline.

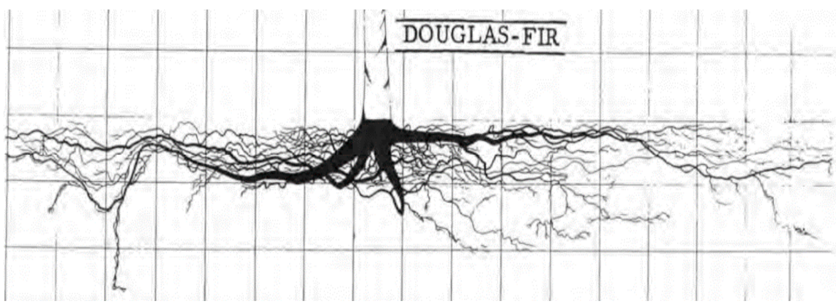

Figure 4. Actual foundation system of mega-flora (Berndt and Gibbons 1958). Maximum penetration is less than 1m. 90% of the coarse root biomass lies within the drip line of the crown.

Figure 5. Exhumed 1st order roots of a Black Hills Ponderosa Pine.

COMPARISON OF MEGA-FLORA FOUNDATIONS WITH OTHER PLANTS

If asked by a student or member of the public to describe a biomimetic foundation, most geotechnical engineers will describe one of the two foundation systems in Figure 1. However, Figures 2 to 5 and 7 show that the shape and form differ greatly from shallow and deep foundations. It is likely that some biomimetic confusion has existed amongst engineers due to common experiences in everyday life. If one is to examine easily available root systems such as nursery grown White Spruce and Douglas Fir ready for transplant to a homestead or Carrots and Dandelions plucked from the vegetable garden, a tap root is easily identified in all four examples. Figure 6 shows this taproot for a dandelion.

Tap roots are important physiologically for small plants, young trees, and a range of vegetation. However, these tap roots to not grow exponentially as a tree grows taller. Figure 4, 5 and 7 show that for mature trees, the remnants of the tap root remain past the initial stages of growth, but that the roots begin to extend outwards as the foliage crown expands to find water and nutrients that are more abundant at the edge of the foliage crown (where water from rainfall and snowmelt are most likely to be). Second order roots are known to penetrate deeper than 2 meters for large tress. However, the 1st order roots are more likely to spread out than penetrate deeply. This is logical, as any geotechnical engineer knows, increasing depth brings increasing effective stress and much more difficult "digging". Trees must conserve energy, thus deeper is not better, as the tree finds root growth easier at shallow depths.

Figure 6. The Root system of a dandelion (a tap root). This Photo by Unknown Author.

Figure 7 presents ground penetrating radar (GPR) mapping of the course 1st order roots of a Ponderosa Pine using the methods and recommendations of (Huisman et al 2003, Kernan et al 2012, Mary et al 2016, and Pawlik 2018) for mapping root structures. This 33m tall pine was found to have no mapped course roots deeper than 1.5 meters, but with the roots extending outwards from the bole upwards of 15 meters. GPR was validated to locating small diameter pipes and roots at 2-meter depths before field work per the recommendations of (Nichols et al 2017, and Raz-Yaseef et al 2013) prior to field work. Pot-hole visual confirmations of root depth and location were performed where available. GPR is ineffective within 0.5 meters of the bole, thus measurements at the bole are not available.

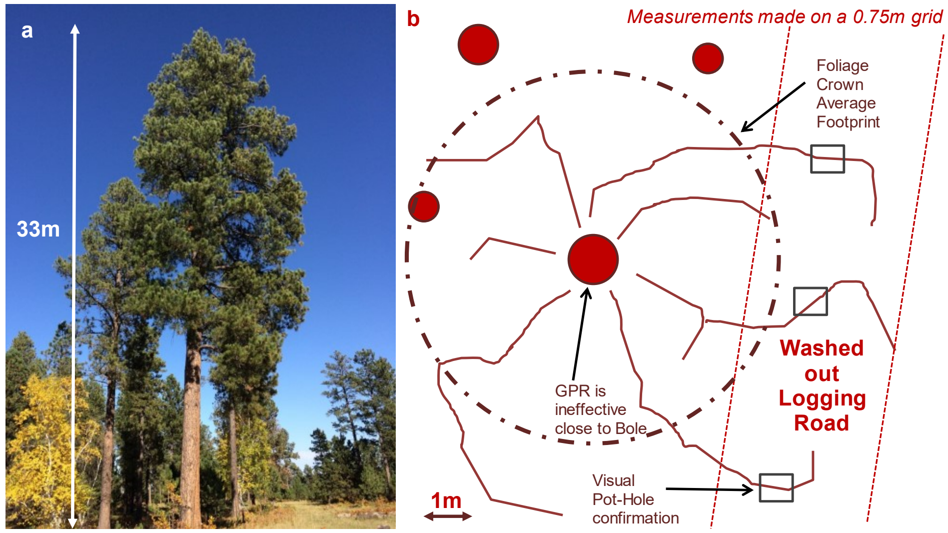

Figure 7. Results of GPR mapping of the coarse root structure of the 2nd largest *Pinus ponderosa* in the Black Hills of South Dakota (a). Boles of other trees shown on the map (b). Shape of the foundation can be seen in the plan-view map (b).

CONCEPTUAL MECHANICS

A review of the biomechanical literature for large tree course roots (Boldrin et al. 2017, Spatz and Bruechert 2000, and Ennos 2000) shows that the behavior of large tree course roots in structural stability lay in the capacity of the roots for developing axial tension and axial skin friction along the roots. Figure 7 shows that the roots of very large trees can extend great distances (up to 50% or perhaps greater of the height of the tree, extending beyond the dripline) rather than descending deep. Thus, axial compression is not a primary mechanism for the tree's stability. Granted, the compression of roots below the bole (see Figure 4) plays a role in the stability. Granted also that the moment (overturning) resistance of the roots beneath the bole play a role in the stability, it is the tensile strength and development of axial geotechnical skin resistance along the outside of the course roots that generate much of the structural capacity of the mega-flora foundation system.

For White Spruce and cousin species this is readily seen in toppled specimens that occur in windstorms. Figure 8 shows one such recent topple of a White Spruce set apart from a stand of spruces. Each tree in the area measures 25 meters or taller. Several spruces sit apart from the main stand. The specimen in Figure 8 had damage to its course roots from streambank erosion that none of the surrounding spruces had. Depth to rock at the site is about 2meters, but large cobbles are found in the upper 2m, limiting root anchorage opportunities into rock. Note that the roots under the bole have completely pulled out once the tensile capacity and geotechnical skin friction resistance were compromised approximately 5 meters from the bole.

MATERIALS AND MATERIAL PROPERTIES

Samples of the roots from the toppled tree in Figure 8 and trees in the area (both in stand and around the stand) were provided courtesy of the biologists at Custer State Park in South Dakota in collaboration with the United States Forest Service and the South Dakota Division of Forestry. Small samples of exposed roots were tested for moisture content, strength, and ductility.

Figure 8. Toppled Black Hills White Spruce in Custer State Park, SD. Toppled Spruce is located within an area composed of a large stand of the same species and several other specimens not within the stand. Many specimens in the area in excess of 25m in height, with some exceeding 35m.

Moisture contents in the fallen tree had reduced over time to 15% or less, but the moisture contents in the other tree roots met or exceeded 100% per the moisture content methods and definition used in forestry (USDA 1999). Compressive Strength and modulus perpendicular to the grain in the roots fallen tree were approximately 2MPa and 8GPa respectively using means in-part recommended by Boldrin et al. (2017), while strength and modulus in the standing trees were 16% to 20% less. It is known that the strength of wood increases as the wood dries, so these findings are consistent with known relationships (Green et al. 1989). However, the important observation in the field, supported by the literature (Madsen 1975; USDA 1999), is that as the wood of a root dries, it shrinks. This indicates that shrinkage may be a critical cause of the toppling of the tree in Figure 8. Much of the geotechnical capacity of a root is the increase in soil density and effective stress around the root as it grows. The volume expansion of the roots causes locally higher stress states around the root. Coupling of increased stress with the roughness of a bark-covered root lends to high frictional contact (as observed by Wu et al.1988a and 1988b). As the roots dry, they shrink, reducing the frictional contact and geotechnical axial skin friction capacity of the root. Despite the increase in strength of the elements themselves, the system weakens overall and collapse can occur. Rotting undoubtedly also plays a role in reduction of the structural capacity of the roots.

CONCLUSIONS

Engineers have much to learn about the mechanics, materials, and behaviors of the foundation systems of mega-florae, the very large and tall trees that we see every day, whose foundation systems are minimal compared to anthropogenic foundations that support similar axial, lateral, and torsional loads. Much of the foundation capacity of mega-florae comes from the axial tension capacity and axial geotechnical skin friction capacity of the course roots. As we learn more about tree roots and the role of tree roots in the structural capacity of mega-florae there are enormous opportunities for engineers and scientists to improve anthropogenic foundation systems. However, there is are enormous gaps in our understanding that must first be filled.

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