# Biologically-inspired insights into soil arching and tunnel stability from the topology of ant nests

## Insights biologiquement inspirés sur l'arcade du sol et la stabilité du tunnel à partir de la topologie des nids de fourmis

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ABSTRACT: The emergence of anthill castings as a popular and innovative art form has revealed the great complexity of the topology and architecture of the nests constructed by “wild” ants. Through detailed study of several nest castings as well as the soil in which they were excavated, this paper presents insights into the “expertise” in soil mechanics that ants have developed through the process of evolution. The magnitude of the capillary and frictional forces, estimated from grain size distribution and friction angle measurements, respectively, provide explanations for the mechanisms that these insects utilize to their advantage to excavate deep tunnels and sizable chambers in cohesionless soils. Furthermore, this paper presents measurements of the geometrical attributes of the nests that enhance their overall stability by means of soil arching. The insights gained in this study are complemented by preliminary Discrete Element Modelling and Network Analysis simulations which show that the combined mechanisms of capillarity, friction and soil arching can be readily exploited to make more efficient use of the underground space.

RÉSUMÉ: L'émergence de fonte de fourmilier comme une forme d'art populaire et innovante a révélé la grande complexité de la topologie et l'architecture des nids construits par des fourmis «sauvages». Grâce à une étude approfondie de plusieurs coulées de nids ainsi que du sol dans lequel elles ont été fouillées, cet article présente un aperçu de l '«expertise» en mécanique des sols que les fourmis ont développé au cours du processus d'évolution. L'ampleur des forces capillaires et frictionnelles, estimées, respectivement à partir de la distribution granulométrique et des mesures de l'angle de frottement, explique les mécanismes que ces insectes utilisent à leur avantage pour creuser des tunnels profonds et des chambres importantes dans des sols sans cohésion. En outre, cet article présente des mesures des attributs géométriques des nids qui améliorent leur stabilité globale par le biais de la voûte du sol. Les connaissances acquises dans cette étude sont complétées par des simulations préliminaires de modélisation d'éléments discrets et d'analyse de réseau qui montrent que les mécanismes combinés de capillarité, de frottement et d'arcs de sol peuvent être exploités facilement pour utiliser plus efficacement l'espace souterrain.

KEYWORDS: Bio-inspiration, ants, soil arching, tunnel stability, force chains, DEM, network analysis.

## 1 INTRODUCTION

Based on a couple of thousand years of experience, humans have developed innovative techniques to leverage the subsurface for a variety of beneficial functions. In contrast, nature has had the benefit of several billion years to initially design and subsequently evolve the manner in which flora and fauna practice subsurface engineering. This paper examines how nature has evolved its solutions and identifies enhancements that humans could better exploit in the future through a deliberate mimicking of what nature has achieved. In particular, a comparison of selected aspects of ant-soil interactions are used to illustrate where significant potential exists in the emerging field of bio-geotechnics. The paper describes some salient characteristics of the manner in which nature designs its technology solutions, and in turn, how this approach can be used to augment how humans conceive and design new processes.

As a measure of the interest in and potential for this approach, the US National Science Foundation funded four US universities (Arizona State University, Georgia Institute of Technology, New Mexico State University and the University of California Davis) through an $18.5M cooperative agreement to establish the Centre for Bio-mediated and Bio-inspired Geotechnics (CBBG) (www.biogeotechnics.org) to develop bio-geotechnical engineering processes and solutions inspired by nature to transform the design, construction, operation and maintenance of resilient and sustainable civil infrastructure and resource development systems. While CBBG is the first civil infrastructure focused initiative of this scale, bio-inspiration and bio-mimicry have periodically emerged as sources of solutions to human challenges, particularly in the past few decades. Well known examples of bio-mimicry include “Velcro” or hook and loop which was inspired by how plant burrs attached to animal hair, the shape of the leading engines of high-speed “Bullet” trains which were inspired by the shape of the Kingfisher’s beak and the directional adhesive on the feet of Gecko’s which enables robots such as the “Stickybot” to climb vertical smooth surfaces. A comparison of the interface between a plant burr and a textile and the hook and loop structure of “Velcro” is shown in Figure 1.

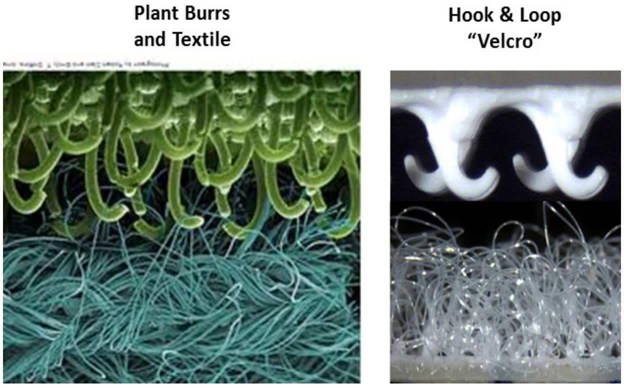


Figure 1. Comparison of plant burrs and “Velcro”.

## 2 ANTS AND SOIL MECHANICS

It has been estimated that ants use less than 0.1% of the energy that the most advanced human tunnelling machines do to excavate the same volume of soil. It is believed that ants are able to do so since they perform their tunnelling activities using a variety of approaches which seek to minimize the amount of energy expended at each step including tunnelling around obstacles, not removing particles that are deemed critical to supporting the surrounding soil particles (particles that are part of primary force chains) and creating clumps of several smaller particles as appropriate before removing them from the tunnel. These insights have been gleaned from both observing their behaviour while tunnelling and studying the characteristics of castings of the ant hill structures they create. Images of fire ant and harvester ant structures are compared in Figure 2.

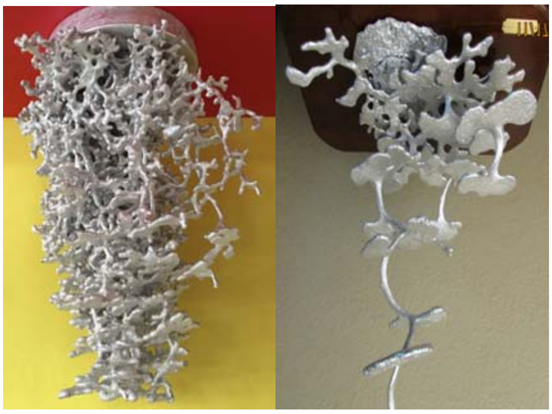


Figure 2. Harvester ant nest casting after removal of soil.

### *2.1 Ant Structure Topology*

As part of the present study, the topologies of a number of different any hill structures were quantified to provide insight into the complex structures produced by ants through their tunneling activities. Properties quantified included overall depth as well as maximum width and width variation with depth. To determine the incremental volume of the various ant hill structures as a function of depth, a technique which involved the gradual immersion of each structure in a container of water and recording the volume of outflow as a function of immersion depth was utilized. This yielded plots as shown in Figure 3.

From such results, other derived measurements including cumulative volume (Figure 4), normalized cumulative volume and shape normalized cumulative volume were derived to identify differences between the structures created by different ants in different subsurface conditions.

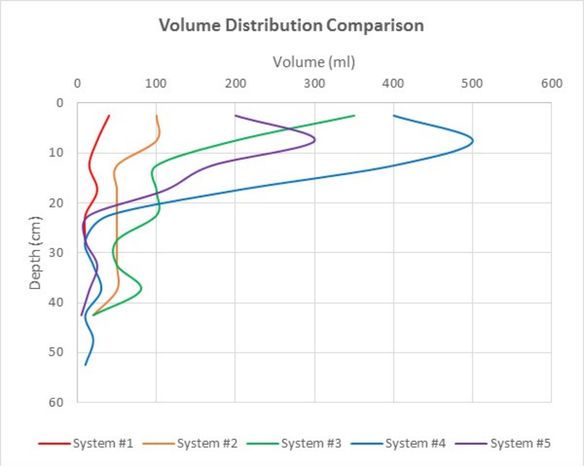


Figure 3. Incremental Volume-Depth Relationships of Structures

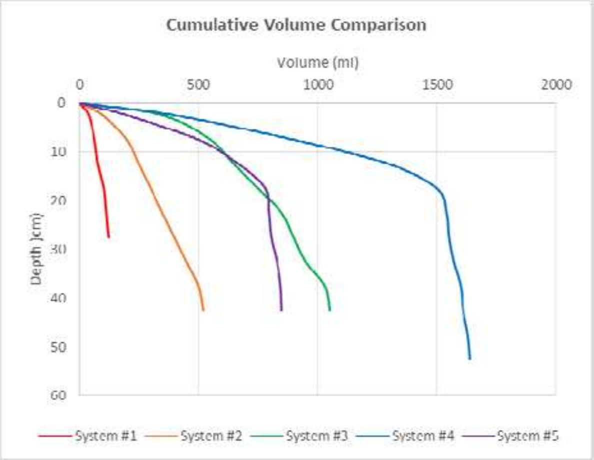


Figure 4. Cumulative Volume-Depth Relationships of Ant Structures

### *2.2 DEM Simulations*

In the current study, Discrete Element Modeling (DEM) simulations were conducted using PFC2D software (Itasca, Inc.) to model and analyze the effects of arching on the stability of cavities within granular media. Contact forces were calculated using a linear contact model. To construct the model, 10,000 particles, ranging in size from 0.004 to 0.01 times the container width, were randomly poured inside a rectangular container. Once the assembly reached a state of equilibrium, particles were removed to form a cavity and fixed parallel bonds were created at particle contacts in order to simulate capillary forces that enabled the formation of stable cavities.

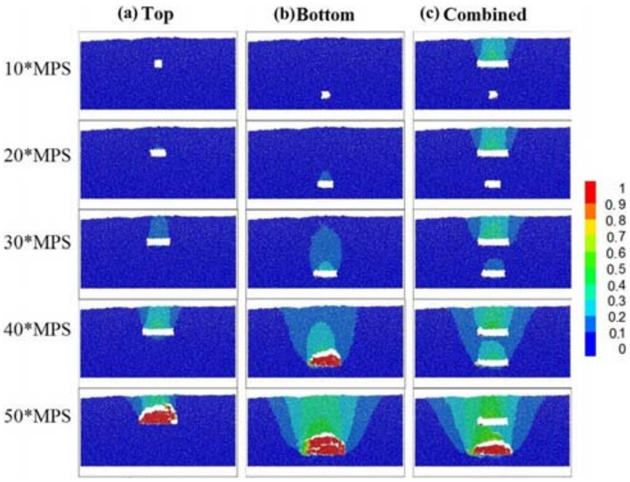


Figure 5. Particle displacements as a result of the presence of cavities at different locations.

As shown in Figure 5, the stability of cavities was examined in 15 different cases, consisting of cavities of different sizes and in different locations within the assembly. The width of the cavities was varied in proportion to the Maximum Particle Size (MPS) in multiples of 10. The height of the cavities was fixed to 10*MPS, while their width was varied from 10-50*MPS. For the combined cavity simulations, the upper cavities had a fixed width of 40*MPS. As shown in the figure, the top cavity collapsed when it reached a width of 50*MPS (Figure 5a), while the bottom cavity collapsed when it reached a width of 40*MPS (Figure 5b). The decreased stability of the bottom cavity as compared to the top one is a result of the higher overburden stress acting at the cavity ceiling. For the combined case (Figure 5c), the lower cavity was more stable than for the bottom only case (Figure 5b). In fact, the lower cavity for the combined case was stable at a width of 40*MPS and collapsed only when its width was enlarged to 50*MPS. The presence of the upper cavity altered the state of stresses in its vicinity, orienting the principal stresses horizontally around the rectangular cavity. This resulted in smaller vertical stresses acting on the ceiling of the lower cavity as compared to the case when the upper cavity was not present. This effect can be observed in the force chain maps, which are diagrammatic representations of the normal forces between particles, where thicker lines correspond to larger forces, as presented in Figure 6. The results of these simulations show that complex excavation geometries with overlying cavities promote stability by means of the modification of the state of stresses. It should be mentioned that the increase in stability was not observed when circular cavities were simulated, possibly because the zone of altered state of stresses was smaller. This is a compelling evidence that can explain the reason, as shown in Figure 2, why chambers in ant nests have flat and elongated shapes instead of spherical shapes.

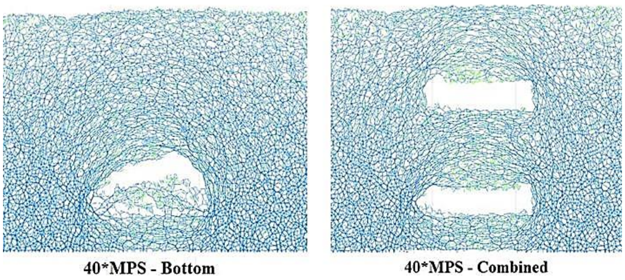


Figure 6. Force chains for single and double cavities.

### *2.3 Network Analysis and Tunnel Stability*

In network science, network analysis is the study of graphs representing the communication among nodes which are connected to each other through edges. This science has application in different disciplines including sociology, electrical engineering, and biology to name but a few (Butts, 2008; Merrill et al., 2008). In geotechnical engineering, a network of granular soil particles (nodes) are connected to each other through different types of particle-particle interactions such as normal forces, shear forces, and coordination number (edges). Of these, normal contact force (NCF) plays the most dominant role in the particles network structure. Figure 7 shows the network interaction of soil particle #1 with its four immediate neighbors through inverse of NCF. In the shortest path problem, this choice of particles network will be described.

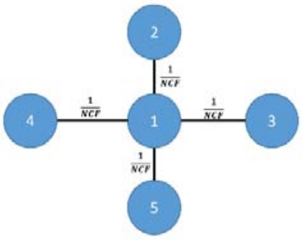


Figure 7. Network structure of soil particles

#### *2.3.1 Critical Pathways Analysis*

The shortest path determines "critical pathways" in granular material. In this study, the well-known Dijkstra's algorithm is applied to this purpose (Cormen et al., 2009). Figure 8 shows the hierarchical steps to compute horizontal critical pathway in a synthetic packed particle structure generated by the PFC software. Figure 8a and 8b show the stable structure of packed particles and resulting force chains, respectively, under a 50 kPa stress. All the top and bottom particles are connected to a source and sink node with the same edge weight (Figure 8c). Dijkstra's algorithm is applied from a source node to a sink node which leads to the computation of "failure path" shown in Figure 8d. The failure path consists of particles carrying the highest normal forcse by considering 1/NCF as an edge weight and the "weak path" consists of particles carrying the lowest normal forces with the NCF edge weight.

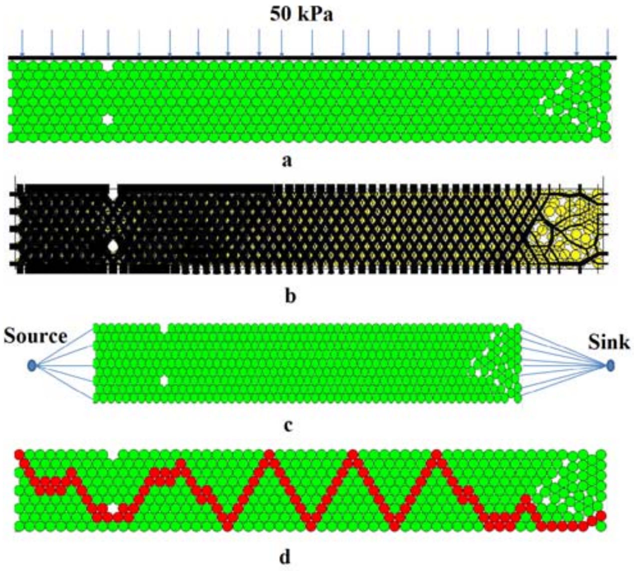


Figure 8. Failure path in horizontal direction

#### *2.3.2 Tunnel Stability Analysis*

According to studies by Espinoza & Santamarina, 2010 and Sudd, 1970, ants follow a "grab-rake-transport' sequence for removal of each particle. However, before removing any particle, they appear to perform a small test on each particle to measure how tightly a particle is held. In fact, ants choose particles carrying the lowest forces according to a classical mechanics perspective. In this study, critical pathway analysis is employed to show tunnel stability after removing the critical pathway. Figure 9 shows the vertical failure and weak path. By removing these critical pathways and letting the microstructure rearrange again to an equilibrium stage based on DEM, the particles movement are computed (color-coded picture in Figure 9). The average movement of all particles in the failure path analysis is calculated as follows:

$$\varepsilon = \frac{\sum_0^m \Delta d_i}{m}$$

where m is the number of particles, $\Delta d_i$ is the movement difference for each particle and $\varepsilon$ is the global movement threshold according to the failure path.

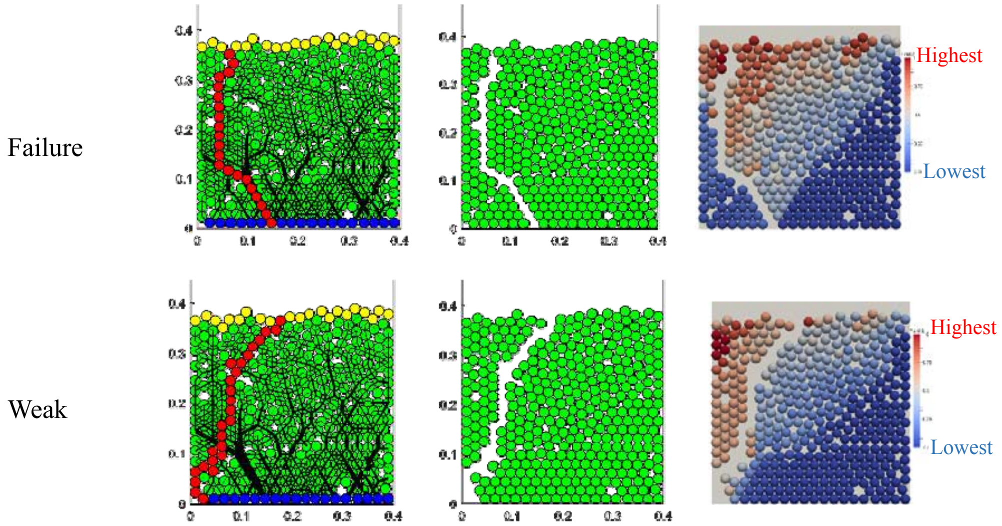
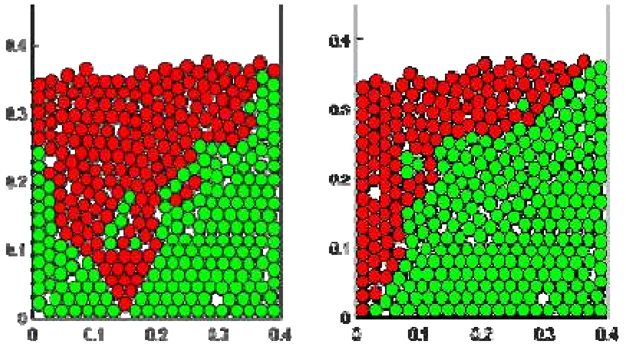


Figure 9. Vertical failure and weak path

Figure 10a shows that after applying the threshold, 47.7 percent of particles (red color) can induce microstructural instability by removing the failure path. In the case of weak path (Figure 10b), 32.5 percent of particles can lead to this instability. This study reveals that removing the weak path can reduce the structural instability by about 15 percent. Therefore, the explained particle picking choice by ants can significantly reduce the potential for tunnel collapse.



a b

Figure 10. Collapsed particles after reaching the equilibrium

## 3 CONCLUSIONS

This paper has presented findings from an ongoing study that is exploring how ants are practicing soil mechanics as they develop underground spaces. In that they appear to do so in a very efficient manner, developing an understanding of the principles they follow offers significant potential for humans to adapt our current techniques to more efficient and sustainable solutions. Based on the present study, a number of conclusions are provided:

- The topology of ant hill structures reflects the subsurface conditions (e.g. soil type, stratigraphy, density, moisture content) and ant type.
- The overall configuration as well as individual shapes of underground ant structure openings are optimized to take advantage of arching and other soil behavior phenomena to yield stable configurations.
- DEM simulations provide valuable insight into these phenomena and the observed topology of ant hill structures.
- Utilization of network analysis provides a complementary approach to extract insight into the principles that guide ants as they develop underground spaces.

## 4 ACKNOWLEDGEMENTS

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