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ANALYSIS OF FAILURE SURFACE OF PLANT ROOT ANALOG IN EXTENSION

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Summary: The attributes of fibrous root systems of plants were investigated for their potential incorporation into geotechnical applications that resist tensile loads, such as anchor foundations, piles, and soil nails. For this particular study, the morphological components of fibrous root systems were varied to identify their role on the global mechanical behaviour of soil during extension. X-ray tomography was utilized to capture the evolution of the failure surface both with displacement and as the root analog geometry was altered.

1. INTRODUCTION

Bio-inspired design offers a new paradigm with regards to engineering; instead of limiting the possibilities to our own ideas, why not utilize the existing evolved and optimized solutions of nature. Not only are extant biota multifunctional and adaptable, but they are also inherently in alignment with the environment, which is critical for today's world that demands an increasing direction towards sustainable and resilient infrastructure. Perhaps, the fibrous root systems of plants, which are effective at resisting pullout forces from herbivores, can provide geotechnical engineers with new insight for the design of more efficient foundations and reinforcement (Ennos 2000). Yet, much is still unknown about the mechanical behavior of fibrous root systems in extension and in particular, the various attributes of the root system that affect the uplift capacity. This paper presents a preliminary parametric study into the morphological parameters that contribute to an increase in the root pullout resistance of a fibrous root system analog. Three root models were fabricated using 3D printing technology with varying geometries. The failure surfaces of the soil as the root models were displaced upwards were captured using an X-ray CT scanner, and they were then visualized by performing digital image correlation (DIC) on 2D slices of the reconstructed, image sequence. The shape of the shear localizations for each case was analyzed, and mechanisms to explain the resulting surfaces were hypothesized. Characterization of the rupture surface is particularly relevant for the formulation of an analytical solution to predict uplift capacity.

2. EXPERIMENTAL METHOD

To perform this study, the authors utilized the X-ray CT scanner (i.e. Comscan ScanXmate D200RSS900) at the Port and Airport Research Institute (PARI) in Yokosuka, Japan. The experimental procedure consisted of 2 main steps: 1) the preparation of the soil container, comprised of a relatively dense Toyoura sand specimen ($D_R \approx 80\%$) with an embedded root analog, and 2) X-ray CT scanning of the soil specimen at every 0.5 mm of vertical, root analog displacement with simultaneous recordings of force and displacement. For each root analog, scanning was performed for a minimum of 9 increments for a total of 4.0 mm of analog displacement, which fully captured the ultimate uplift force and most importantly, the development of the failure surface. After scanning, the reconstructed 3D image set was radially resliced through the centers' of the soil specimen and root analog and parallel to the direction of displacement. Digital image correlation was performed on the sequential image set to determine local soil displacement. A quadrilateral "mesh" was generated using the displacement values at points, and then the incremental, local shear strain for each quadrilateral element was calculated.

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3. RESULTS

For this particular study, the internal branching angle and the number of branches were varied, and as both of these parameters were increased, the pullout resistance of the model root also increased. The local shear strain map captures the shear localization within the soil, which corresponds to the global failure surface. Interestingly, the shape of the failure surface is similar to that of shallow anchor plates exposed to uplift forces (Meyerhof and Adams 1968). In addition, the intersection of the failure surface with the root branch varied for each analog, which is hypothesized to be the combined effect of soil arching and the stiffness contrast between the soil and model root. Additional evidence for the occurrence of arching between the root branches for the various models will also be presented.

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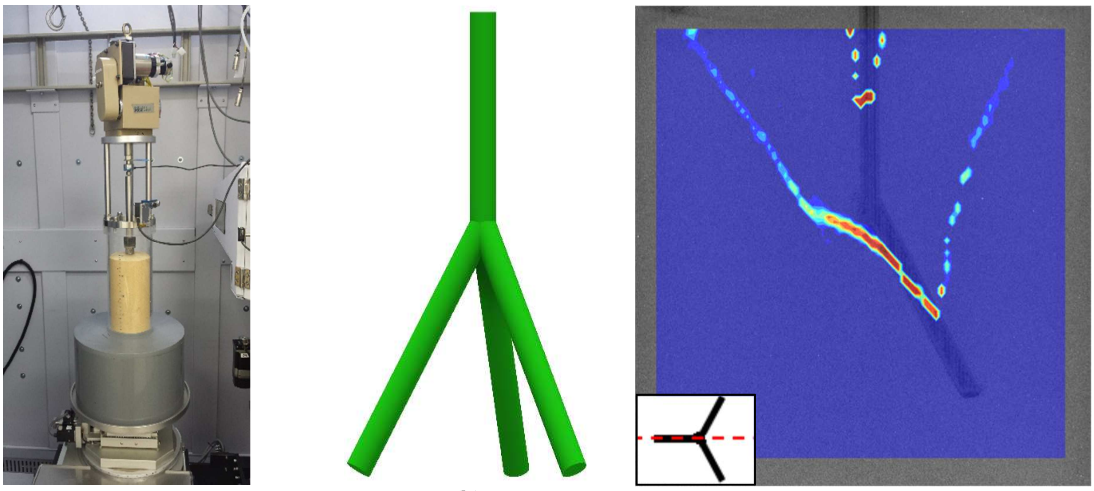

(a) (b)

Figure 1: (a) Experimental setup (X-ray CT scanner, acrylic soil container, and loading device with attached load cell and reflective-type photoelectric displacement sensor), (b) 3D model of fibrous root system analog, (c) X-ray CT image overlain with local shear strain map (model: 3 branches, 50mm branch length, 30° internal branching angle). The schematic in the lower left corner reflects the slicing plane (dashed line) in the XY plane of the 3D image.