Numerical investigation of failure mechanism during pullout of root inspired anchorages

Ilija Vego[1,*], **Francesca Ceccato**[1], **Paolo Simonini**[1], **J. David Frost**[2],
Seth D. Mallett[2] **and Simonetta Cola**[1]

[1] Department of Civil, Environmental and Architectural engineering (DICEA),
Università degli Studi di Padova
Via Marzolo 9, 35131, Padova (Italy)
ilija.vego@gmail.com

[2] School of Civil and Environmental Engineering, Georgia Institute of Technology,
790 Atlantic Dr. NW, Atlanta. GA. 30332 (United States of America)

Abstract By looking at nature, modern and sustainable engineering solutions can be developed. For instance, fibrous root systems, have inspired new prototypes of foundations, tiebacks or anchorages. A possible configuration of these innovative shapes is a central shaft branched out with multiple arms. Small-scale experiments have shown how root inspired anchorages can bring benefits in terms of pullout capacity and material efficiency (Mallett et al., 2018). However, the failure mechanism of the pullout of these anchors, is not yet fully understood. This paper contributes to examining this issue by means of numerical simulations conducted via the Material Point Method (MPM). Different geometries have been investigated, such as a 3-branched, a 6-branched and a plate anchor system. Special attention is given to the volume of mobilized soil and the shape of the failure surface generated during the anchor pullout. The numerical results are compared with those of small-scale experimental tests presented in Mallett et al. (2018, 2017).

Keywords: root inspired anchorage, MPM, pullout

1 Introduction

In the last few years, new problems correlated to climate change and expansion of metropolitan areas posed considerable challenges for engineers. The solutions to such issues can be found by observing natural structures. Some researchers are currently looking at biology (for instance to ants, ant nests, worms or plant roots) in order to find inspiration and solutions to geotechnical problems (Frost et al., 2017).

This paper builds on recent experimental work on root inspired anchorage systems (Mallett et al., 2017; Mallett et al., 2018; Frost et al., 2017). The aim of these studies is to design new bio-inspired prototypes for deep foundations or anchorages, taking inspiration from plant roots. Roots are indispensable for a plant. They have evolved to provide sustenance, water and resistance from wind or uprooting by herbivores (Ennos 1990, Ennos 2000). In particular, this research study is focused on plants characterized by fibrous root systems, such as the common pea (*Pisum sativum*) or maize (*Zae mays*), since they are particularly able to resist uprooting.

Small-scale experimental tests proved that root inspired anchorages have potential mechanical and material advantages over conventional anchorage systems (Mallett et al., 2018). Nevertheless, the behaviours and soil mechanisms involved while pulling out those new prototypes of anchors are not yet fully understood, due to issues that can appear while performing tests in a laboratory. In order to gain a better understanding of the failure mechanisms involved with these innovative anchorage systems, numerical simulations have been performed. This study applies the Material Point Method (MPM), which is a continuum-based particle method that simulates large displacements by means of Lagrangian material points (MP's) moving through an Eulerian grid (Sulsky, Zhou and Schreyer, 1995). The MP's carry all the information of the continuum; in contrast, the computational grid does not store any permanent information and can be redefined at the end of each time step. A review of the method can be found in Fern et al. (2019). The numerical analyses are performed herein using the dynamic explicit code Anura3D-v2019.2 (www.anura3d.eu), which implements a full 3D MPM formulation and is therefore suitable to simulate the three-dimensional soil deformations induced by the movement of the root-inspired anchorage elements. The software has previously been successfully applied for soil penetration problems and anchor pull-out (Ceccato, et al., 2016; Phuong et al., 2016; Ceccato, et al., 2017).

Numerical simulations allow for better visualization of what is happening under the soil surface. This paper presents and compares the results of the numerical simulations of a conventional plate and two different root-inspired anchors. The simulations allow for visualization of the sliding surface and the volume of sand that is mobilized during the anchor uplift for different shapes of the anchor.

2 Experimental study

This numerical study on root inspired anchors simulates small-scale experimental studies conducted at the Georgia Institute of Technology (Mallett et al., 2017 and Mallett et al., 2018). Taking inspiration from fibrous root systems, several anchors were designed. The prototype anchors were obtained by 3D printing with acrylonitrile butadiene styrene (ABS) thermoplastic plastic (Fig. 1a). Root anchorages are embedded in a soil test box (34 cm × 34 cm × 30 cm) filled with dry Ottawa F110 sand at a relative density of 80% and pulled out vertically at a displacement rate of 1÷50 mm/minute while measuring the resistance (Fig. 1b).

The experimental tests are designed to investigate how morphological parameters, such as the embedment depth, the anchor height, the number of branches, the branch length or the angle of branching affect the uplift behaviour.

The experimental study showed that root inspired models have promising advantages. Indeed, their resistance was found to be more than 3 times higher compared to linear straight shaft elements. Also, since manufacturing a root inspired anchor nominally requires less material than a plate anchor, branching brings benefits to the pullout capacity in terms of material efficiency. Laboratory tests proved that models with three branches are the most efficient geometrical configuration (Mallett et al. 2018 and Vego 2019). Notwithstanding these insights, through an experimental test program, it was problematic to understand the complete pullout behaviour, particularly the soil kinematic process, motivating a numerical investigation on root inspired anchors.

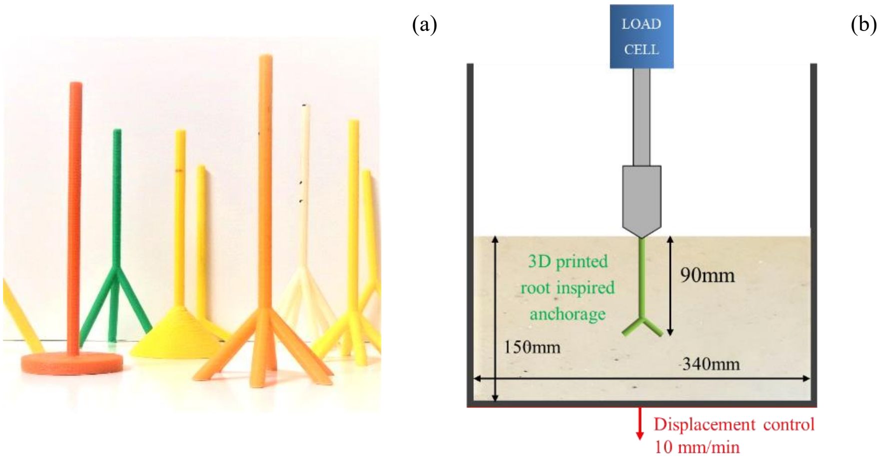

Fig. 1 3D printed anchorages examples (a) and sketch of the pullout experimental test (b)

3 MPM numerical study

Observing what happens below the surface of the experimental soil box is possible only by means of particular and sometimes expensive equipment. It was possible for example, to visualize the failure surface by performing digital image correlation (DIC) of the uplift process through x-ray scans (Mallett et al., 2017). In contrast, numerical simulations allow for investigation in more details of the root pullout behaviour, including the shear localization or the ultimate failure surface.

The experimental results led the numerical study to focus on three particular models: a conventional plate and two root inspired anchors, found to be efficient configurations. Both were characterized by a branching angle of 60° (the angle is the one between vertical and branch axes), but with 3 and 6 branches, respectively. The base width of all three models is 5 cm (Fig. 2).

The geometry of the numerical model replicates the experimental tests. Therefore, the embedment of each anchor is 9 cm. The soil domain, in which the anchor is installed, is 16,5 cm high and 17 cm wide (from the anchor vertical axis).

Moreover, by taking advantage of the symmetry of the problem, the computational effort can be reduced by considering only a slice of the real test. For the plate anchor a

20° slice was created, while for the root inspired anchors, the slices were of 30° and 60° (Fig. 2) respectively.

The domain is discretized into 4-noded tetrahedral elements. The optimal discretization has been determined by means of preliminary numerical analyses. The mesh size is smaller near the anchor (around 2.5 mm) where the x-ray scans showed that the deformation was significant (≈0.5 mm). Accordingly, 10 or 20 MPs per element are used near the anchor, where high deformation gradients are expected, while 4 MPs per element are used further away from the anchor.

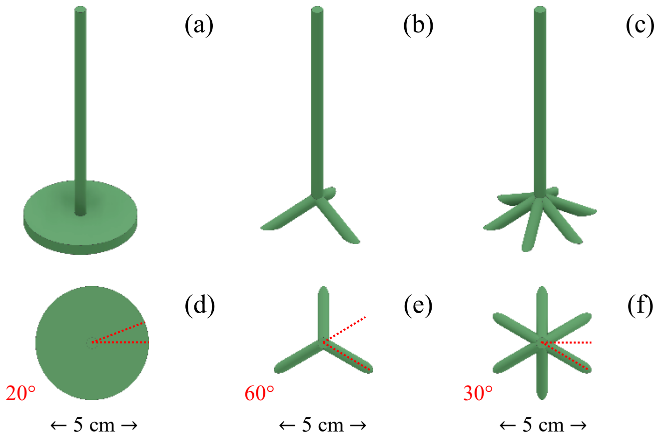

Fig. 2 Anchorages chosen for the numerical investigation and their respective top view and slice angle of analysis: plate(a)(d), root inspired with 3 (b)(e) and 6 branches (c)(f)

The prescribed velocity of extraction was applied to all MPs belonging to the anchorage element, so that the material could be considered completely rigid. The velocity rate is 0.01 m/s, which is higher than the value used for the experimental studies, where the rate was from 1 to 50 mm/minute. These laboratory tests were found to be rate independent, however the decision to use a faster value in the numerical model was made with the aim of decreasing computational time.

Table 1 Sand properties in the numerical model

Sand properties	
Material type	Dry material
Porosity solid [-]	0.376
Density solid [kg/m^3]	2000
K_0 value solid	0.5
Material model solid	Mohr - Coulomb
Young modulus [kPa]	20000
Poisson ratio [-]	0.3
Friction angle [°]	31° or 51°
Cohesion [kPa]	0.01
Dilatancy angle [°]	0°

The computational efficiency is further increased by the mass scaling procedure (Ceccato and Simonini, 2019), with a mass scaling factor of 100, which allows for increasing the critical time step size by a factor of 10 times. The contact between the anchor and the soil is considered completely rough. Parametric analysis with friction coefficients equal to 0.0, 0.4 or 1.0 showed no substantial difference. Numerical sand properties of anchorage and soil are summarized in Table 1.

Simulations where performed using two different values for friction angle, 31° and 51°. Those are the critical friction angle (known by means of previous experimental tests) and the peak friction angle (analytically calculated by. a formula proposed by Bolton 1986), respectively.

4 Numerical results

The numerical simulations were divided in 20 load-steps, each lasting 0.025 sec. Therefore, with a constant prescribed velocity of 0.01 m/s, the maximum extraction displacement was 5mm, a value sufficient to reach or exceed the peak resistance in each experimental pullout test. The advantage of using a numerical method (in this case 3D MPM) is the possibility of analysing the uplift behaviour of root inspired anchorages. In this paper, the aim is to visualize the size of the volume of mobilized soil and the shape of the sliding surface developing during the extraction. Therefore, primary attention was given to MPs displacement, building contour maps and focusing on particles with a magnitude displacement greater than or equal to 1×10^{-2} mm, which was considered the value at which the MP displacement could have been considered significant or not.

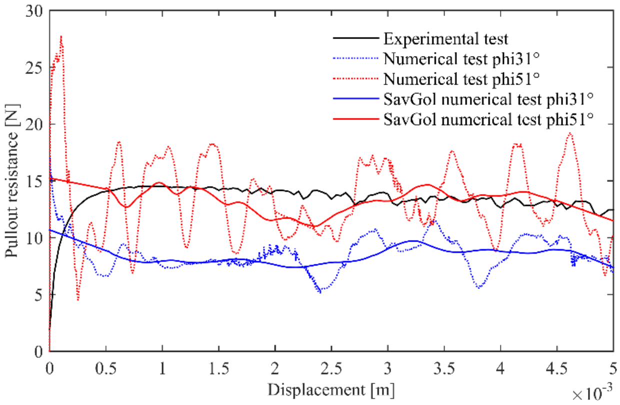

Fig. 3 Experimental and numerical pullout resistance for a 6-branched root inspired anchor

As previously indicated, three different anchorages were analysed, each one for two values of friction angle (31° and 51°). Plotting and filtering the numerical pullout resistance of a 6 branched anchor reveals how a simulation with φ=51° yields results closer to the experimental test than one with φ =31° (Fig. 3). A Savitzky-Golay filter was used to post-process the results, due to the high-oscillations caused by the mass-scaling effect.

Fig. 4 and Fig. 5 show the MP displacement contour map for each design analysed. Each anchor is coloured in purple, since they have reached the maximum displacement (5 mm). Going radially outwards the MP displacement magnitude reduces. This reduction is more significant for the root inspired anchors compared to the plate anchor.

As previously indicated, a MP has been considered mobilized only if its displacement magnitude was higher than 1×10^{-2} mm, a value 500 times smaller than the maximum. All anchorages, even the root-inspired ones, create a circular profile on the soil top surface, regardless the presence of branches. However, branched anchors mobilize a smaller number of MPs (therefore volume of soil) than a conventional plate anchor (this is even clearer for the case of $\varphi = 31°$ than for $\varphi = 51°$).

The evolution with time of the shearing surface was also observed (Fig 6 and Fig 7). While extracting a root-inspired model, the shearing surface does not go immediately outwards, like it does with the plate anchor, suggesting a later and slower formation of the failure surface.

The maximum radius of the failure surface from the centre is ≈8.5 cm, ≈5 cm and ≈6.5 cm, respectively, for plate, 3-branched and 6-branched anchors, for the case of friction angle 31°, while for friction angle of 51°, they are ≈9 cm, ≈7.5 cm and ≈7.5 cm. It is clear that the mean radius of the failure surface of a root model increases with the number of branches, mobilizing a higher volume of soil, which means having a higher pullout resistance, but also losing importance in terms of efficiency, since the volume of the anchor itself is increasing too.

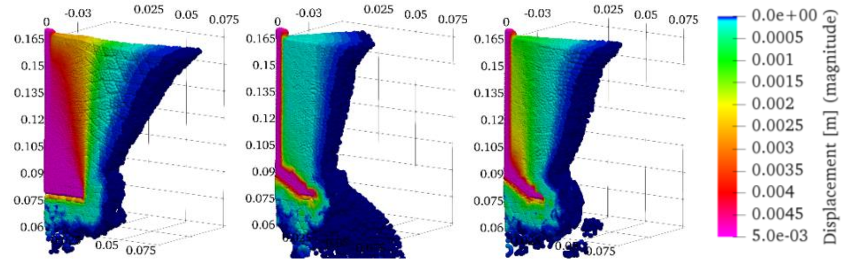

Fig. 4 Volume mobilized by the anchors (plate, 3-branched and 6 branched) during pullout (φ=31°)

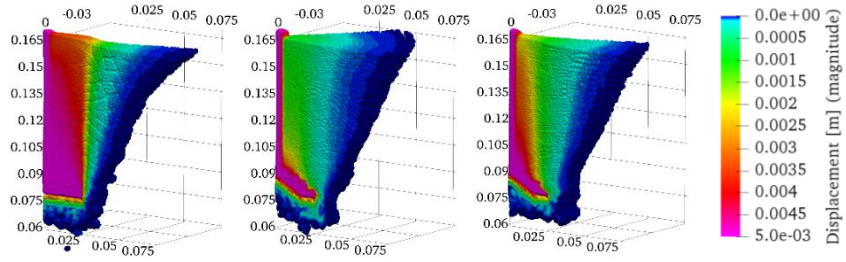

Fig. 5 Volume mobilized by the anchors (plate, 3 branched and 6 branched) during pullout (φ=51°)

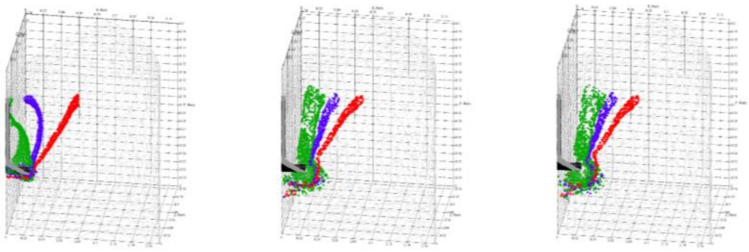

Fig. 6 Sliding surface evolution in time for plate (red), 6-branched (blue) and 3 branched (green) anchors, φ=31°

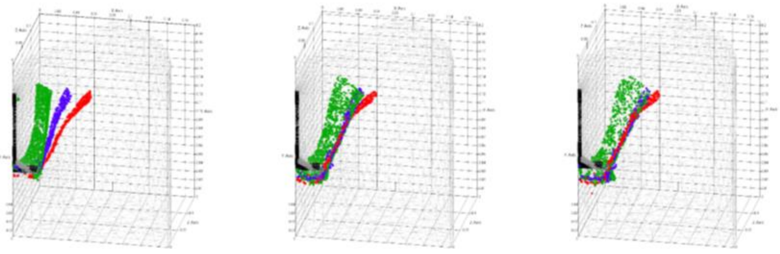

Fig. 7 Sliding surface evolution in time for plate (red), 6-branched (blue) and 3 branched (green) anchors, φ=51°

5 Conclusions

This paper shows how MPM simulations can be used to provide insight into the failure mechanisms of root-inspired anchorages. Experiments using branched anchors have proven to be of a high interest, especially compared to a conventional plate anchor.

The visualization of the process is easier numerically rather than experimentally. The shape of the sliding surface can be determined without any particular tool and isolated from all other objects that are around it. The size of the shear surface appears to increase with the number of branches and is influenced by the friction soil angle. Also, it has been shown that simulations (using the Mohr-Coulomb criterion) with a friction angle of 51°, can provide results of pullout resistance of an anchorage quite similar to the physical pullout experiments, despite the oscillations present due to the mass-scaling effect. Future extension of the research could focus on using more advanced constitutive models to better capture the stress-strain response of soil and softening behaviour.

Further, since the branches also have the capacity to bend, the effect of anchor stiffness can be evaluated. Finally, group-effects and full-scale behavior can be investigated numerically.

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