Mechanics of plant root pullout from soil

(M. Kinoshita, T. Yamaguchi, in preparation.)

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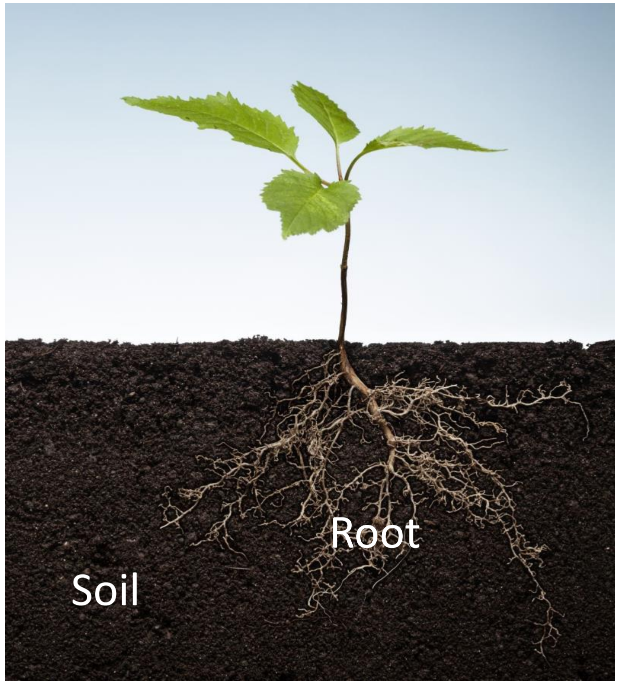
新学術領域研究
（複合）

Background: Mechanical functions of plant roots



Functions of plant roots
- Adsorption of water and nutrients
- Storage of carbohydrates
- Support of plant’s body
- Strengthening and Toughening of soil

Question:
How do plant roots support their bodies and toughen soil?


Landslide


Lodging of trees

Plant-Soil interactions are one of the most important topics in
- Forest Science
- Crop Science
- Geoscience
- Civil Engineering

Background: Previous studies on root mechanics

<u>Experiment</u>

- Force-Displacement characteristics
- Geometrical factors
- Model root

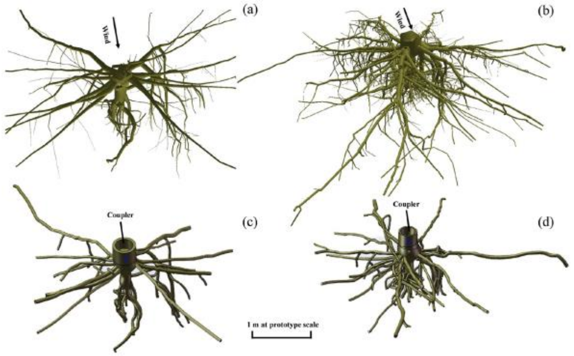
<u>Mechanical/mathematical modeling</u>

- Soil mechanics + Simple root geometry
- FEM/DEM simulations
- Root Bundle Model

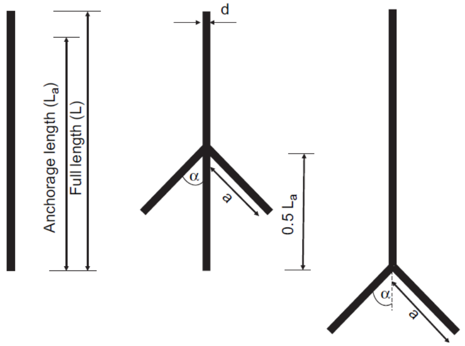
However,

- Details on **structure-soil interactions**
- Effect of **geometry and elasticity of roots**
- **Theoretical features**

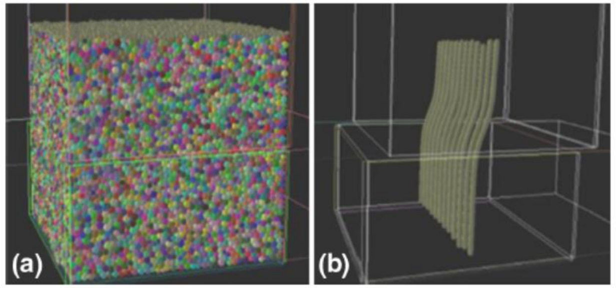
have been poorly understood.



X. Zhang et al., Plant Soil 456:289-305 (2020)



S. B. Mickovski et al., Eur. J. Soil Sci. **58**, 1471 (2007)



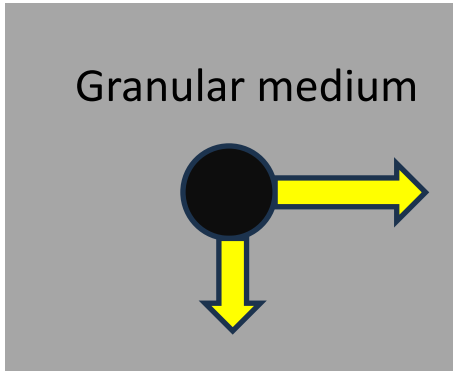
Z. Mao, M. Yang, F. Bourrier, T. Fourcaud, Plant Soil **381**, 249 (2014)

Background: Granular physics viewpoint

Resistance force acting on granular matter

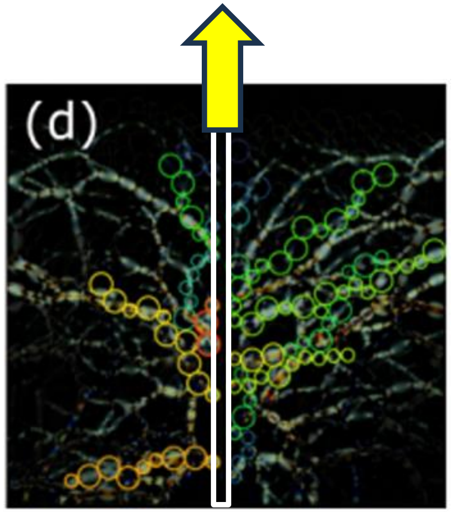
Cyrindrical/Spherical object in steady motion

T. A. Brzinski et al., Phys. Rev. Lett. 111, 168002 (2013)



2D photoelasticity experiment during pullout of a rod

F. Okubo, H. Katsuragi, Modern Phys. Lett. (2020)



F. Okubo, H. Katsuragi, Modern Physics Letters B, (2020).

Objectives

- To investigate the effects of root structure and elasticity on the pull-out behavior.
- To elucidate the mechanisms in a quantitative manner.

Approaches

- Pullout experiments with systematic parameter change
- Theoretical description

A “Digged-out” tree root
(at Hokkaido University forest)

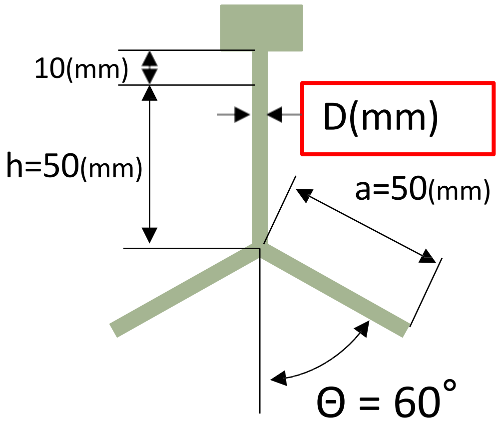
Pull-out experiment

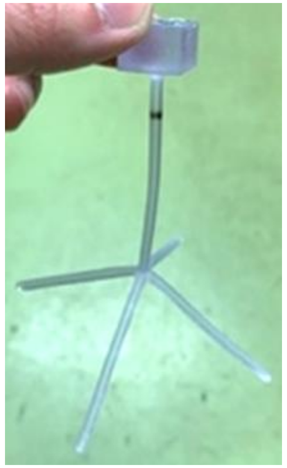
- Root → **3D printed model**

Fabricated with 3D printer (Form3, Formlabs)

Material: Resin (E = 808 MPa), Rubber (E = 25.5 MPa)

Diameter: D = 1, 1.5, 2, 3, 4, 5, 6, 7, 8 (mm)



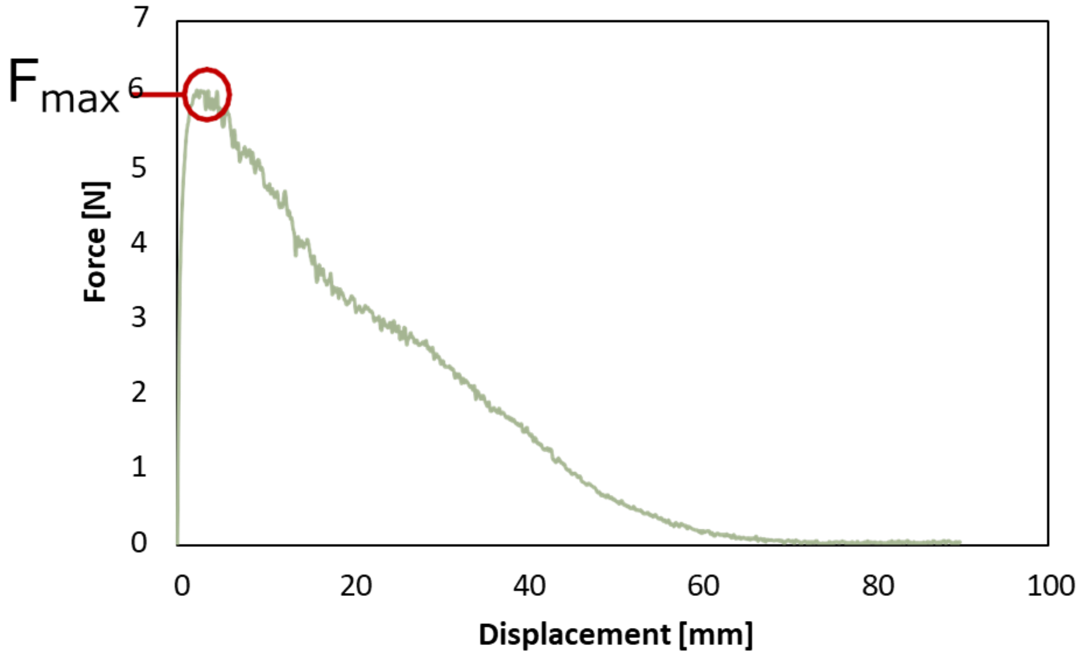


- Soil → **Glass beads**

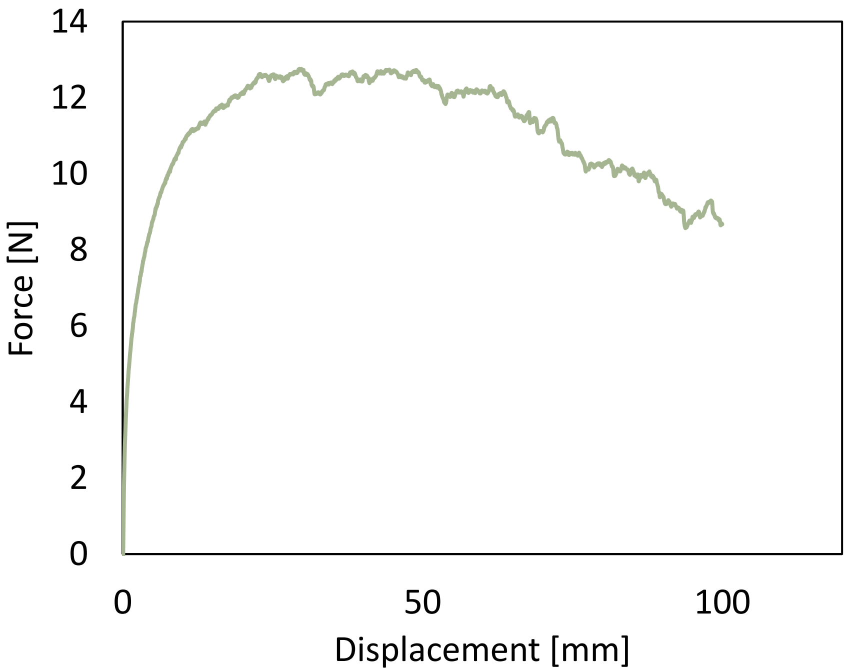
We mixed beads with three different sizes (0.2, 0.5, 1 mm) by 1:1:1 (in volume)

Pull-out behavior for our model and actual plants

3D-printed model root



Actual Plant root

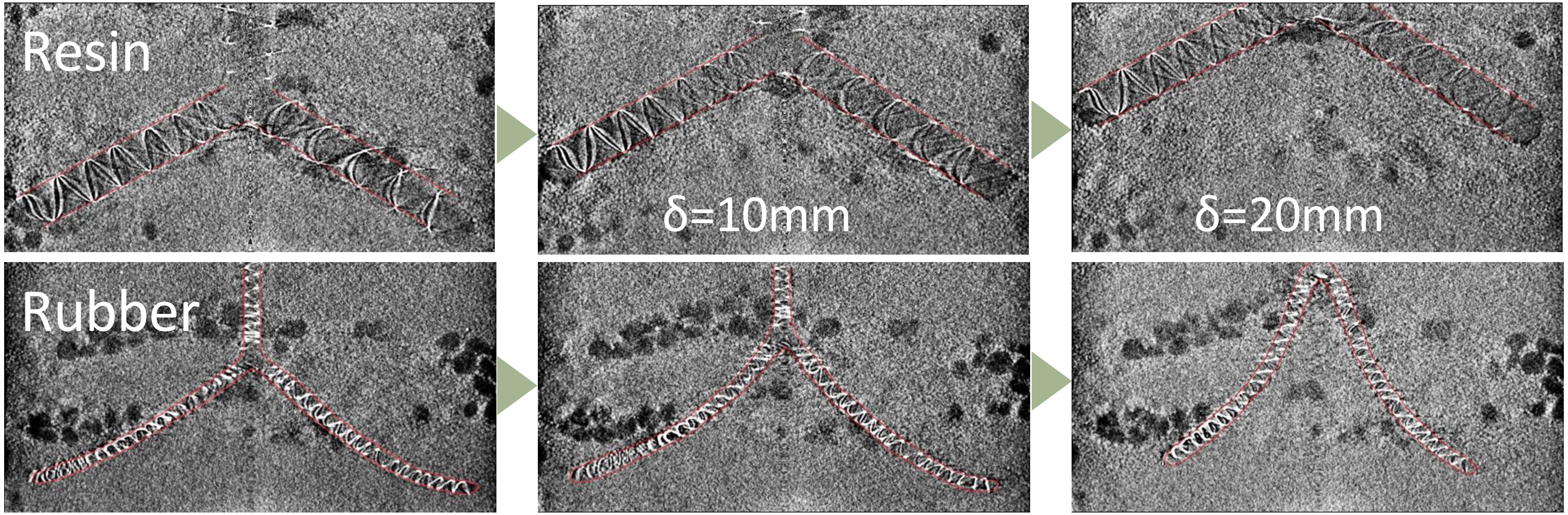


Ardisia crenata
(マンリョウ)

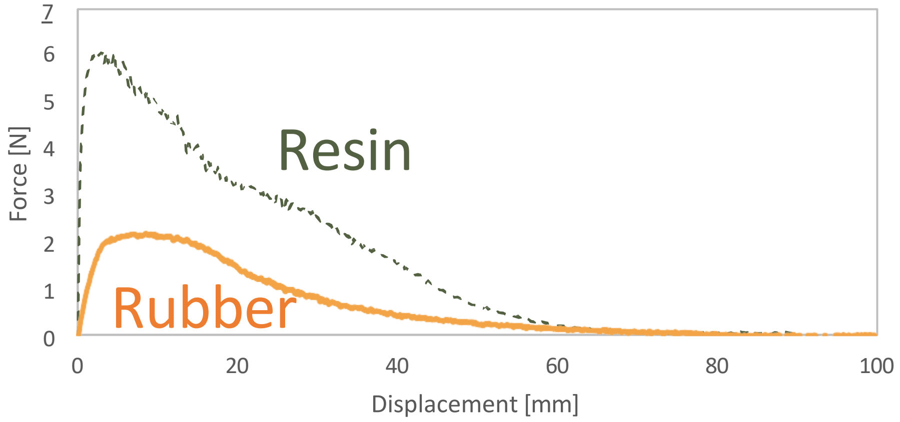
After reaching F_{max} at small displacement, monotonic decrease was observed for both 3D-printed model and actual plant.

Results: Pull-out behavior

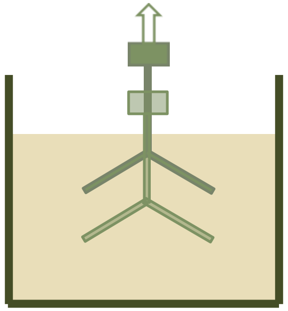
X-ray CT image



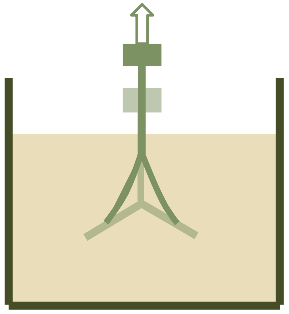
Force-Displacement curve



Resin→Keep its original shape



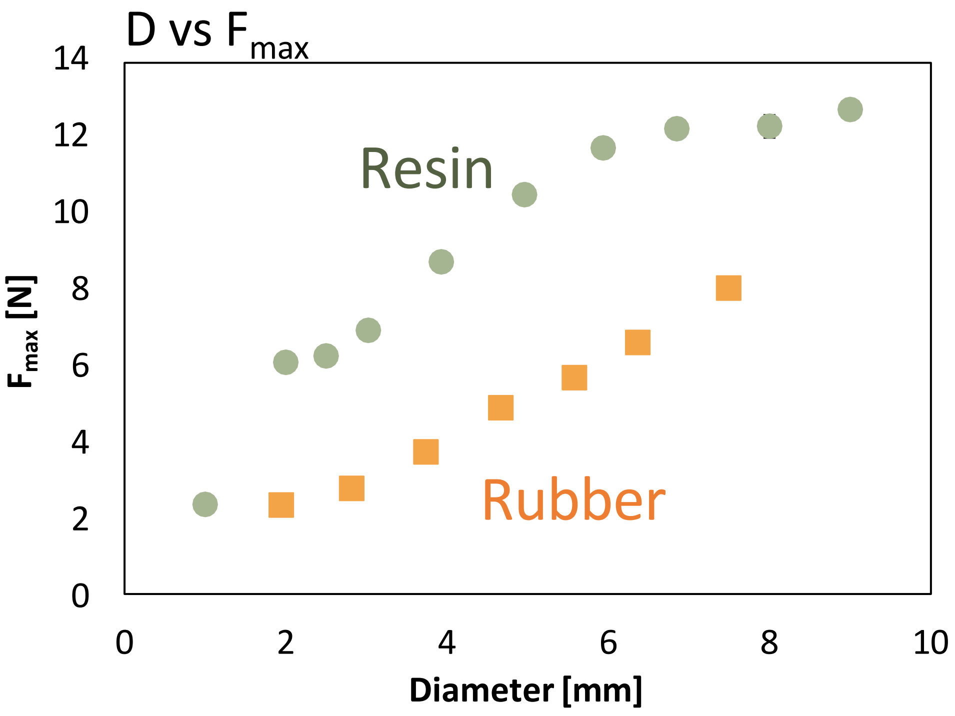
Rubber→Shrink



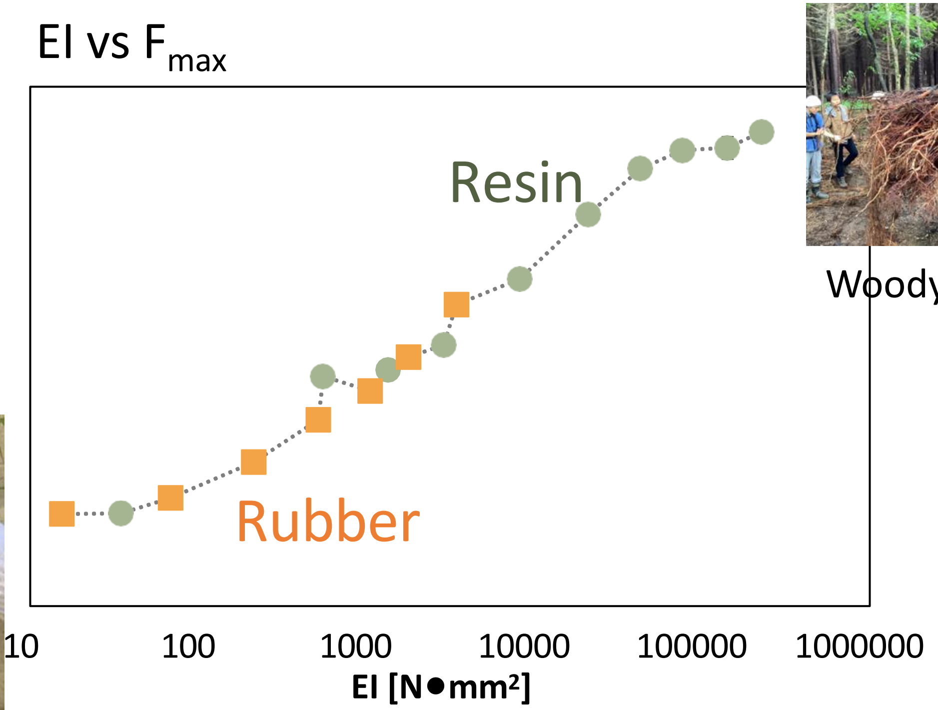
A factor to determine the maximum force

Bending rigidity (= $EI = E\frac{\pi}{64}D^4$)

E: Young's modulus
I : 2nd moment of cross-section
D: Diameter



Different trends appear



Woody plant

Herbaceous plant

A "master curve" is obtained

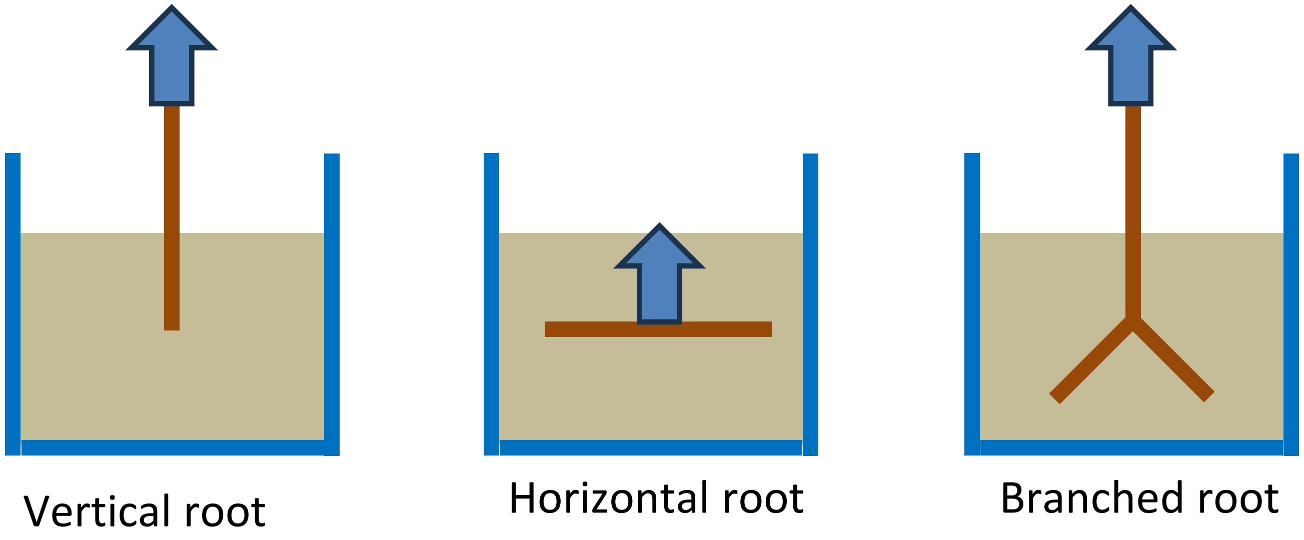
Description with theoretical models

To calculate the maximum force **step by step**

Step 1: Vertical root

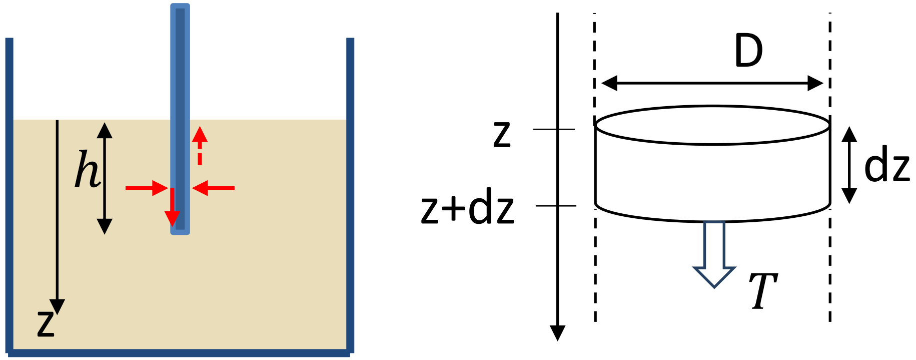
Step 2: Horizontal root

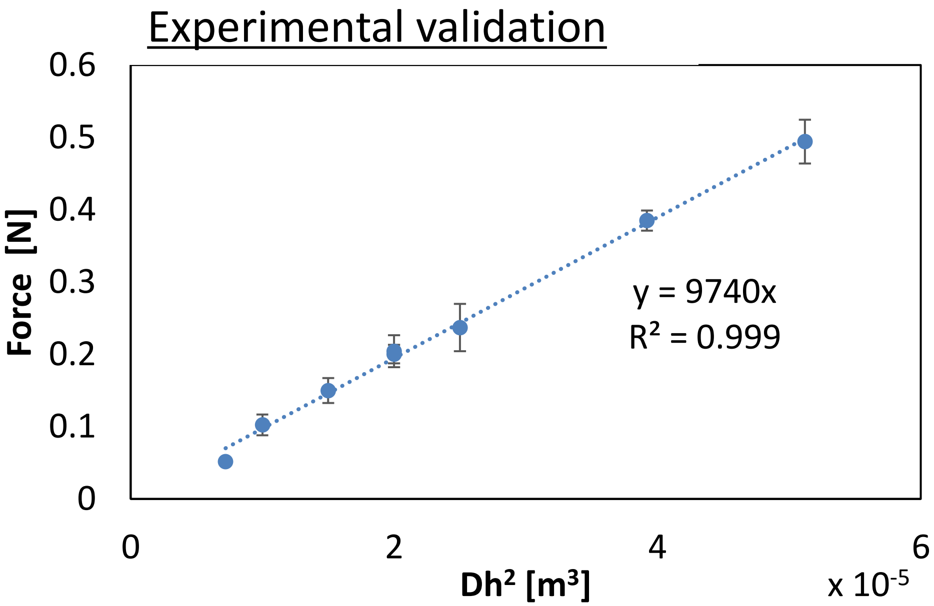
Step 3: Branched root



Theory 1: Vertical root

Pullout of a smooth tap root → **Friction**





- Lateral stress at depth z (Janssen's formula)

  $\sigma(z) = K\rho g\, z$ ρ: Density, g: Gravity constant

  K: Lateral pressure coefficient

- Frictional stress

  $\tau(z) = \mu_{max}\sigma(z)$ μ_{max}: Maximum friction coefficient

  (cf. $F_{max} = \mu_{max}F_N$)

- Maximum force

$$F_{tap} = \frac{K\rho g\pi\mu_{max}}{2}Dh^2 \quad F_{tap} \propto D, h^2$$

$F_{tap} \propto D, h^2$ is reasonable

Theory 2: Horizontal root

Tracking particle motions of glass beads during pull-out

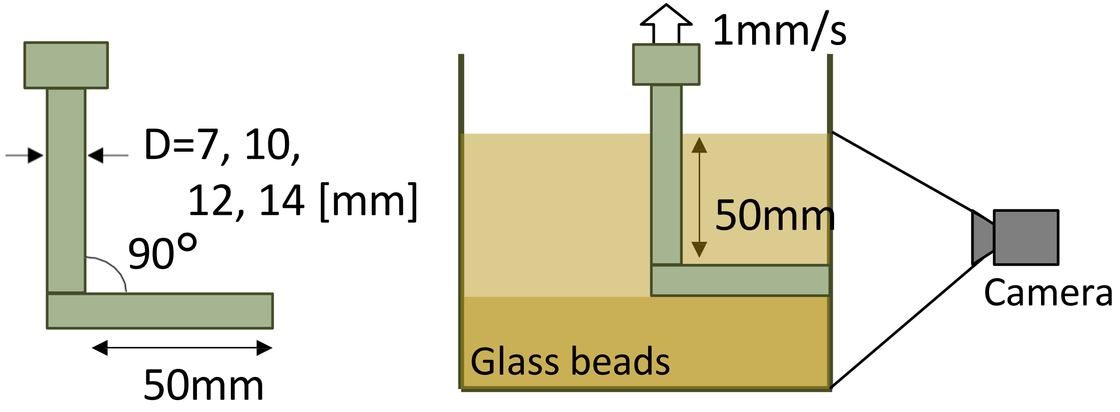
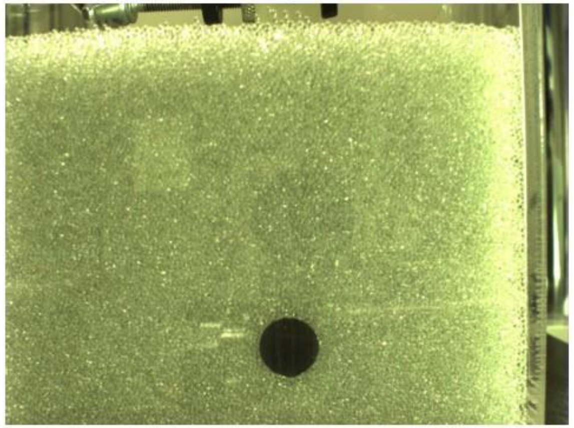
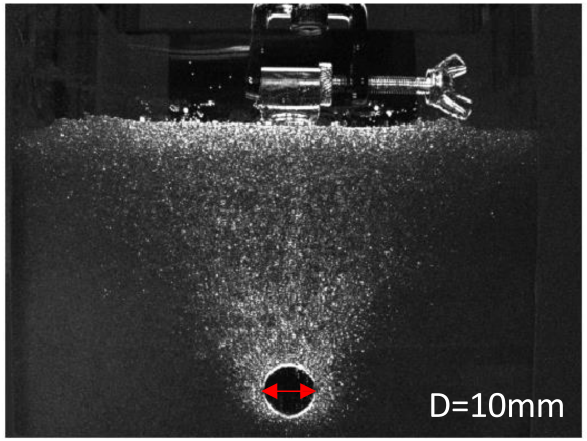


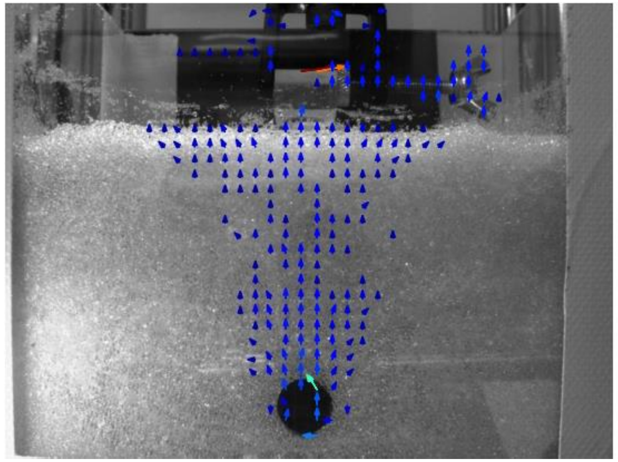
Image 1



Extracting particle motions around the force peak

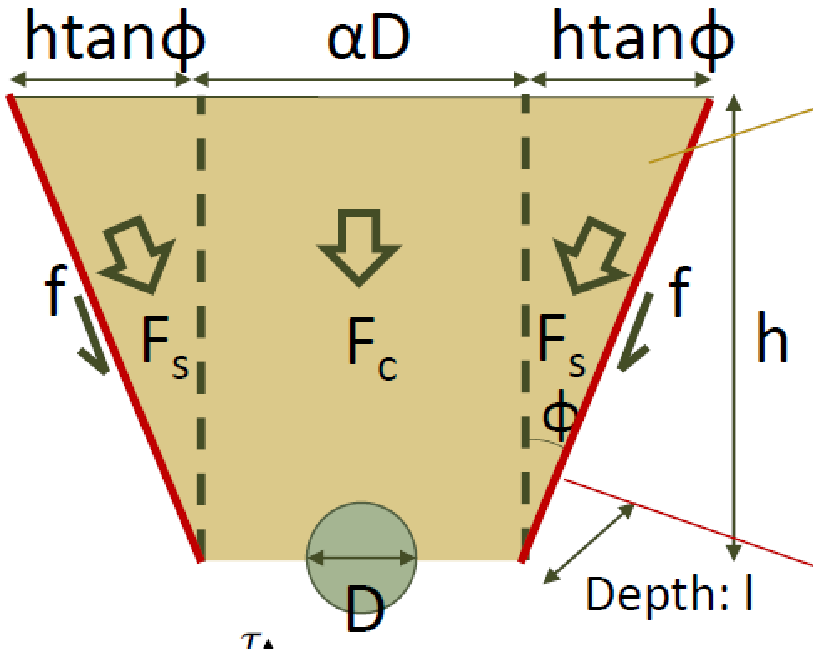


Subtraction of two consecutive images



Displacement vector

Theory 2: Horizontal root



[Weight of glass beads in the trapezoidal region]

F_c (中央の長方形部分) $= \rho g \alpha D h l$

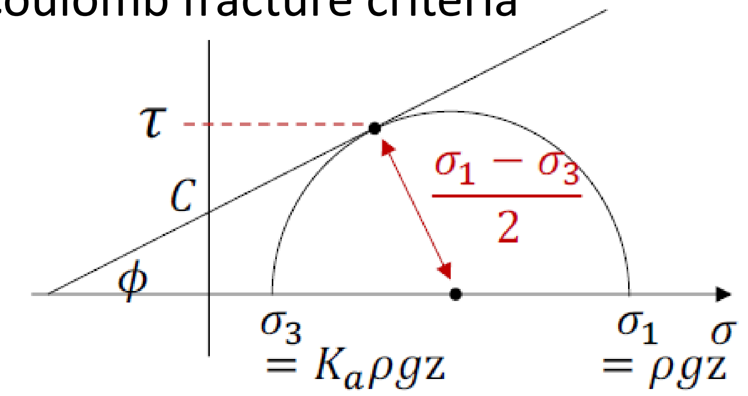
F_s (両サイドの三角形部分) $= 2\rho g \cdot \frac{1}{2} h^2 l \tan\phi \cdot \cos\phi$

$= \rho g h^2 l \sin\phi$

ϕ: Internal friction angle

[Friction force on the shear plane]

Mohr-Coulomb fracture criteria



<u>Friction stress at depth z</u>

$$\tau = \frac{1 - K_a}{2} \rho g z \cos\phi$$

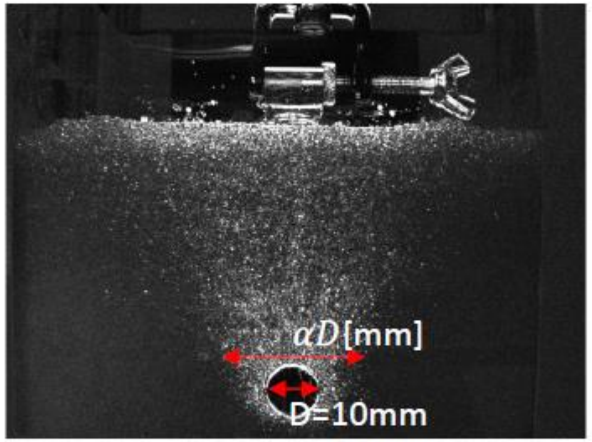
K_a: 主動粉体圧係数

<u>Total friction force</u>

$$f = \frac{1 - K_a}{2} \rho g h^2 l \cos\phi$$

Theory 2: Horizontal root

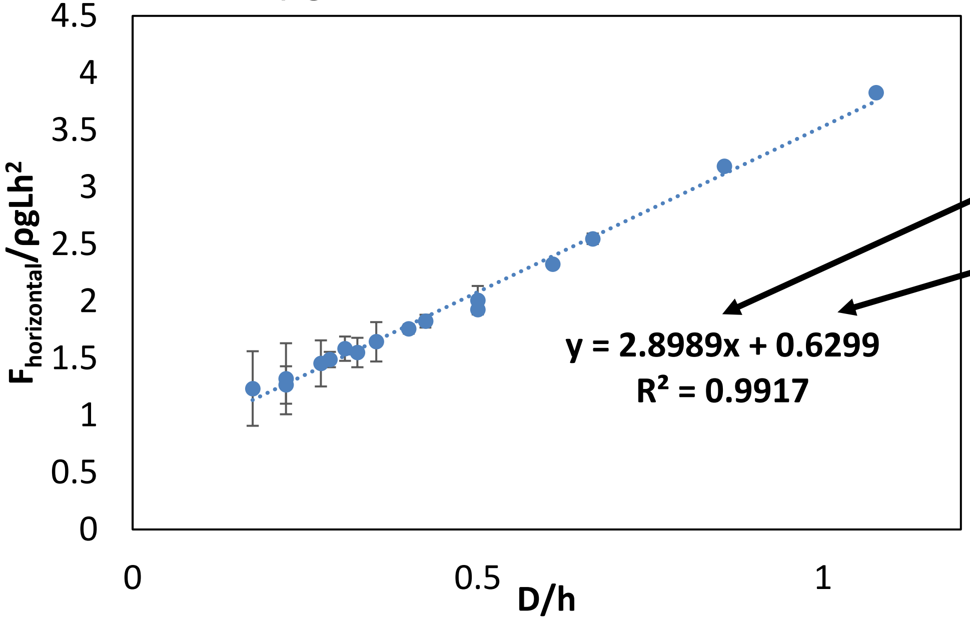
- Total force in the horizontal root



$$F_{horizontal} = F_c + (F_s + f)\cos\phi$$
$$= \rho g h^2 l\{\alpha \frac{D}{h} + \cos\phi\left(\sin\phi + \frac{1-K_a}{2}\cos\phi\right)\}$$

$$\frac{F_{horizontal}}{\rho g h^2 l} = \alpha \frac{D}{h} + \cos\phi\left(\sin\phi + \frac{1-K_a}{2}\cos\phi\right)$$

$\frac{D}{h} - \frac{F_{horizontal}}{\rho g h^2 l}$ plot



$\phi = 26$ [°]

$$\frac{F_{horizontal}}{\rho g h^2 l} = \alpha \frac{D}{h} + 0.64$$

2～3?

$\alpha = 2.90$

$$\cos\phi\left(\sin\phi + \frac{1-K_a}{2}\cos\phi\right) = 0.63$$

$$\frac{F_{horizontal}}{\rho g h^2 l} = 2.9 \frac{D}{h} + 0.63$$

Good agreement

Theory 3: Branched root in the flexible and rigid limits

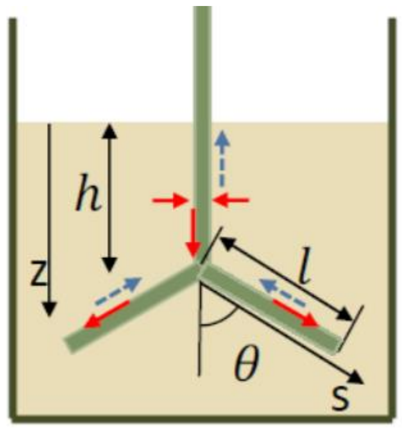
- Flexible limit
  - Friction force on the lateral roots

Pullout with pure sliding
(No fracture of soil)

$$F_{lat\_fri} = \rho g \pi \mu_{max} D(\frac{1+K}{2} + \frac{1-K}{2}\cos 2\theta)(hl + \frac{\cos\theta}{2}l^2)$$

  - Total pull-out force

$$F_{flexible} = F_{tap} + 4F_{lat\_fri} = \rho g \pi \mu_{max} D\left[\frac{1}{2}Kh^2 + \{(1+K) + (1-K)cos\, 2\theta\}(2hl + l^2\cos\theta)\right]$$



Theory 3: Branched root in the flexible and rigid limits

- Rigid limit

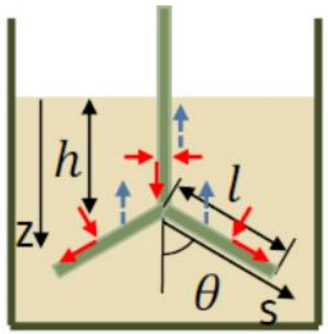
Pullout with soil fracture

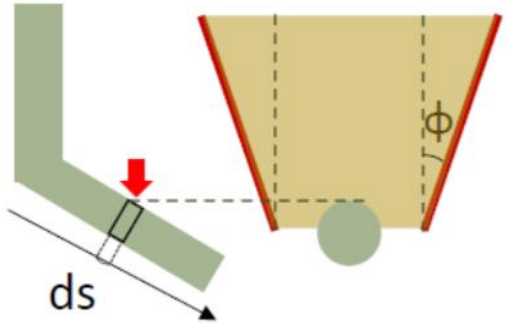
  - ➢ Fracture resistance from soil

$$F_{lat\_res} = \rho g l \sin\theta \left\{\alpha D \left(h + \frac{\cos\theta}{2} l\right) + \cos\phi \left(\sin\phi + \frac{1-K_a}{2}\cos\phi\right)\left(h^2 + hl\cos\theta + \frac{1}{3} l^2 \cos\theta^2\right)\right\}$$

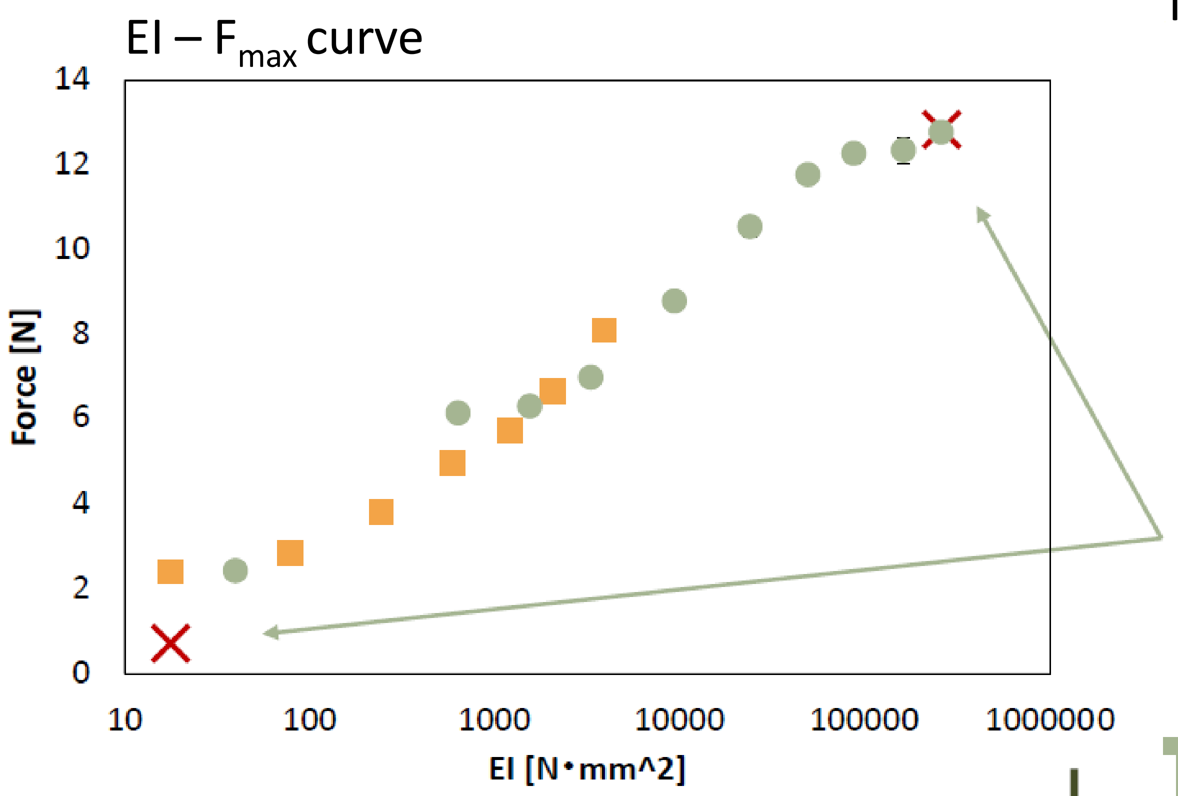
  - ➢ Total pull-out force

$$F_{stiff} = F_{tap} + 4(F_{lat\_fri}\cos\theta + F_{lat\_res})$$





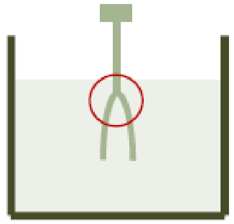
Theory 3: Comparison with experiment



Input Parameters

$$\rho = 1.60\ \mathrm{g/cm^3}\ ,\ K\mu_{max} = 0.39,$$
$$h = l = 5.0\times10^{-2}\ m, \quad \theta = \pi/3$$

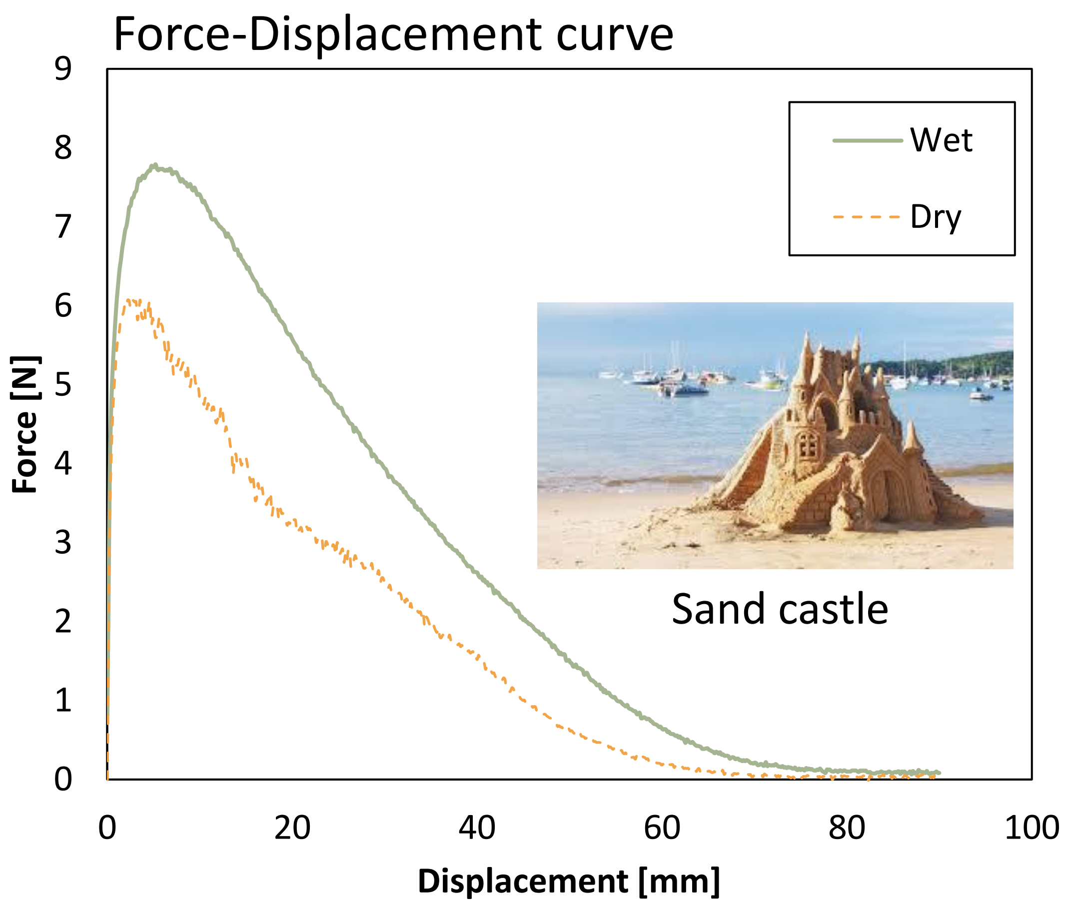
Predicted values for the samples of D = 2mm (rubber) and D = 9mm (resin)

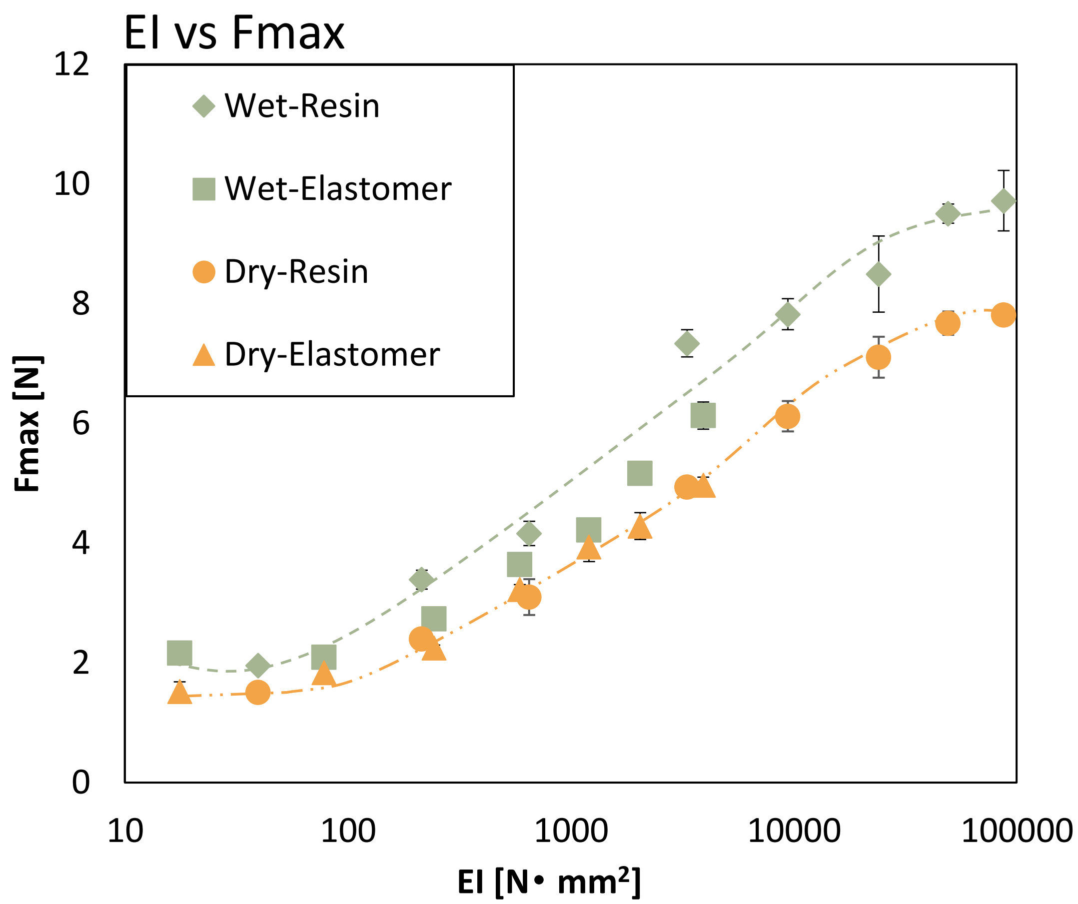


Deviation for the D = 2mm rubber sample is considered to be the resistance for the neck part.

Pullout experiment in wet conditions

Volume fraction of water: 4%

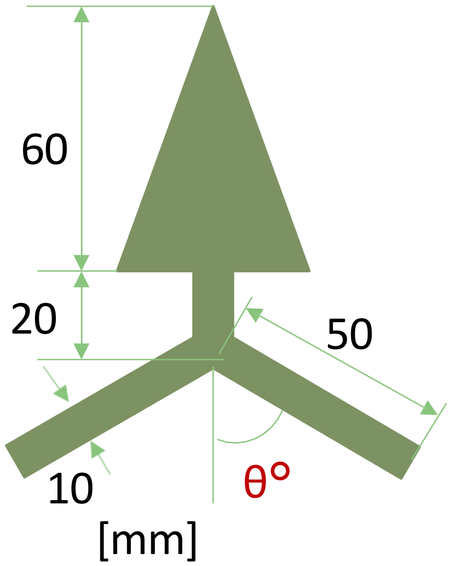


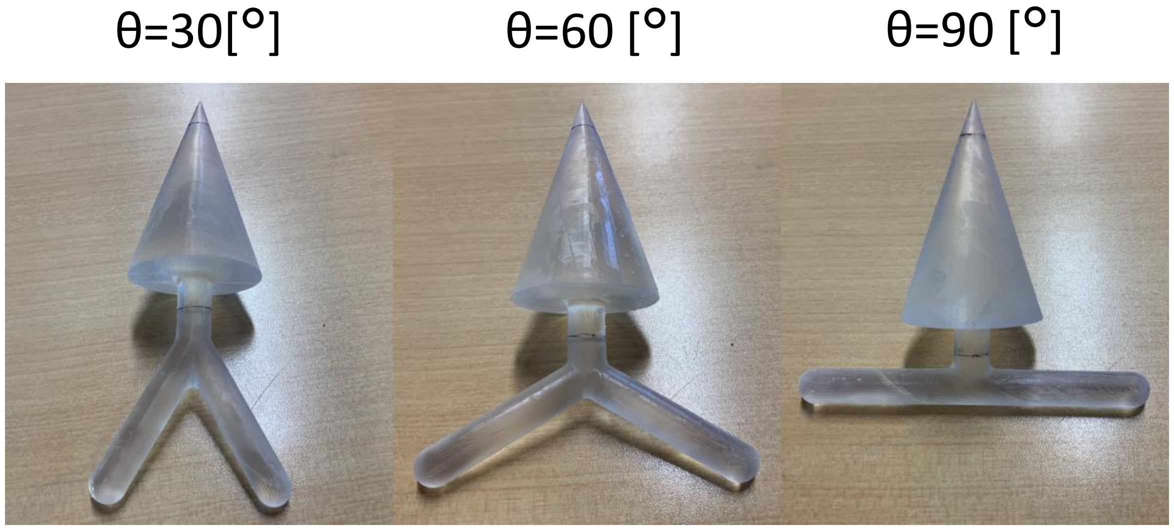


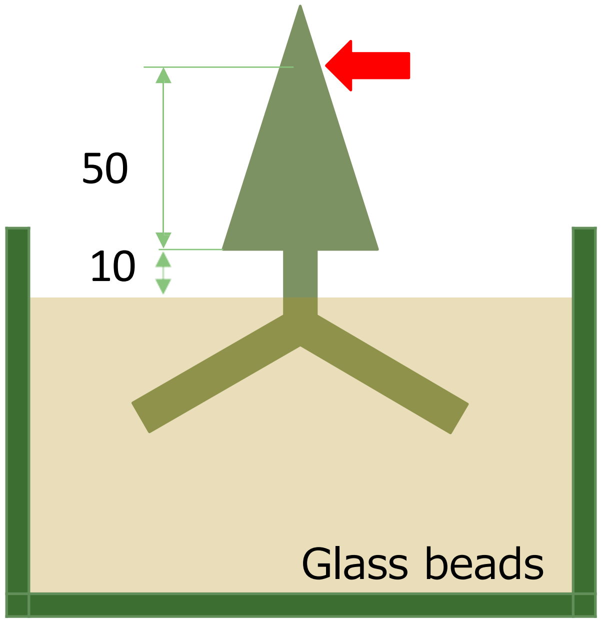
Pushover experiment

- Cedar-like model (T/R ratio ≒3*)

Branch Angle θ=15, 30, 45, 60, 75, 90 [°]

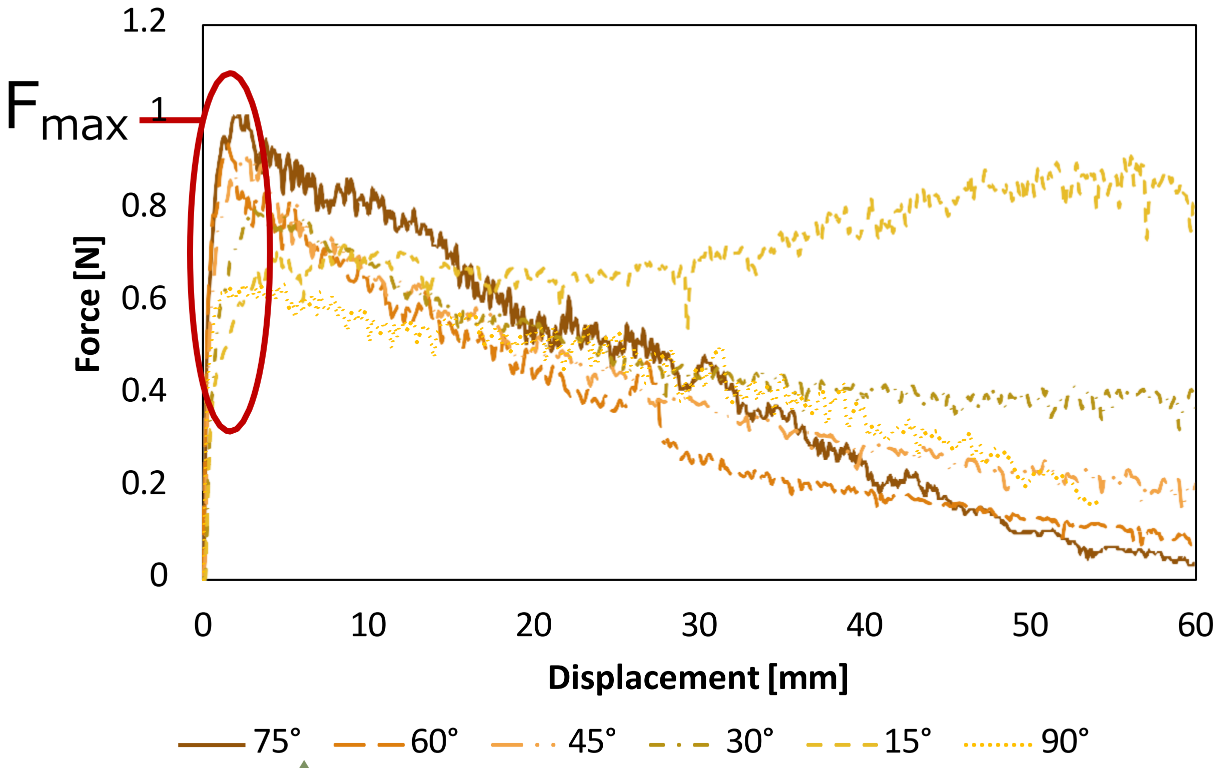






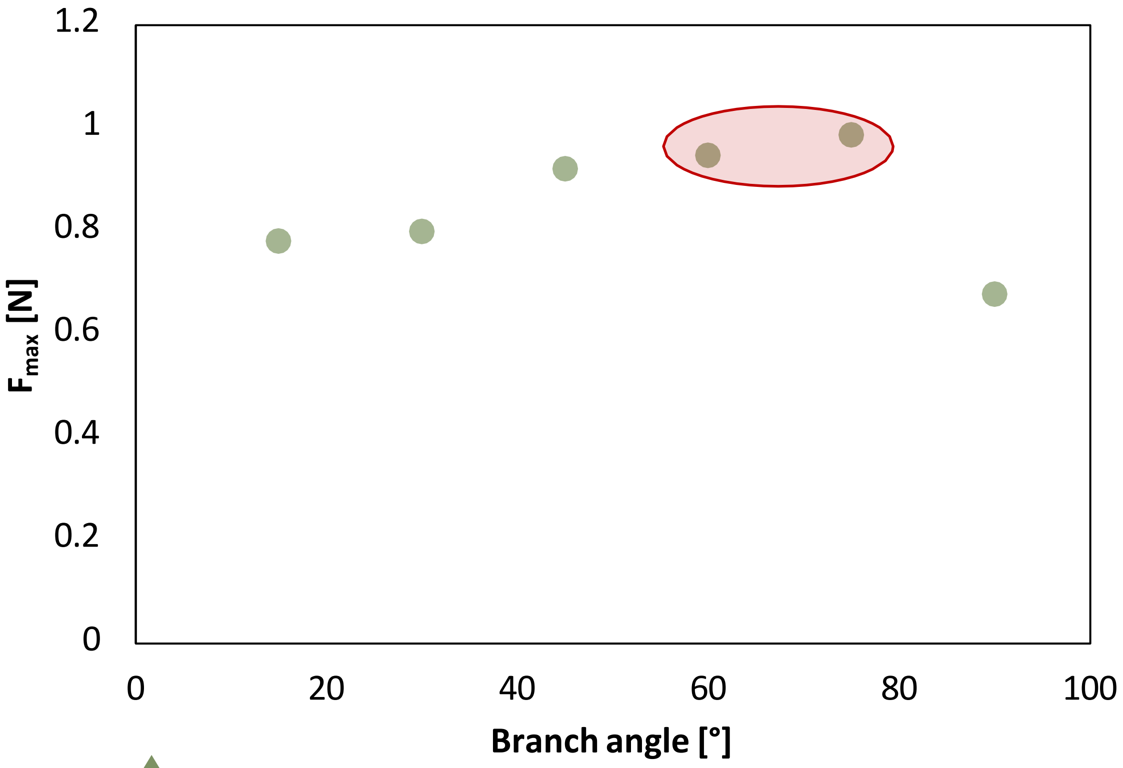
Pushover strength

Force-displacement curve



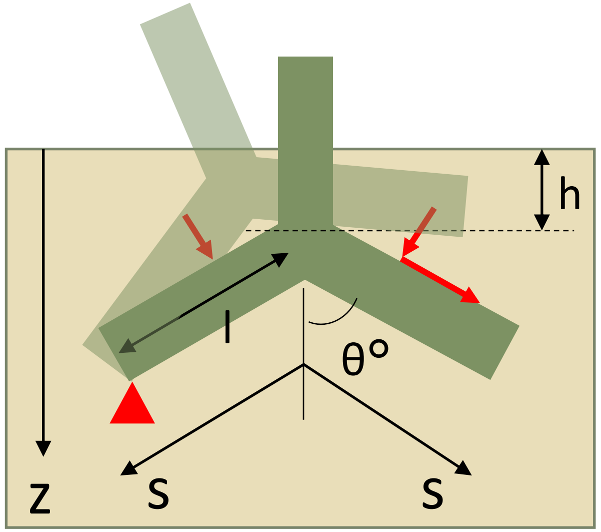
Pushover Force reaches maximum in the early stage

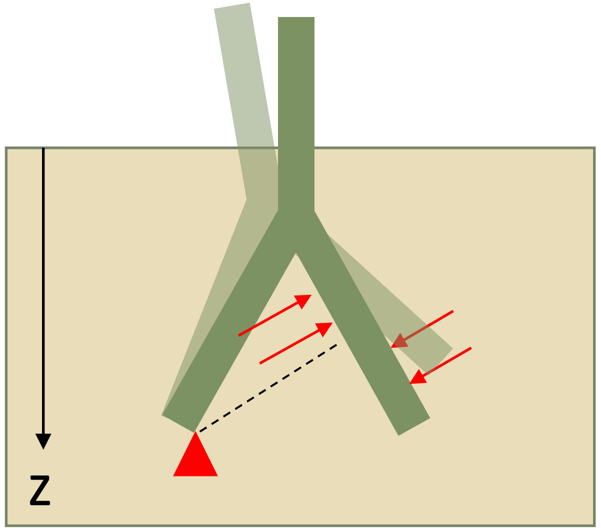
Branch angle - F_{max}



F_{max} reaches a maximum around 60 to 75°

Theory on Pushover





We assume that the stress at fracture is proportional to soil pressure.

$$\sigma(z) = \sigma_{max} p(z)$$

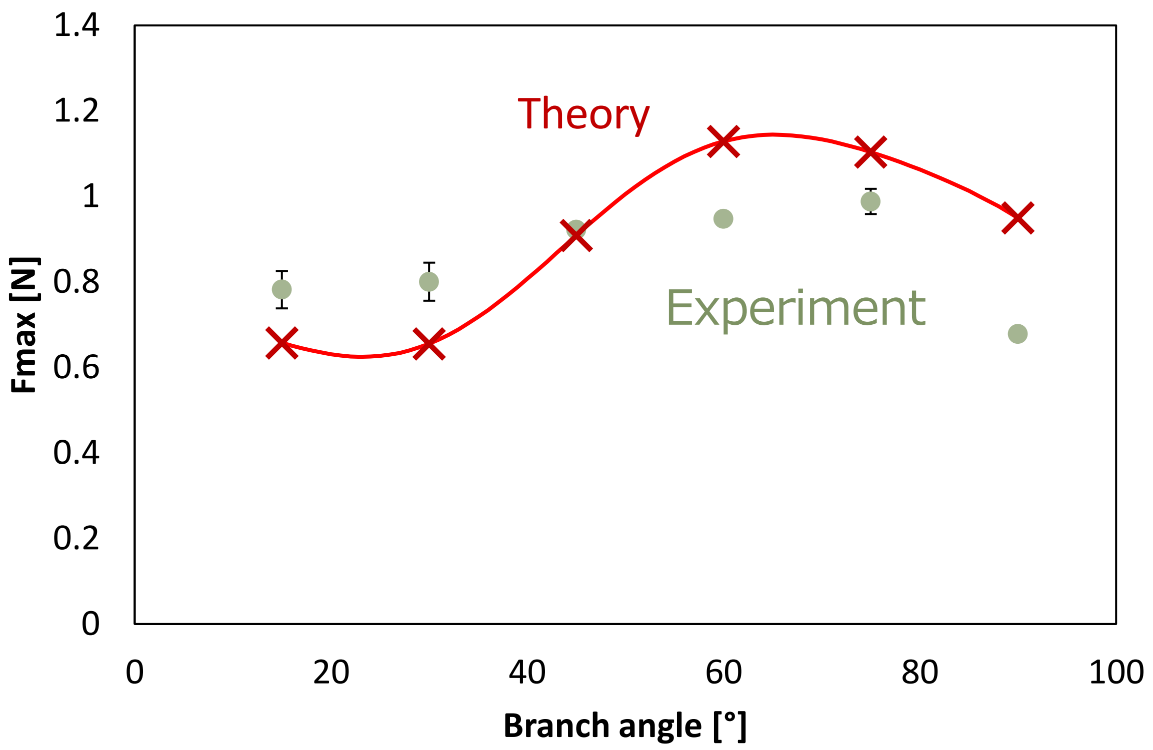
Total moment

$$\mathrm{M} = \frac{\rho g \pi \sigma_{max} D l^2}{2} \left(\frac{8}{3} l \cos\theta^7 - 4l\cos\theta^5 + 4h\cos\theta^4 + l\cos\theta^3 - 6h\cos\theta^2 + \frac{2}{3} l\cos\theta + 3h \right)$$

$$+ \frac{\rho g \pi \sigma_{max} D}{2} h^2 \left(\frac{h}{6} + \frac{l\cos\theta}{2} \right) + \rho g \pi \mu_{max} D \left(hl + \frac{1}{2} l^2 \cos\theta \right) l \sin\theta \cos\theta$$

Calculation result

Branch angle vs F_{max}



The theoretical curve exhibits an optimum angle ≒ 65°,
in reasonable agreement with experimental results.

The balance between depth and width is important.

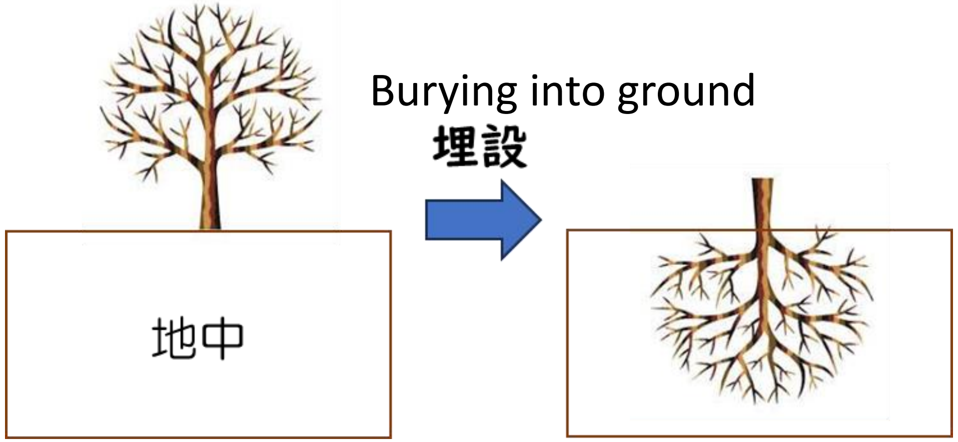
Summary and Future plans

<u>Summary</u>

- We simplified the root structures and conducted pull-out experiments.
- We obtained a strong correlation between bending rigidity and maximum force.
- We successfully described the maximum forces in the flexible and rigid limits.

<u>Future Plans</u>

- Modeling and prediction of mechanical behavior for more realistic root structures and soil
- Engineering application: Soil-reinforcement of slopes using aboveground parts of a tree.



Thank you very much for your attention!

Ex. Rice in budding and growth

Root geometry and soil conditions change with time.
⇒Is it possible to predict pushover strength during budding and growth?