School of Science
and Engineering
University of Dundee

Quantification of mechanical and hydrological root-reinforcement

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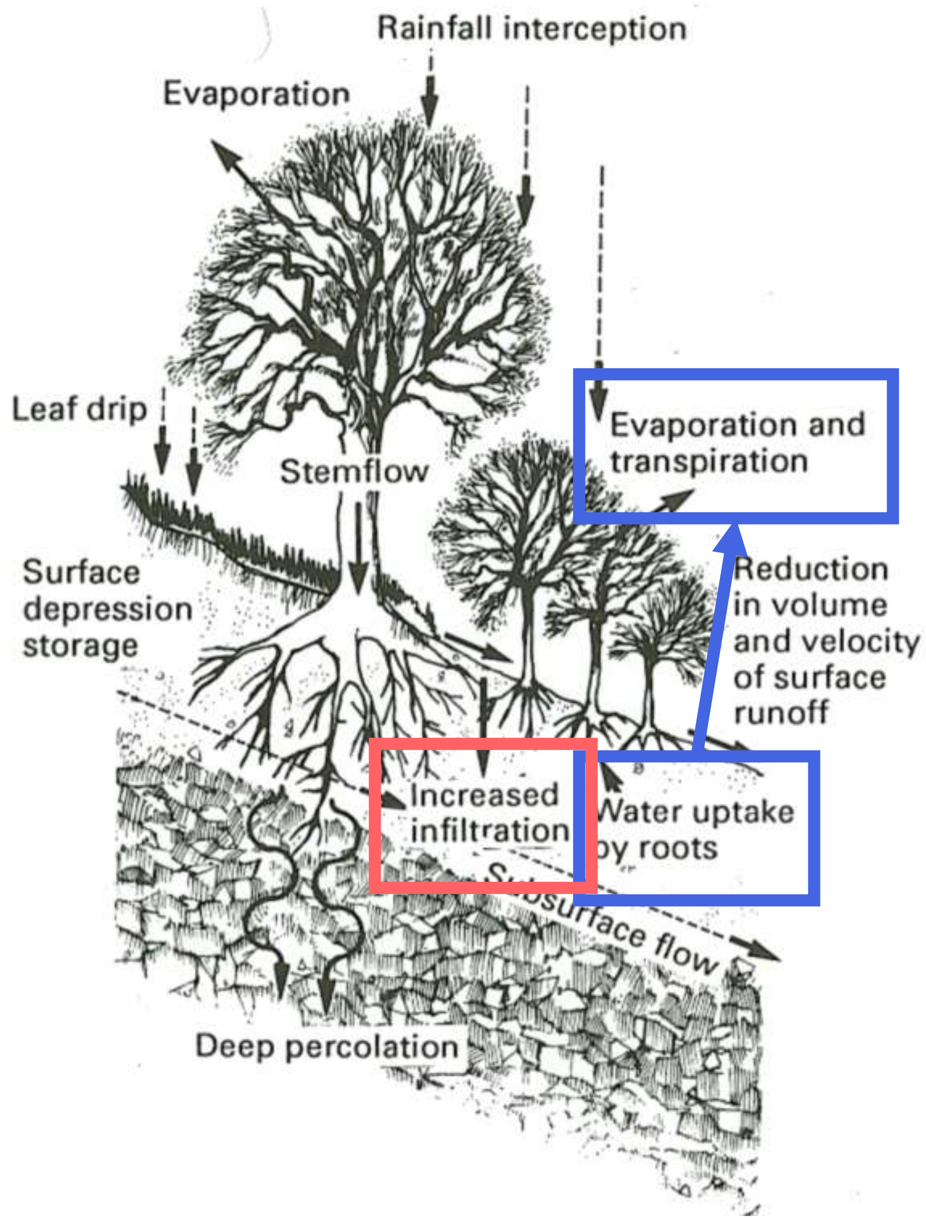
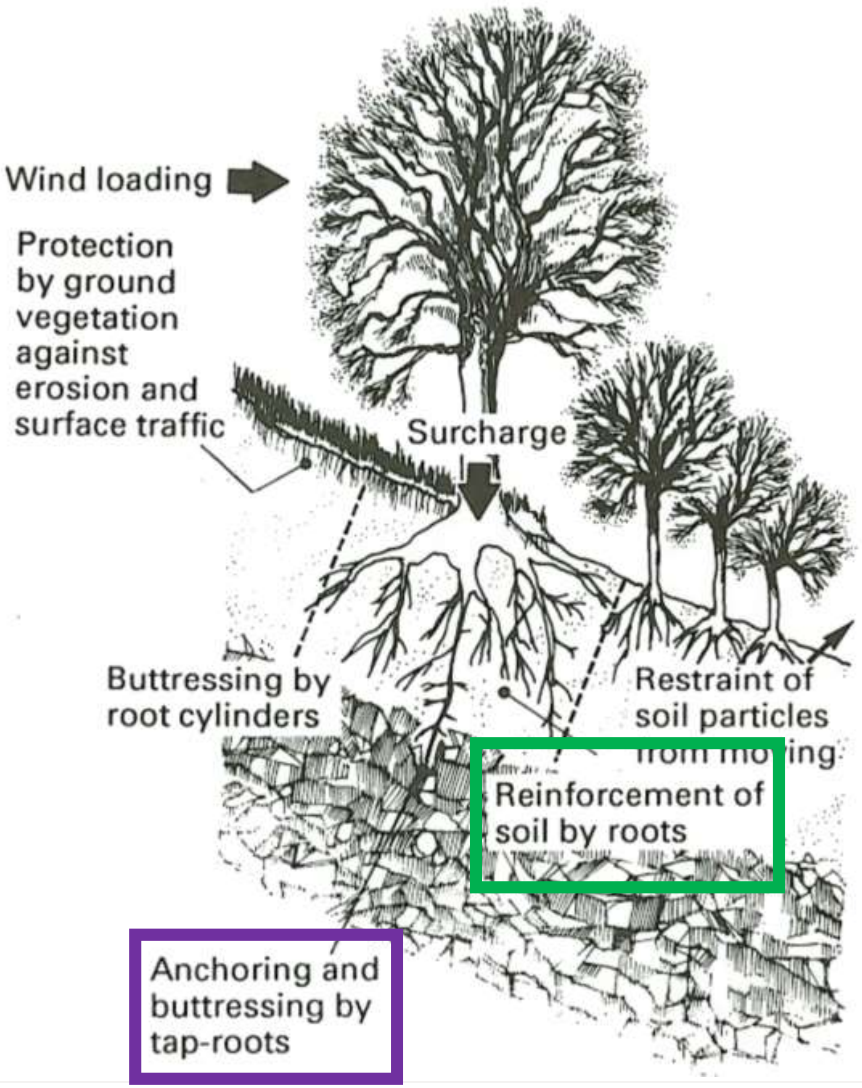
Hydrological root-reinforcement

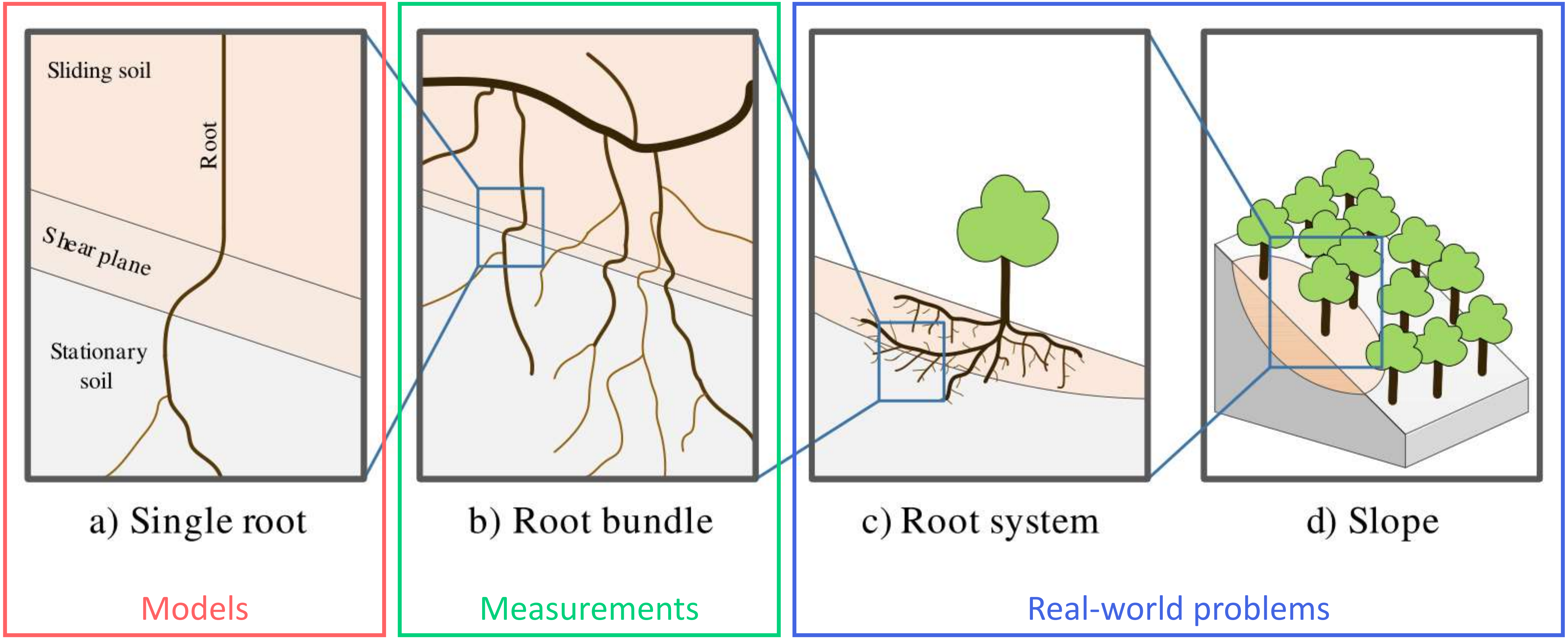


Mechanical root-reinforcement



Coppin & Richards (1990). "Use of Vegetation in Civil Engineering"

A problem of scales



After Schwarz et al. (2010). Earth Surface Processes and Landforms 35(3):354–367

Hydrological root-reinforcement

Hydrological reinforcement – a glasshouse experiment

- Ten native shrub species
- Soil density: 1200 kg/m^3
- Matric suction induced after 13 days of evapotranspiration after soil saturation + soil penetration resistance
- Above and below-ground traits

- 🔴 Unrooted soil (C)
- 🟡 Hazel (*Corylus avellane,* Ca)
- 🔵 Holly *(Ilex aquifolium,* Ia)
- 🟢 Gorse *(Ulex europaeus,* Ue)

Boldrin et al. (2017). Plant and Soil 416(1-2): 437–451

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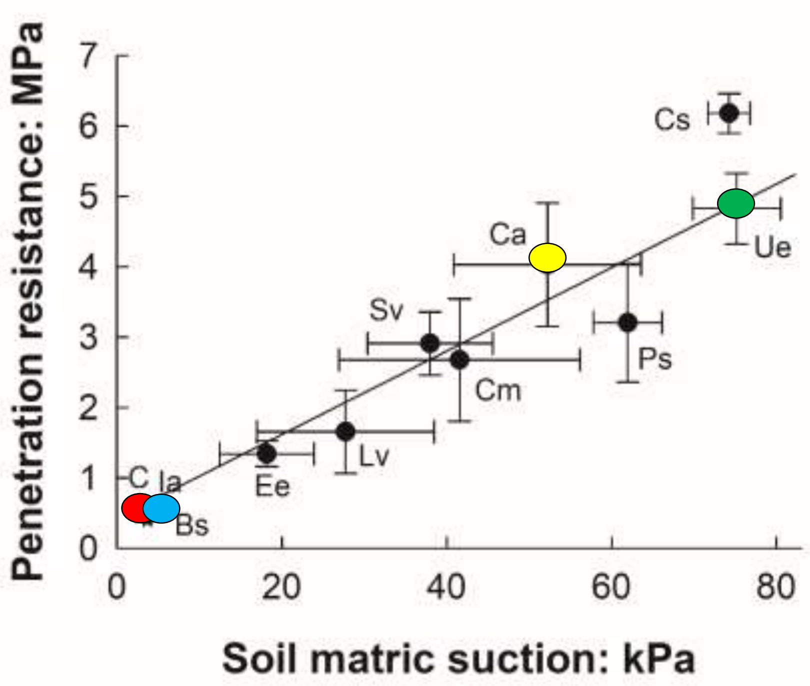

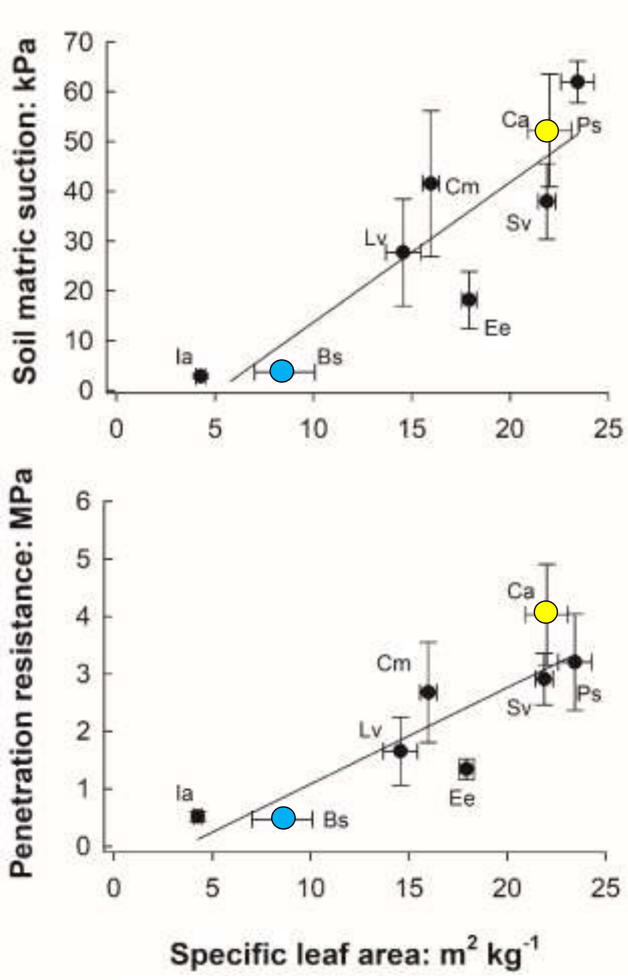

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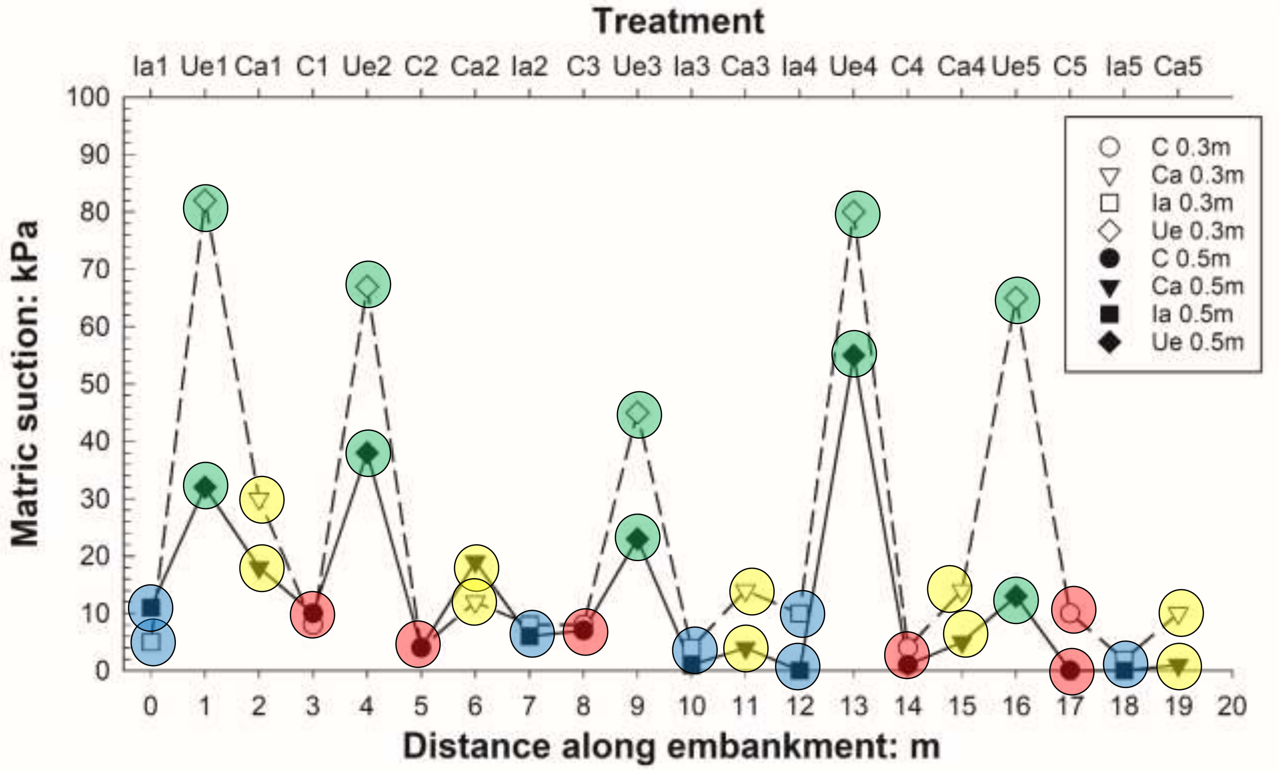
Different plants have different growth strategies → Species matter!

Boldrin et al. (2017). Plant and Soil 416(1-2): 437–451

Hydrological reinforcement - field

- 20 m long embankment section (slope angle of 43°)
- Vegetated with three contrasting species (15 plots)
- Control plots (5 fallow soil plots)
- Matric suction monitoring at 0.3 and 0.5 m



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Boldrin et al. (under review)

Hydrological reinforcement - field

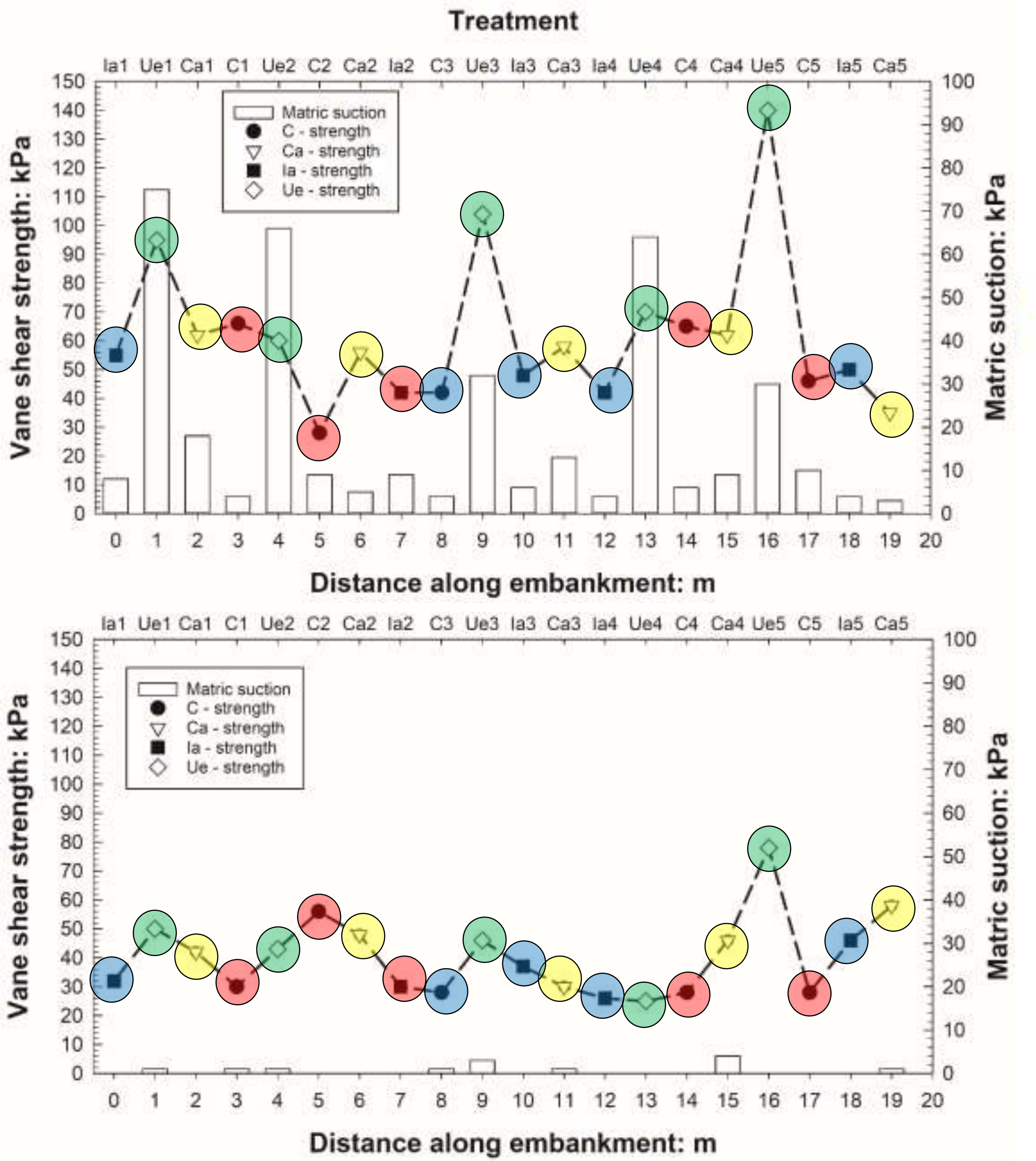
- Vane shear tests at 0.2 m
- Summer (dry) vs autumn (wet)

Root hydrological reinforcement shows ***spatial***, ***temporal*** and ***biological*** variation

- Unrooted soil (C)
- Hazel (*Corylus avellane,* Ca)
- Holly *(Ilex aquifolium,* Ia)
- Gorse *(Ulex europaeus,* Ue)

Summer

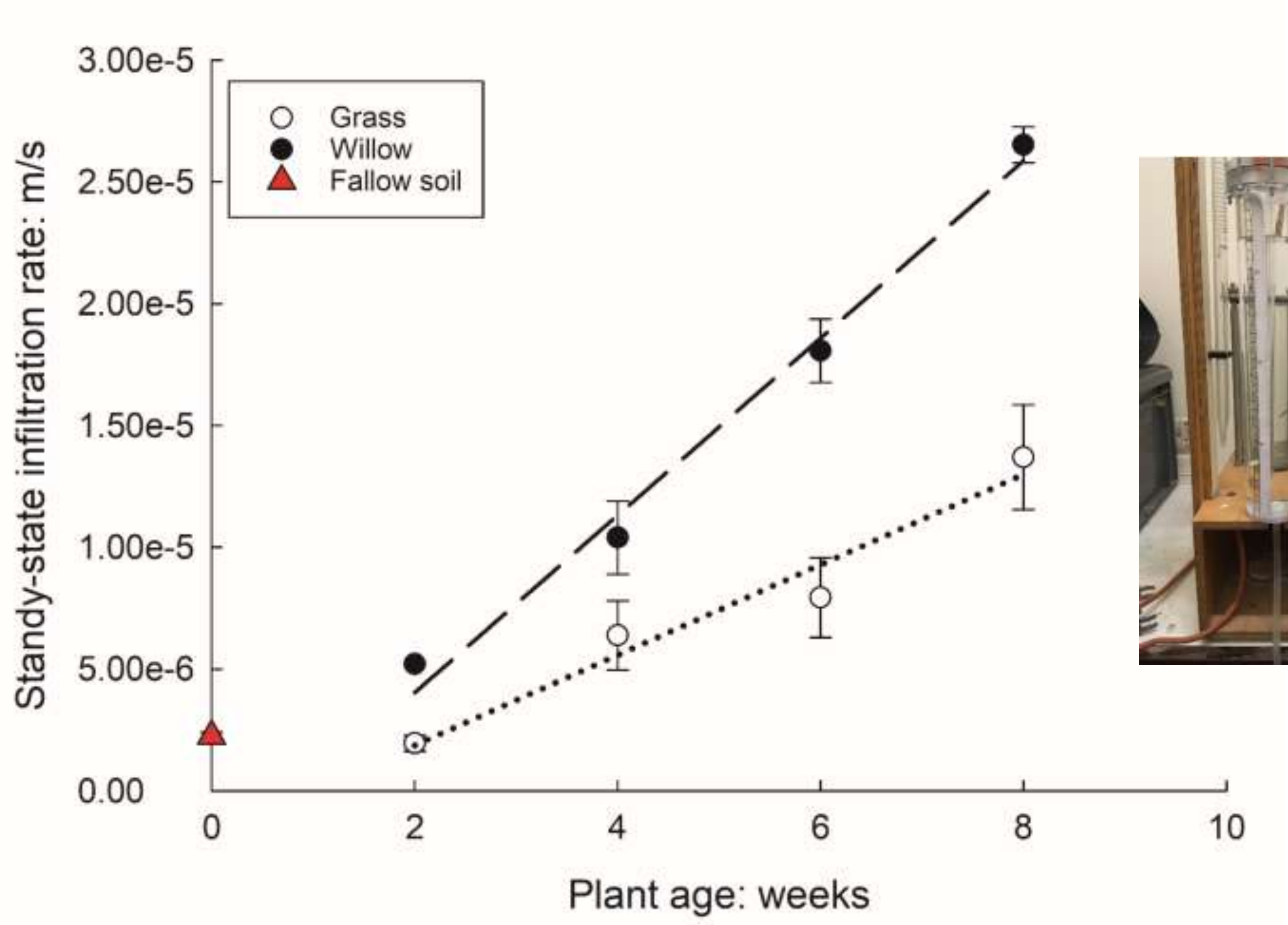
Autumn



Boldrin et al. (under review)

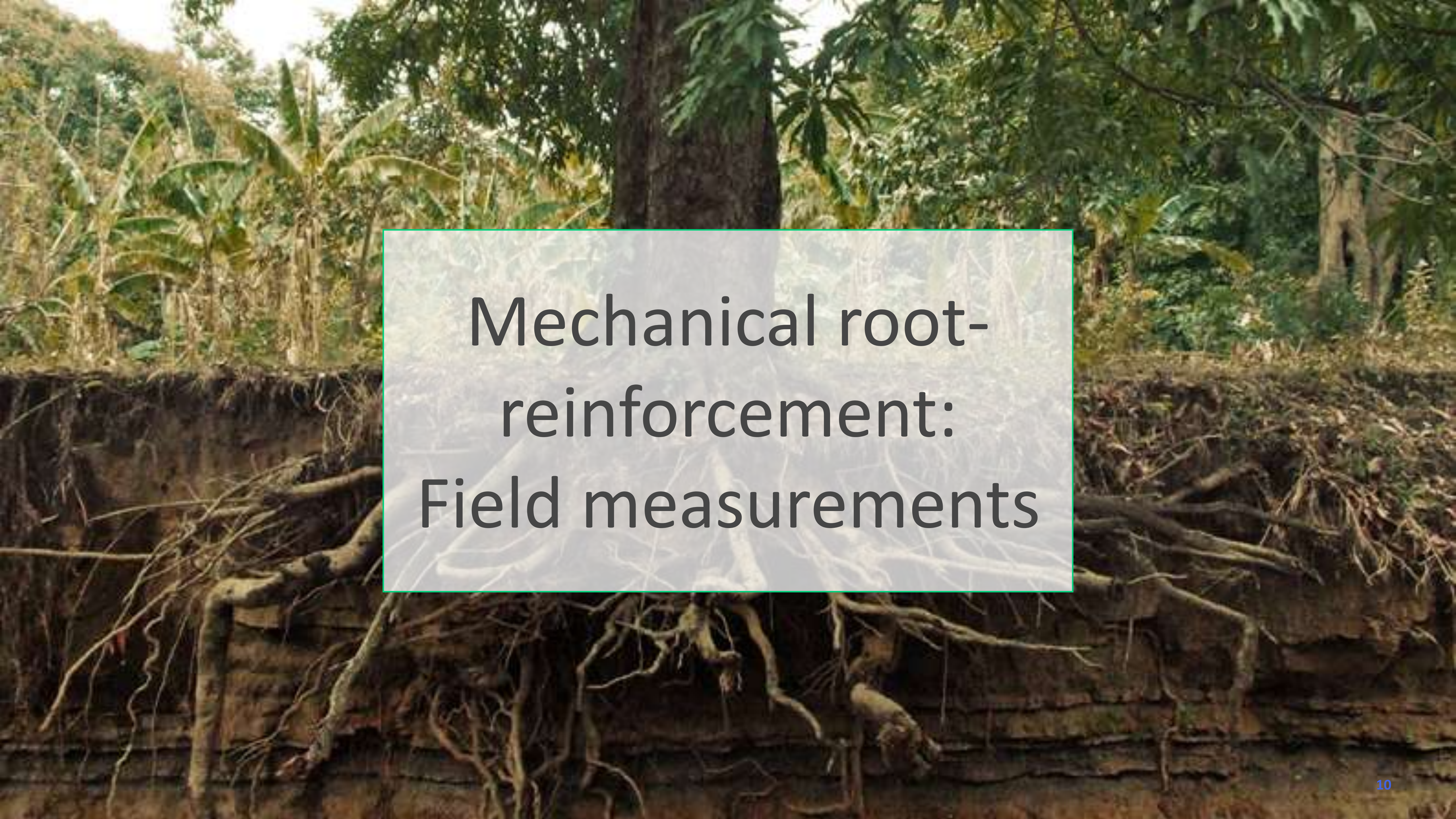
Plants change the hydraulic conductivity of the soil

- Grass (*Lolium perenne* x *Festuca pratensis* hybrid) vs Willow (*Salix viminalis*)
- Control fallow soil
- Constant-head method
- Effect of root growth during time



Root growth alters the structure of the soil!

Leung et al. (2018). Géotechnique 68(7):646-652



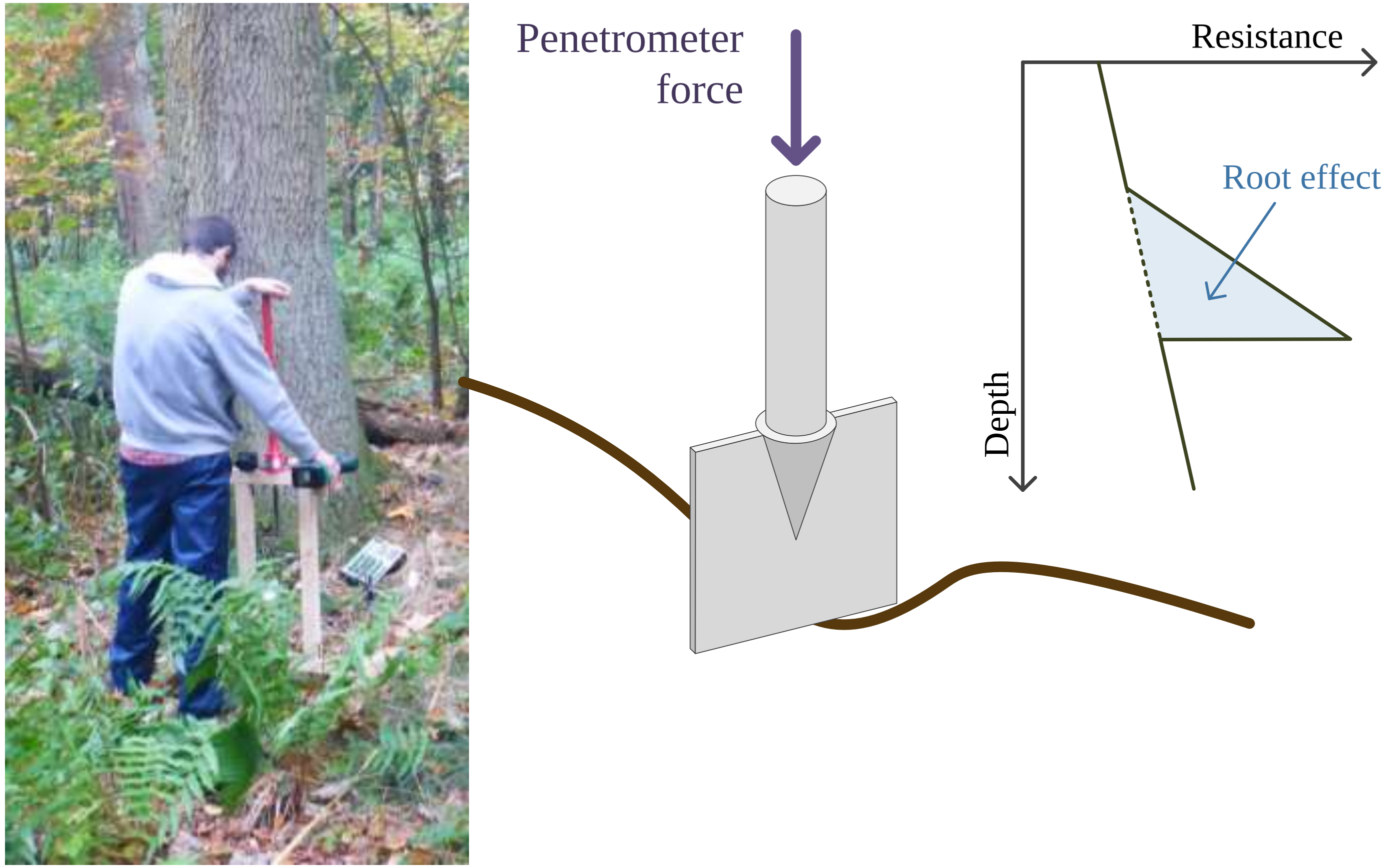
Mechanical root-reinforcement: Field measurements

Large sites

Variability?

Site accessibility?

‘Blade penetrometer’



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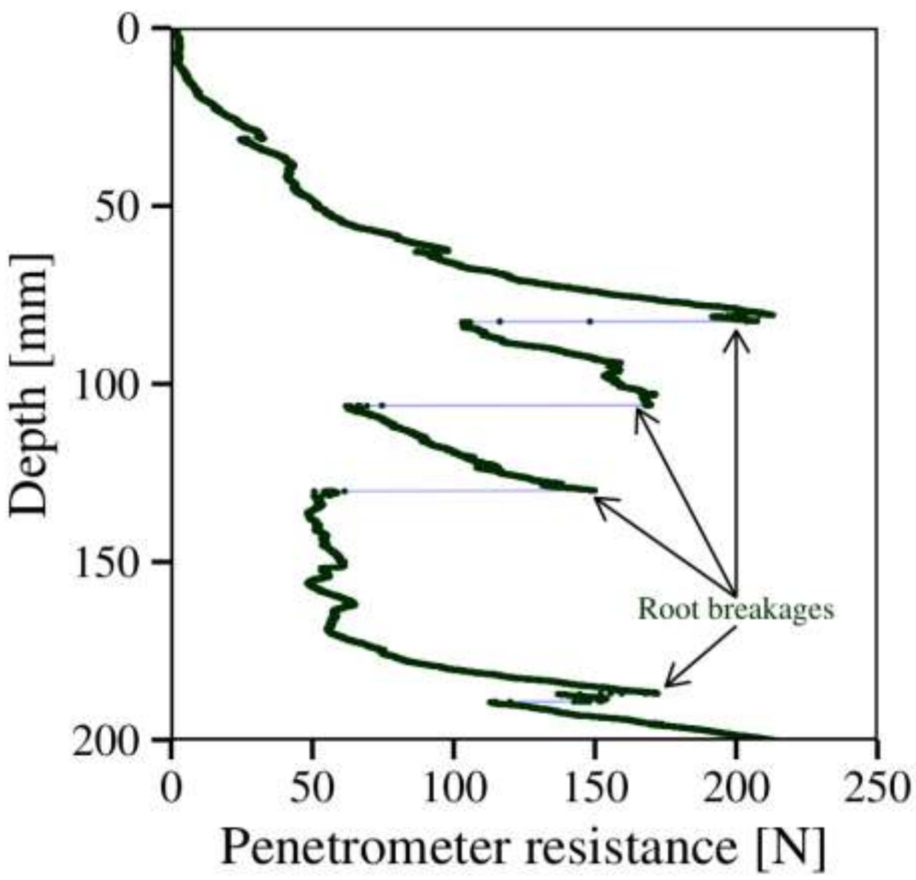
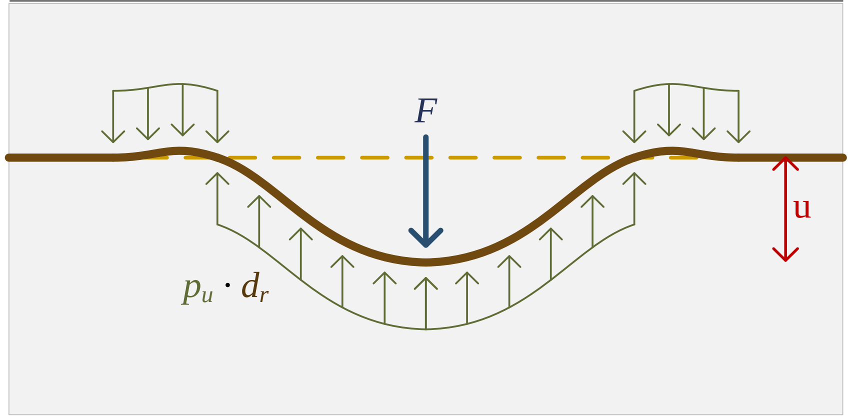
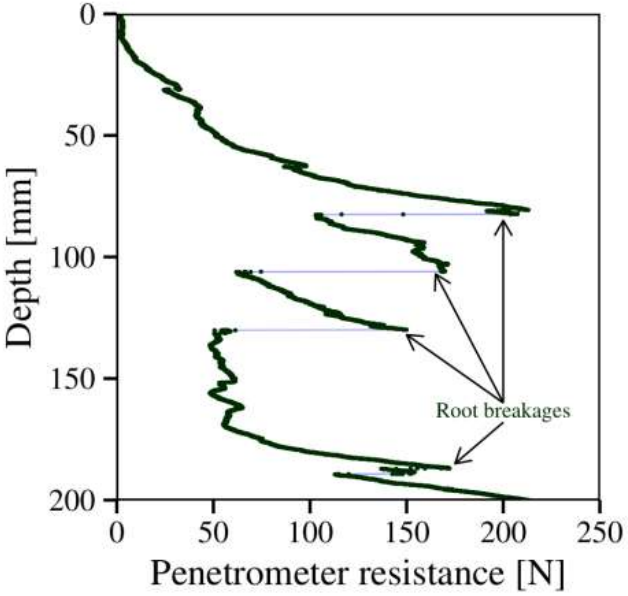


Meijer et al. (2017). Géotechnique 68 (4) 320–331

'Blade penetrometer'

Beam on non-linear elastic foundation

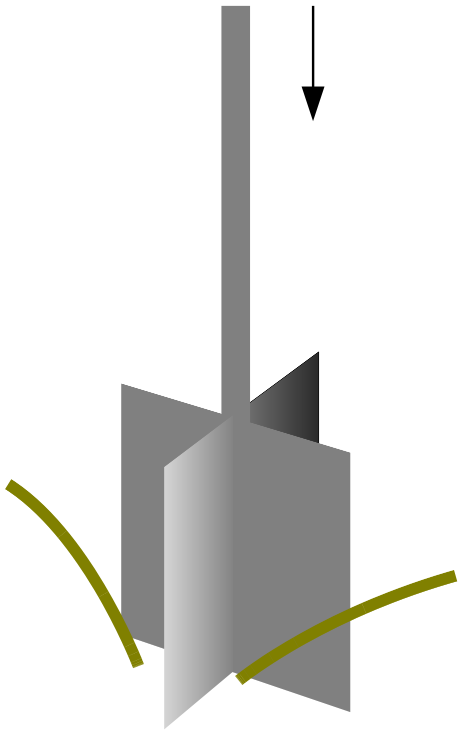




Meijer et al. (2017). Géotechnique 68 (4) 320–331

‘Blade penetrometer’

‘Pin vane’



Meijer et al. (2015). Géotechnique 66 (1) 27–40

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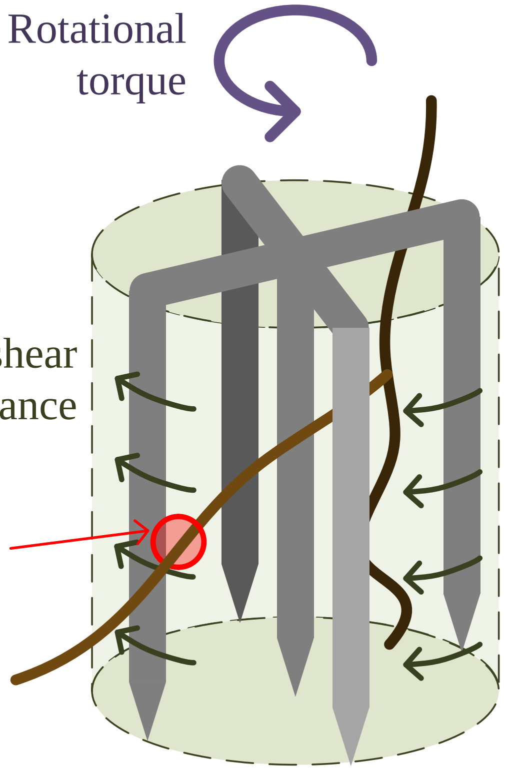

Meijer et al. (2015). Géotechnique 66 (1) 27–40

‘Blade penetrometer’

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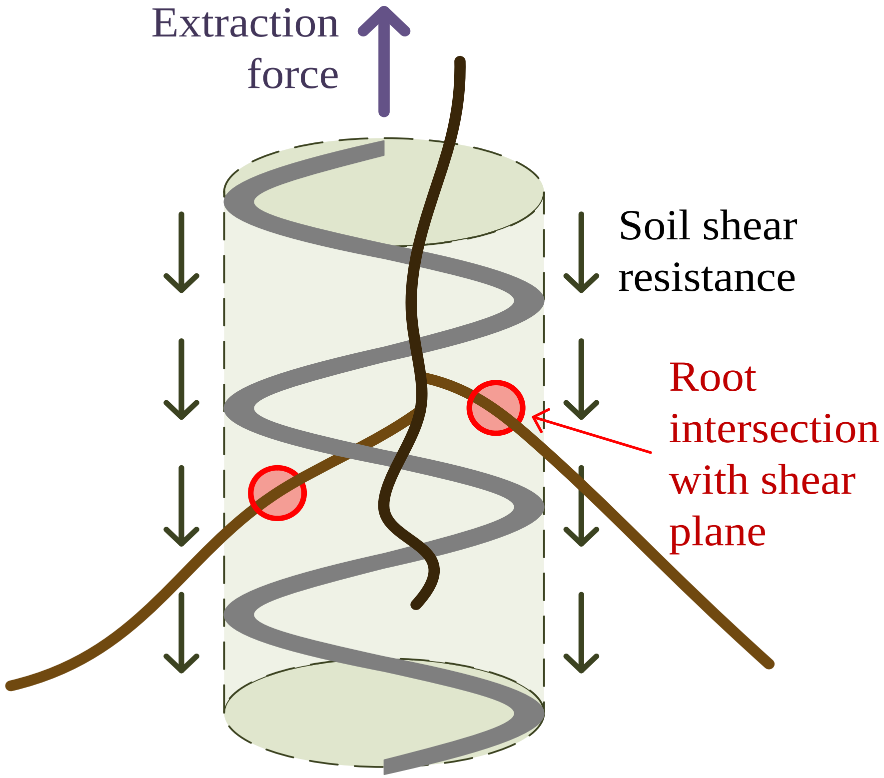

Meijer et al. (2018). Can Geo J 55 (10) 1372-1390

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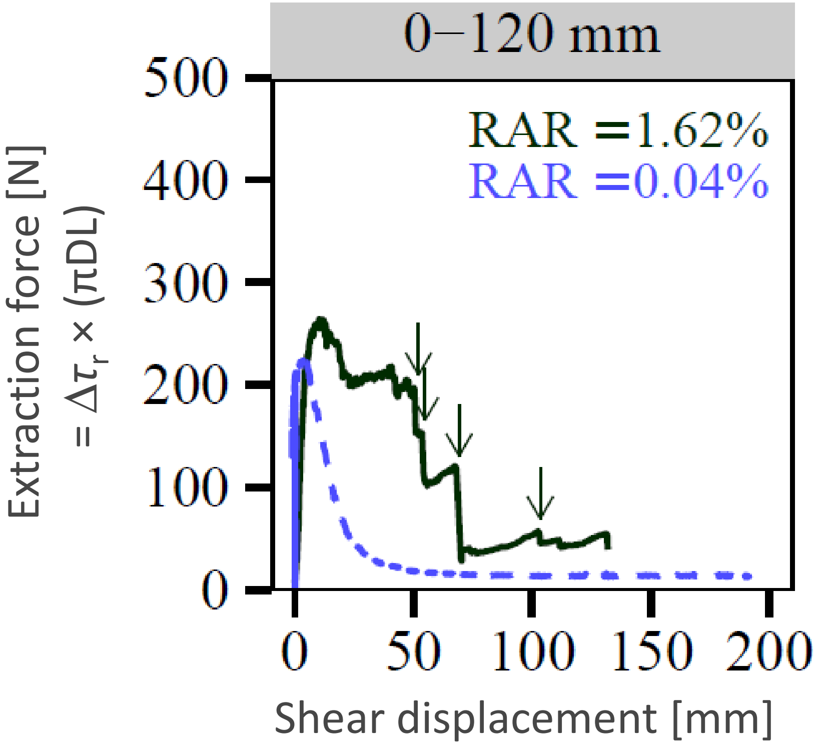


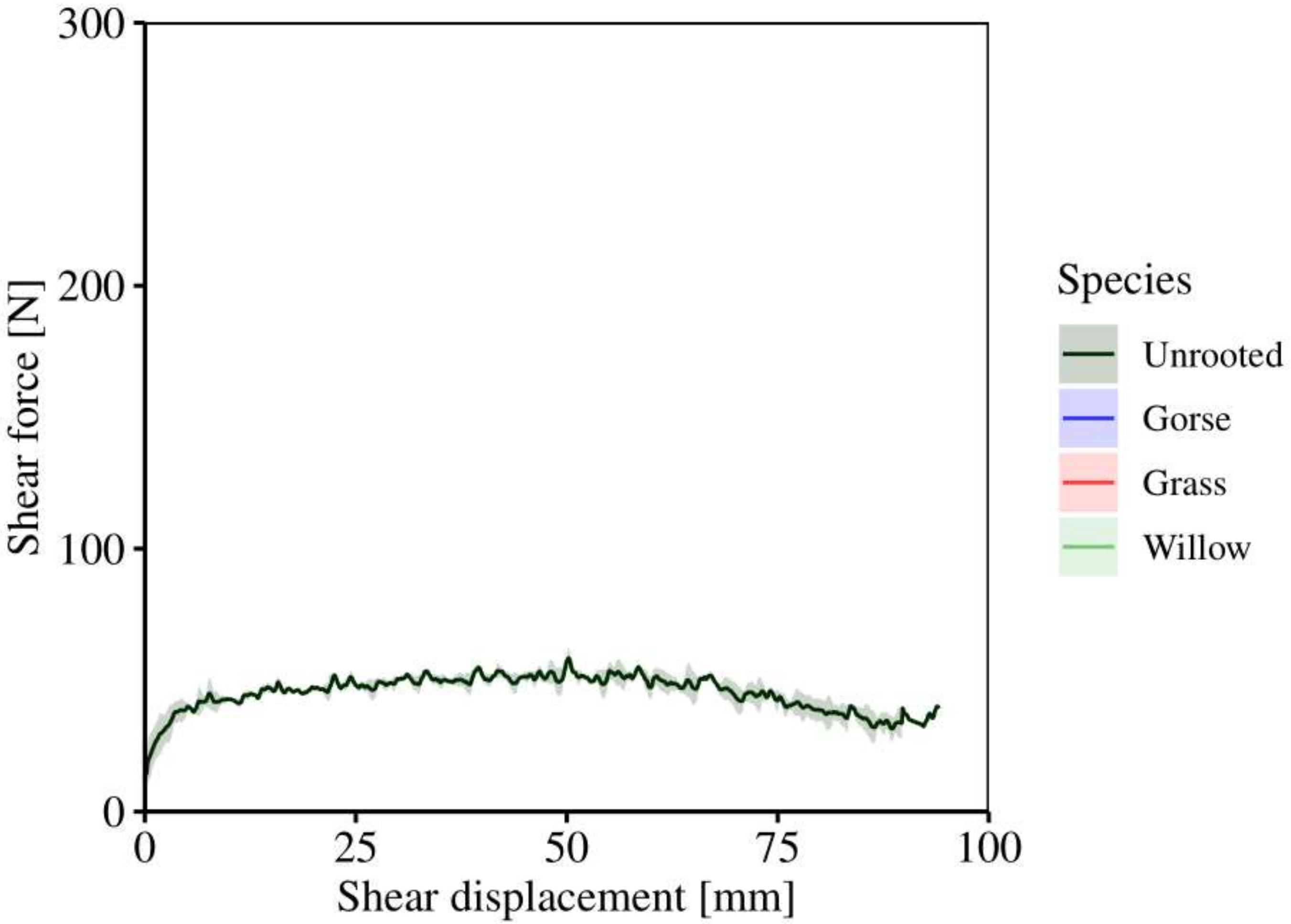
Meijer et al. (2018). Can Geo J 55 (10) 1372-1390

Root-reinforcement – direct shear testing

Large deformations may be required to mobilise mechanical root-reinforcement!

Grass

Willow



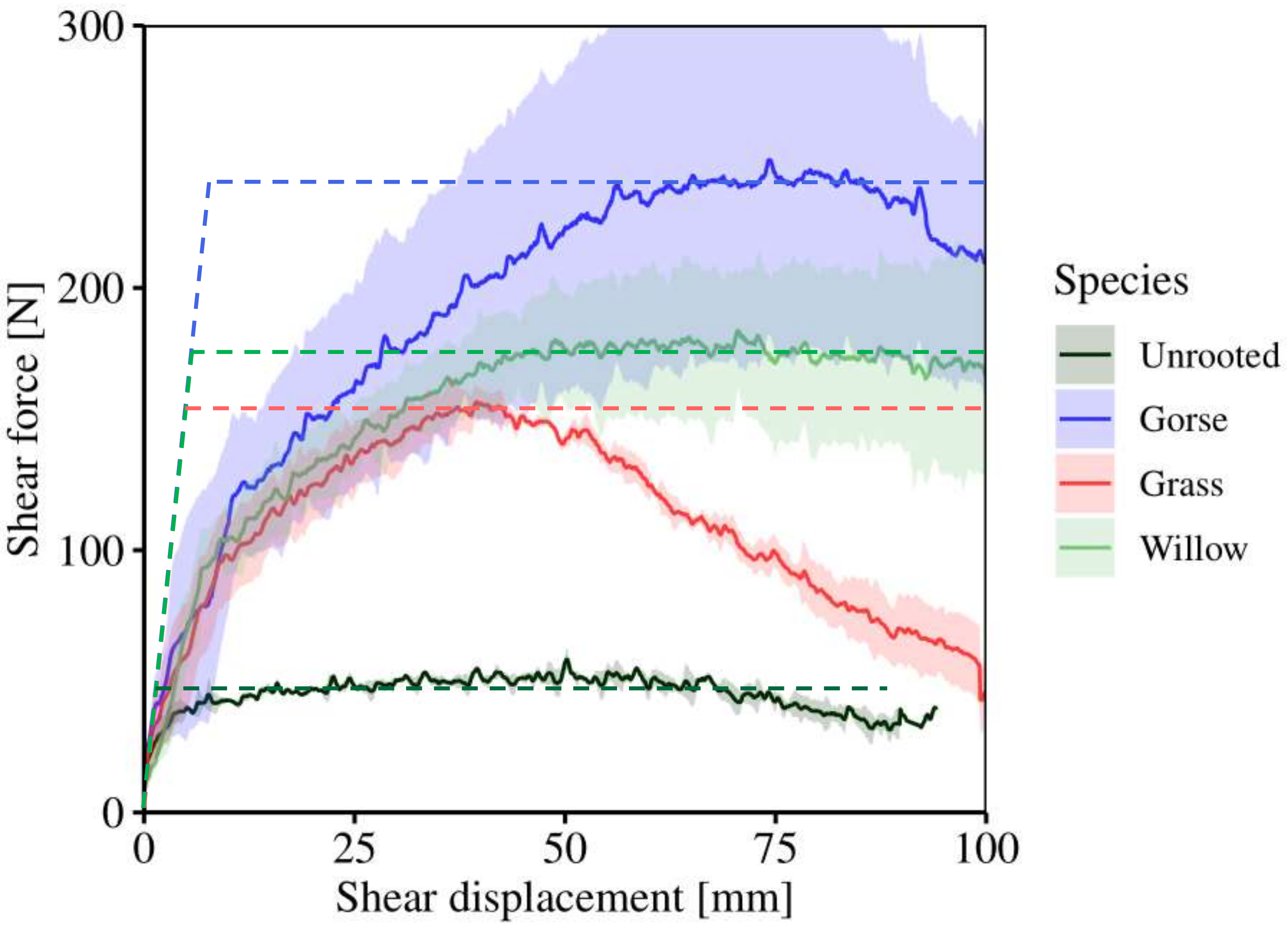
Liang et al. (2017). Ecological Engineering 107:207-227

Root-reinforcement – direct shear testing

Including root-reinforcement as an increase in soil cohesion may not be accurate

Grass

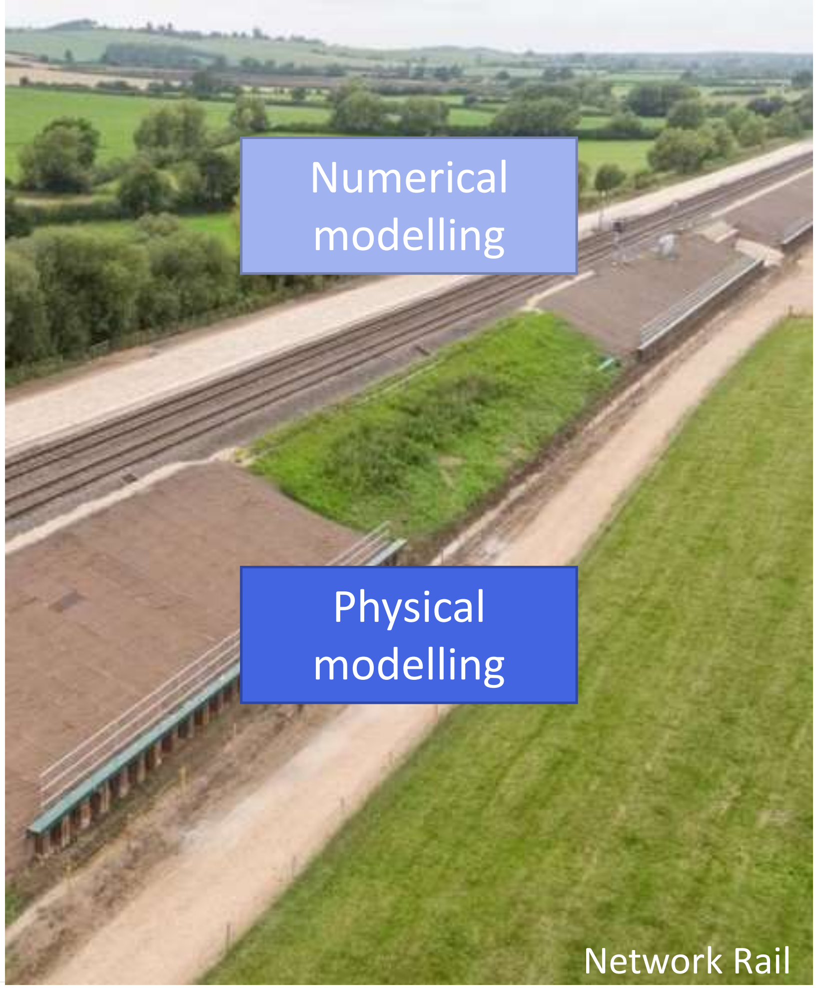
Willow

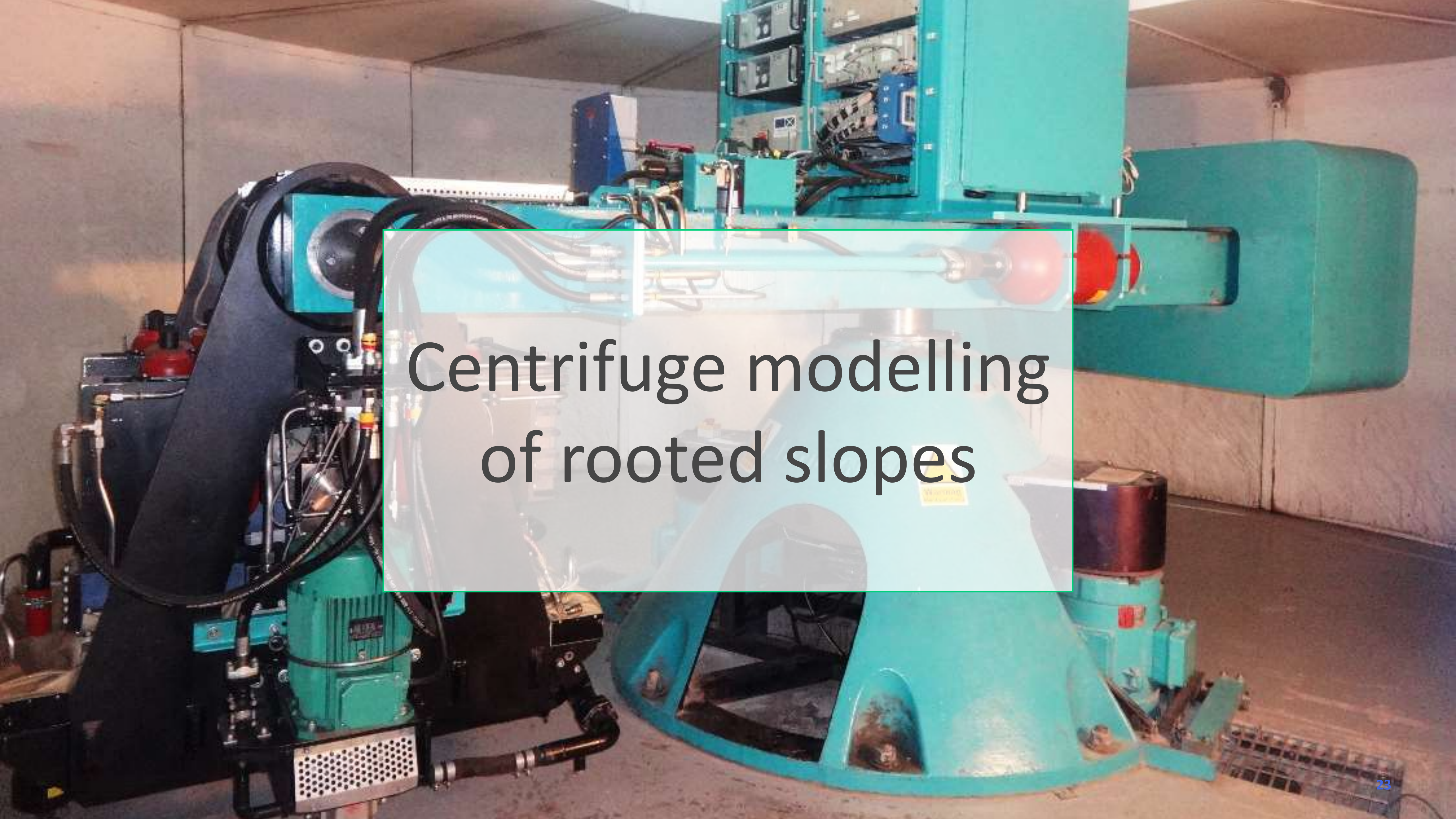


Liang et al. (2017). Ecological Engineering 107:207-227

Root-reinforcement – limit states

Ultimate limit state problems	Serviceable limit state problems

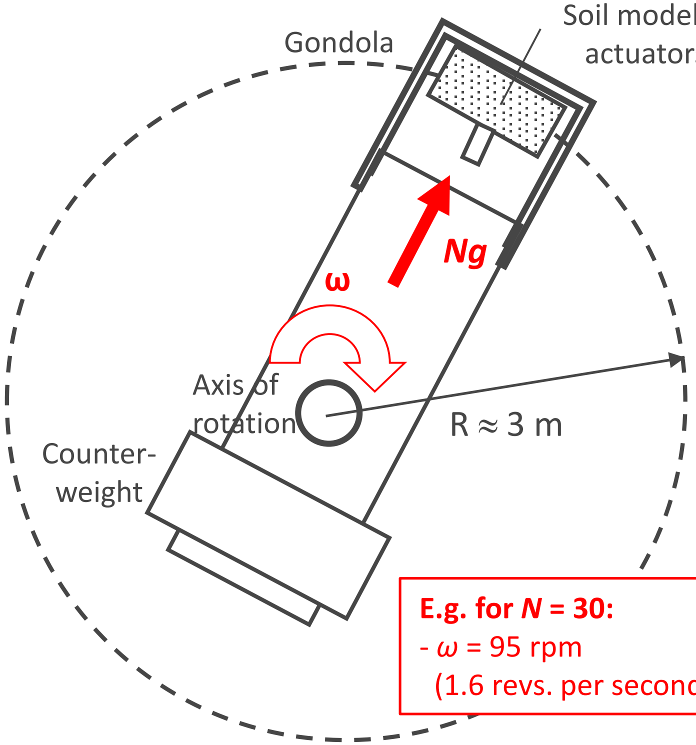




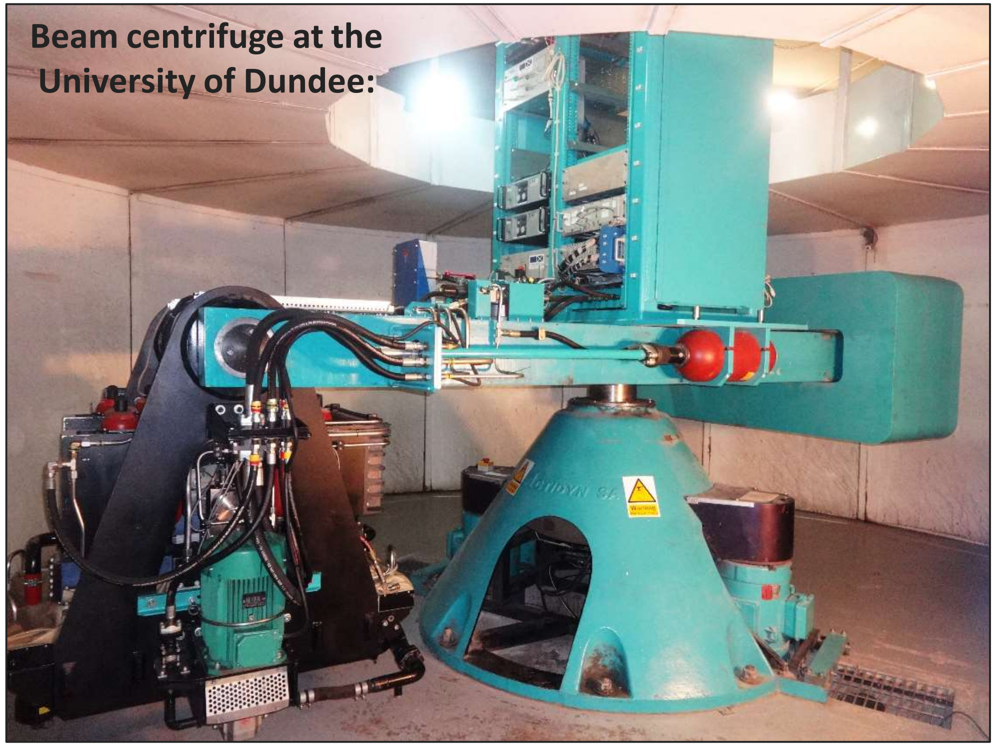
Centrifuge modelling of rooted slopes

Physical model testing - centrifuge

- A centrifuge compensates for the low confining stresses in scaled models.
- A gravity field *N* times larger than *g* is created, for a model at scale 1:*N.*
- Scaling laws map model values to a representative full-scale prototype.



E.g. for *N* = 30:
- ω = 95 rpm
(1.6 revs. per second)



Beam centrifuge at the University of Dundee:

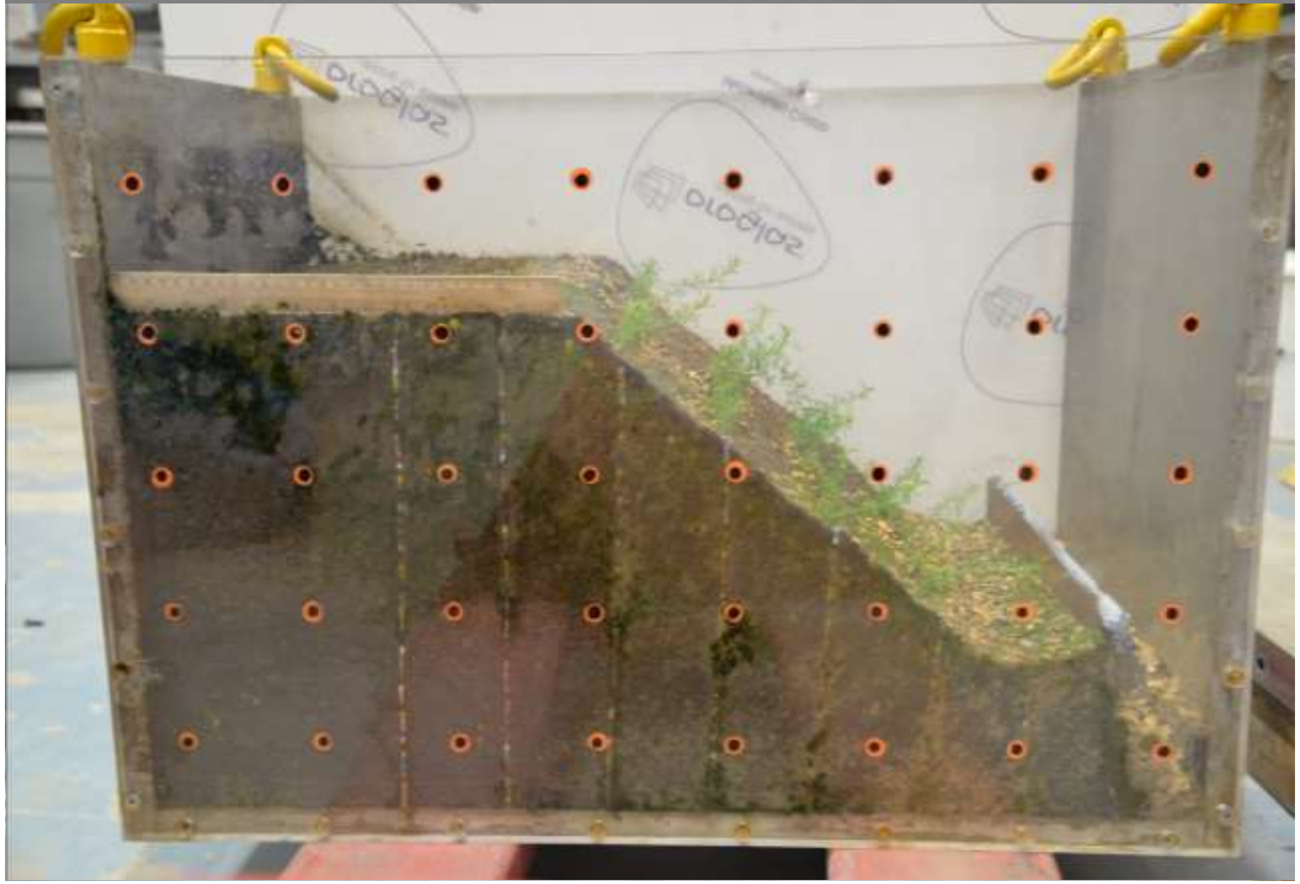
Centrifuge scaling of roots

Trade-off between scaling of:

- Root depth $(1/N)$
- Root diameters $(1/N)$
- Root-reinforcements (1)
- Root volume fractions (1)

➢ Solution? Use young plants, $N = 15$

Slope rooted with gorse, 1300 kg/m^3 dry density



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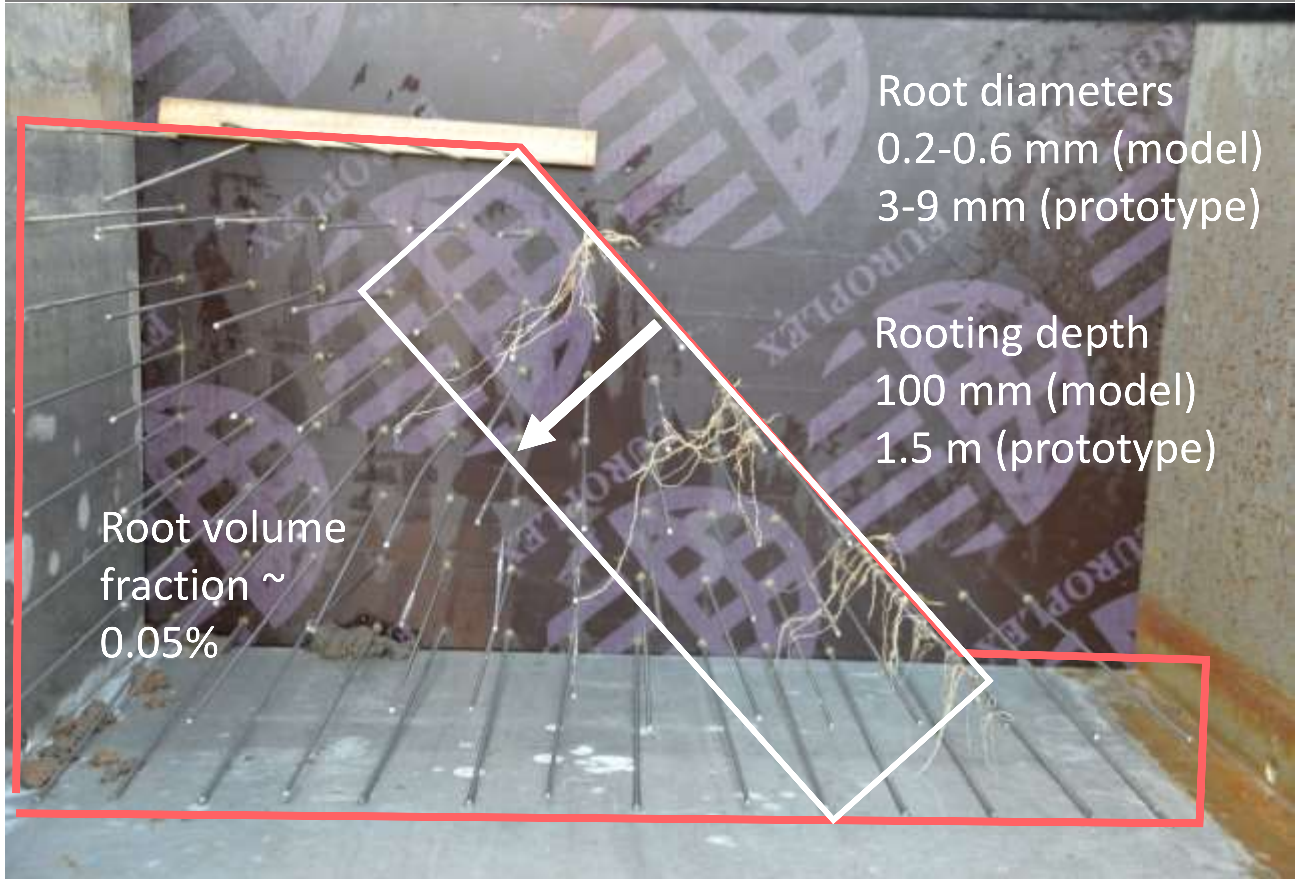
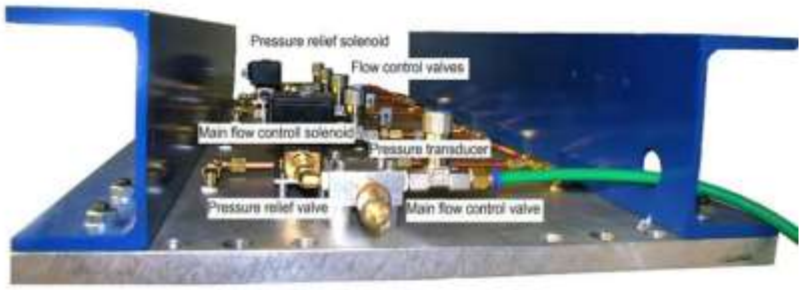
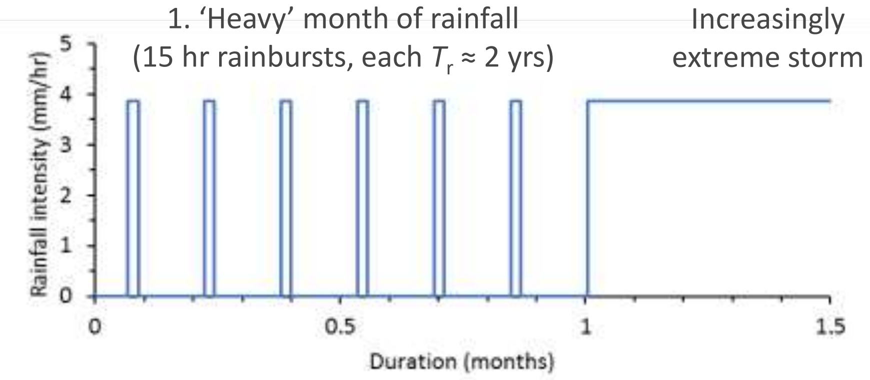


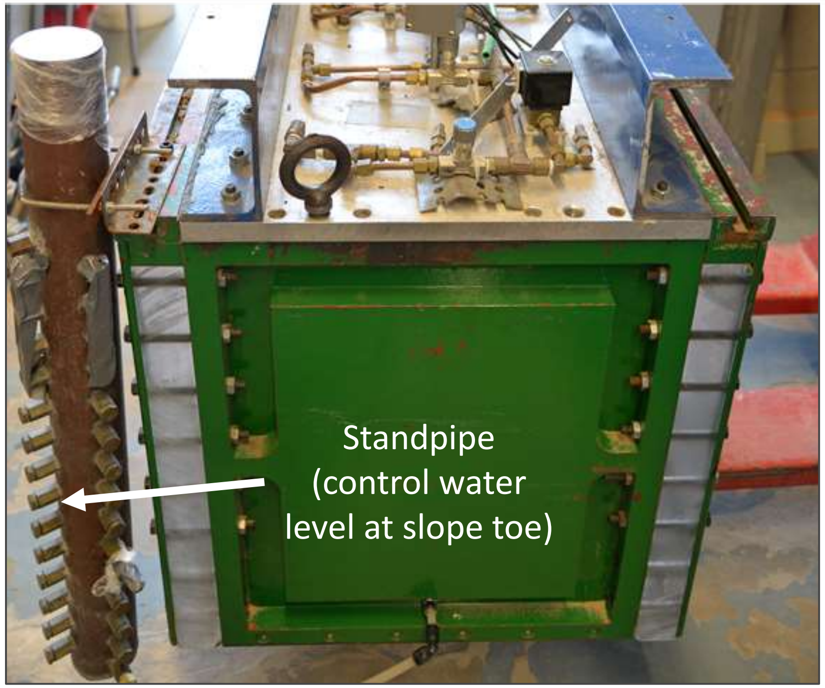
Liang et al. (2017). Ecological Engineering 107:207-227

Centrifuge modelling of slopes with live vegetation

Rainfall simulator (climate chamber):







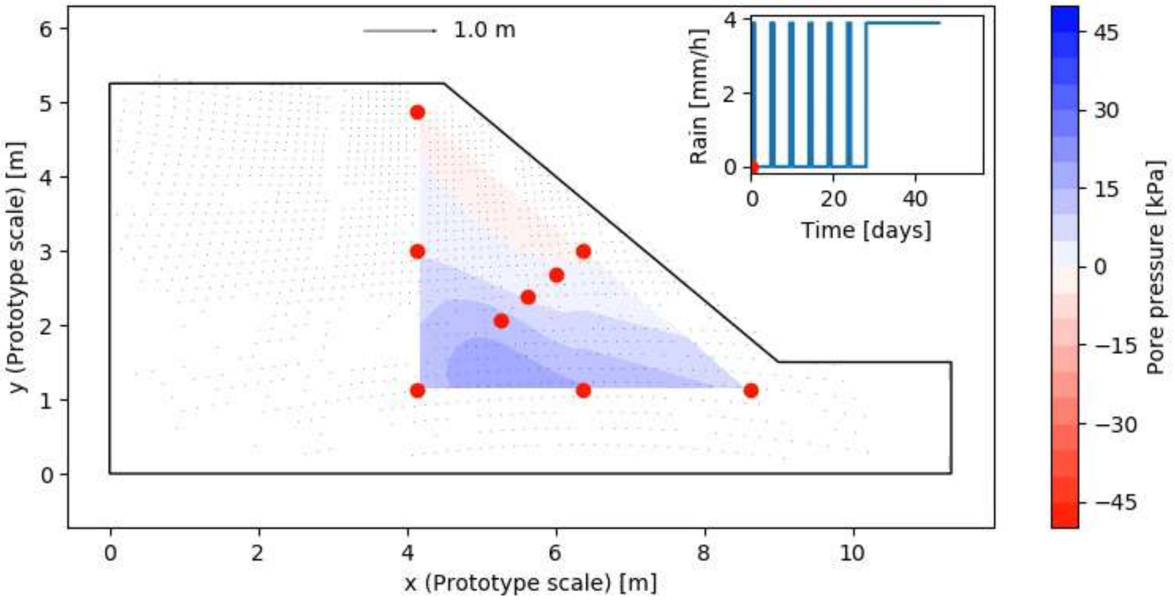
EPSRC
Engineering and Physical Sciences Research Council

Bengough, Knappett & Muir Wood (2015-2019).
Rooting for sustainable performance (EP/M020355/1)

Hydro-mechanical behaviour

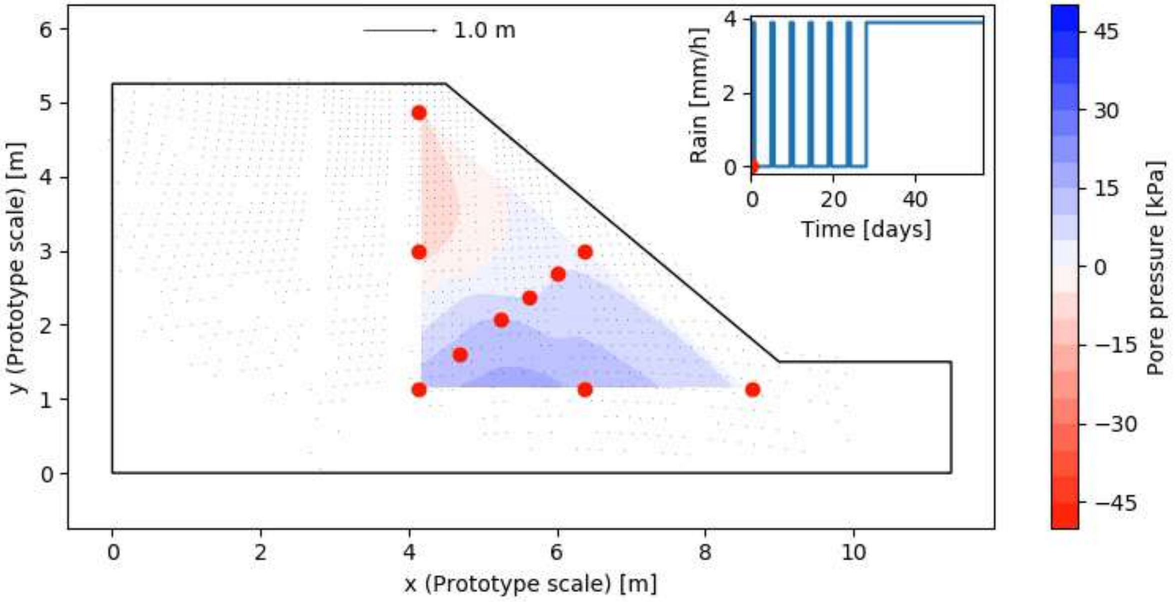
Fallow slope:

- **<u>Month 1:</u> Slip after 2 No. (T_r = 2 yr) rainbursts**
- <u>Month 2:</u> Further extensive deformation during extreme storm



Fully-vegetated slope (willow):

- <u>Month 1:</u> No slip after 6 bursts
- **<u>Month 2:</u> Some small deformation following extreme event (T_r = 10,000 yr), but no catastrophic slide**



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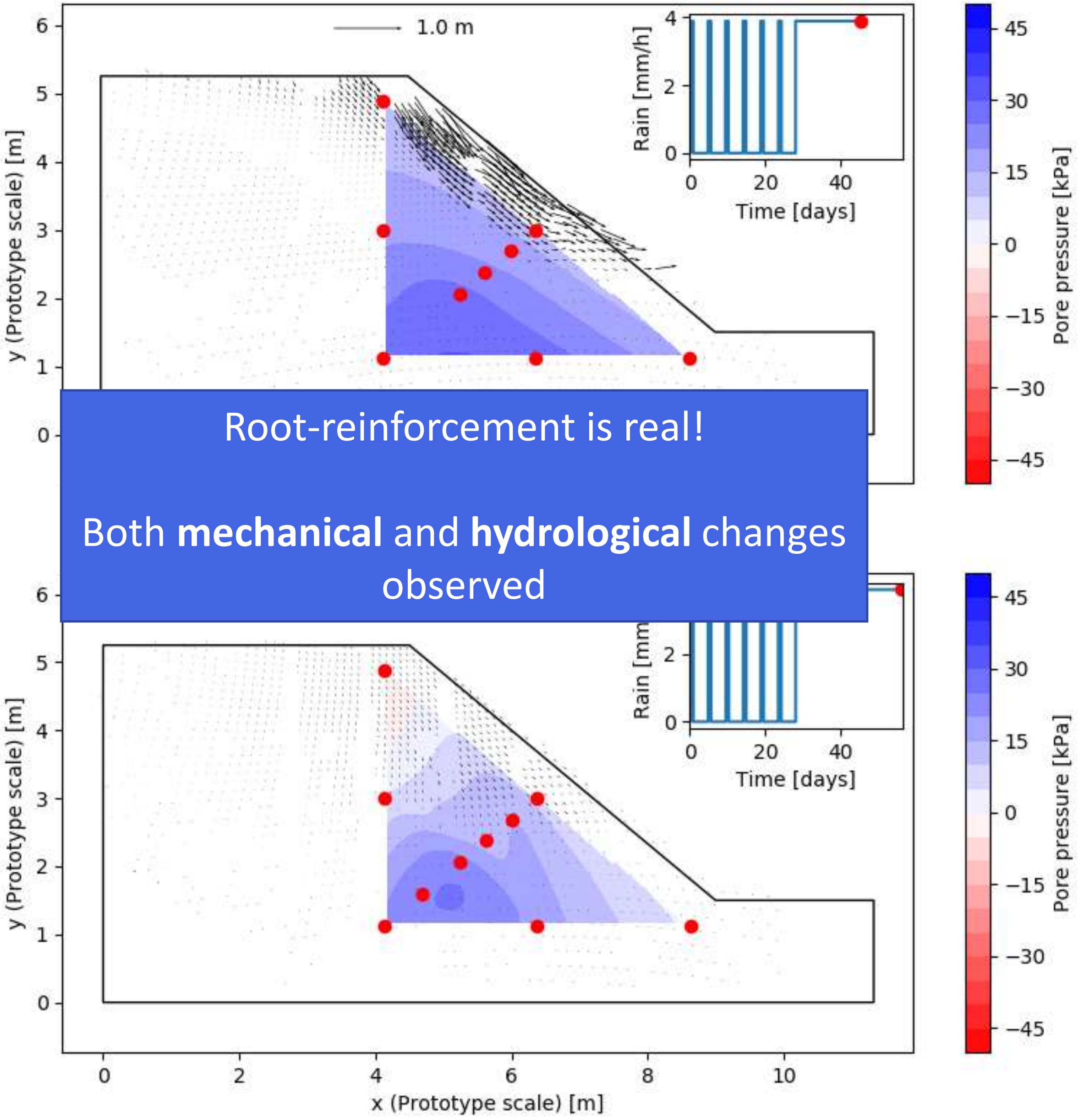
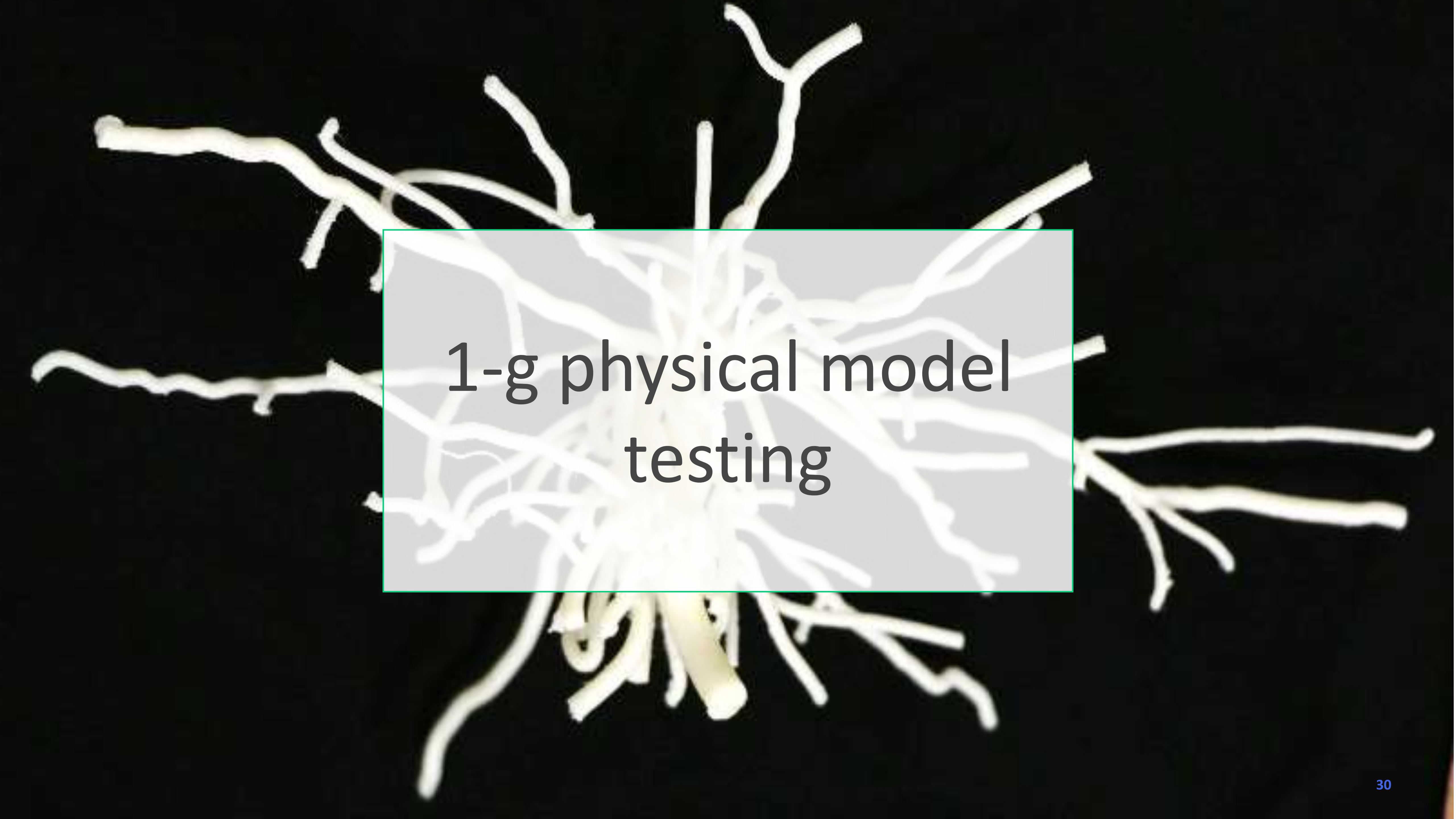


Root-reinforcement is real!

Both **mechanical** and **hydrological** changes observed

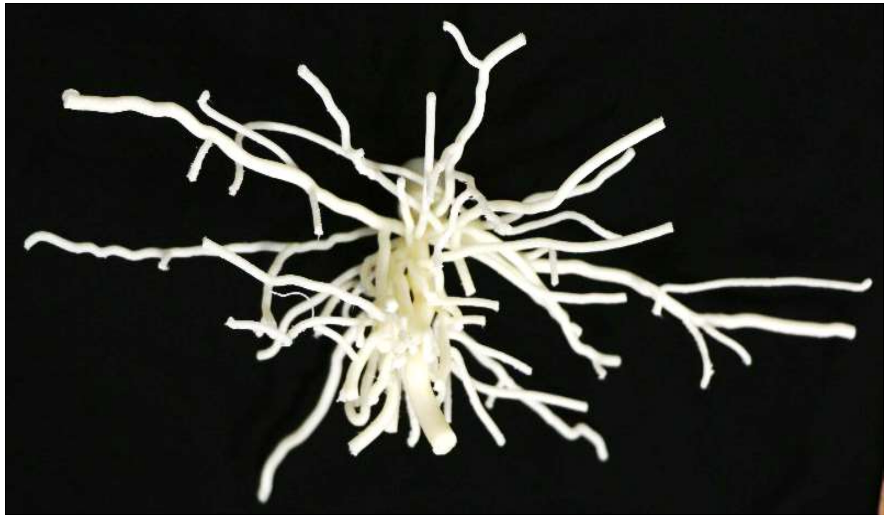
Bengough, Knappett & Muir Wood (2015-2019).
Rooting for sustainable performance (EP/M020355/1)



1-g physical model testing

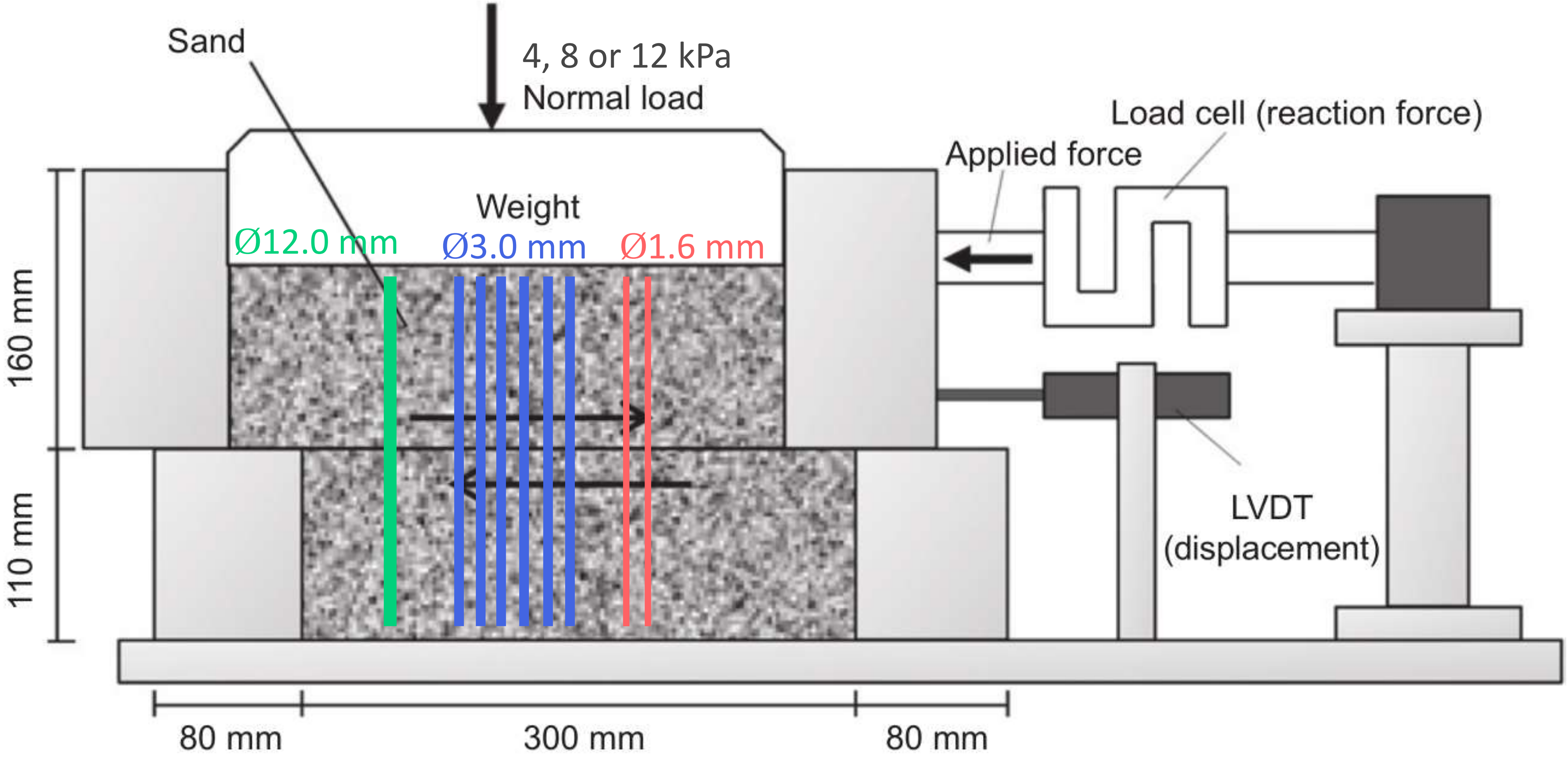
Physical modelling of trees under lateral load (current)

- 3-D printing is being used to create root architecture models based on scanned root data (Danjon & Reubens, 2008).
- Loading tests will investigate **mechanisms of resistance** (e.g. root plate rotation or pull-out?)



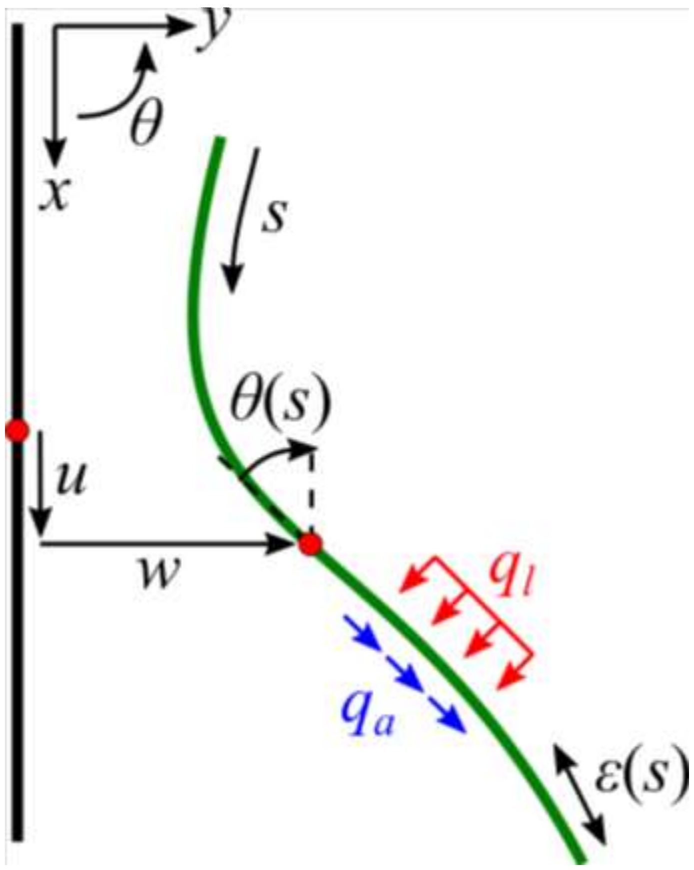
Danjon & Reubens (2008). *Plant & Soil* 303(1-2): 1-34

Large shear box tests in dry sand, reinforced with ABS root analogues



Liang et al. (2015). Géotechnique 65(12):995–1009

Euler-Bernoulli beam theory for large deformations

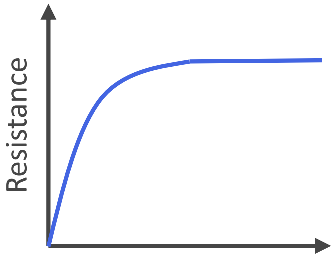


1. Root biomechanical behaviour

- Linear elastic roots
- Axial force: $N = EA\epsilon$
- Bending moment: $M = EI\,\frac{\partial\theta}{\partial s}$

2. Soil-root resistance

- Axial: q_a
- Lateral: q_l



3. Force equilibrium along the root

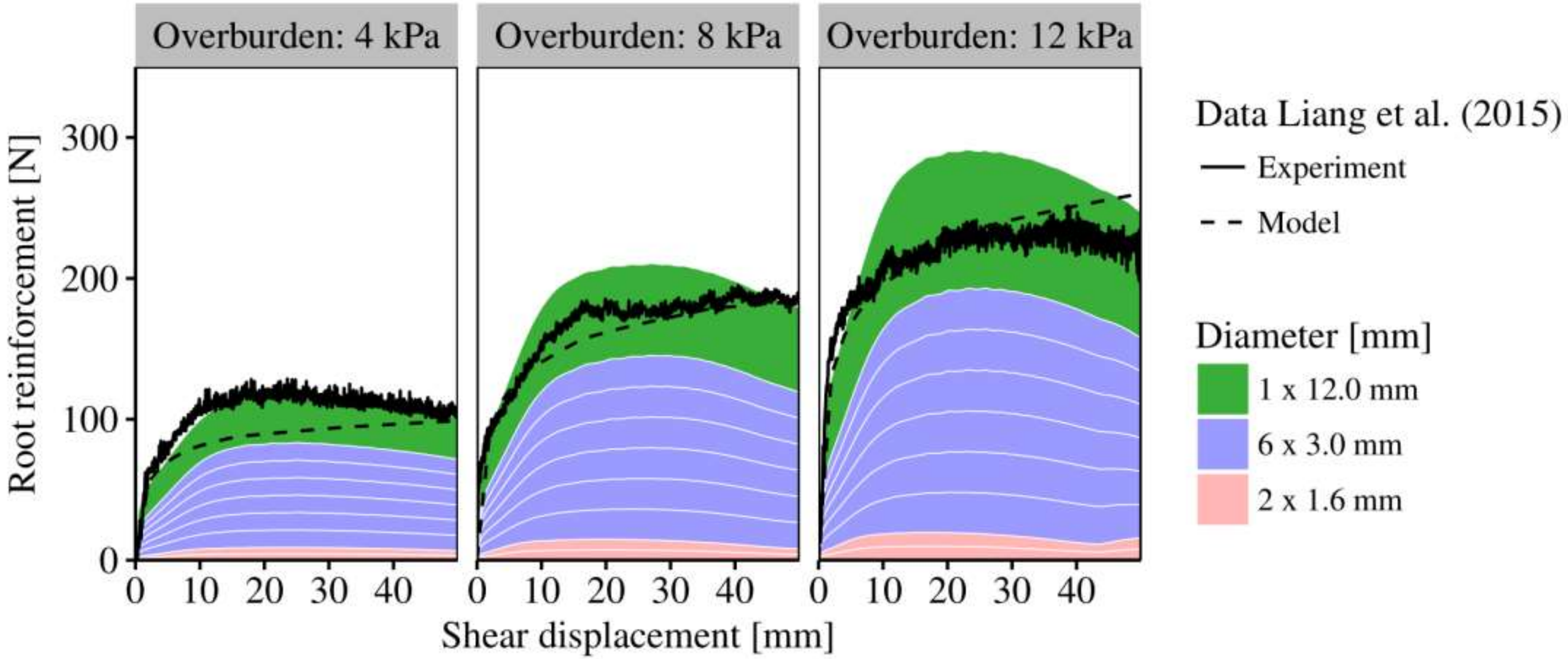
- Axial: $q_a + \frac{\partial N}{\partial s} + \frac{\partial M}{\partial s}\frac{\partial\theta}{\partial s} = 0$
- Lateral: $q_l + N\frac{\partial\theta}{\partial s} - \frac{\partial^2 M}{\partial s^2} = 0$

4. Root positions

- Axial: $\frac{\partial u}{\partial s} = (1+\epsilon)\cos\theta - 1$
- Lateral: $\frac{\partial w}{\partial s} = (1+\epsilon)\sin\theta$

Meijer et al. (2019). Int J Analytical Num 43(3):684-707

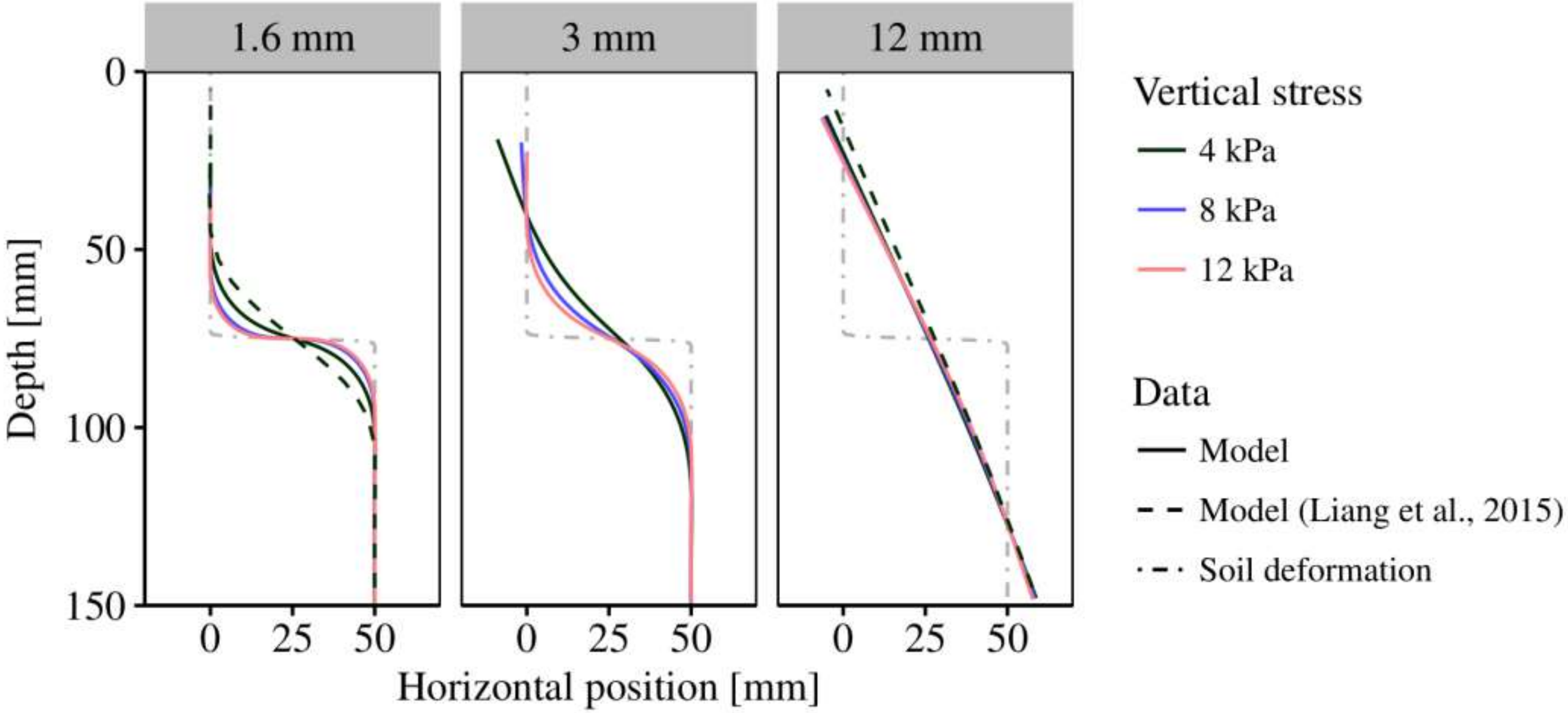
Large shear box tests in dry sand, reinforced with ABS root analogues



Meijer et al. (2019). Int J Analytical Num 43(3):684-707

Large shear box tests in dry sand, reinforced with ABS root analogues

Roots ≠ Roots
Fibres (thin roots) ⇔ Beams (thick roots)



Meijer et al. (2019). Int J Analytical Num 43(3):684-707

To conclude

Root-reinforcement quantification provides us with many challenges:

- Roots vary multiple aspects of soil behaviour simultaneously:
  - Increased soil suctions
  - Changes in hydraulic permeability
  - Mechanical reinforcement of the soil matrix, by both thin and thick roots
- Dealing with spatial, temporal and biological variability
- Field testing + physical modelling techniques

Acknowledgements

Collaborators/researchers:

- Prof Glyn Bengough (UoD/JHI)
- Prof Jonathan Knappett (JHI)
- Prof David Muir Wood (UoD)
- Prof Paul Hallett (U. of Aberdeen)
- Dr David Boldrin (JHI)
- Dr Teng Liang (formerly UoD)
- Dr Ken Loades (JHI)
- Dr Bruce Nicoll (Forest Research)
- Dr Anthony Leung (formerly UoD)
- Xingyu Zhang (current PhD)

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