Geotechnical Centrifuge Modelling: Capturing Complexities To Enable Analytical Solutions

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Scope of Presentation

- Introduction
  - Capturing complexity in analytical models
  - Centrifuge modelling to capture complexity
  - Geotechnical research process
- Examples
  - Soil nailing
  - Root reinforcement of slopes
  - Earthquake soil-foundation-structure interaction (SFSI)
- Conclusions

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Capturing complexity in analytical models

- Analytical methods are particularly valuable in cases where high accuracy is not required or unachievable due to lack of data or level of risk, and where high performance computing time and costs are prohibitive.
- Focus on the development of models for analyses that capture important complexities while being simple enough to be solved analytically and implemented easily.
  - New construction techniques
  - Poorly defined geotechnical systems
  - Screening and assessment of geotechnical systems

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Centrifuge modelling - capturing complexity

- Observations of geotechnical systems inform the development of analytical solutions for assessing stability, calculating movements and for predicting the impact of geotechnical processes.
- Correctly scaled and appropriately instrumented physical models that ***capture the important complexities*** of geotechnical systems can provide an alternative to field measurements.
- Such models allow simulation of geotechnical systems that might be too expensive, time consuming or almost impossible to monitor in the field.

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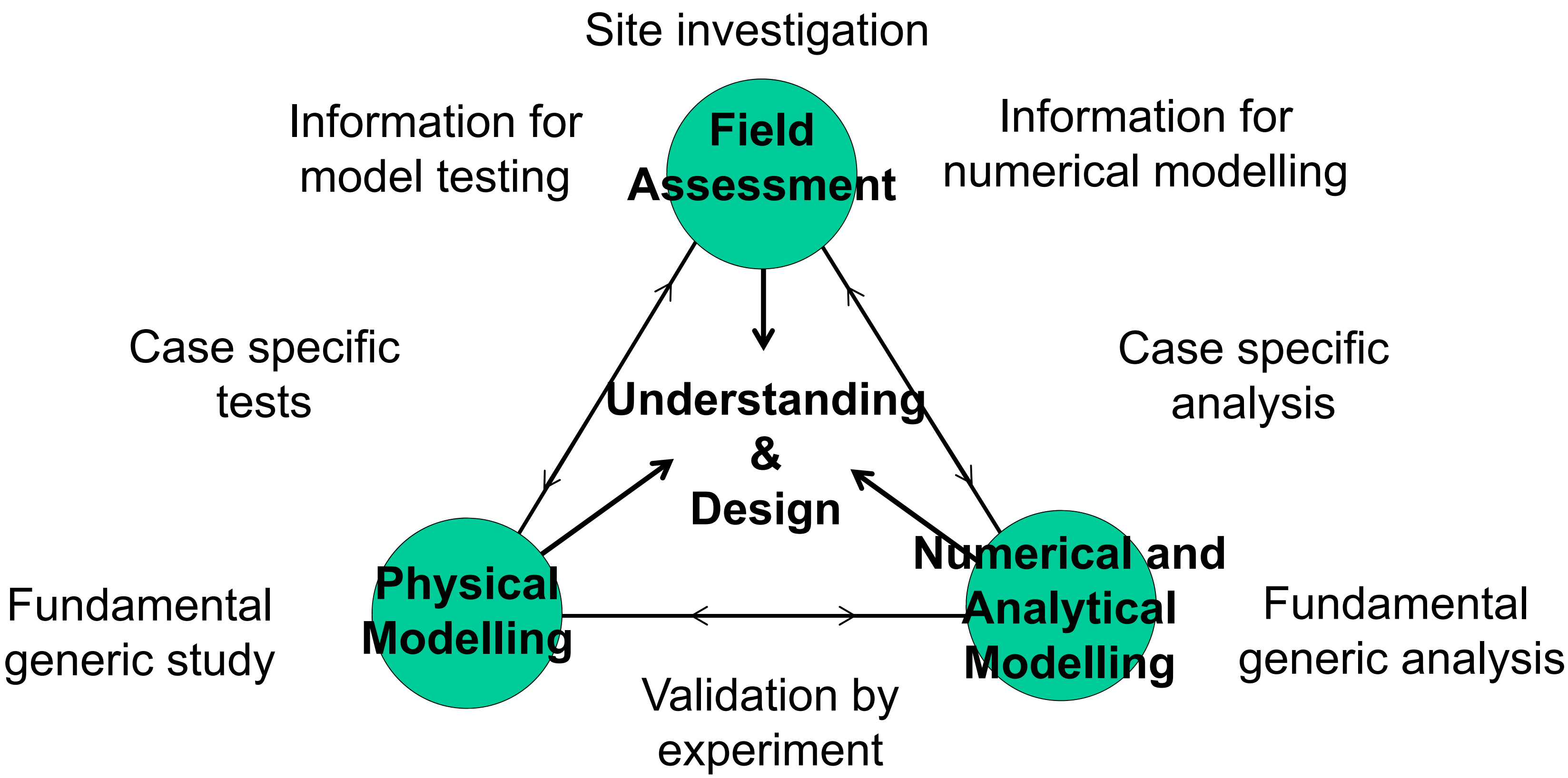
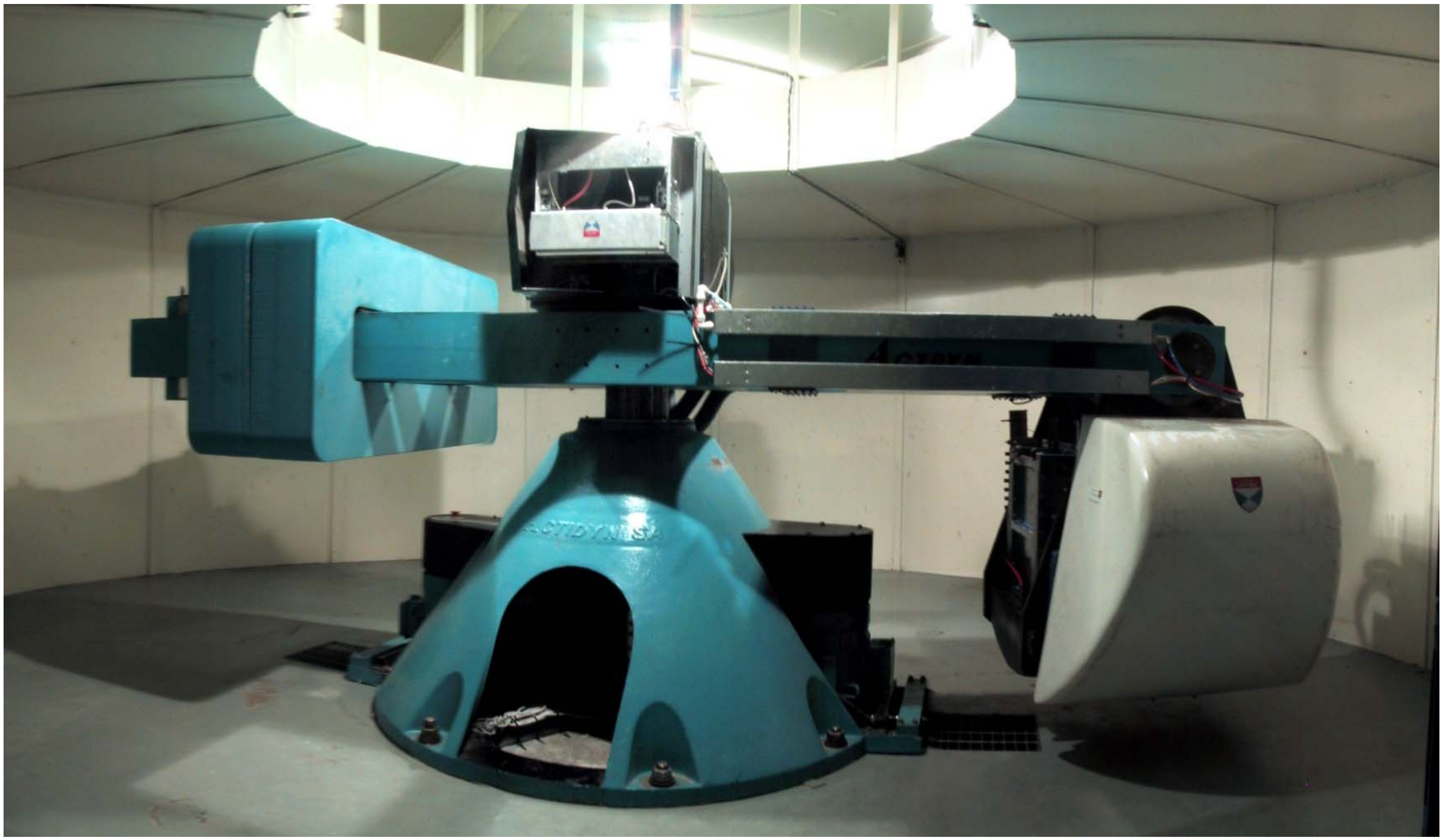
Centrifuge modelling - capturing complexity

- Requirement for similitude between material properties in prototype and model.
- Stress/strain behaviour of soil is highly non-linear, stress level dependent and stress history dependent.
- Close control over material properties and well defined boundary conditions in a model enable repeatability - permitting parametric studies to be conducted.
- Instrumentation and monitoring systems provide quantitative data that may be used both to inform the development and to validate analytical solutions.

Integrated geotechnical research process



Centrifuge modelling
Dundee Geotechnical Centrifuge



150 g-tonne beam centrifuge (Actidyn C67-2)

Centrifuge modelling
Dundee Geotechnical Centrifuge

150 g-tonne beam centrifuge (Actidyn C67-2)

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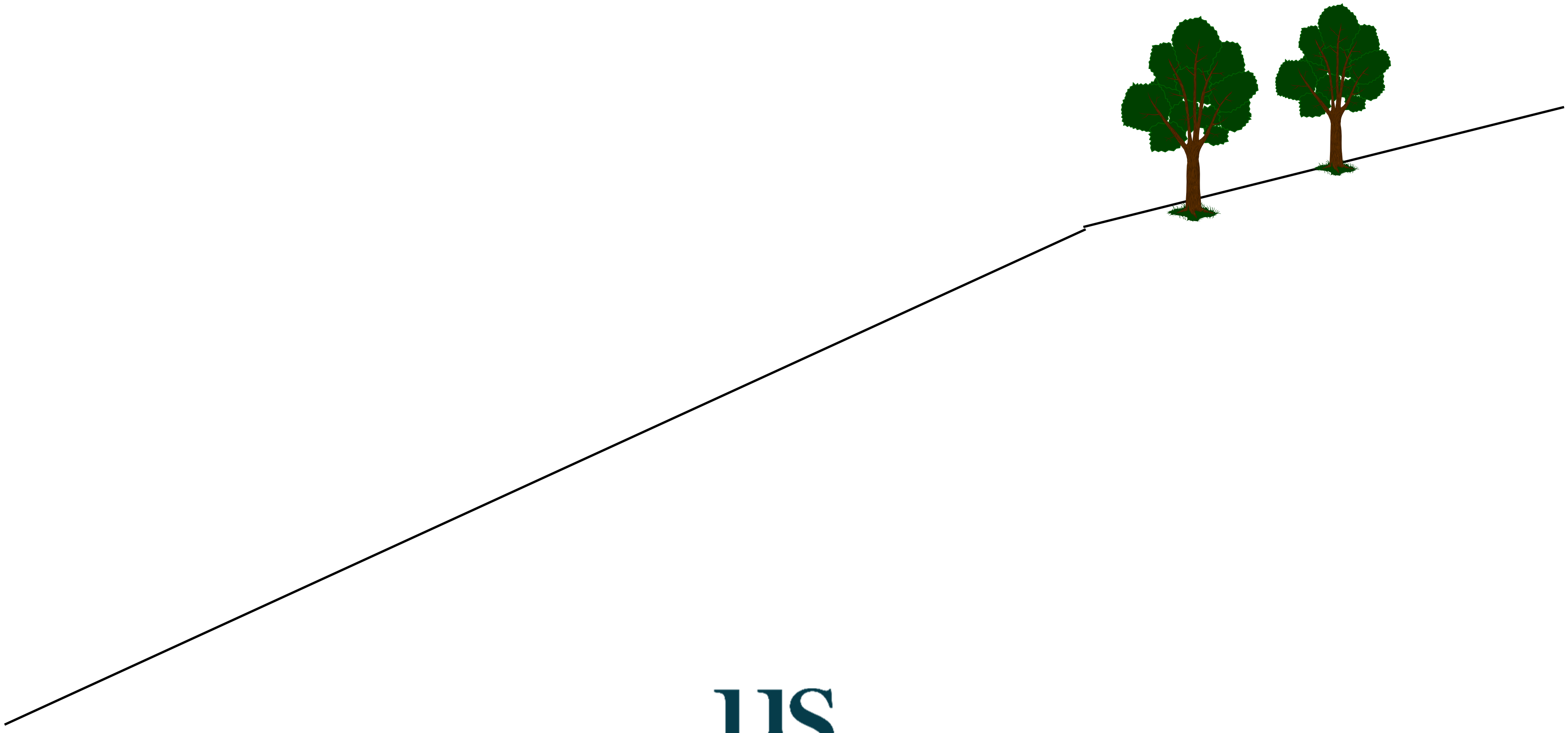
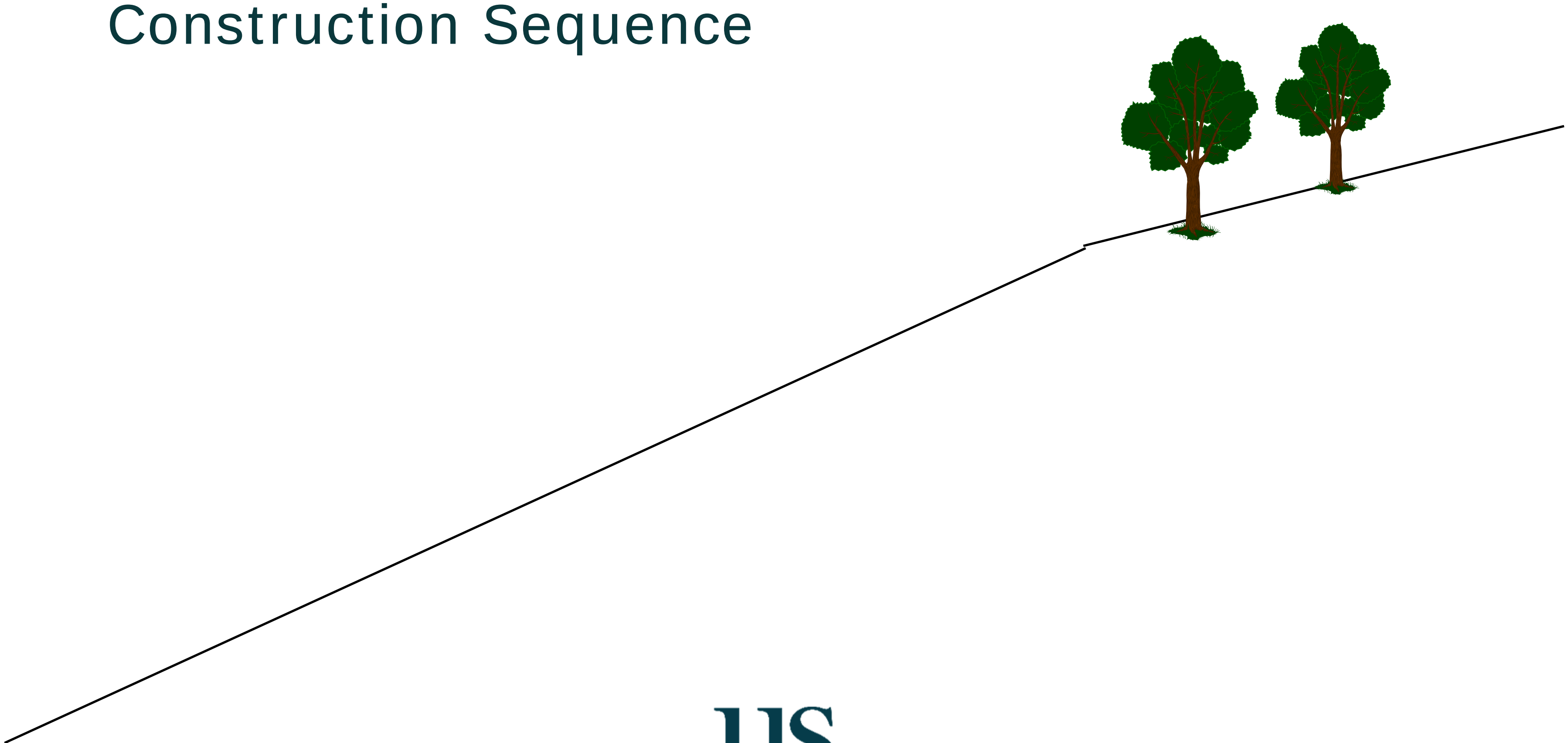
Soil Nailing



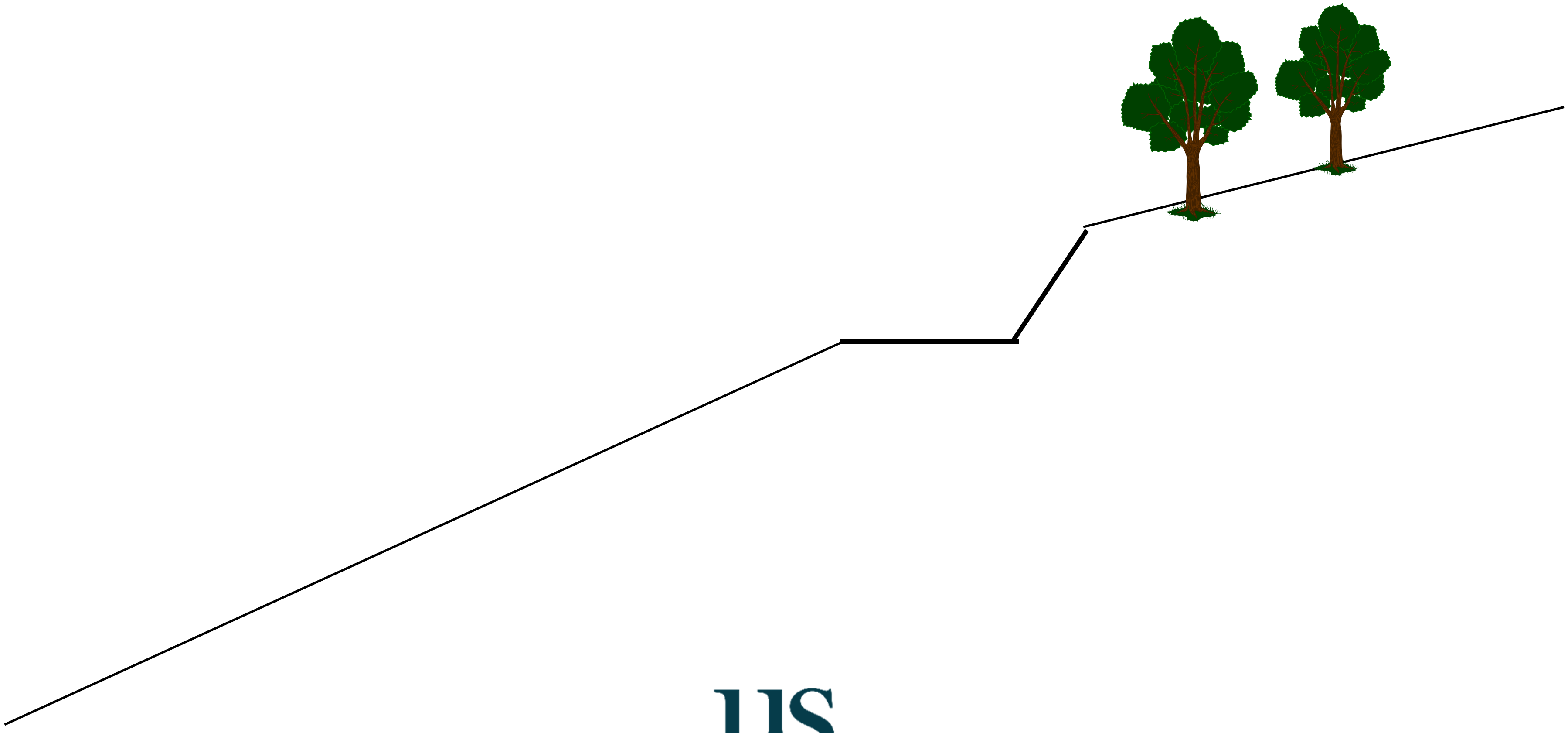
Soil Nailing

Construction Sequence



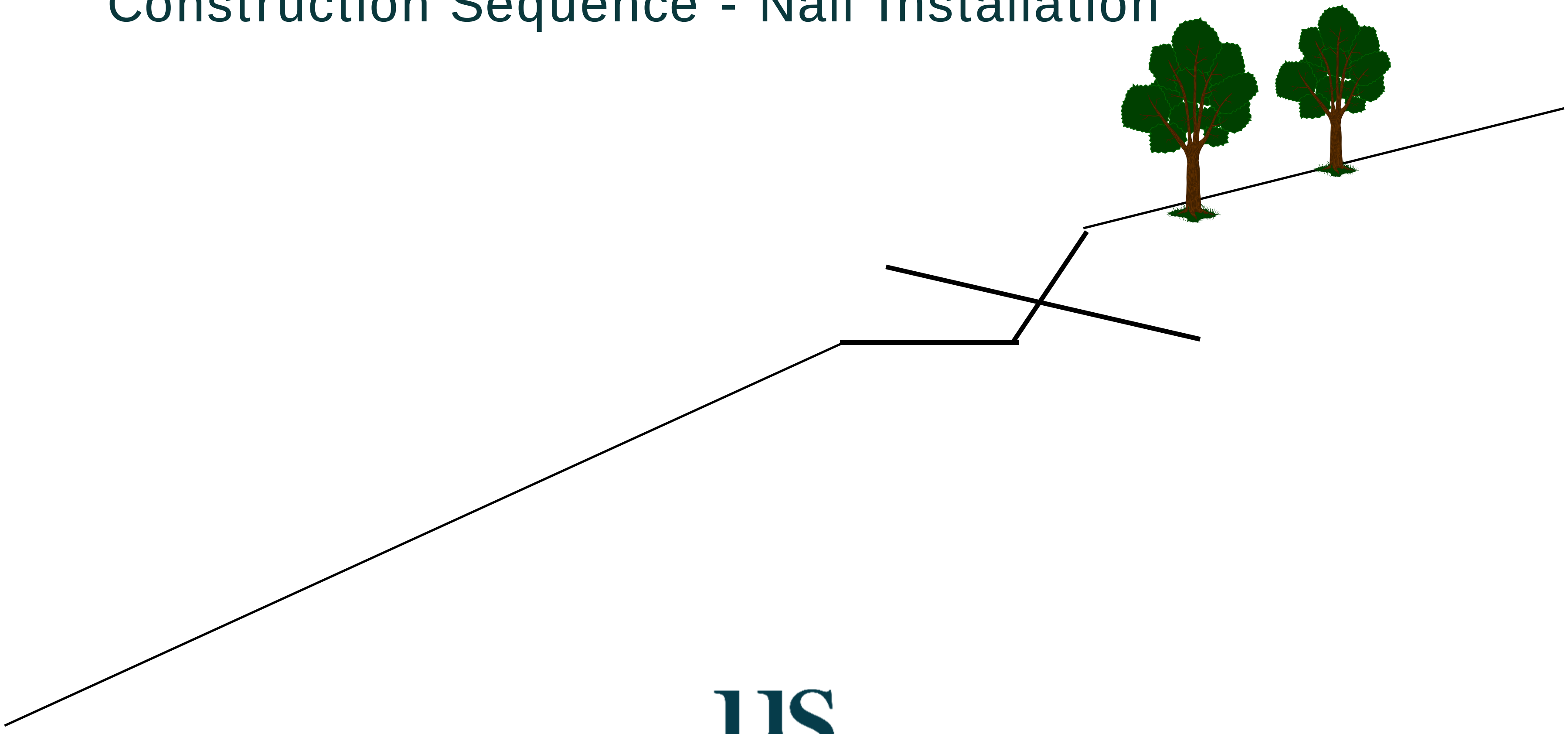
Soil Nailing

Construction Sequence - Excavation



Soil Nailing

Construction Sequence - Nail Installation



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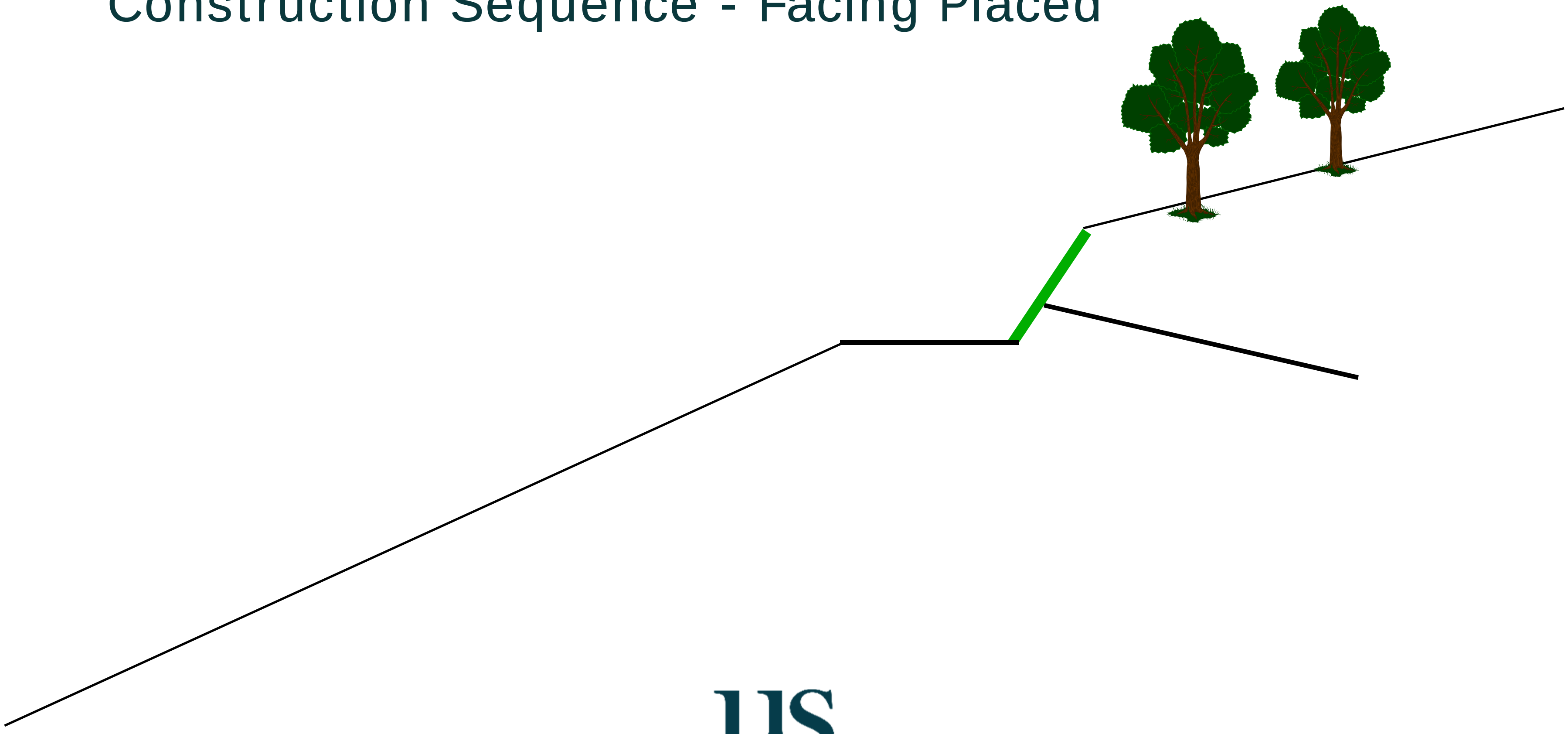
Soil Nailing

Construction Sequence - Facing Placed



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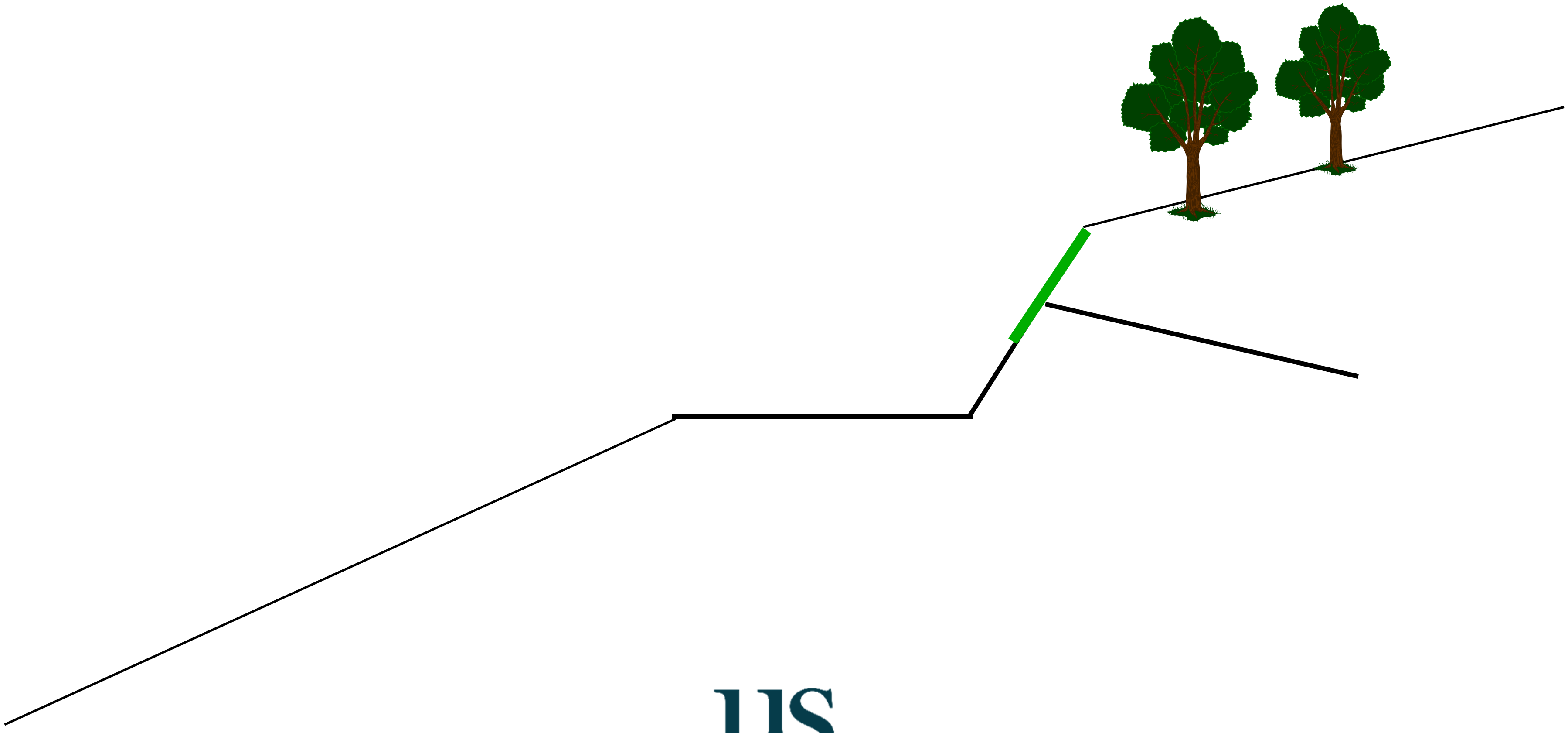
Soil Nailing



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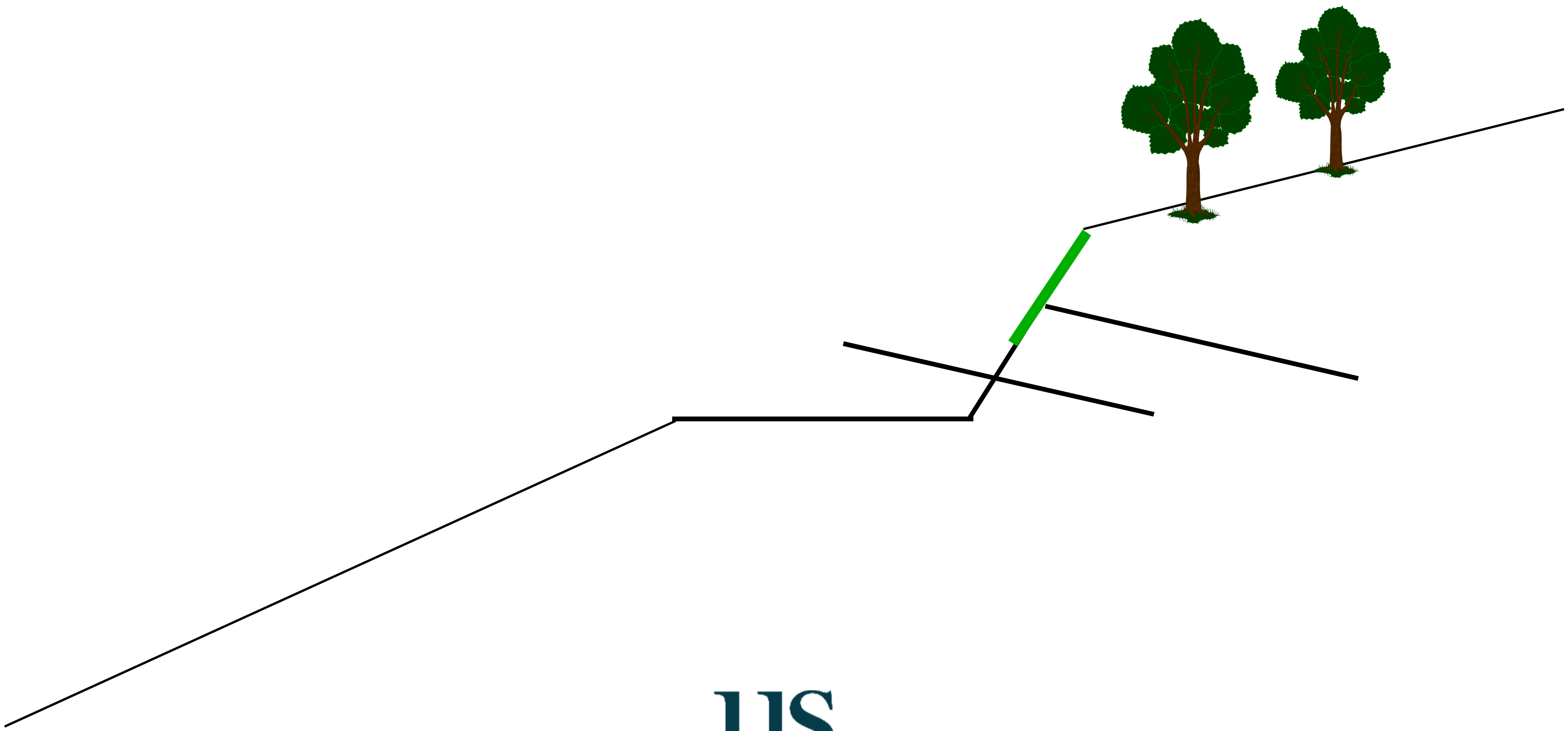

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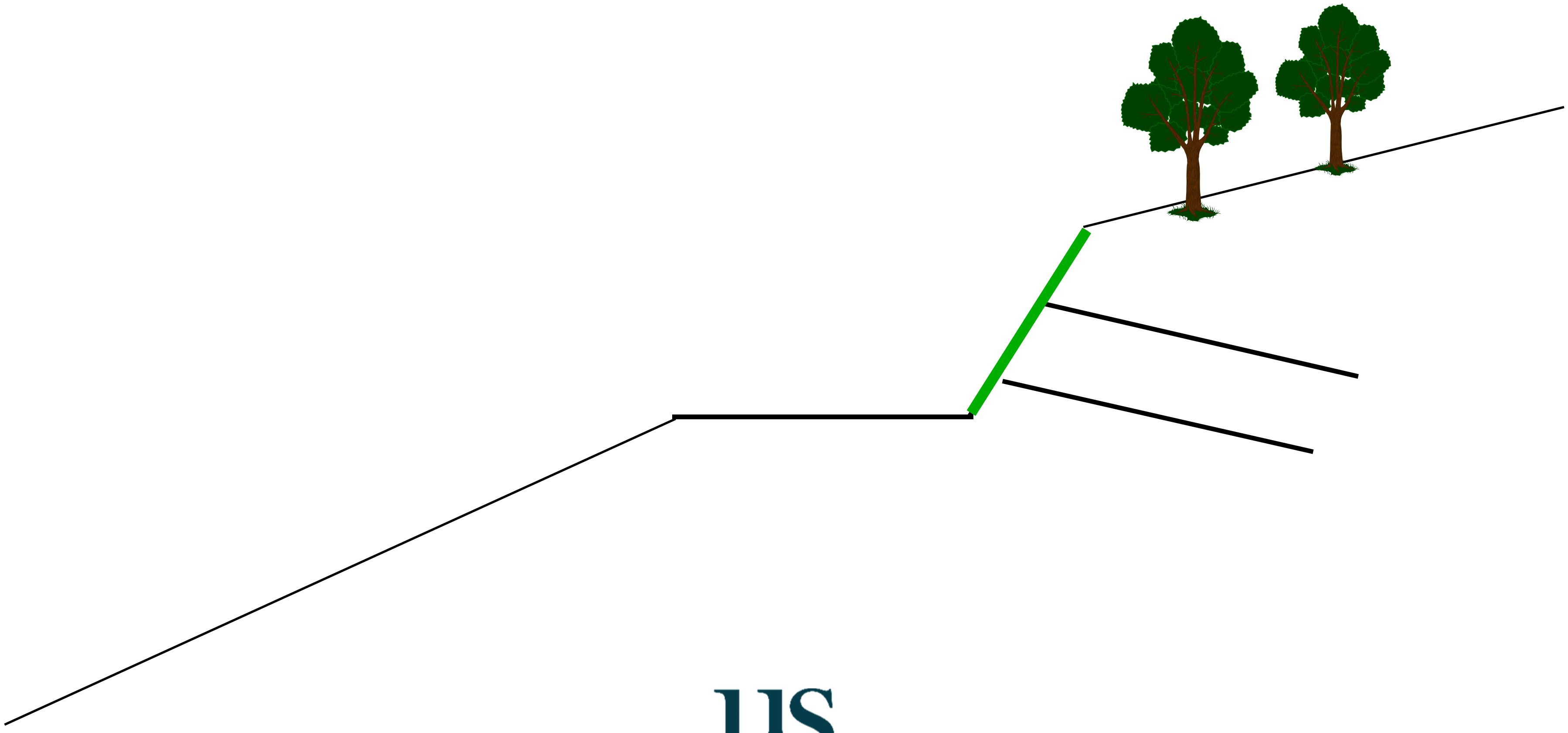

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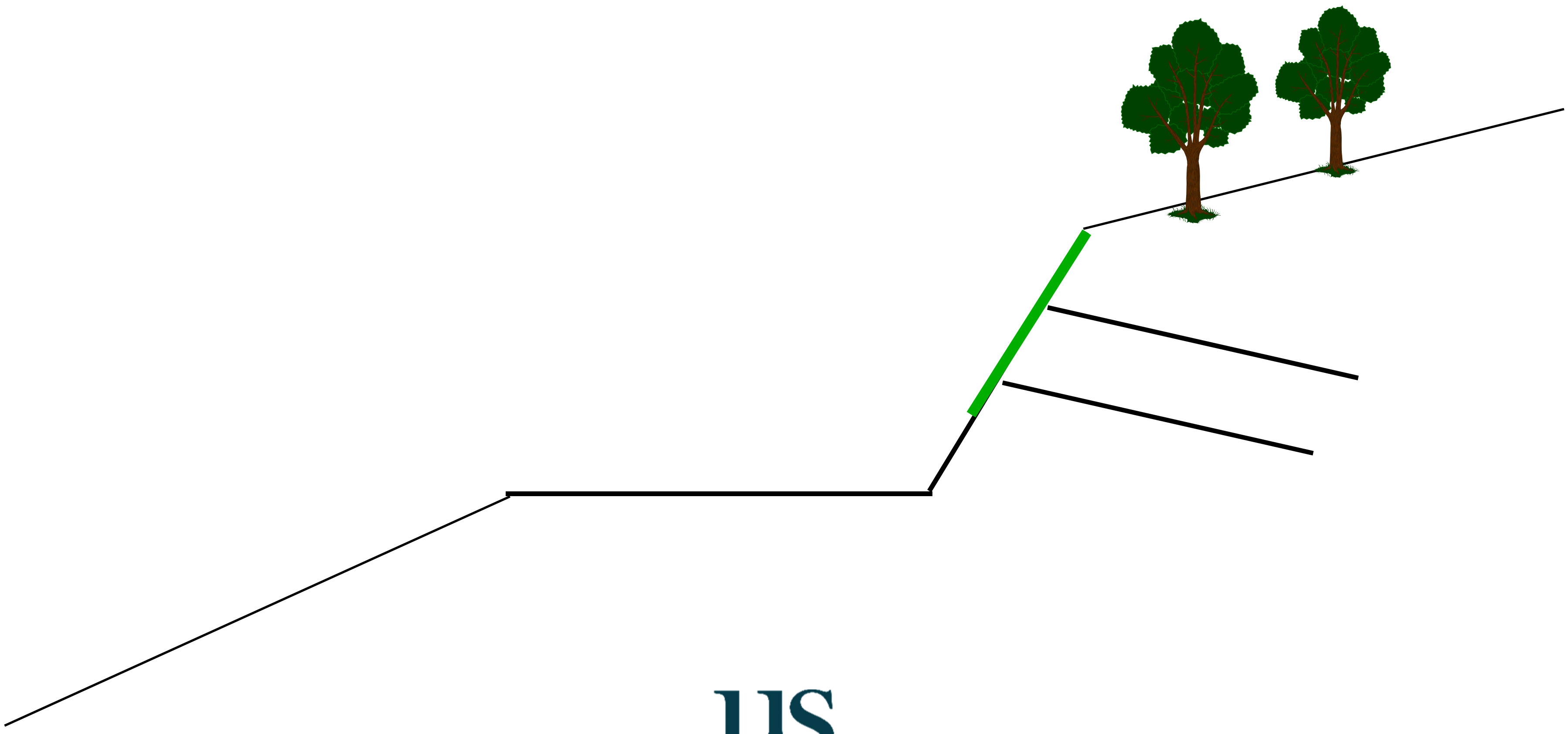

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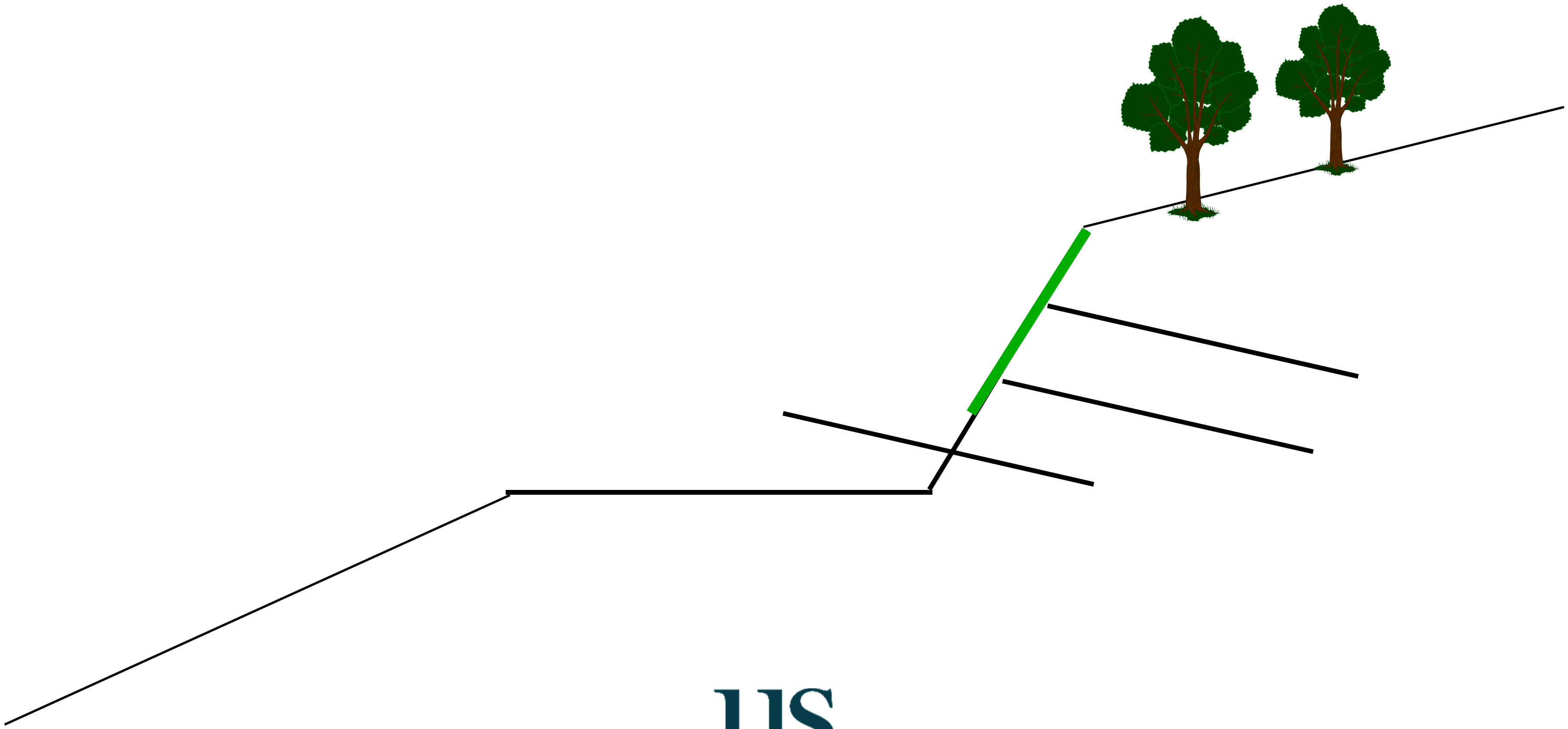
Soil Nailing



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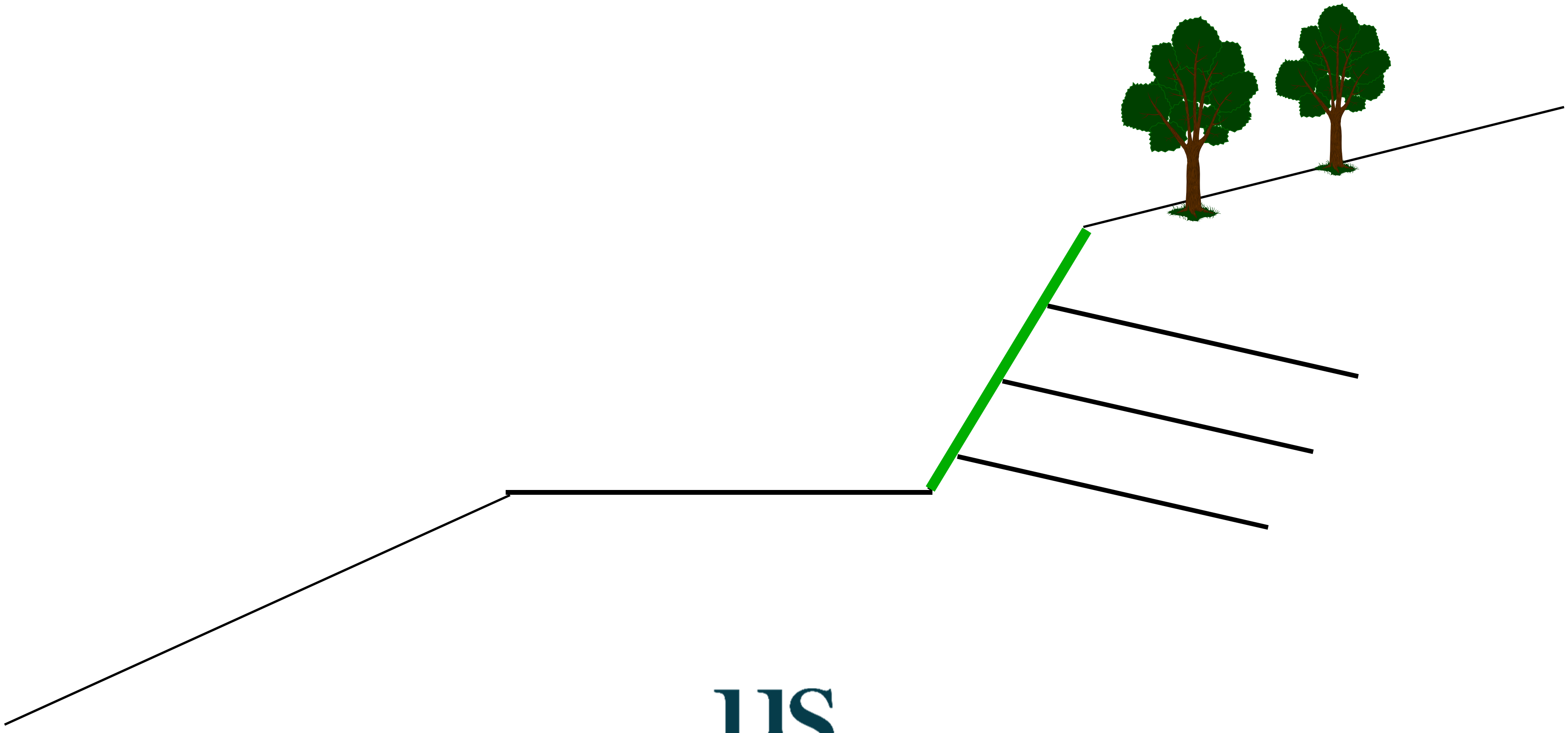

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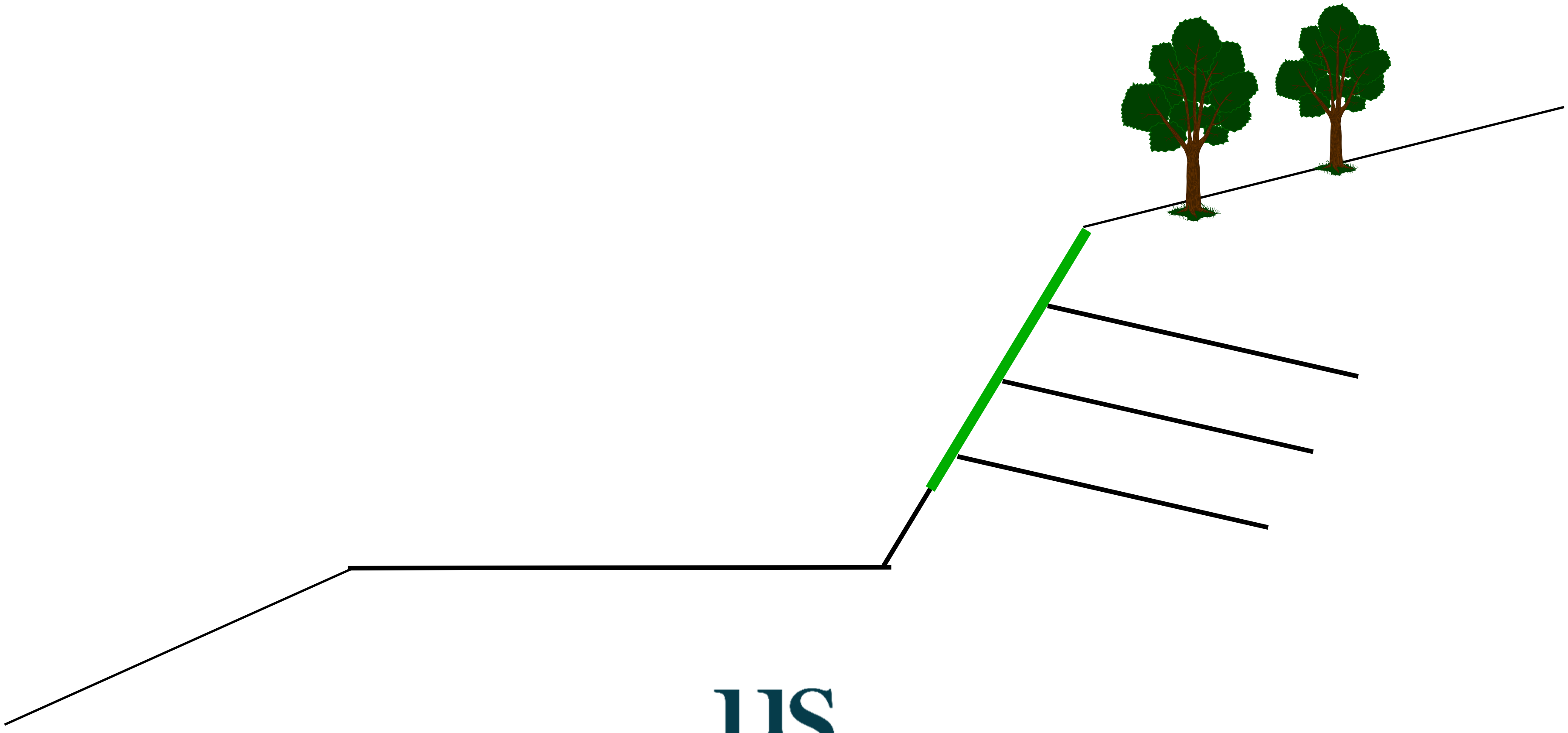

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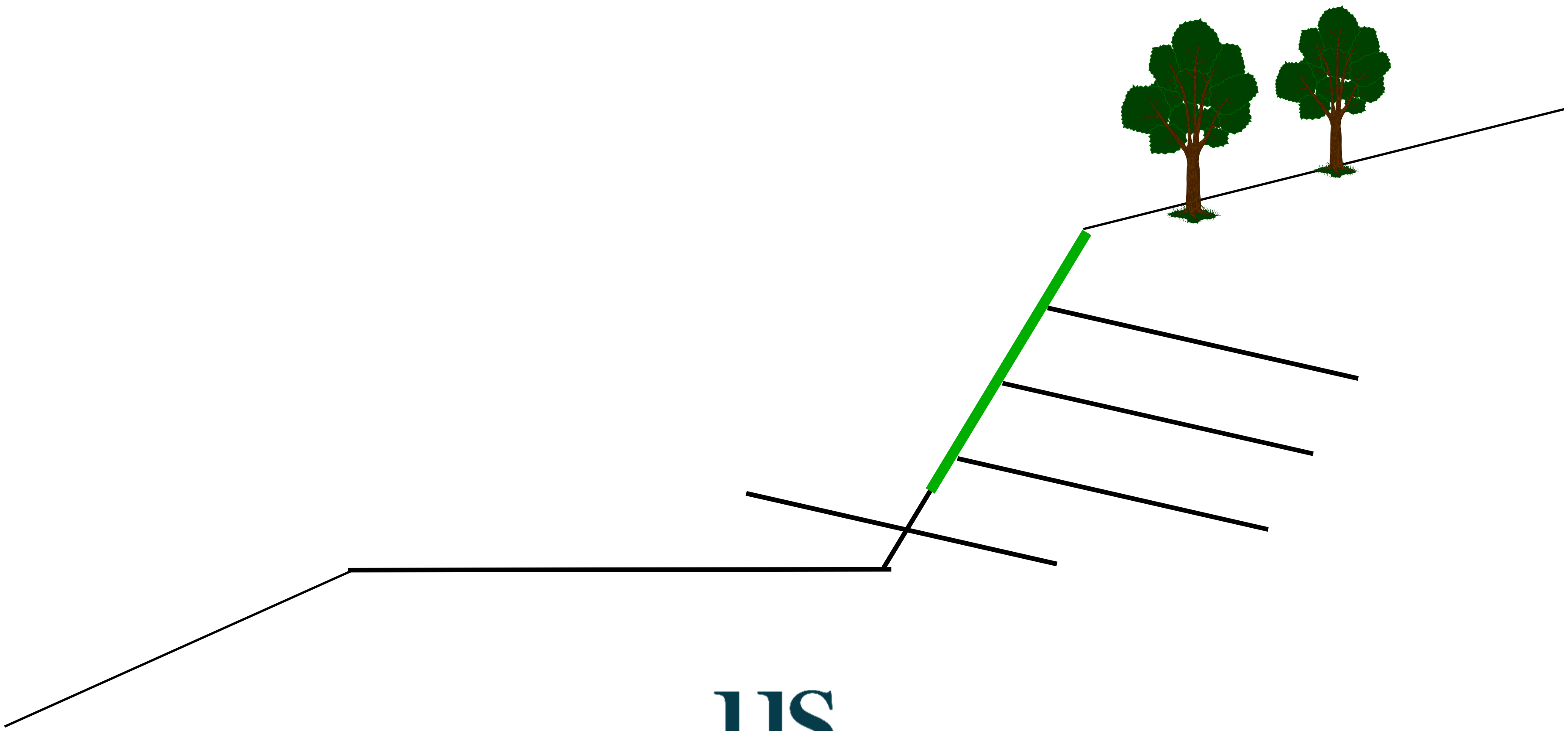

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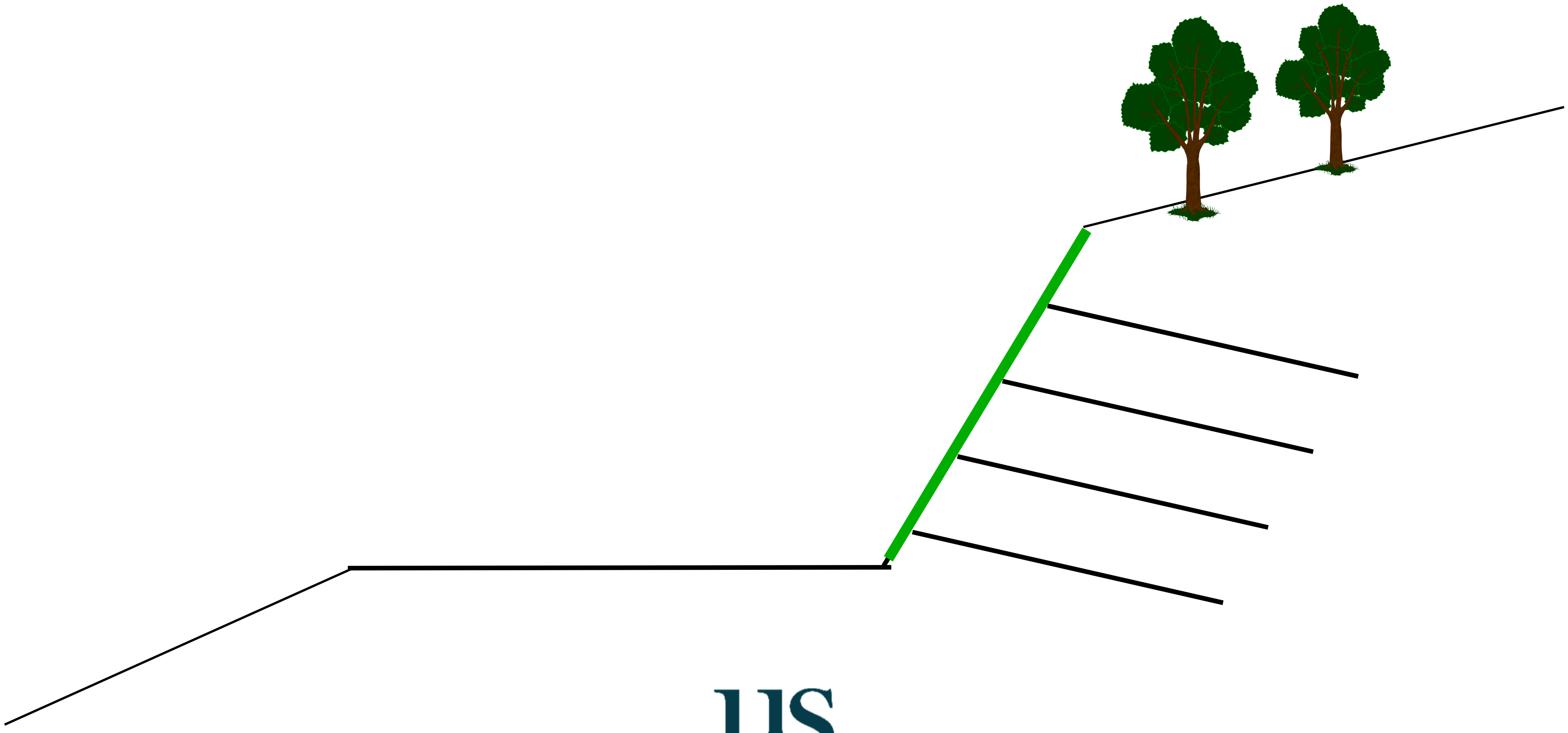

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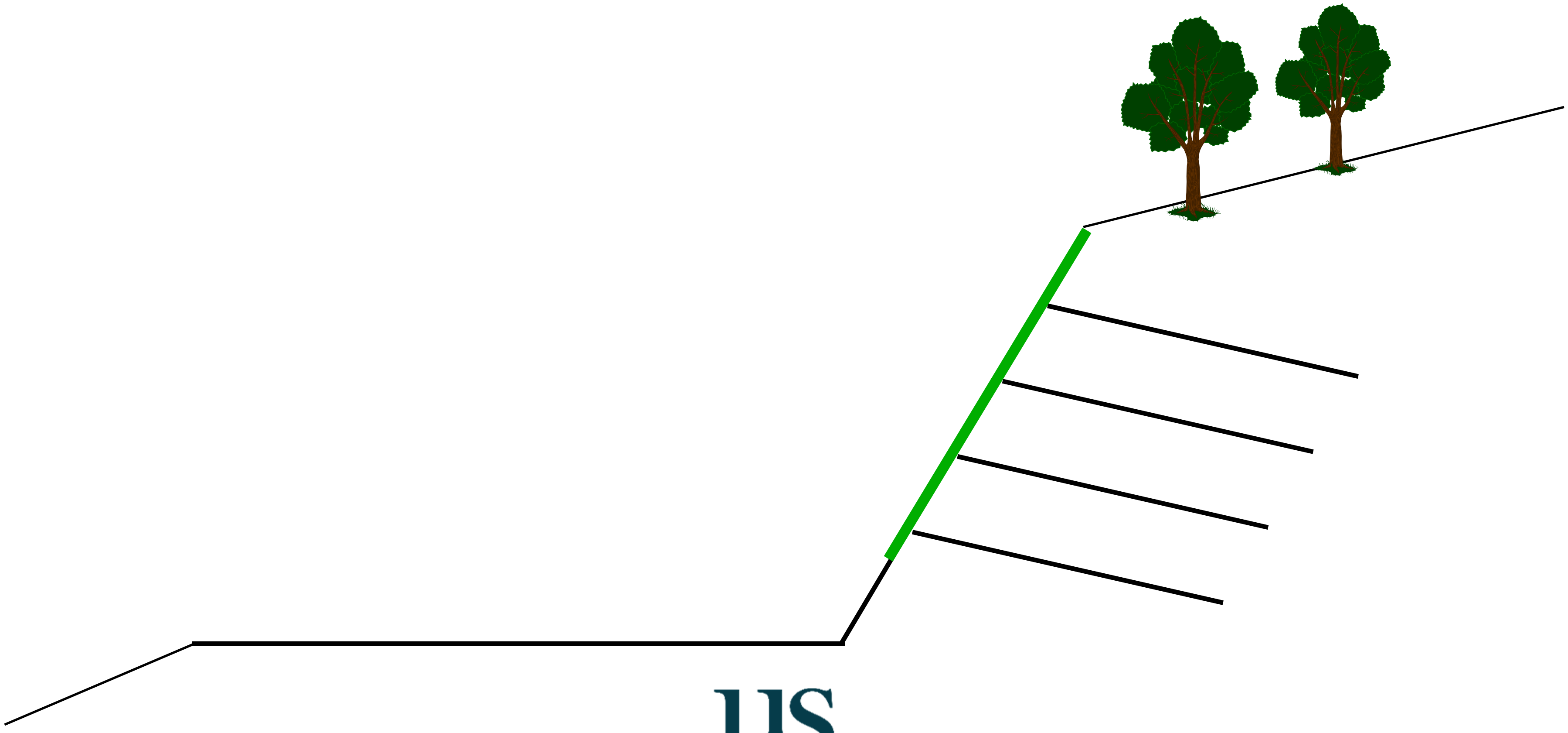

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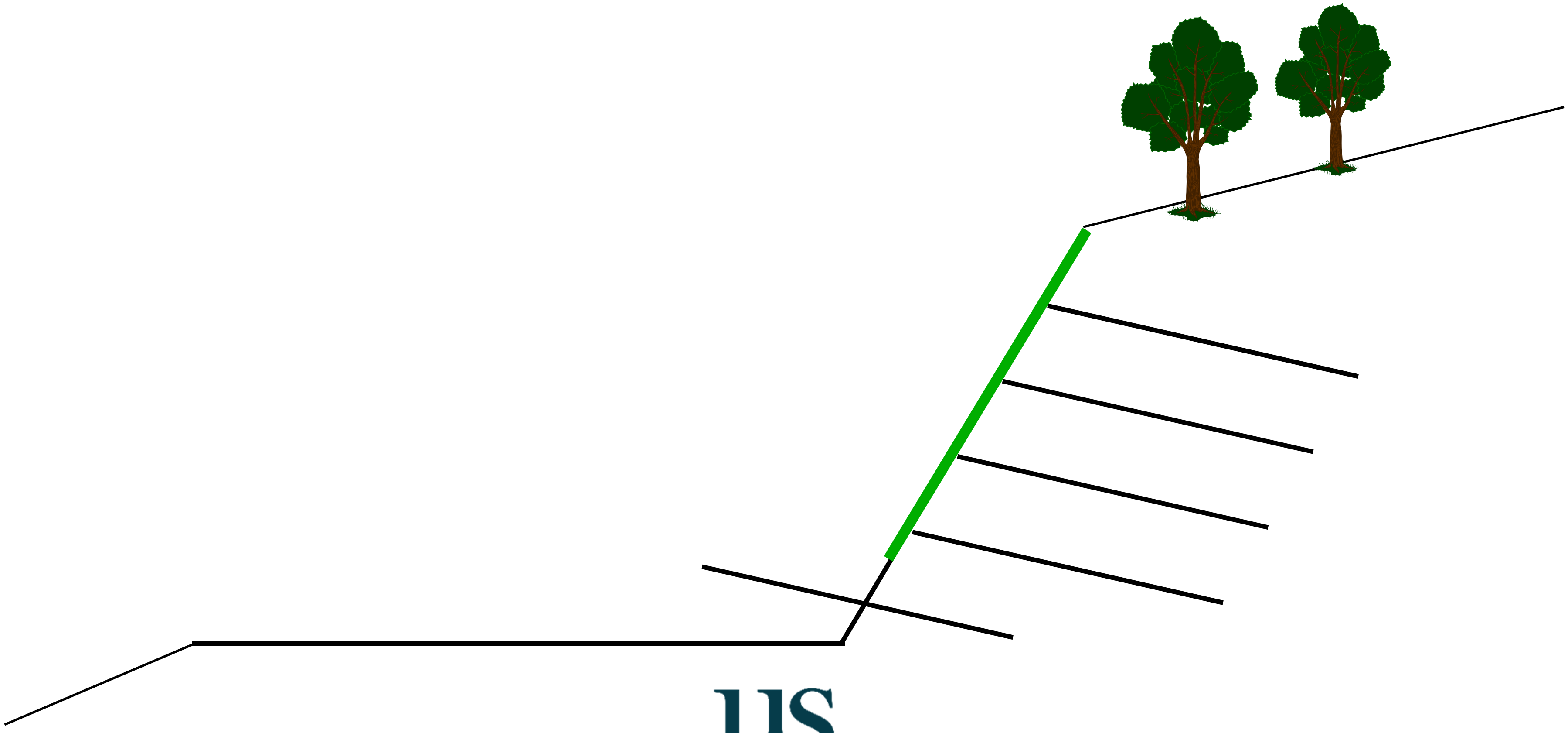

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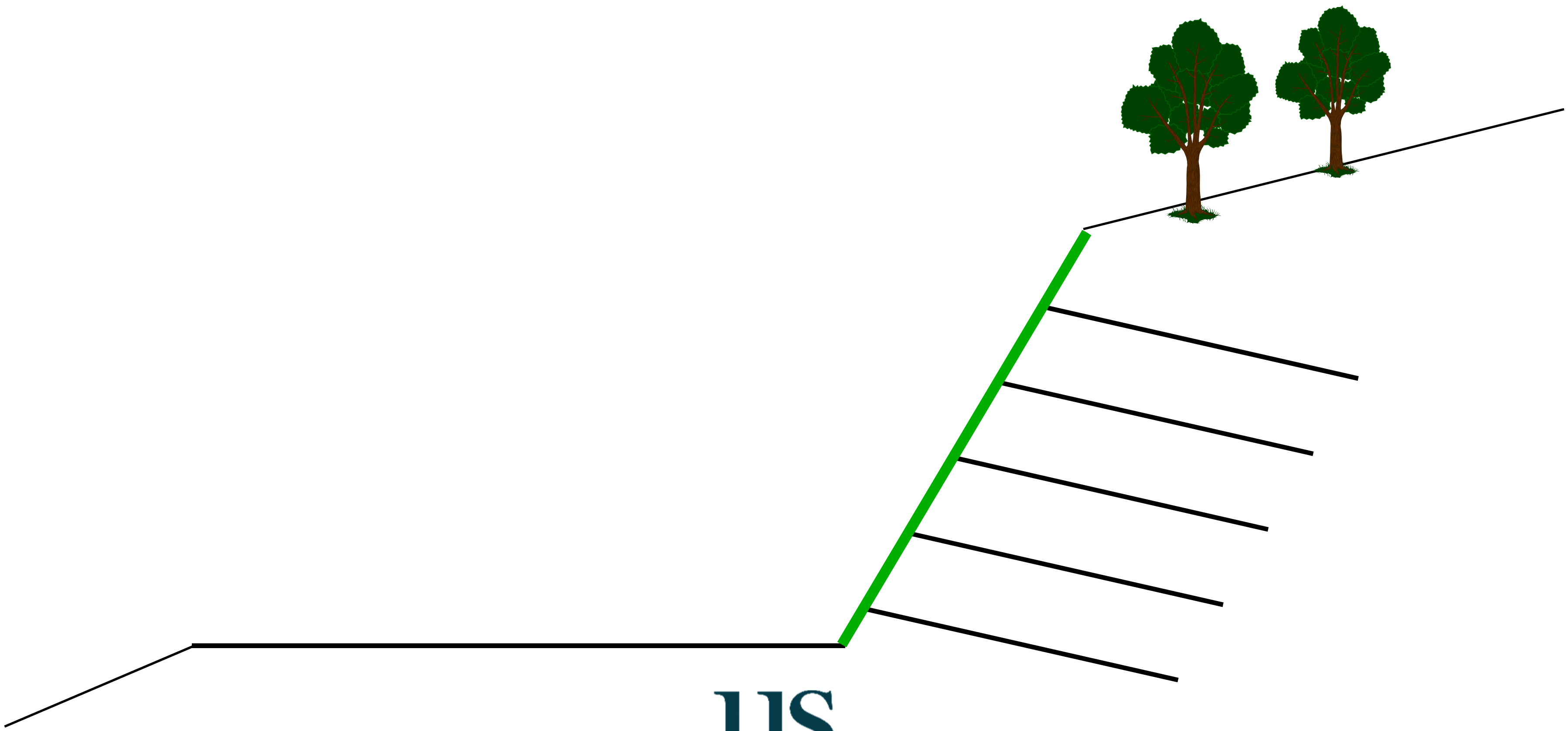

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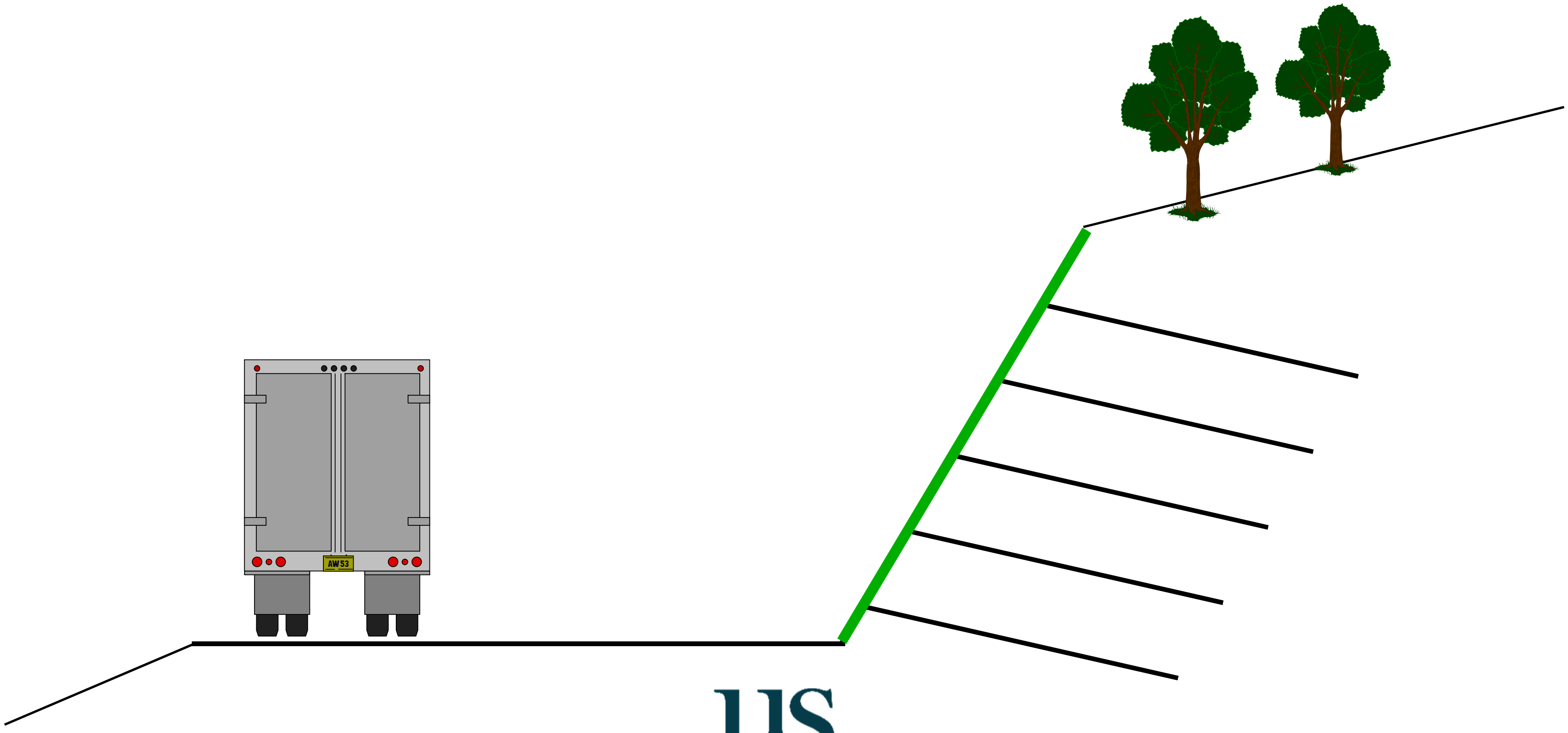
Soil Nailing

Construction Sequence - Completed Structure



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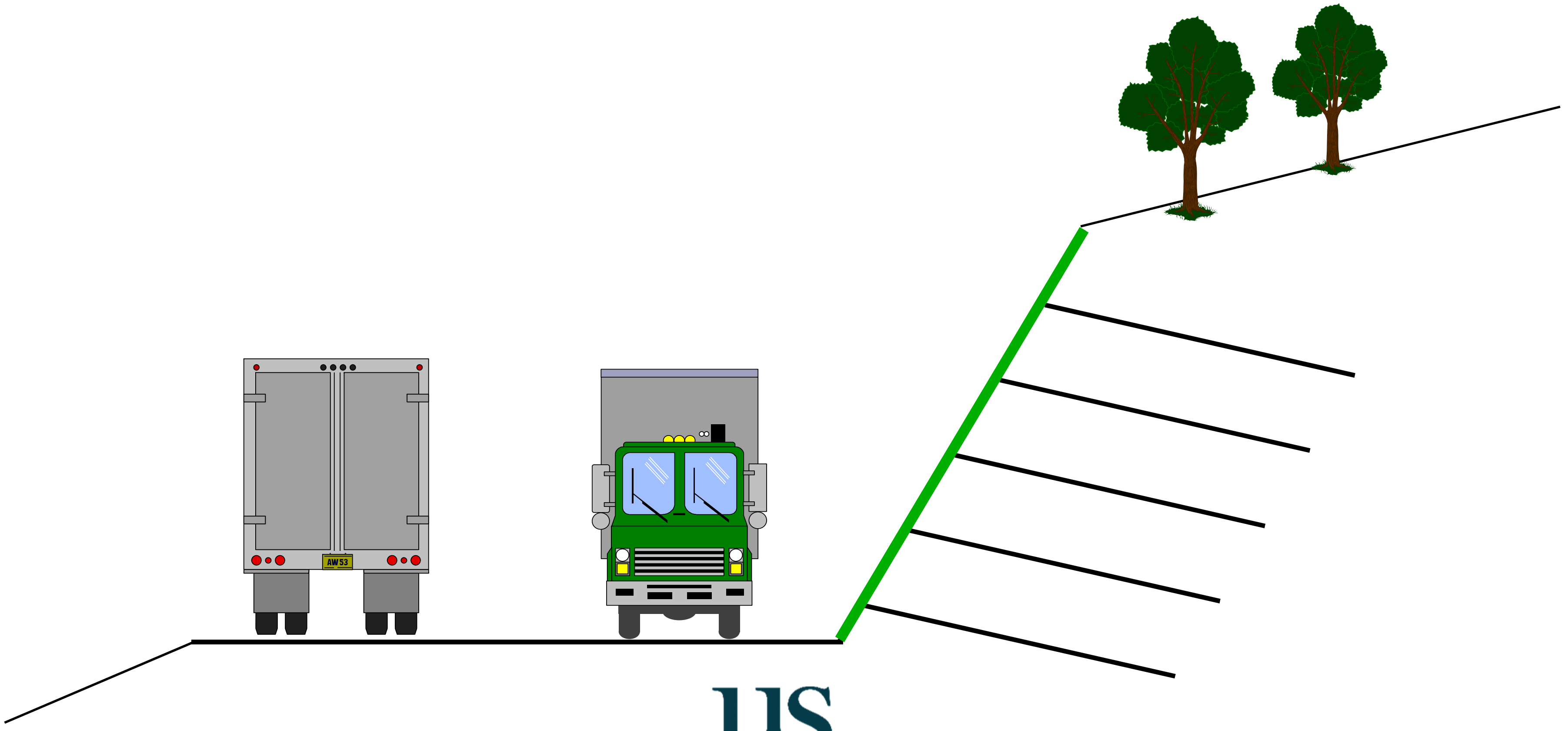

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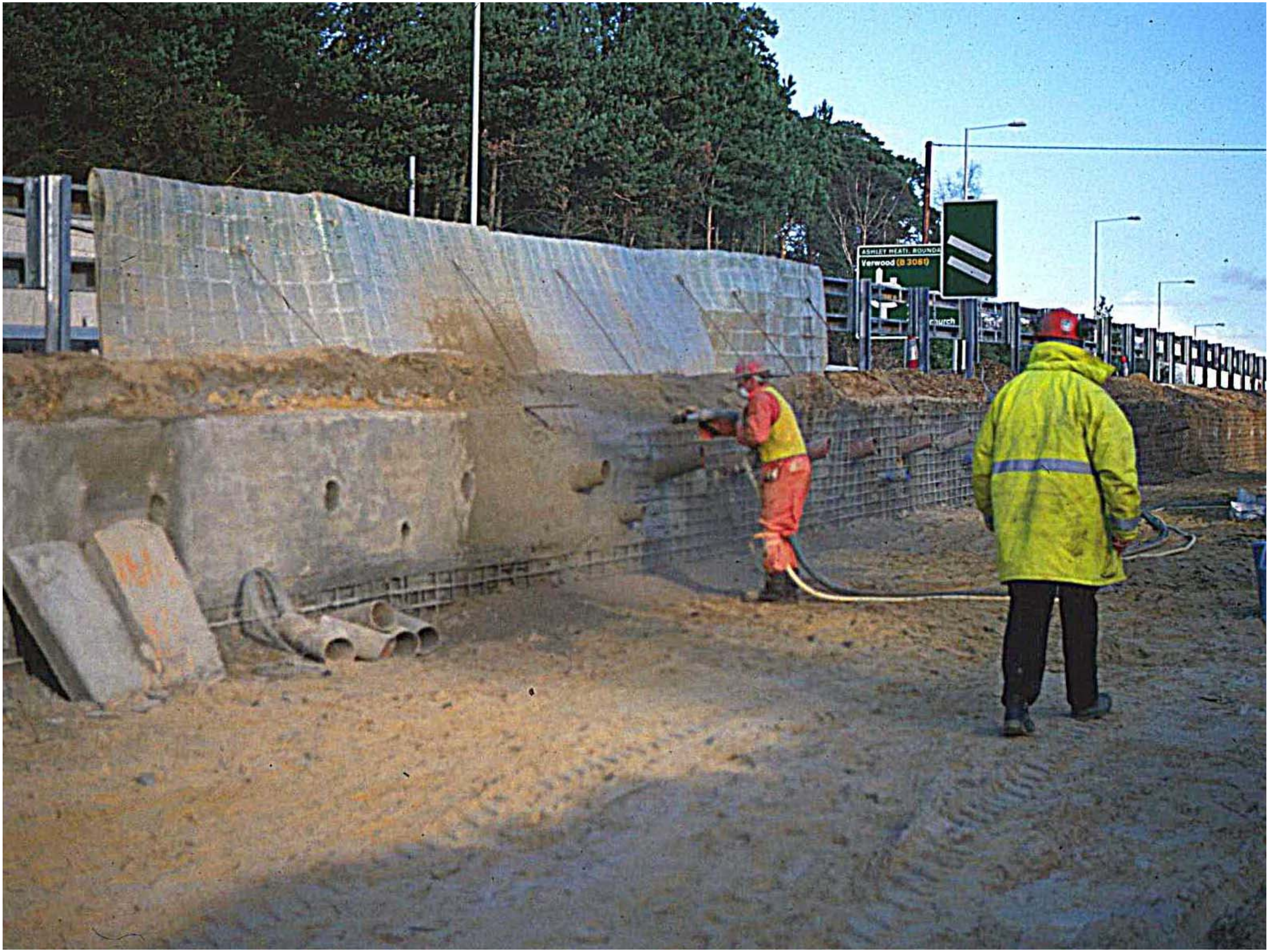

Verwood (B 3081)


ZINC
DRILL
PIPE


HYMAC


DUBLIN
Cementation Foundations Skanska

Soil nailing construction problems

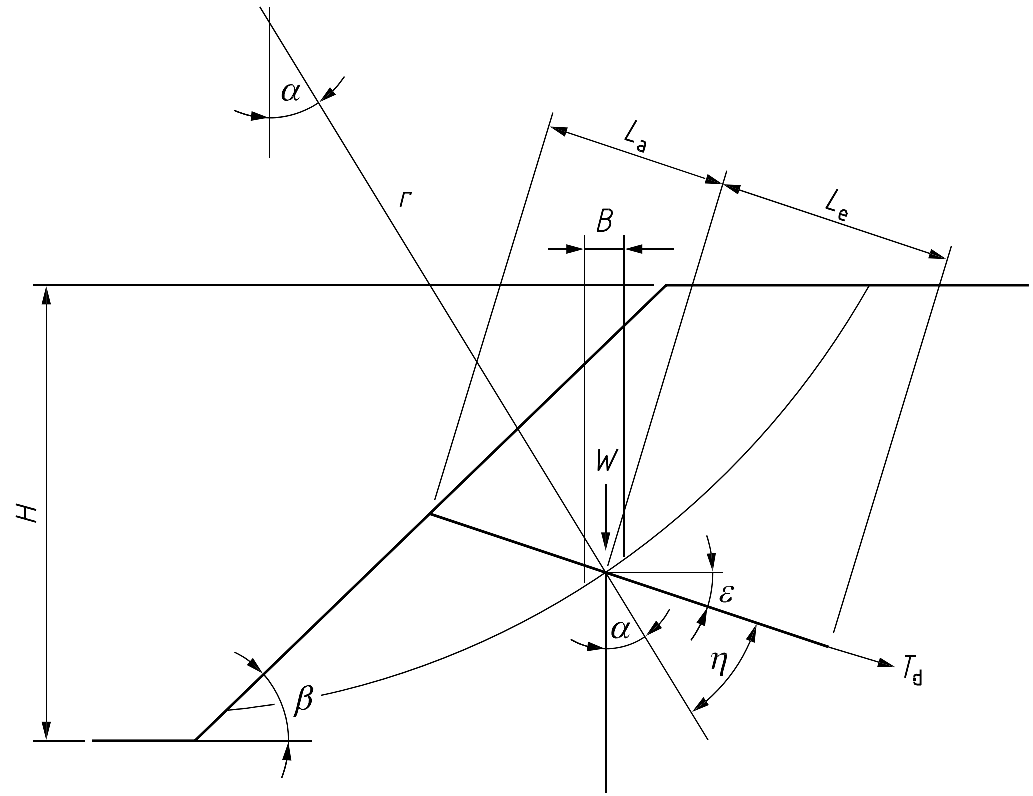
Soil nailing construction problems

Soil nailing

Analysis of internal stability Bishop’s simplified method of slices

Assessment of mechanisms which are either fully contained within the soil nailed zone or pass through some part of it the soil nailed zone or pass through some part of it to ensure:

$$\mathbf{M_{driving} \leq M_{resisting}}$$



B	width of slice (m)
H	height of slope (m)
La	length of nail to base of slice (m)
Le	length of embedment zone (m)
r	radius of slip circle (m)
T_d	design tension in nail at point (kN)

α	angle as defined by Bishop (1955)
β	angle of slope
ε	nail declination
η	angle between normal to slip plane and nail = 90° − *α* − *ε*

after: BS 8006-2:2011 *Code of practice for strengthened/reinforced soils. Soil nail design*

Soil nailing

Summary of factors recommended by commonly used soil nailing design codes

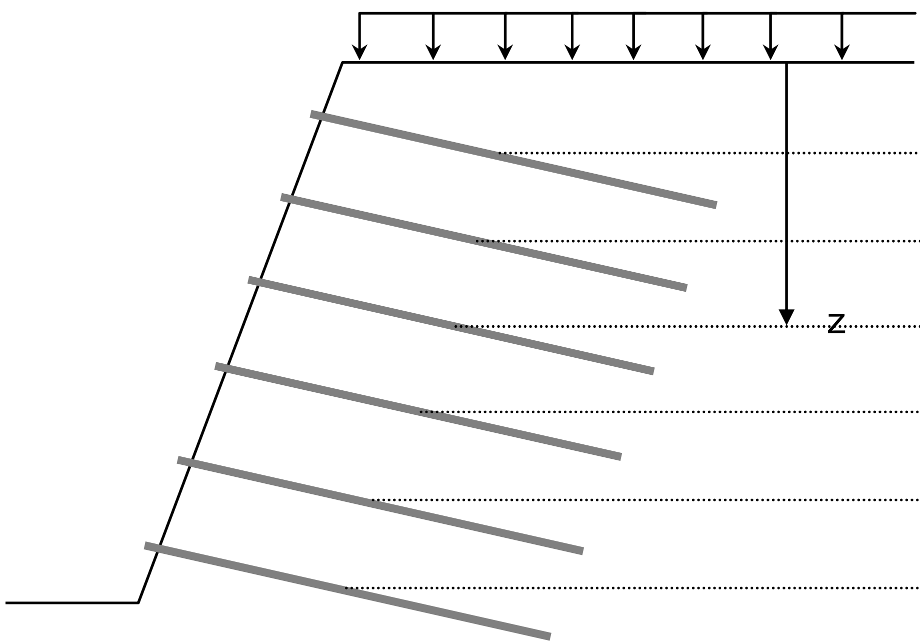
Factor system	BS8081 (permanent)	FHWA SLD	BS8006 (Table 26)	HA68/94	Clouterre	FHWA LRFD	EC7 2004	
Load factors							DA1-1	DA1-2
Soil weight	n/a	1.0	1.5	1.0	1.05/0.95	1.25/0.9	1.0	1.0
Dead surcharge		1.0	1.2	1.0	1.2	1.5/0.65	1.35	1.0
Live surcharge		1.0	1.3	1.0	1.33	1.75	1.5	1.0
Materials								
tan φ’	n/a	1.0*	1.0	min conceivable critical state value	0.77- 0.83	0.7	1.0	0.8
c’		1.0	0.63	< 5kN/m^2	0.61- 0.67	0.9	1.0	0.8
c_u		1.0	1.0	Not used	0.71- 0.77		1.0	0.71
Pore pressures	n/a	1.0	not stated	conservative estimate	1.0	1.0	most unfavourable	
Nail Pullout	2.5 - 3.0	2.0	1.3	1.0 estimate using min conceivable φ’	1.4 - 1.5 tests 1.8 -1.9 charts	1.11	1.5 on characteristic	
Testing	required				required		required	
Overall Stability	1.30	1.35*	1.0 or 1.25	1.0	1.125	1.0	1.0	

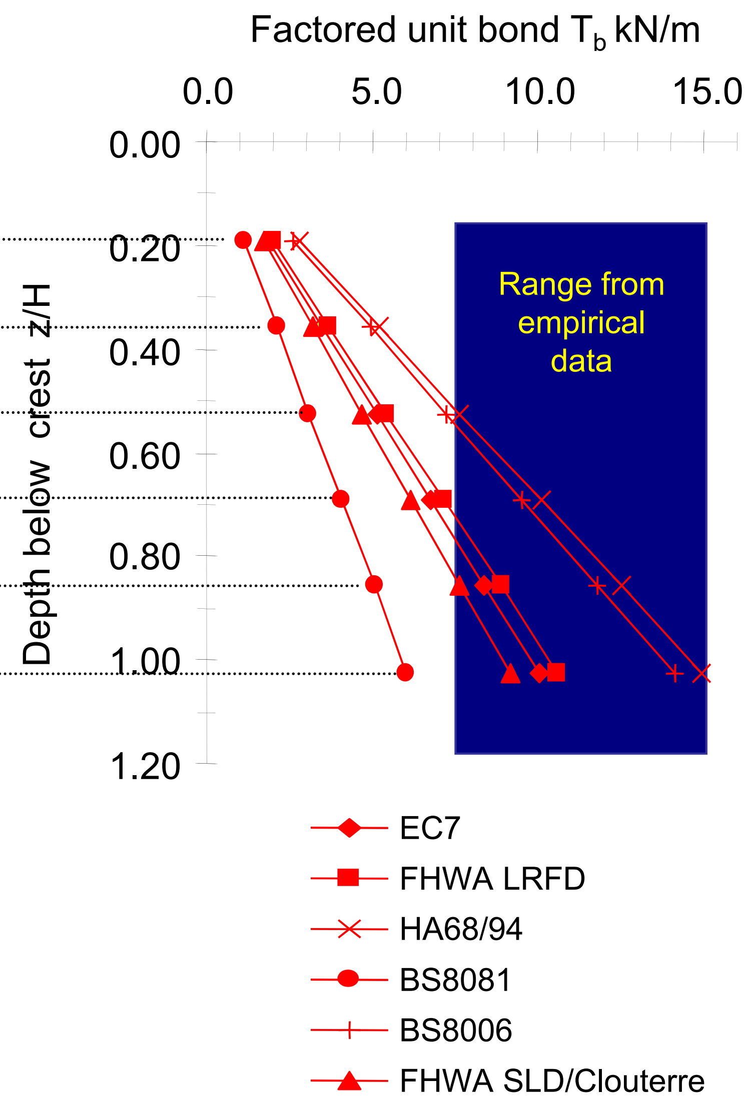
after: CIRIA RP 674: *Soil Nailing: Best practice guidance* (2005)

Soil nailing

Estimating nail pullout resistance using effective stress methods

$T_b = \pi D[K\sigma'_v \tan\delta + c']$





$\phi' = 38$ deg, $\phi'_{cv} = 32$ deg, $c'=0$

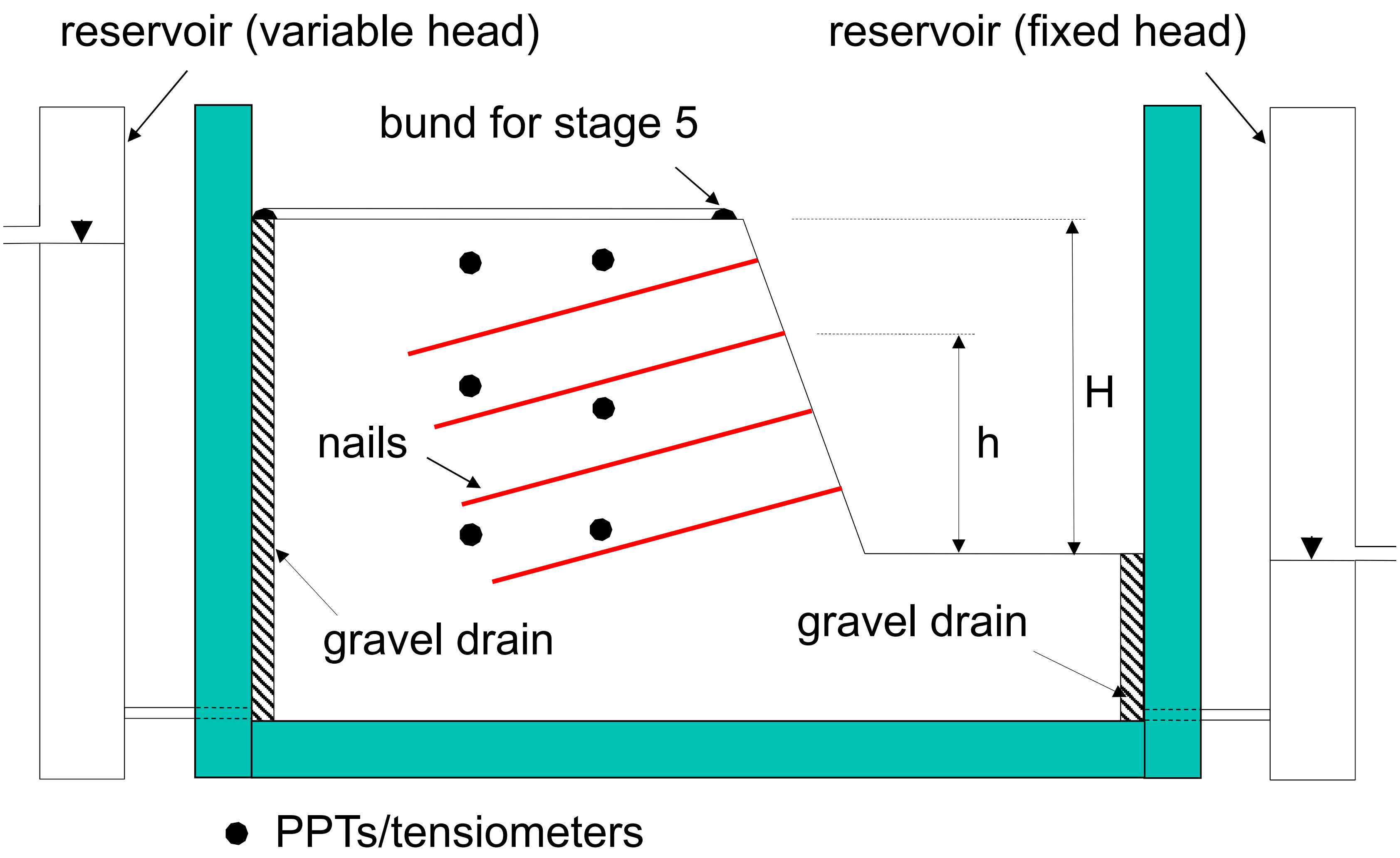
$\gamma = 18.5$ kN/m^3, $r_u = 0.1$

$L_n = 5$m, $D=0.1$m, $K_s = 0.9$

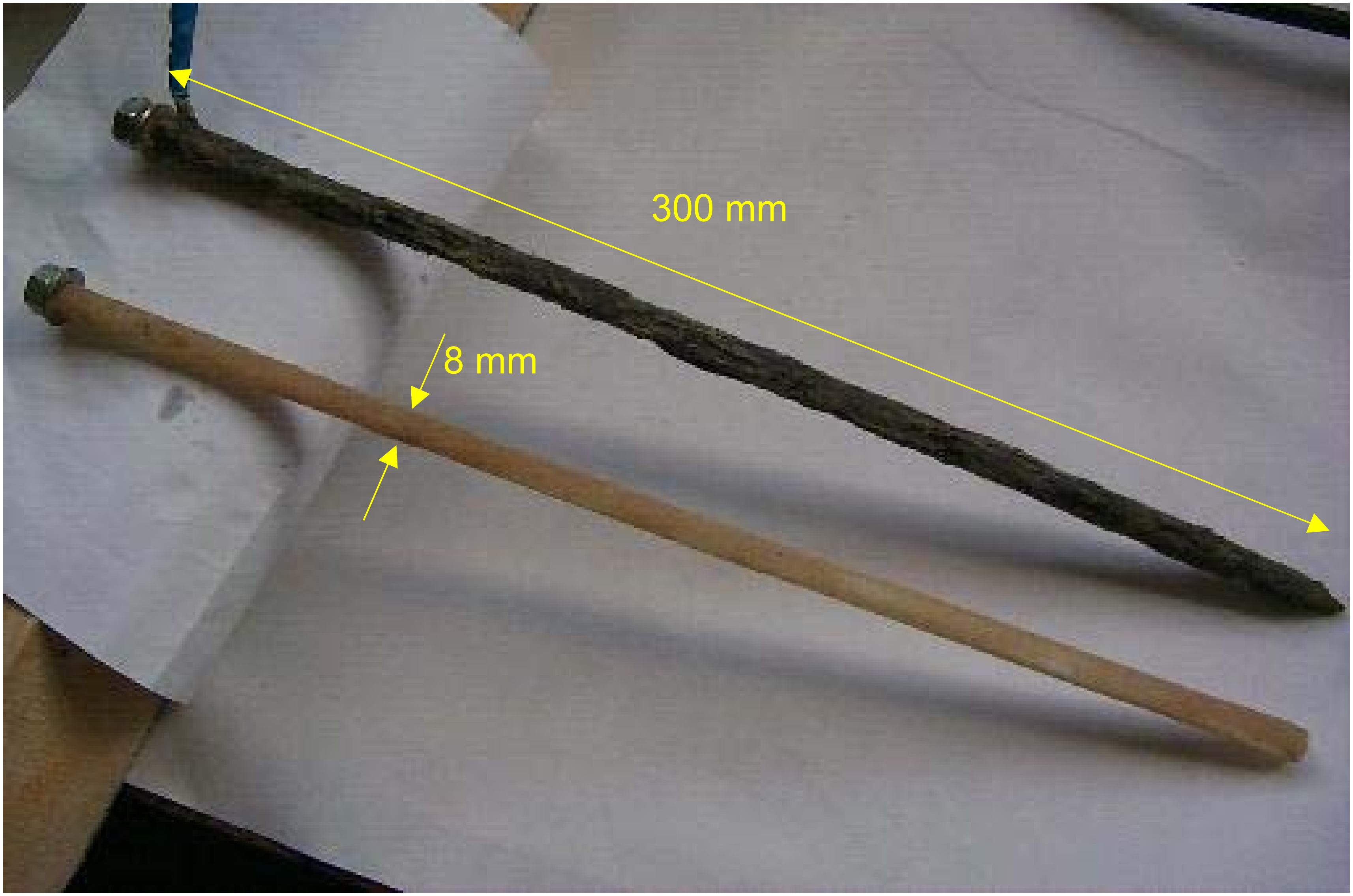
$\delta = 15°$, $S_h = 1$m

after: CIRIA RP 674: *Soil Nailing: Best practice guidance* (2005)

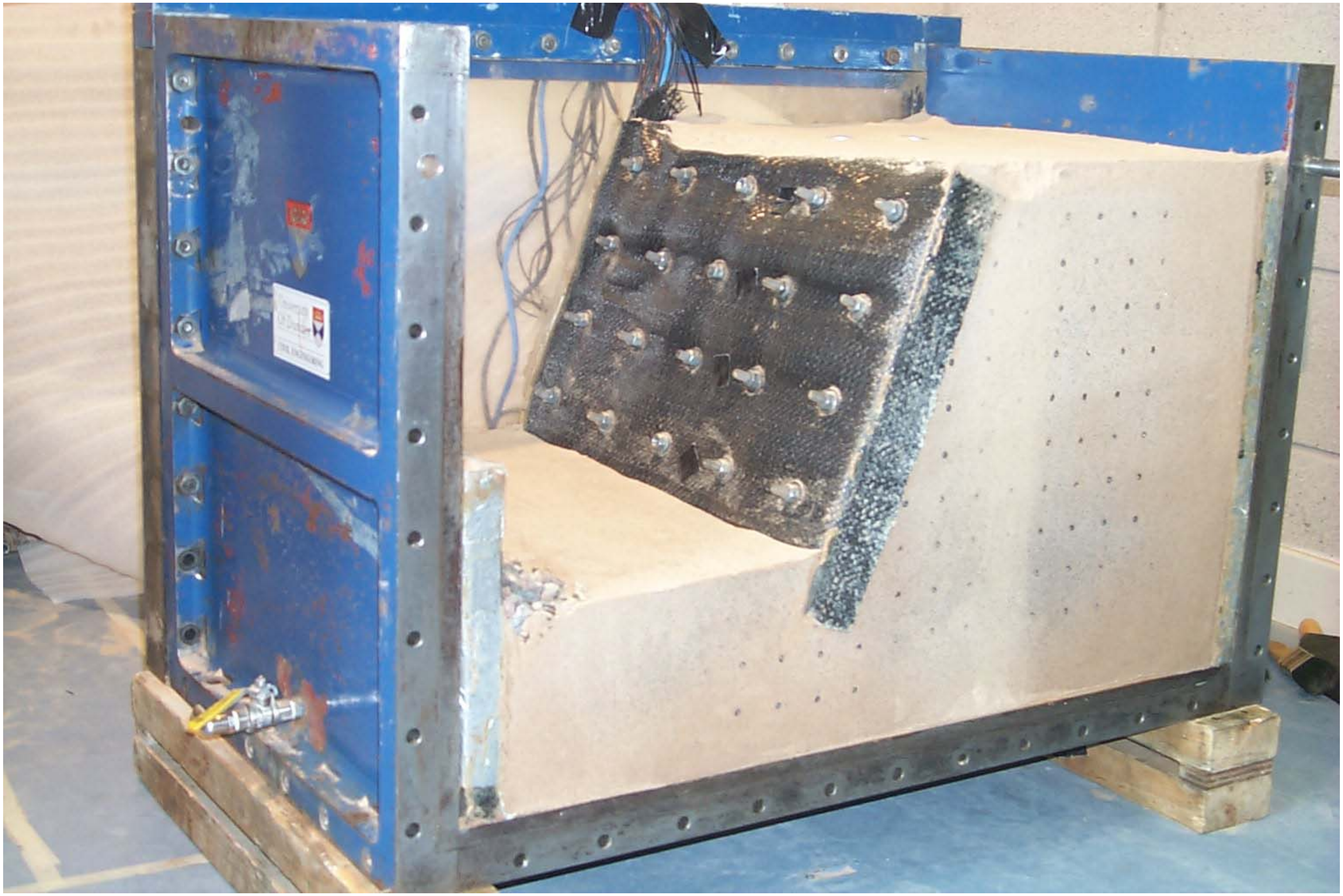
Geometry of centrifuge models



Soil Nailing
Model soil nails



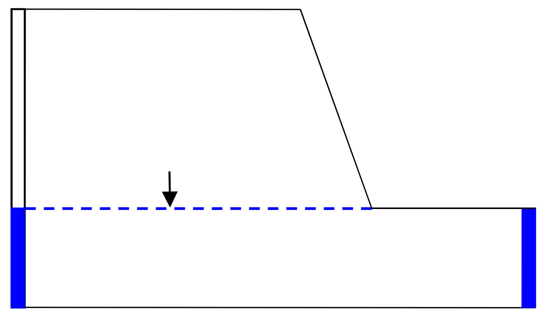
Soil Nailing
Model with flexible facing



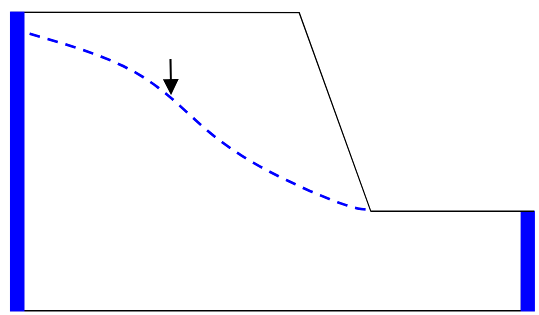

Push bar to open

Soil Nailing

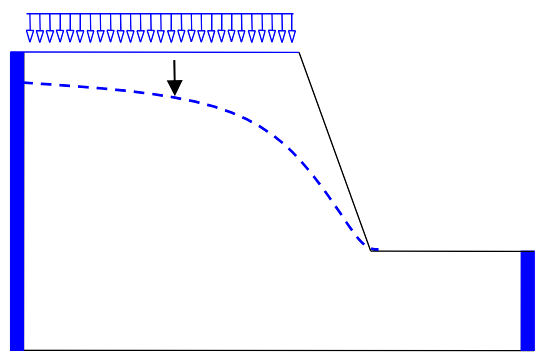
Drainage boundary conditions for each stage



Stage 1 and Stage 3

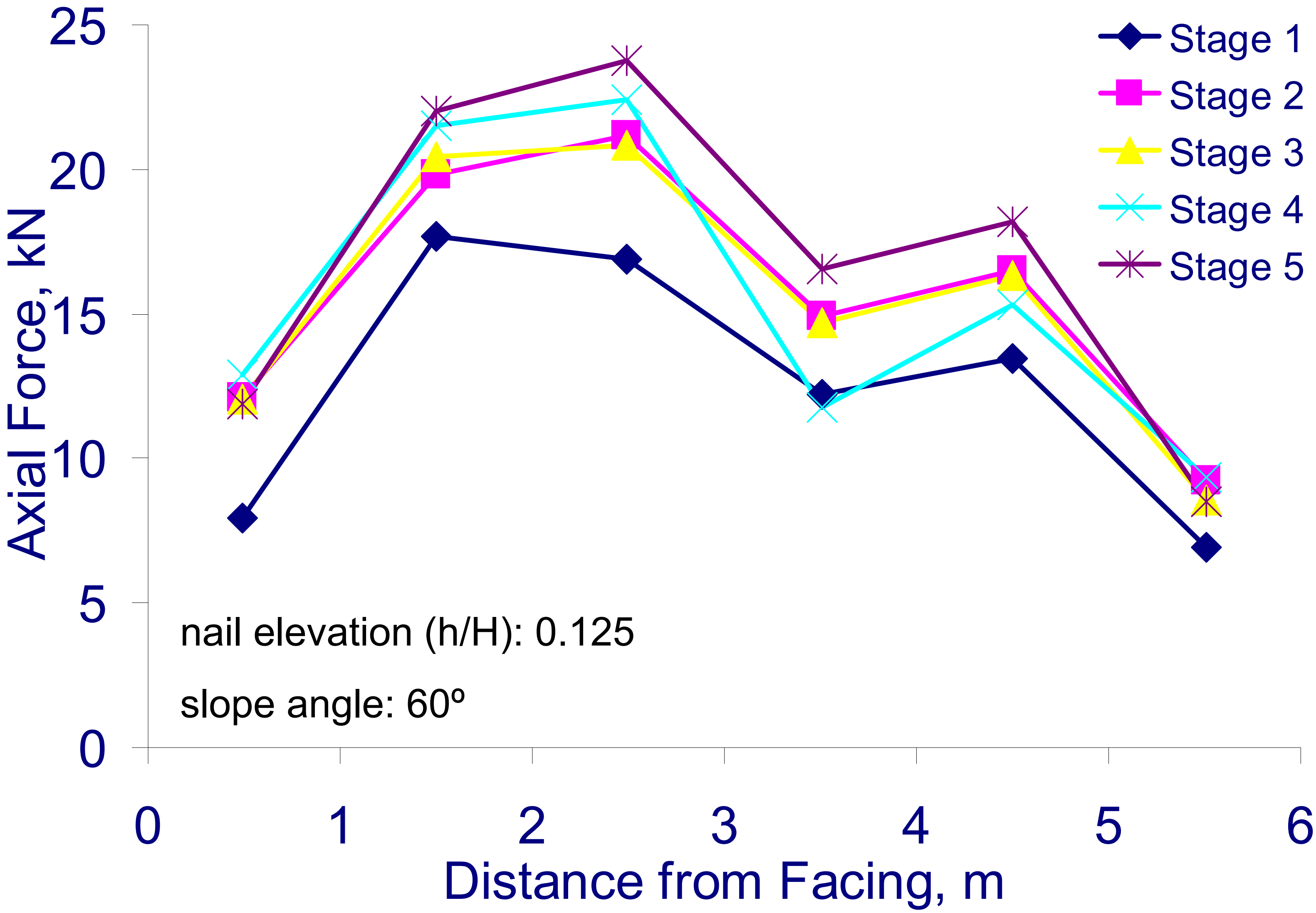


Stage 2 and Stage 4



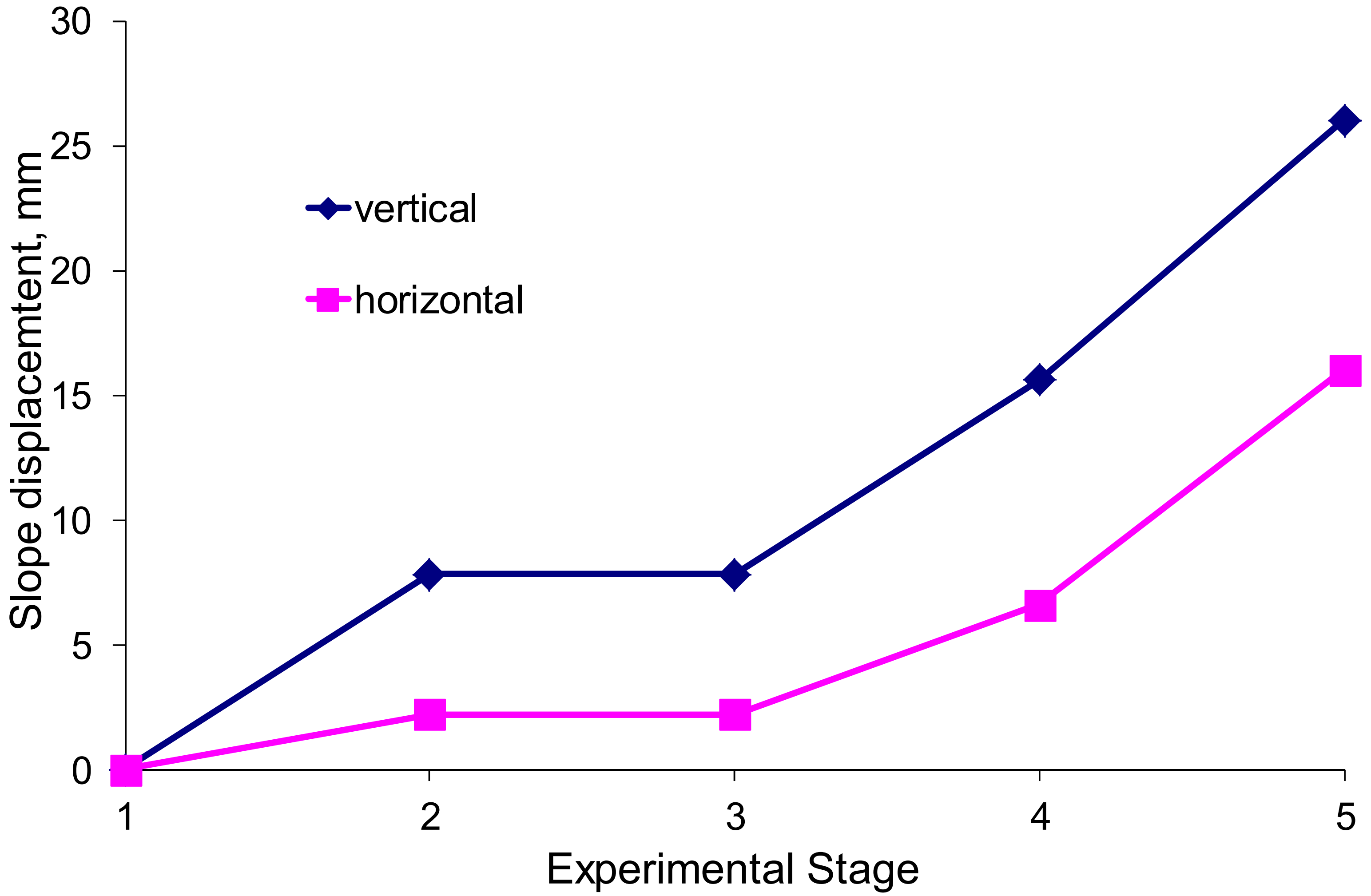
Stage 5

Soil Nailing
Nail axial force



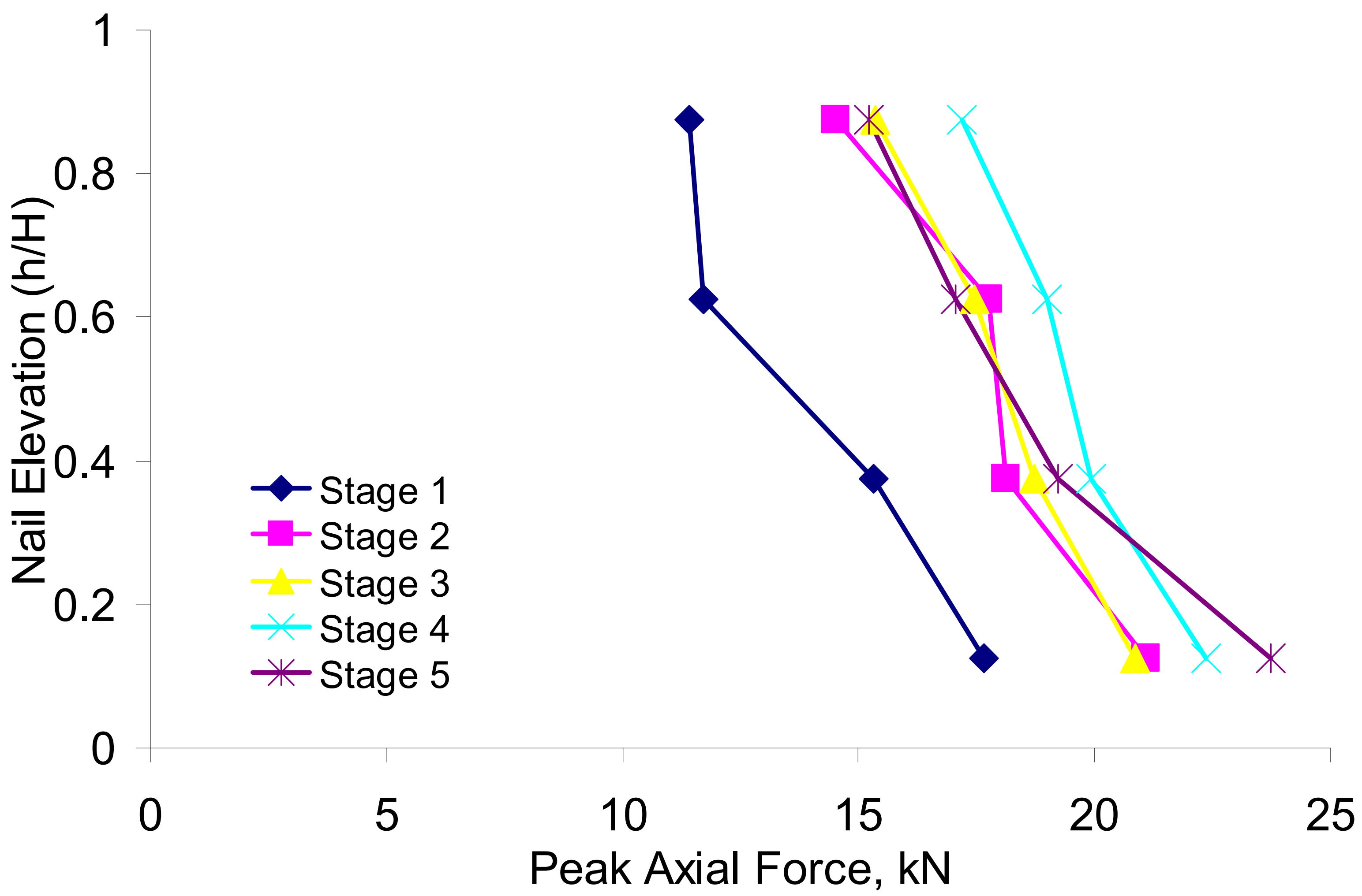
Soil Nailing

Vertical and horizontal displacements (60˚ slope)



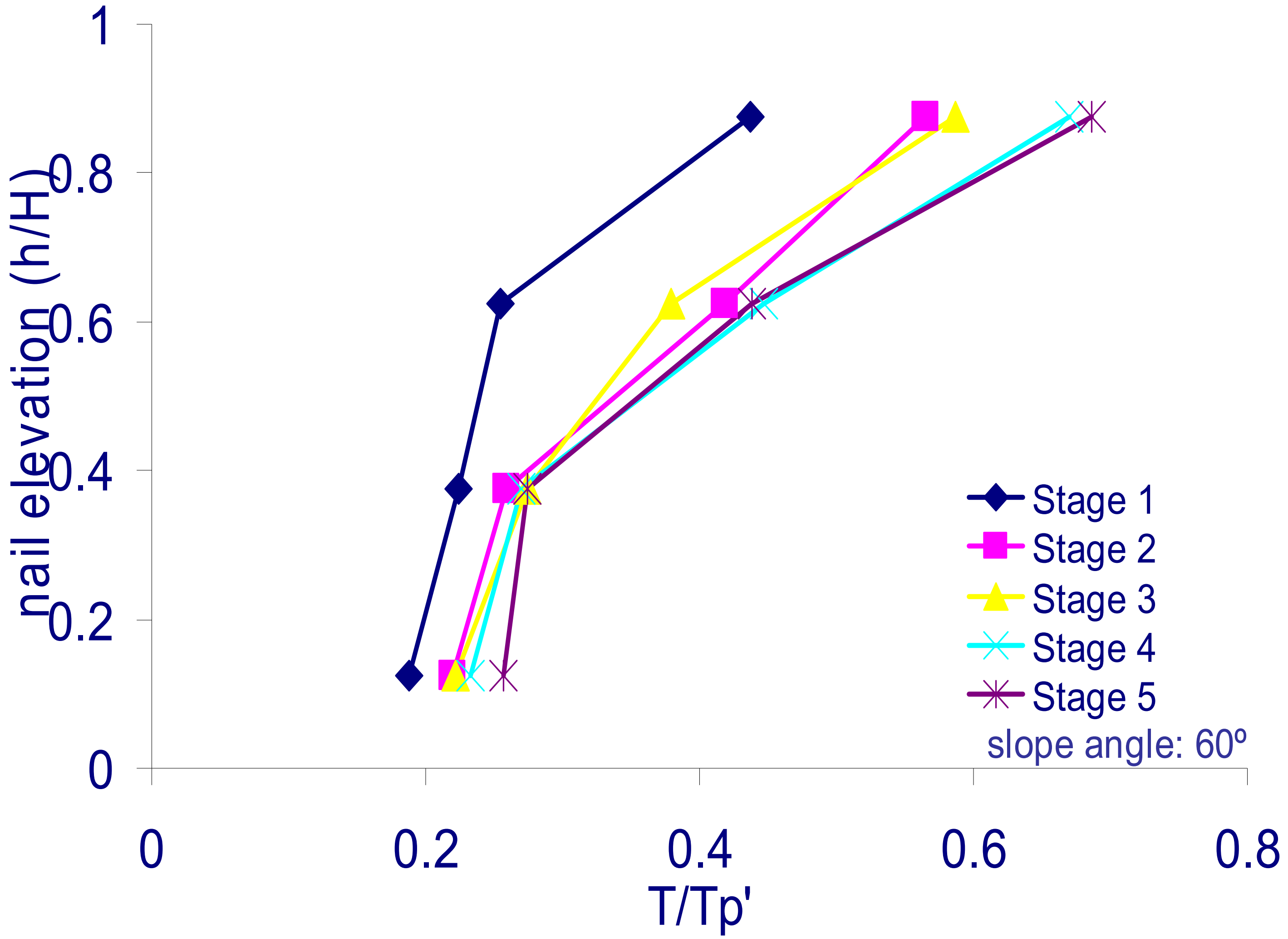
Soil Nailing

Peak axial forces (T) at each experimental stage (60˚ slope)



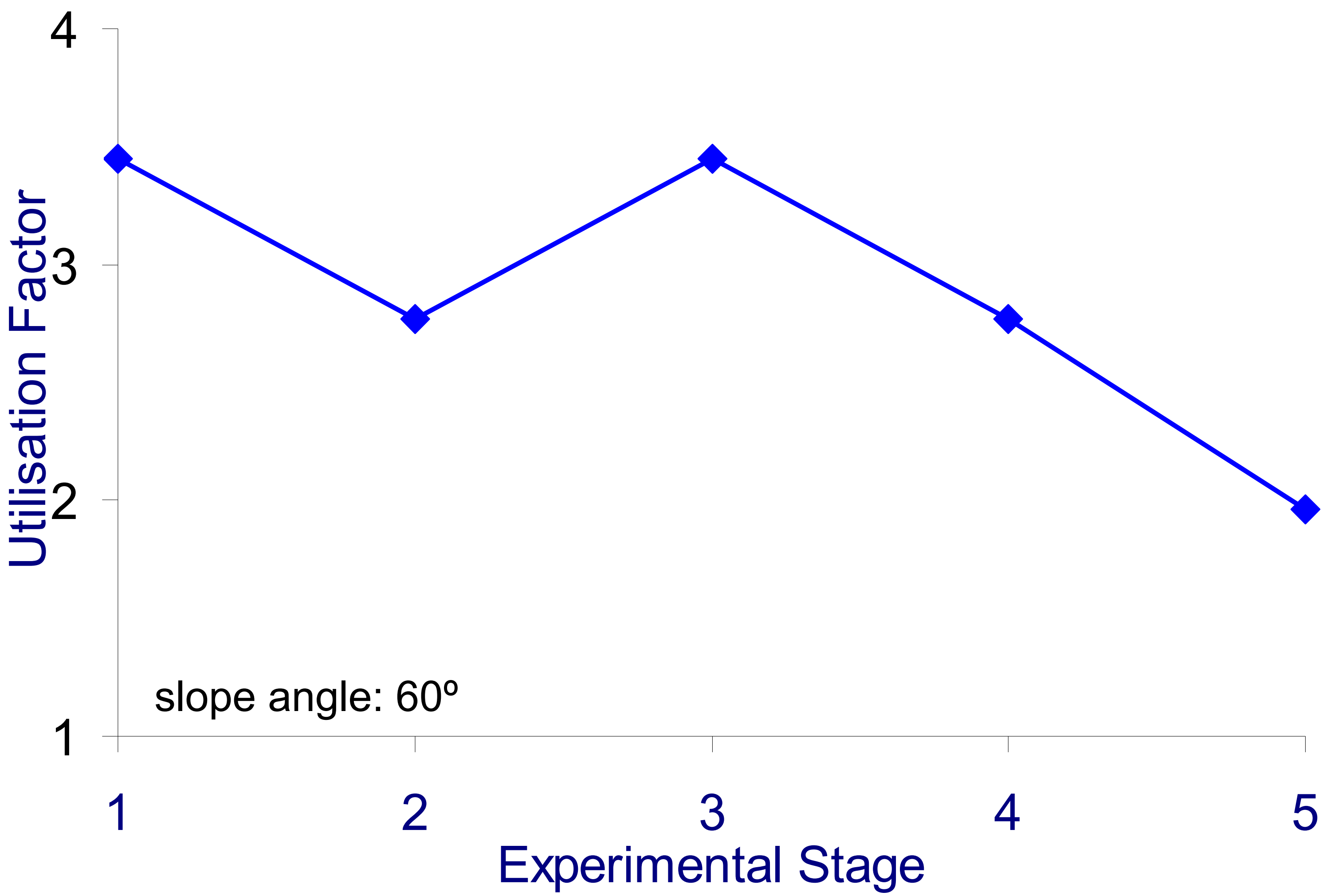
Soil Nailing

Axial forces (T) normalised by theoretical pullout values (Tp')



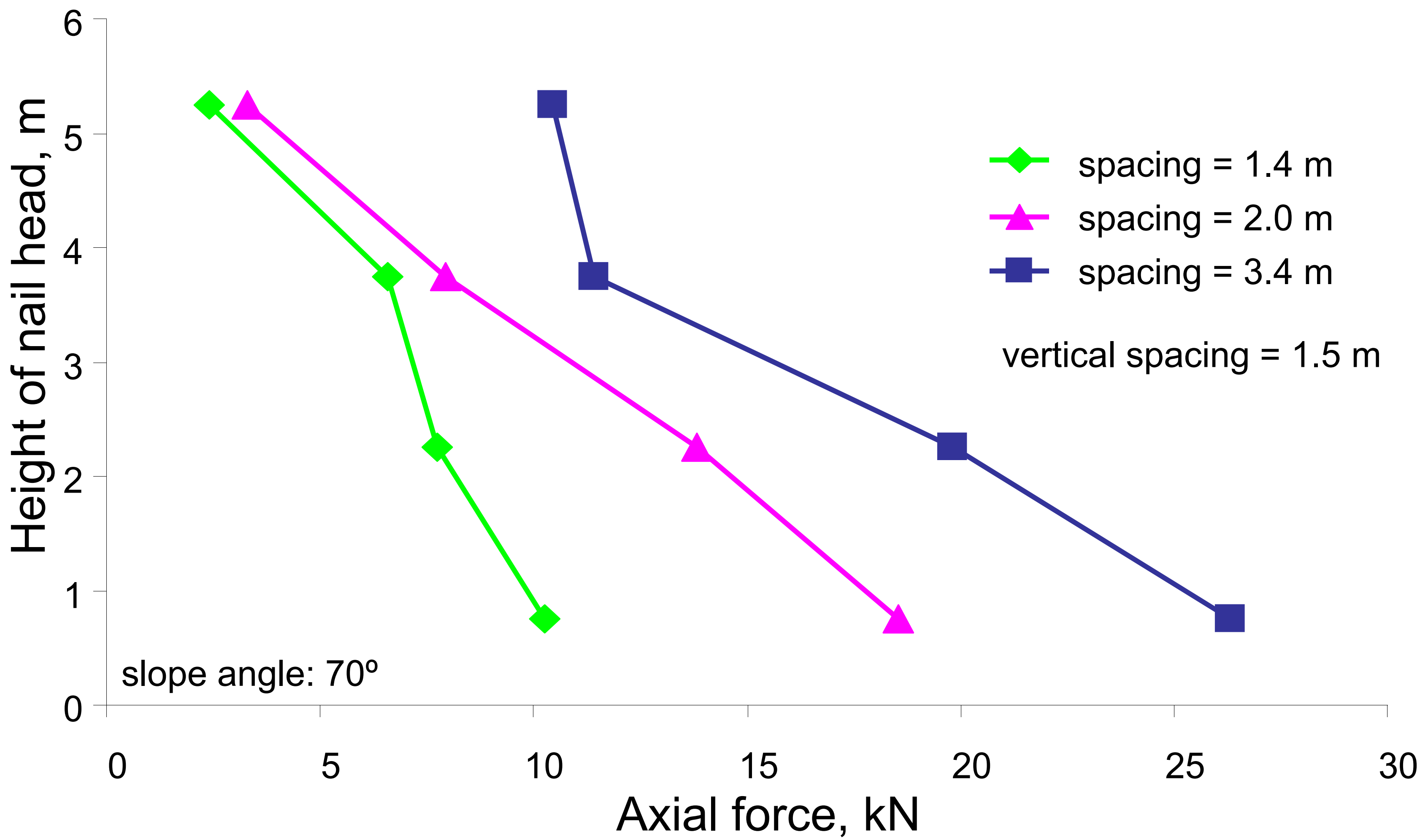
Soil Nailing

Predicted utilisation factor (M_R/M_D)



Soil Nailing

Comparison of horizontal spacing



Soil Nailing

Measured axial forces in nails at different horizontal spacings, S_h
(slope angle: 70°)

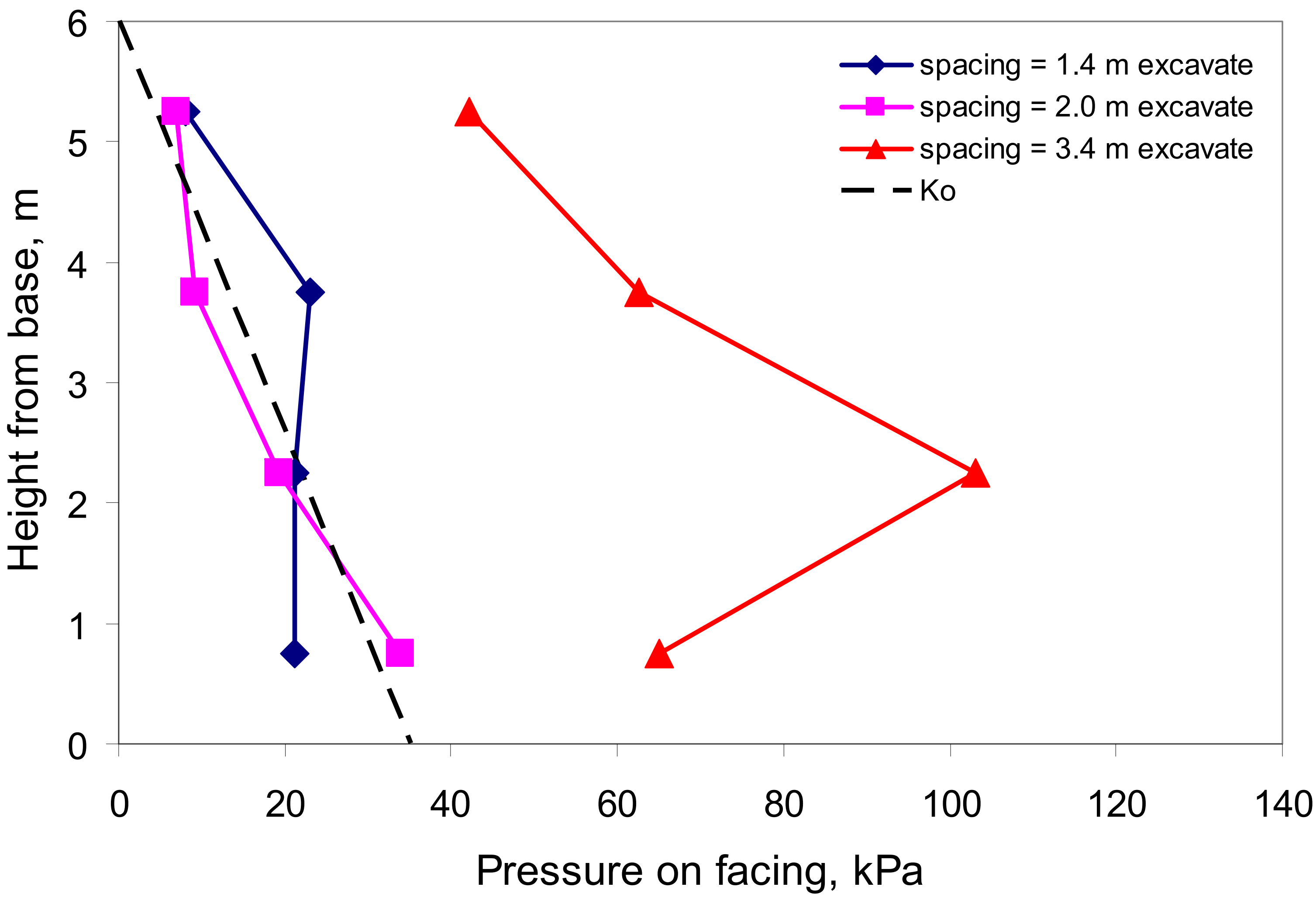
Height of nail head, m	Maximum axial force in nail, T_{max}, kN		
	S_h = 1.4 m	S_h= 2 m	S_h = 3.4 m
5.25	2.4	3.3	10.5
3.75	6.6	7.9	11.4
2.25	7.8	13.8	19.8
0.75	10.3	18.5	26.3
ΣT_{max}	27.0	43.5	68.0
T_{max}/S_h, kN/m	19.3	21.8	20.0

Soil Nailing

Pressure on facing - Miniature total pressure cells attached to facing

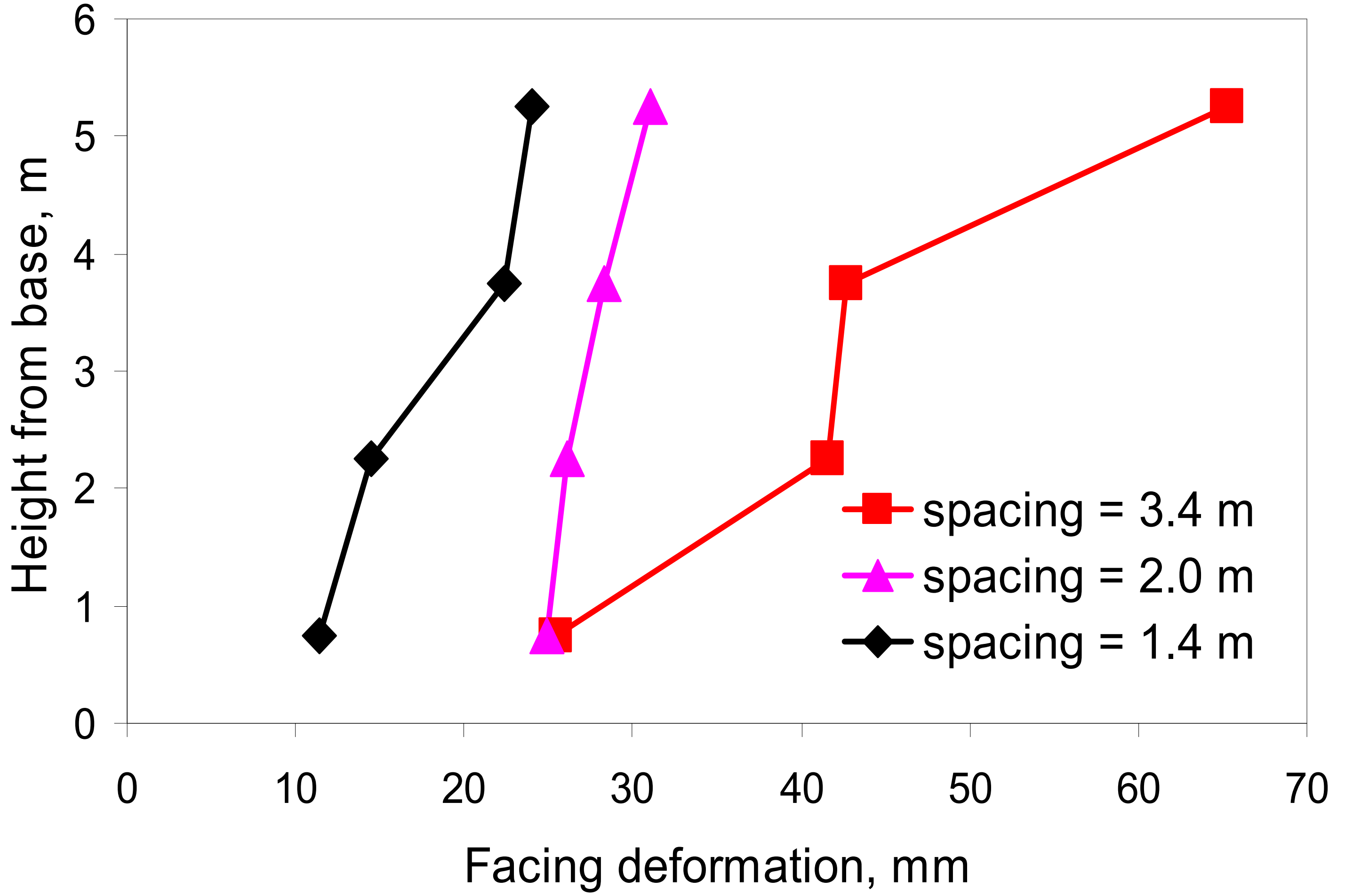
Soil Nailing

Pressure on facing (70 º slope)



Soil Nailing

Lateral facing deformations at test stage 4 (70° slope)



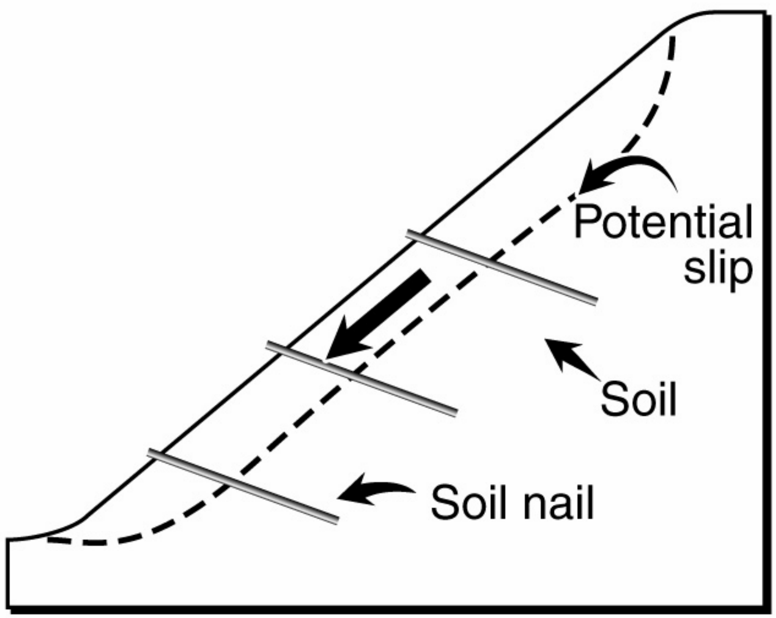
Shallow landslide occurring in cutting

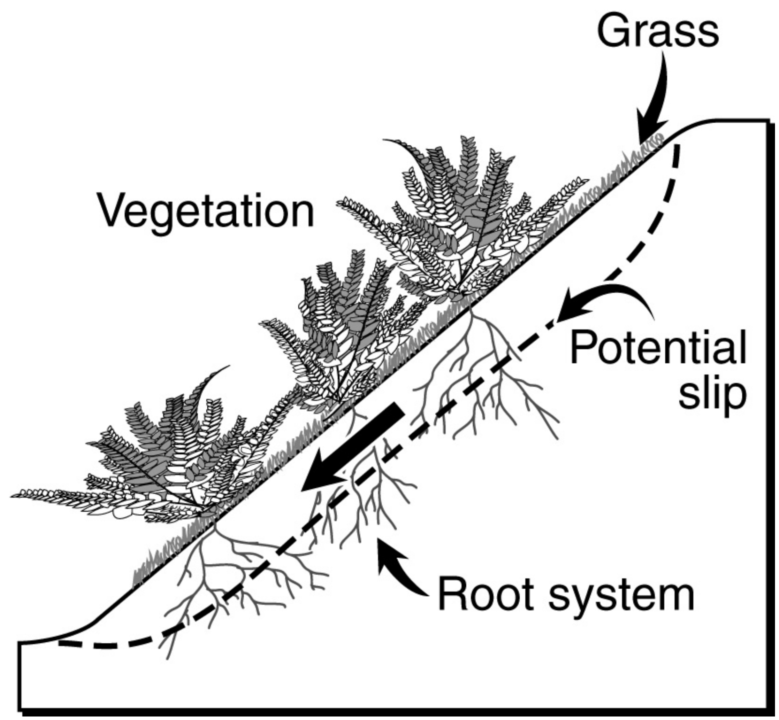
N.B. Tree line is above top of landslide scar, landslide has occurred where there are no deep rooting plants.

Photograph by J E Norris - Eco-Slopes Final Report ECO-SLOPES QLK5-2001-00289

Exposed roots - cut slope in London Clay

Root reinforcement of slopes
Soil nailing versus vegetation for slope stabilisation





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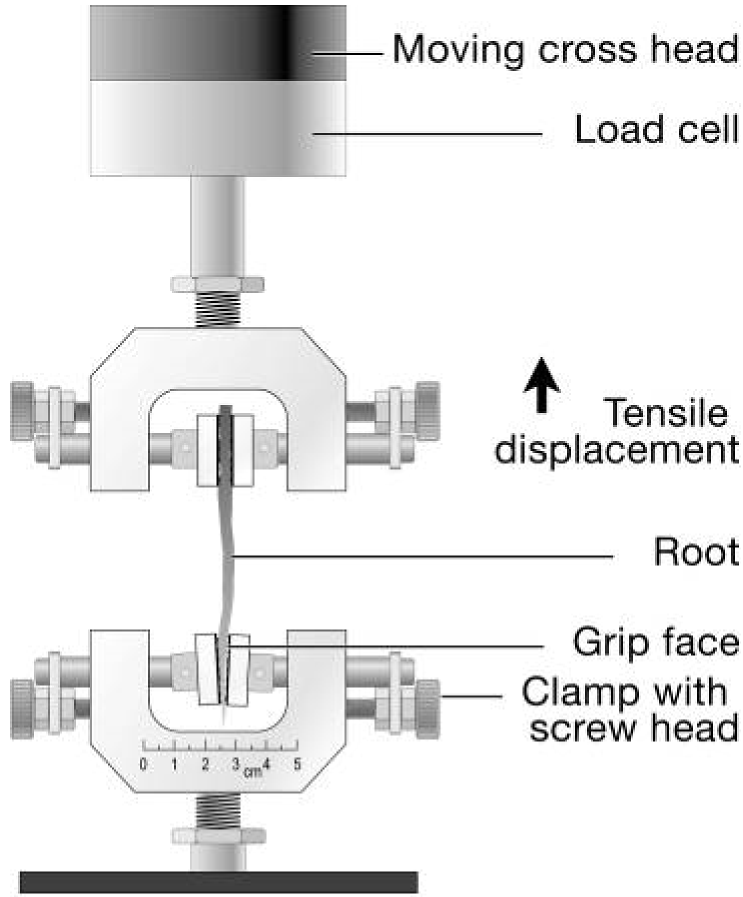
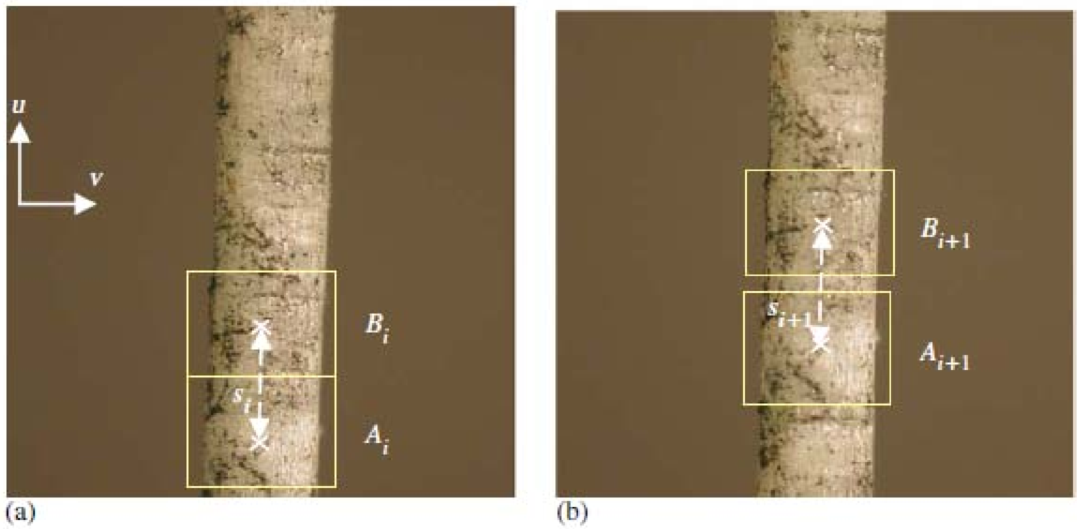
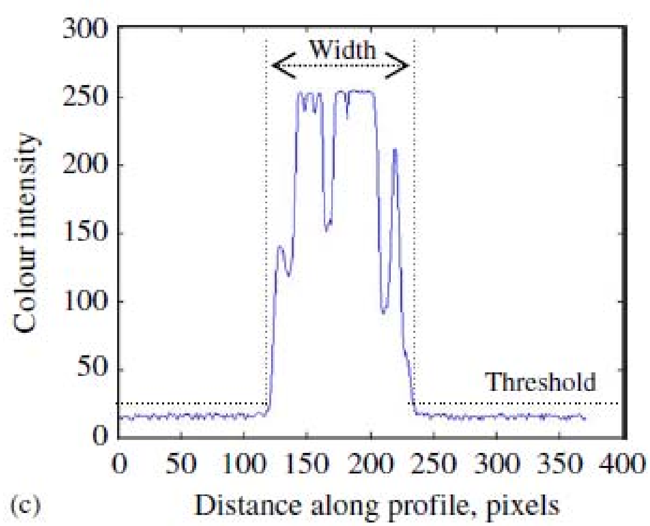
Root reinforcement of slopes
Root soil interaction: tensile strength and stiffness



Root reinforcement of slopes
Root soil interaction: tensile strength and stiffness



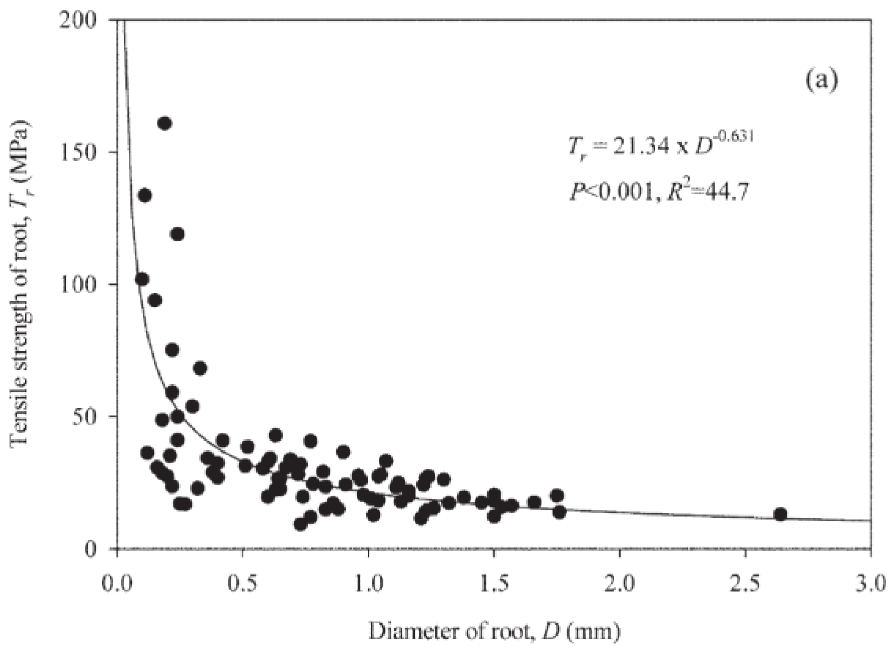
Axial strain calculated using particle image velocimetry (PIV)

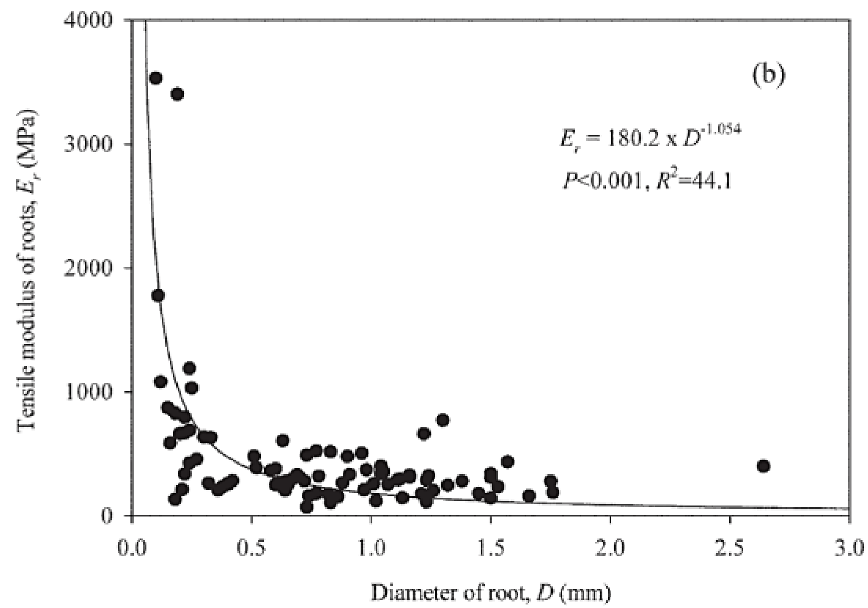


Radial strain measurement using variation in colour intensity

Root reinforcement of slopes

Root soil interaction: tensile strength and stiffness

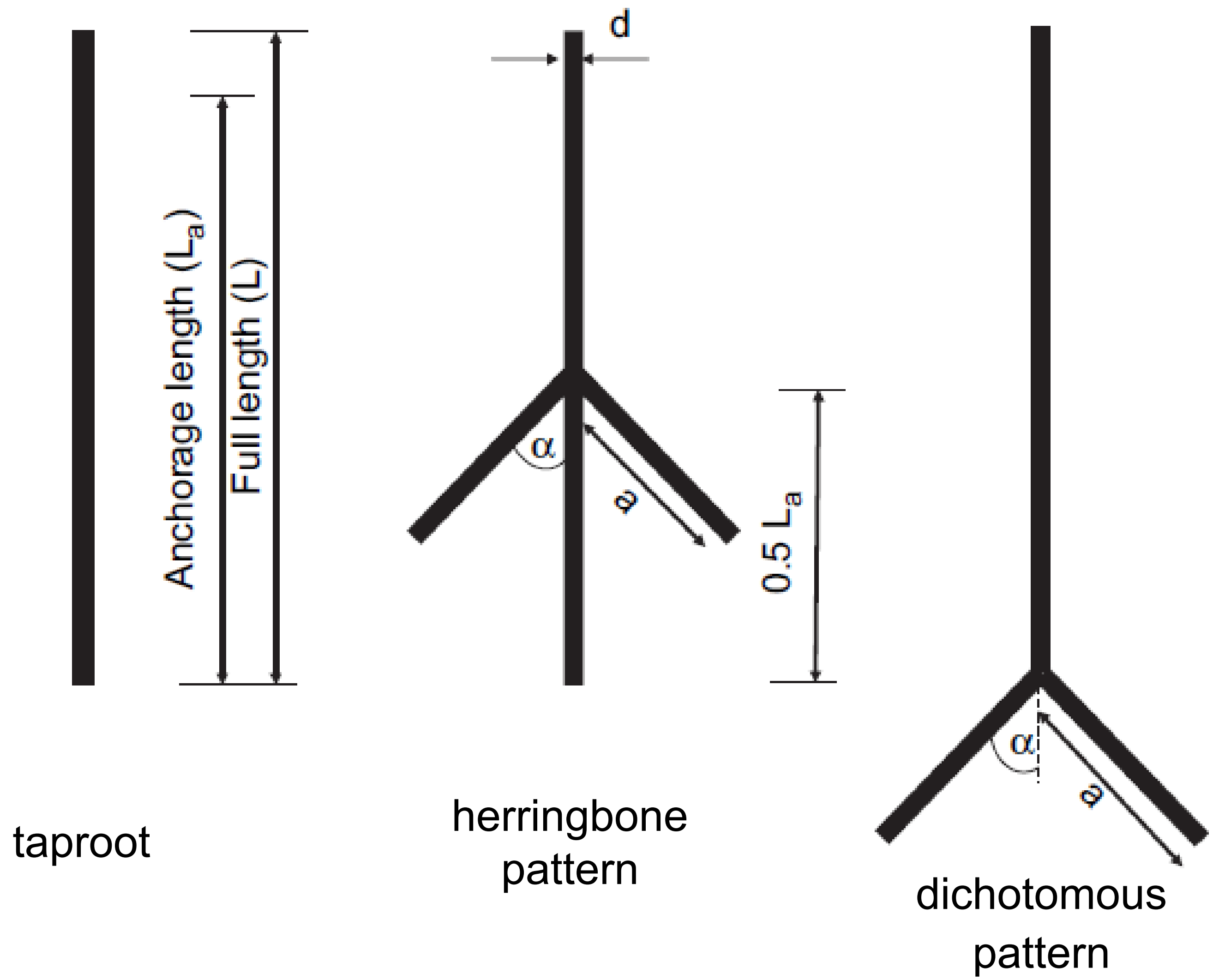




Relationship between (a) the tensile strength and (b) modulus of willow roots and their diameter

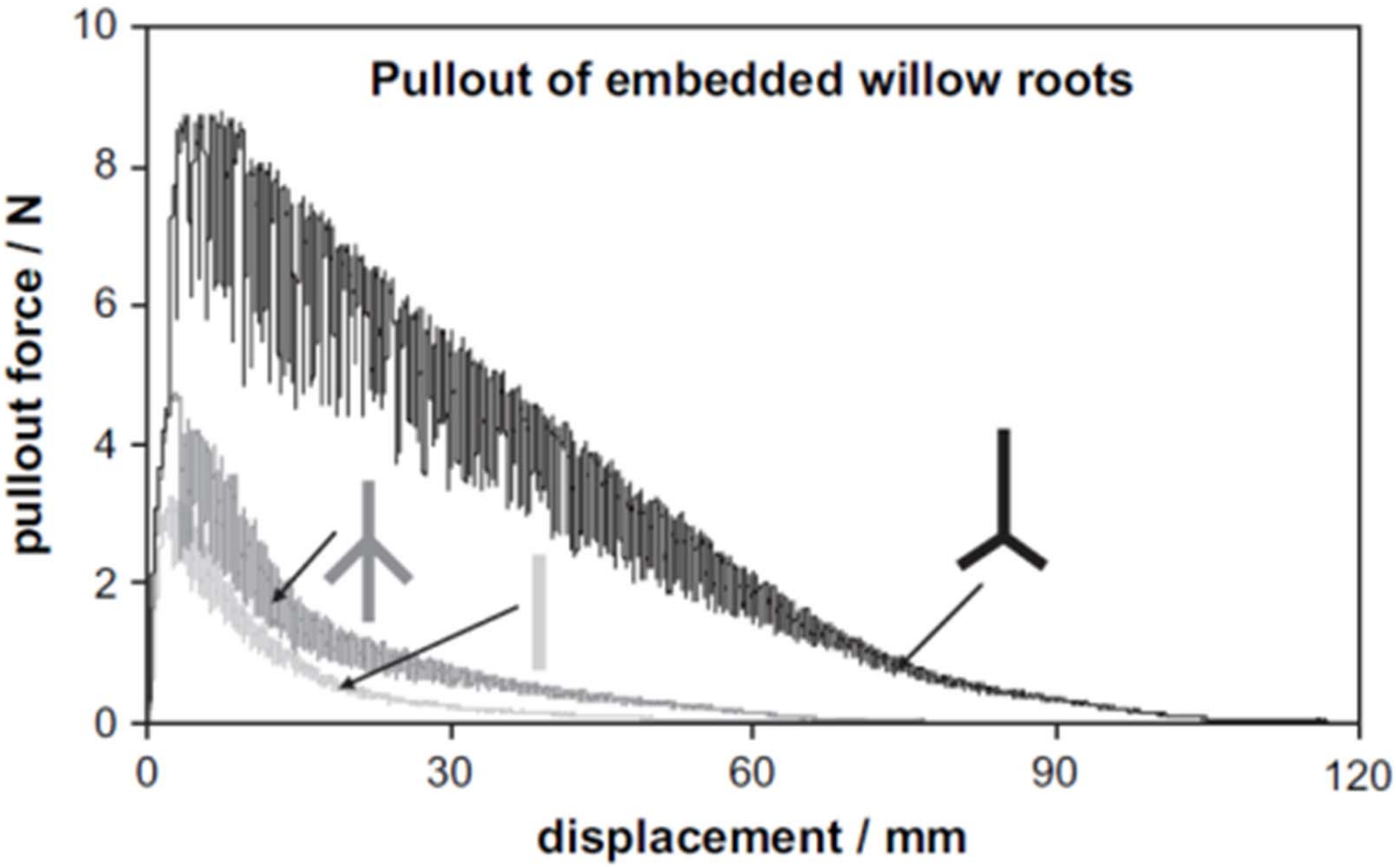
Root reinforcement of slopes

Root soil interaction: effect of root architecture on pull-out



Root reinforcement of slopes

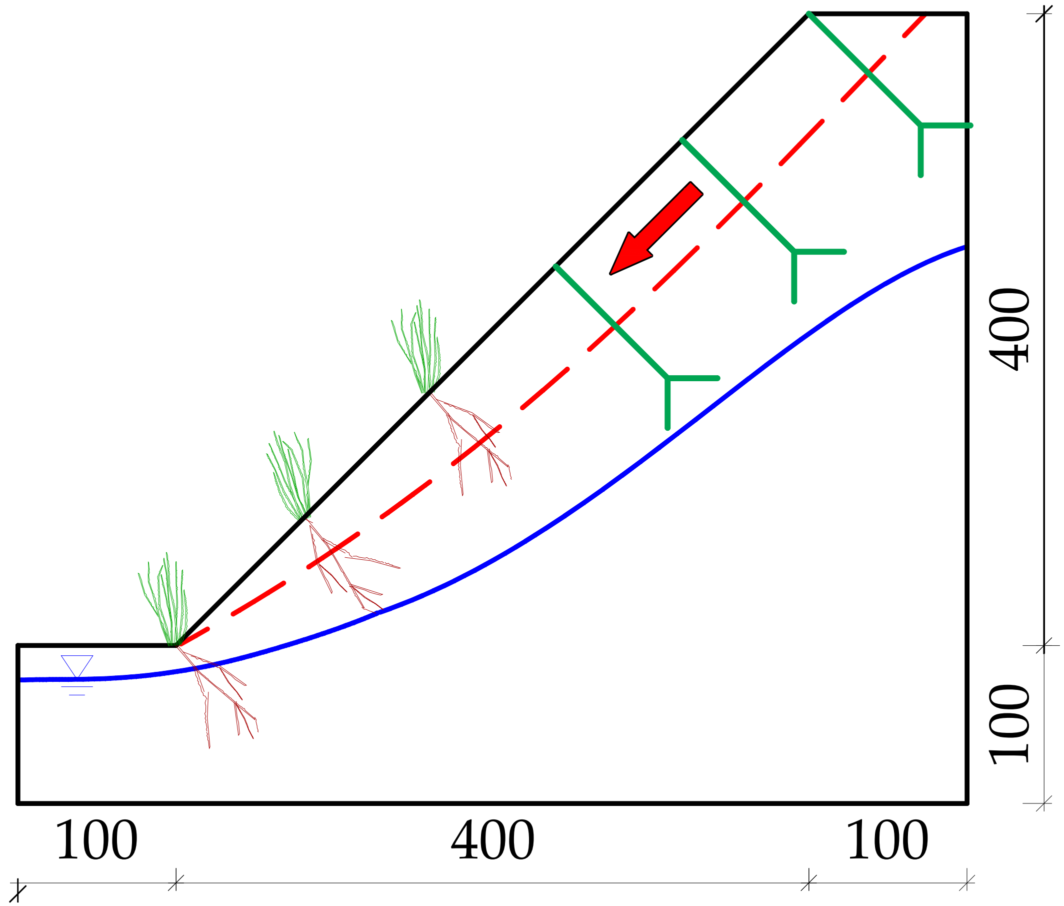
Root soil interaction: effect of root architecture on pull-out



Pull-out resistance of representative samples of embedded willow root segments with different architectures pulled from dry sand

Root reinforcement of slopes

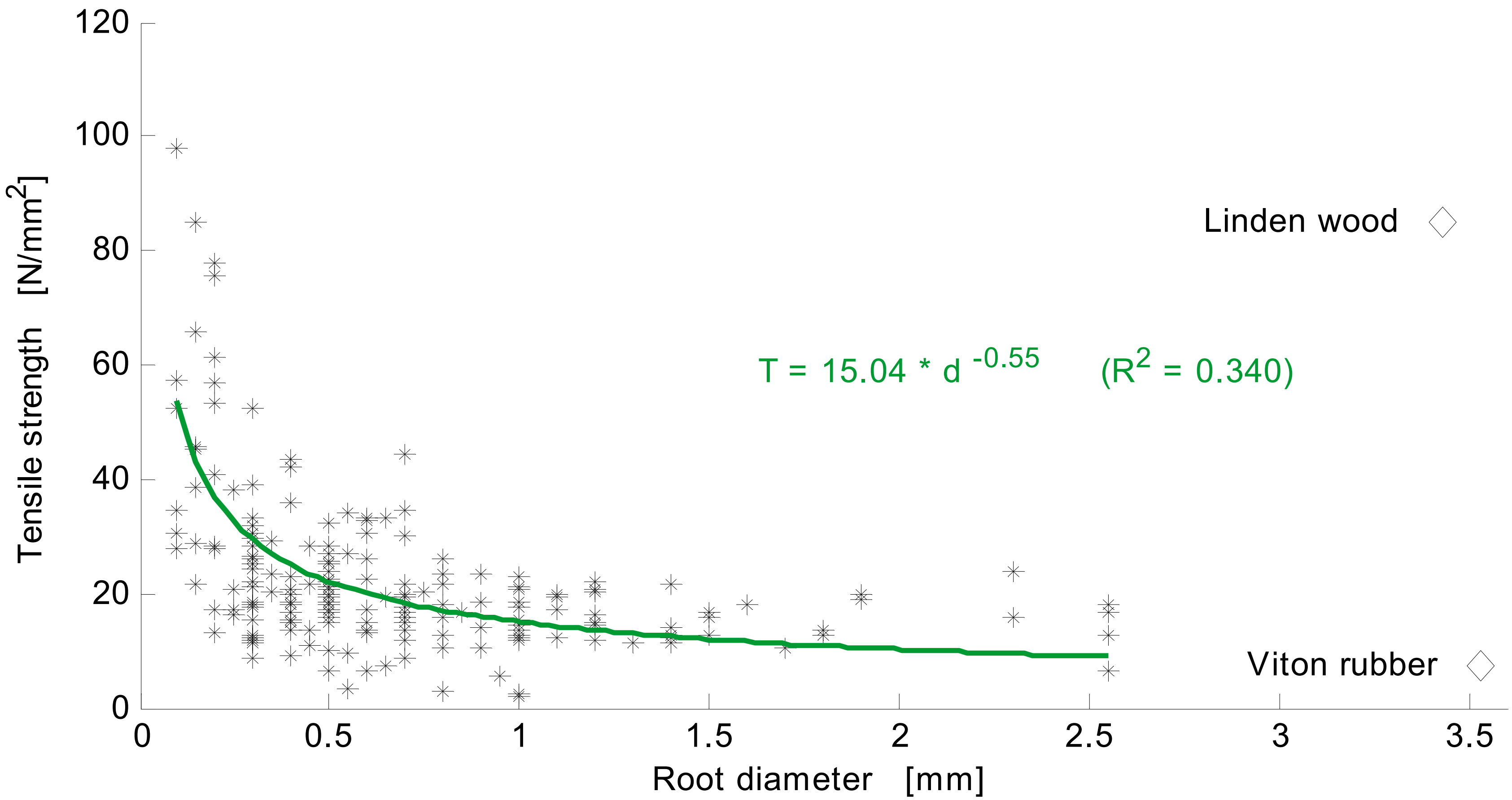
Slope reinforcement: centrifuge model tests



Schematic of centrifuge model of 6.0 m high slope
(dimension in mm in model scale; tests conducted at 15g)

Root reinforcement of slopes

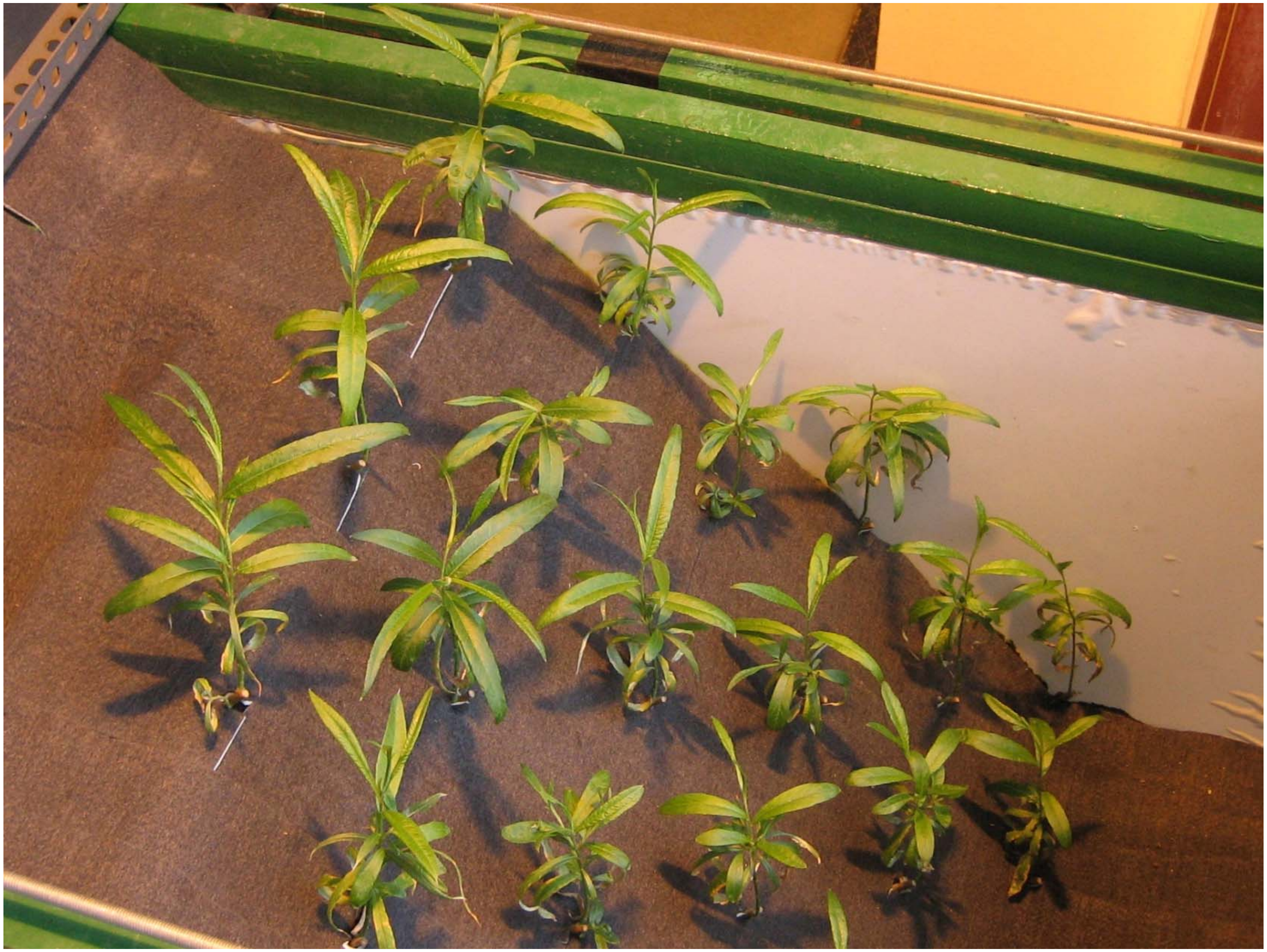
Slope reinforcement: centrifuge model tests



Tensile strength of root analogue material and live roots
(willow plant after 290 days of growth in centrifuge strong box and control tubes)

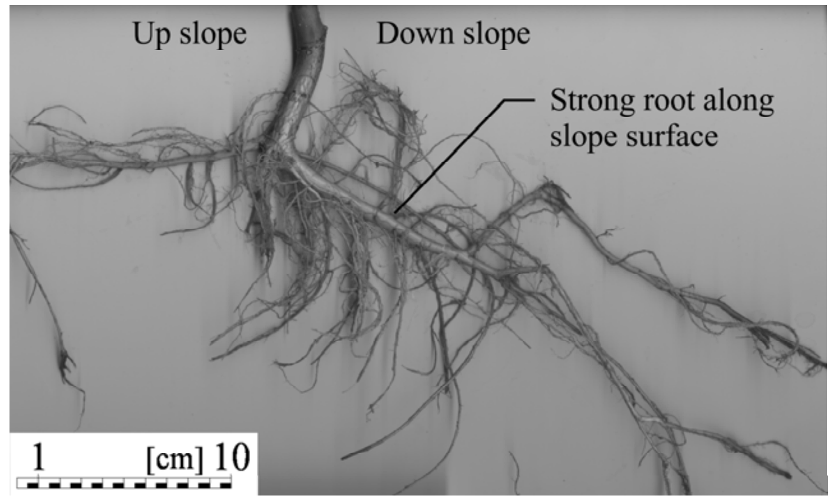
Root reinforcement of slopes

Slope reinforcement: centrifuge model tests (grown willow)



Root reinforcement of slopes

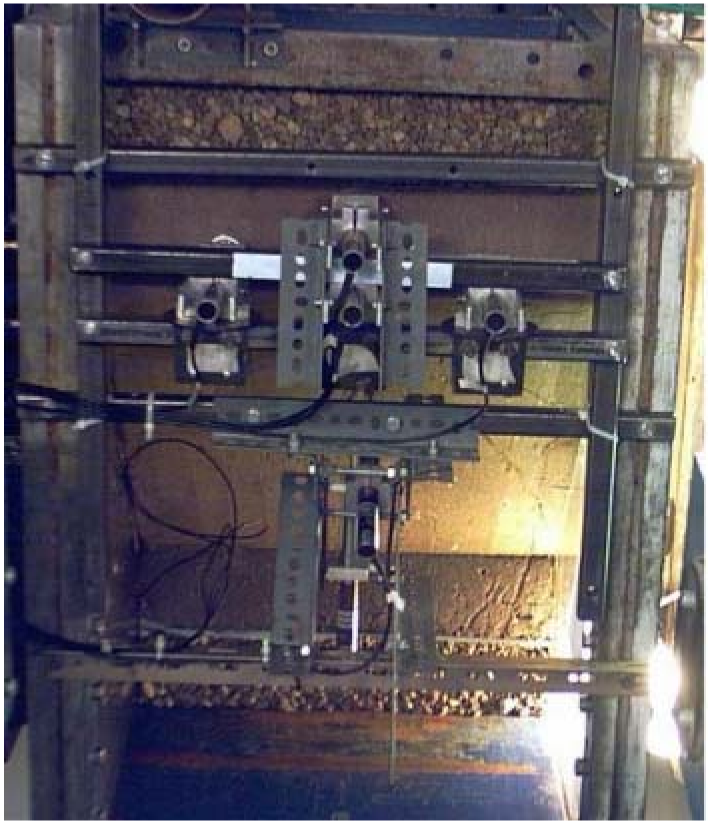
Slope reinforcement: centrifuge model tests (grown willow)

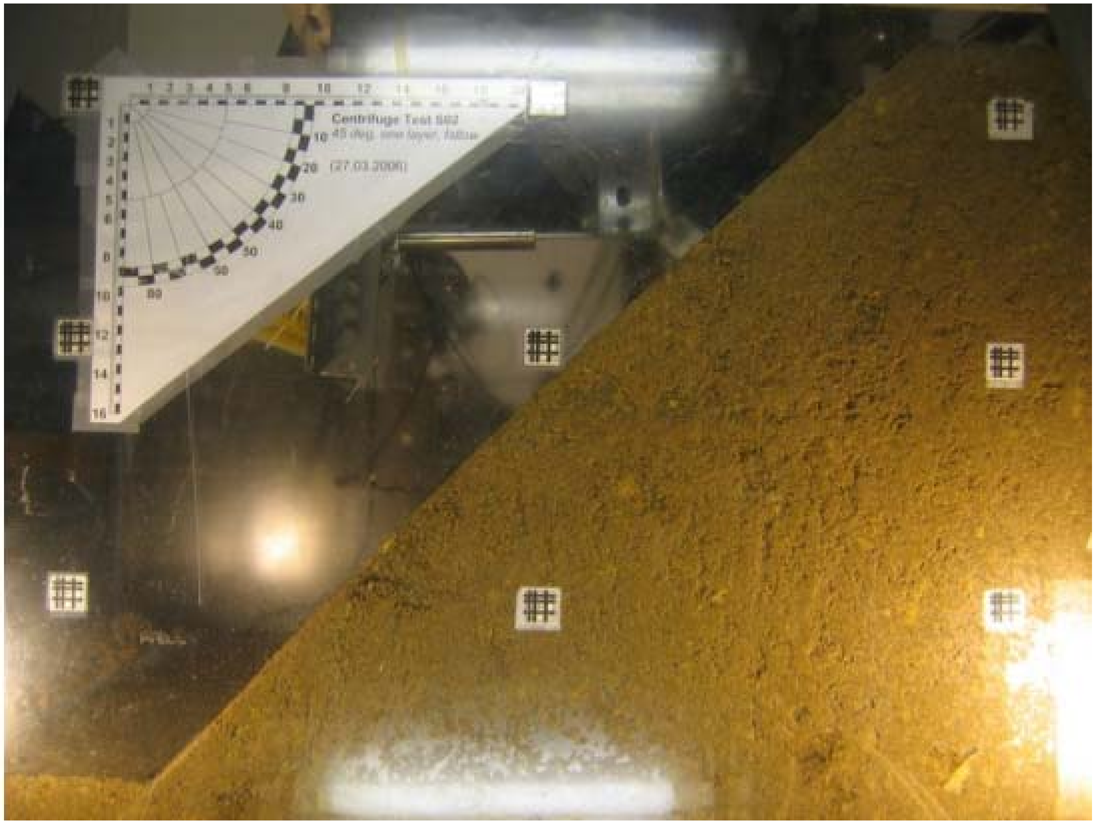


Willow grown for 290 days

Root reinforcement of slopes

Slope reinforcement: centrifuge model tests (fallow slope)





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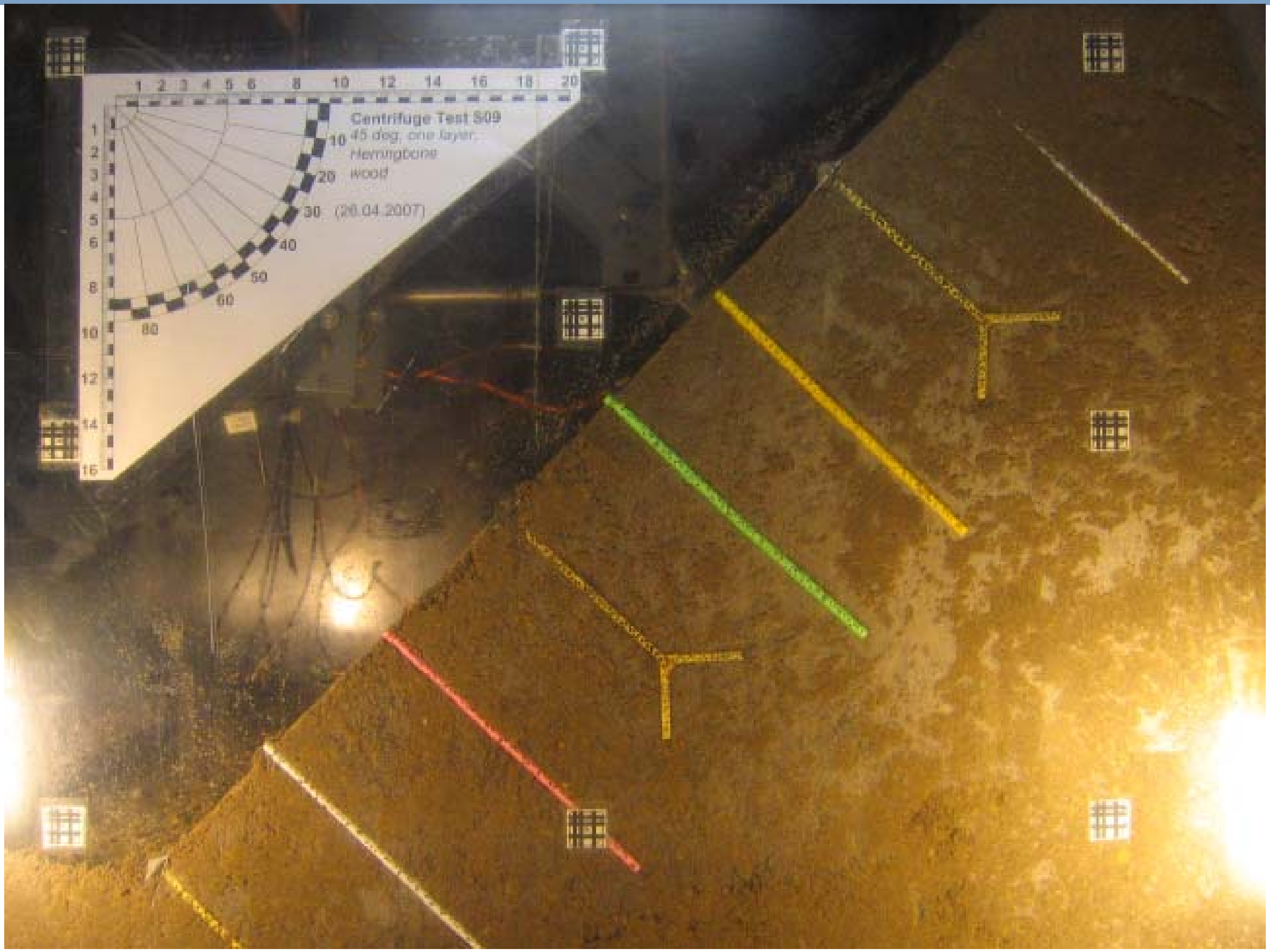
Root reinforcement of slopes

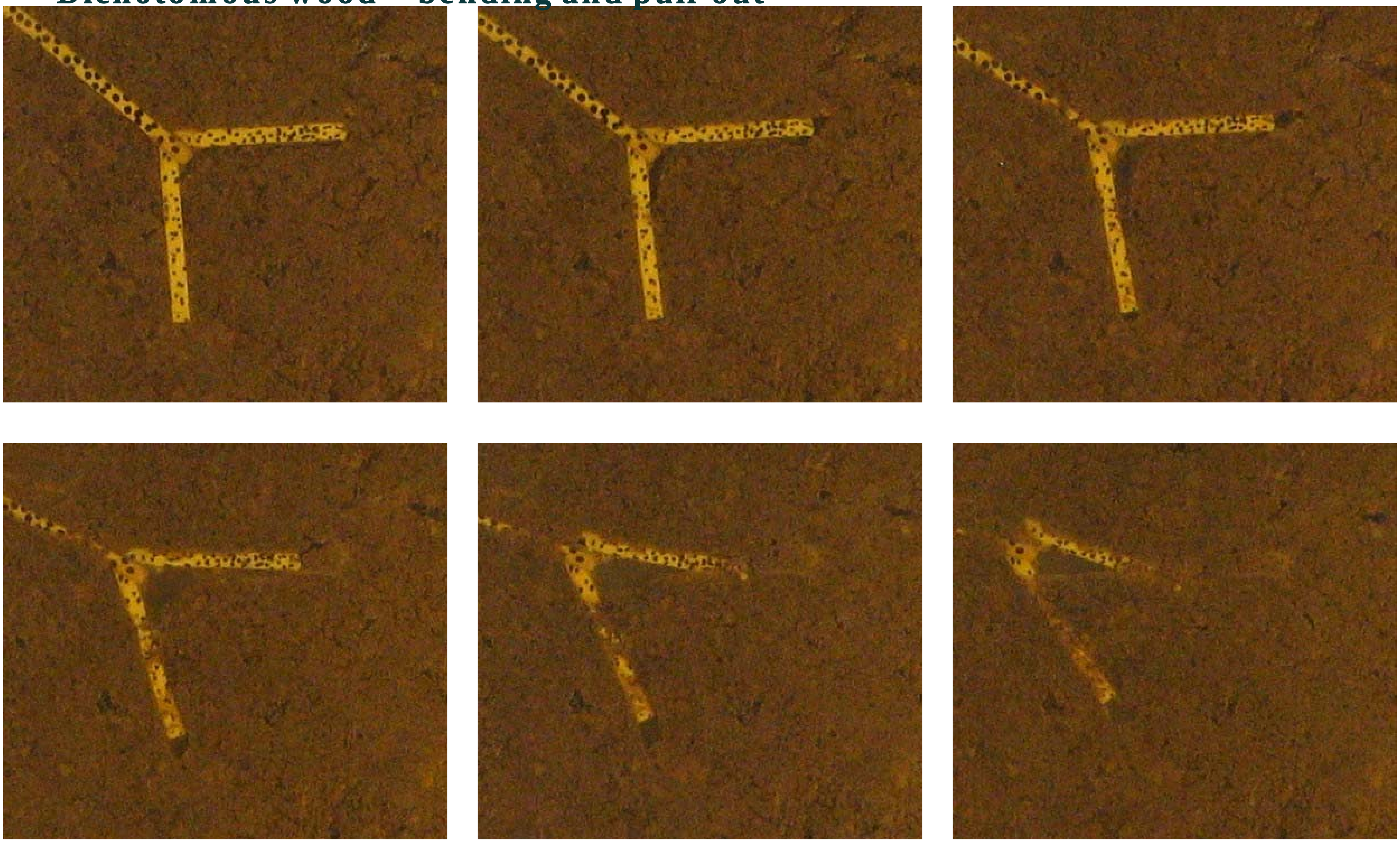
Slope reinforcement: centrifuge model tests (root analogue)



Root reinforcement of slopes

Slope reinforcement: centrifuge model tests (root analogue)

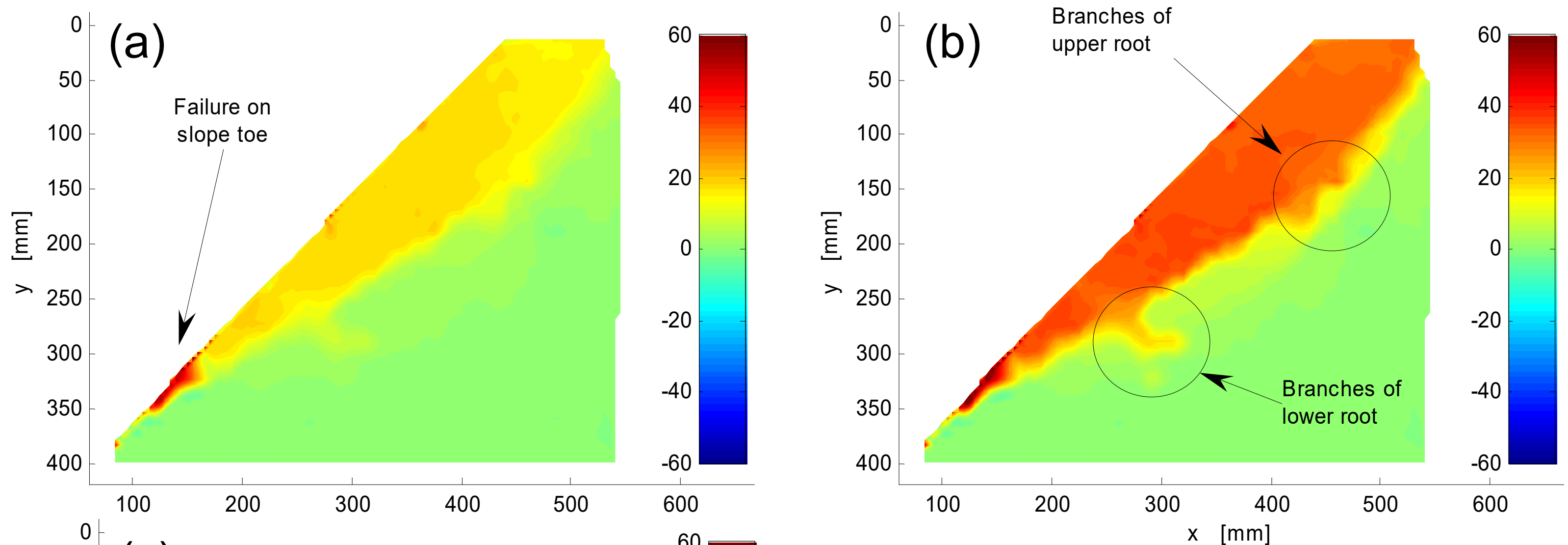
Dichotomous wood – bending and pull-out

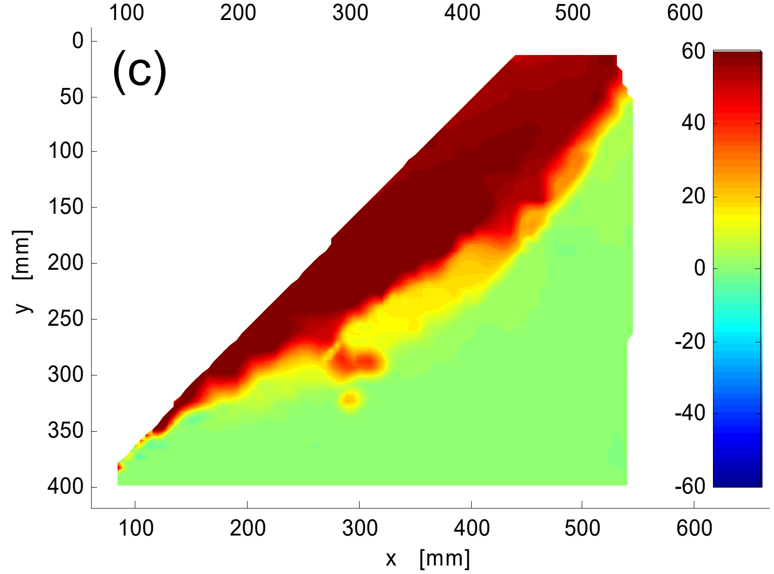


Root reinforcement of slopes

Slope reinforcement: centrifuge model tests (root analogue)

Dichotomous woody root analogues

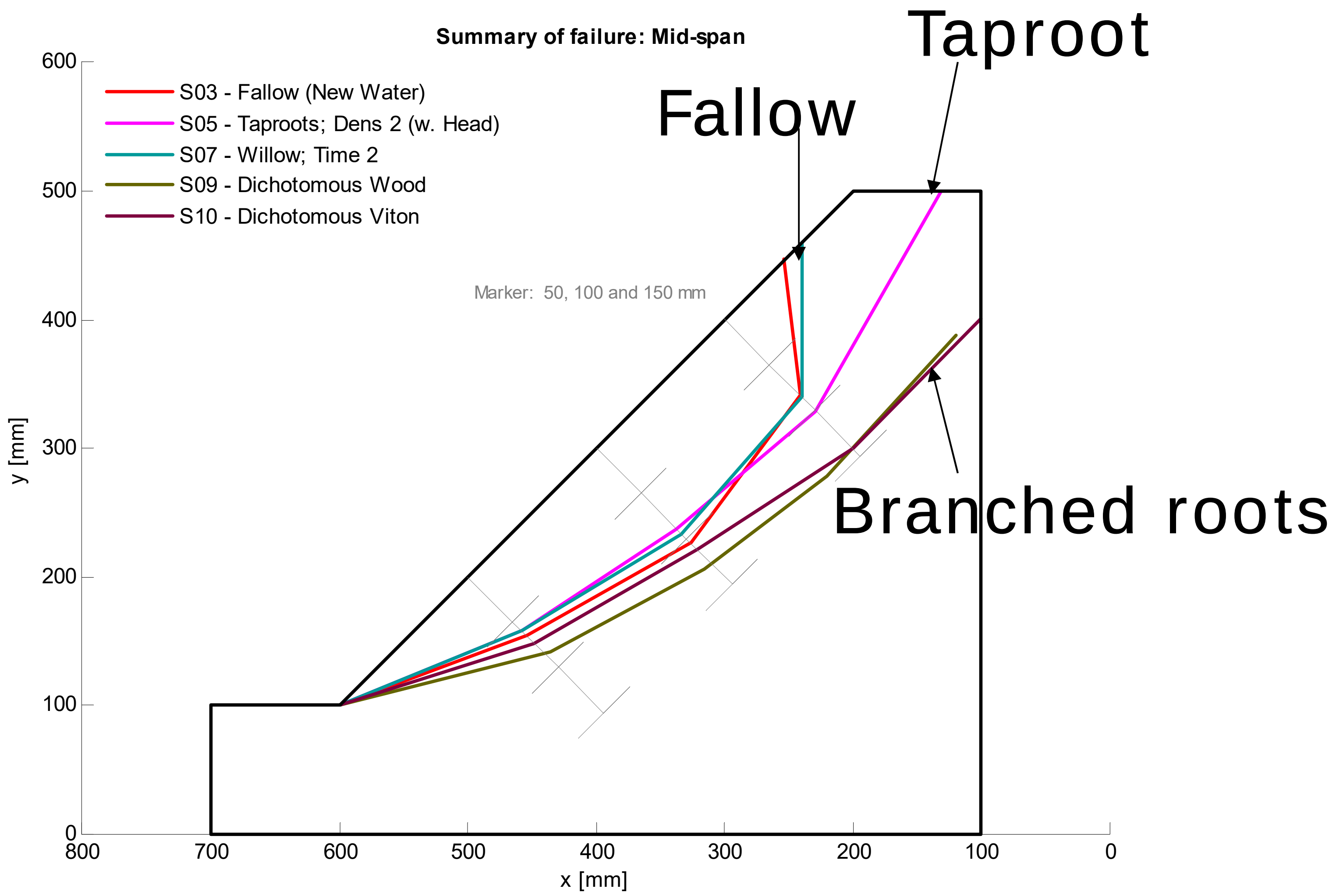




Contour plots of displacement magnitude from PIV analysis as the water table in the model is raised.
(a) Development of shallow slope failure across roots, (b) Start of shear plane migration, (c) Final shear plane below root influence

Root reinforcement of slopes

Slope reinforcement: centrifuge model tests



Root reinforcement of slopes

Slope reinforcement: centrifuge model tests

Slope stability calculations

	Fallow	Taproot		Dichotomous root	
		No root head	With root head	Wood	Rubber
RAR	0	0.0018	0.0005	0.0005	0.0005
FOS	1	0.9	1.0	0.8	0.9
Δc' (kPa)	-	0.6	0.1	2.7	1.2
Δc' pullout* (kPa)	-	1.7	0.5	1.5	1.2
Δc' tension* (kPa)	-	184	51	51	4.4

*values predicted from element tests

Back-calculated change of c′ (Δc′) required to give FOS = 1.0 at failure using Bishop's method (using φ′ = 24.0°, c′ = 5.5 kPa) and comparison with results from reinforcement calculation methods

Earthquake soil-foundation-structure interaction - field data

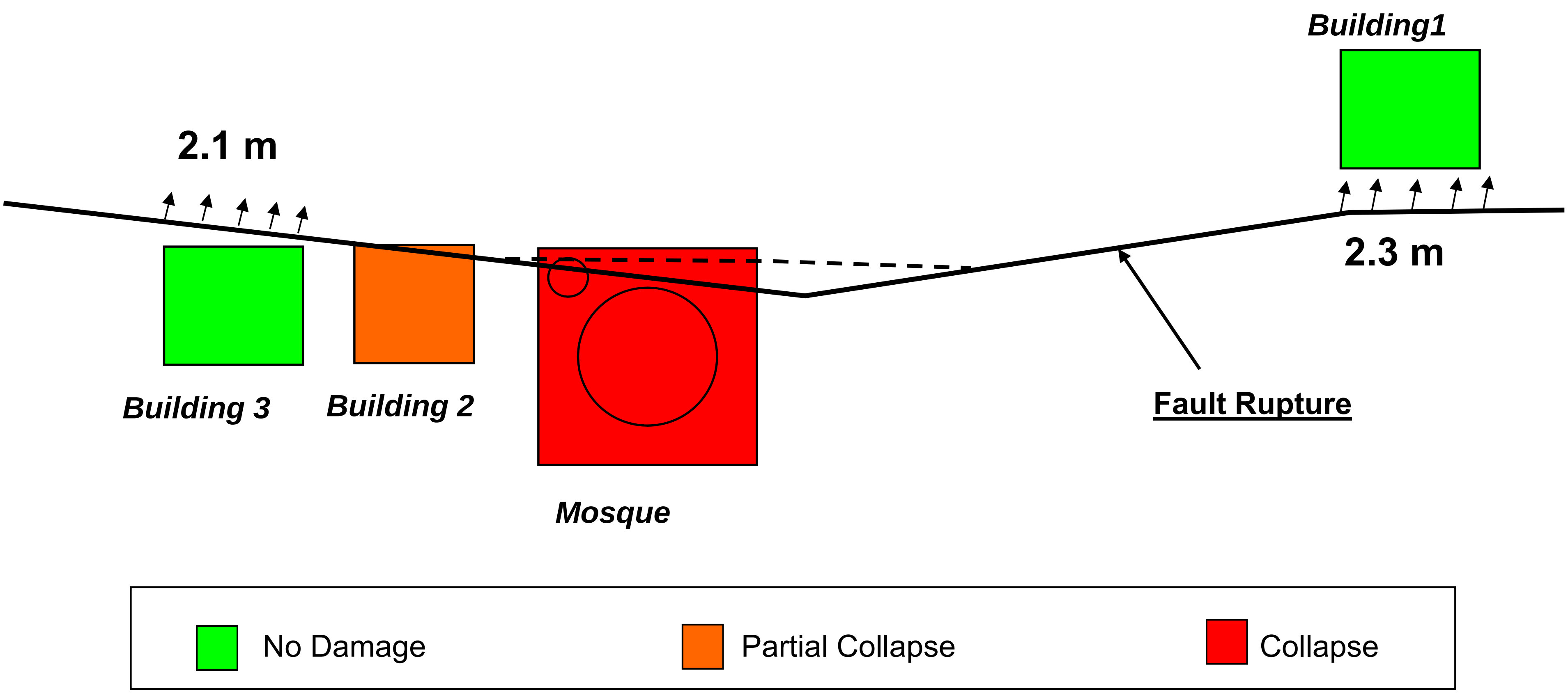
Surface ruptures during the 1999 Chi-Chi earthquake

Earthquake soil-foundation-structure interaction - field data

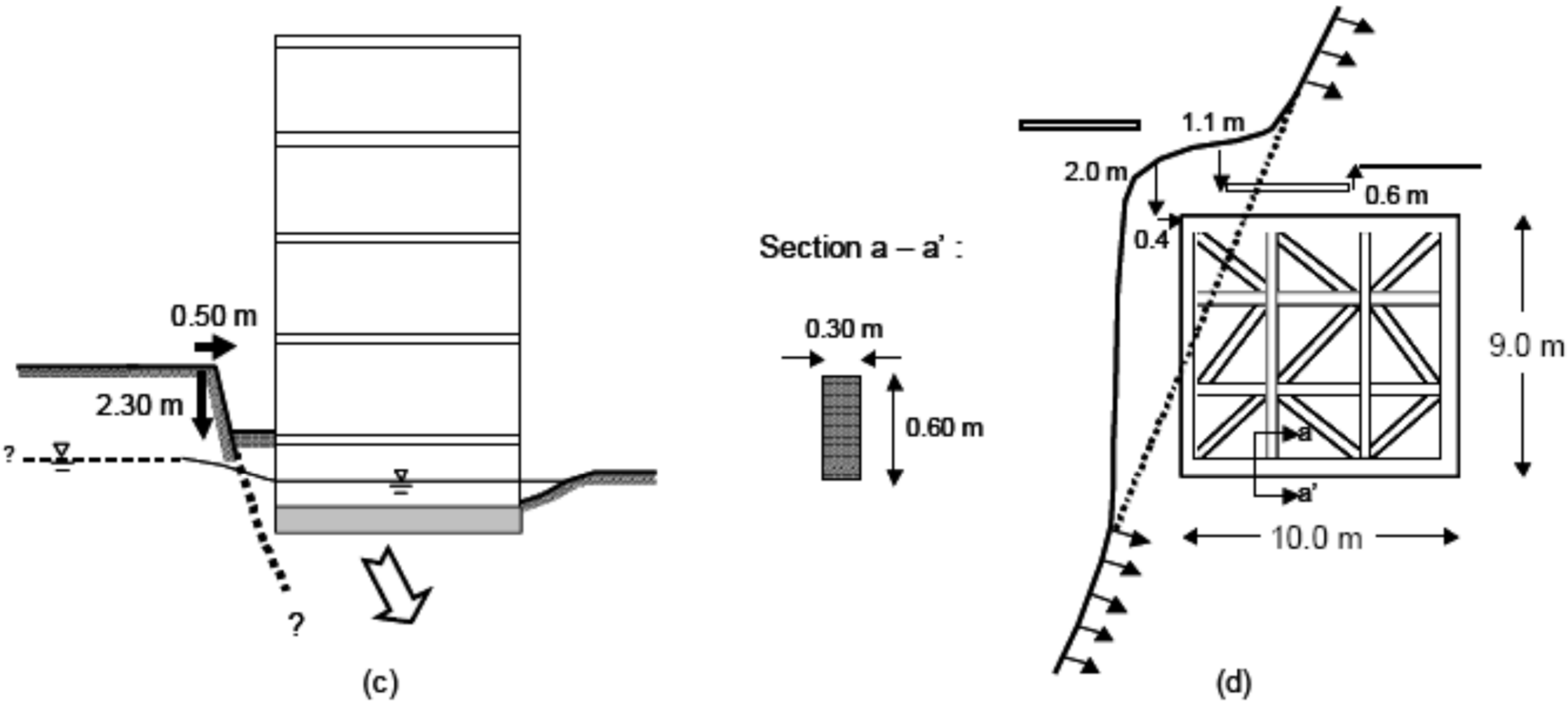
Surface ruptures during the 1999 Chi-Chi earthquake

Earthquake soil-foundation-structure interaction - field data

Fault Rupture at the area east of Gölcük, Turkey (1999)



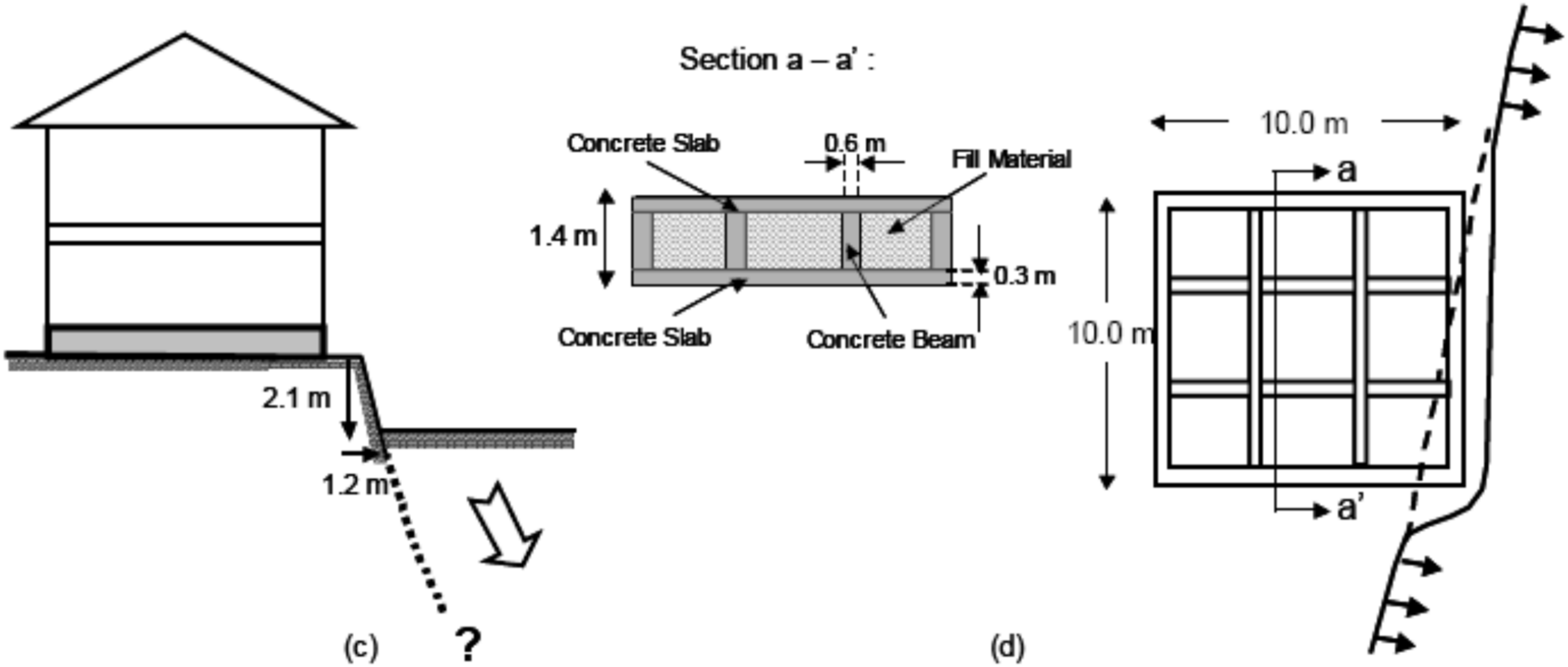
Earthquake soil-foundation-structure interaction - field data



Building 1: 4-storeys + Basement – No Damage

after Gazetas and Anastasopoulos (2007)

Earthquake soil-foundation-structure interaction - field data

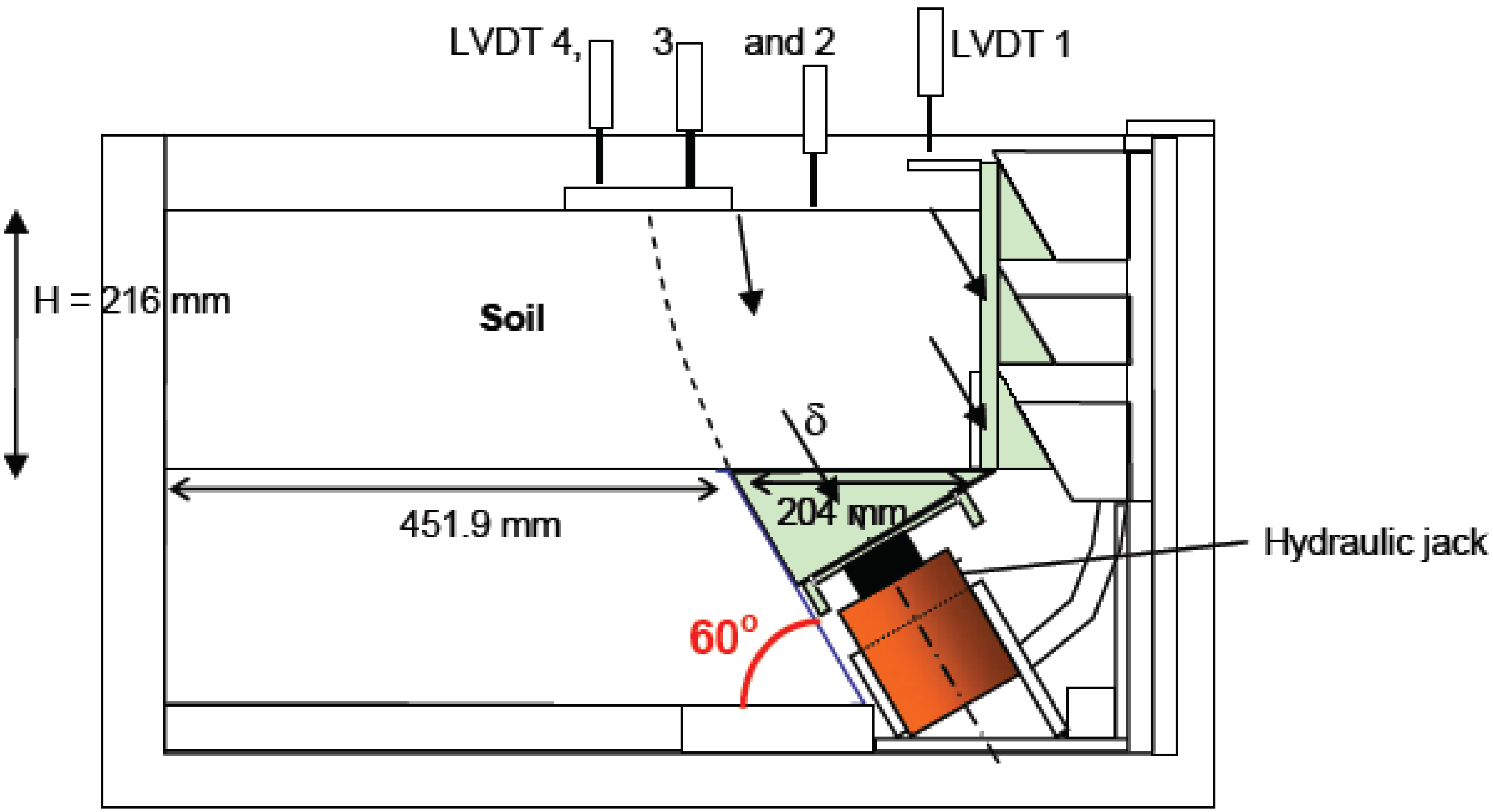


Building 3: 2-stories + attic – No Damage

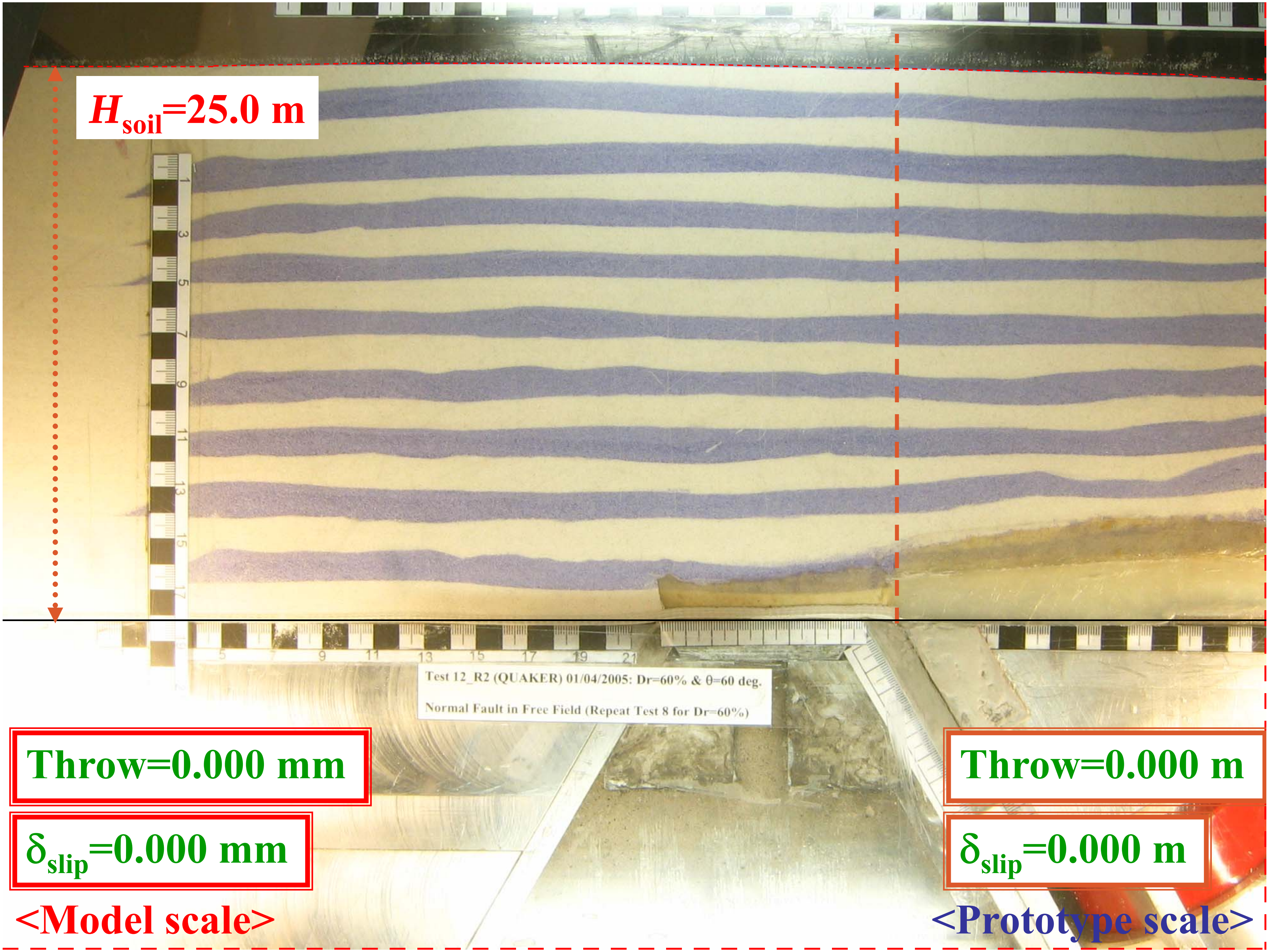
after Gazetas and Anastasopoulos (2007)

Earthquake soil-foundation-structure interaction – model testing

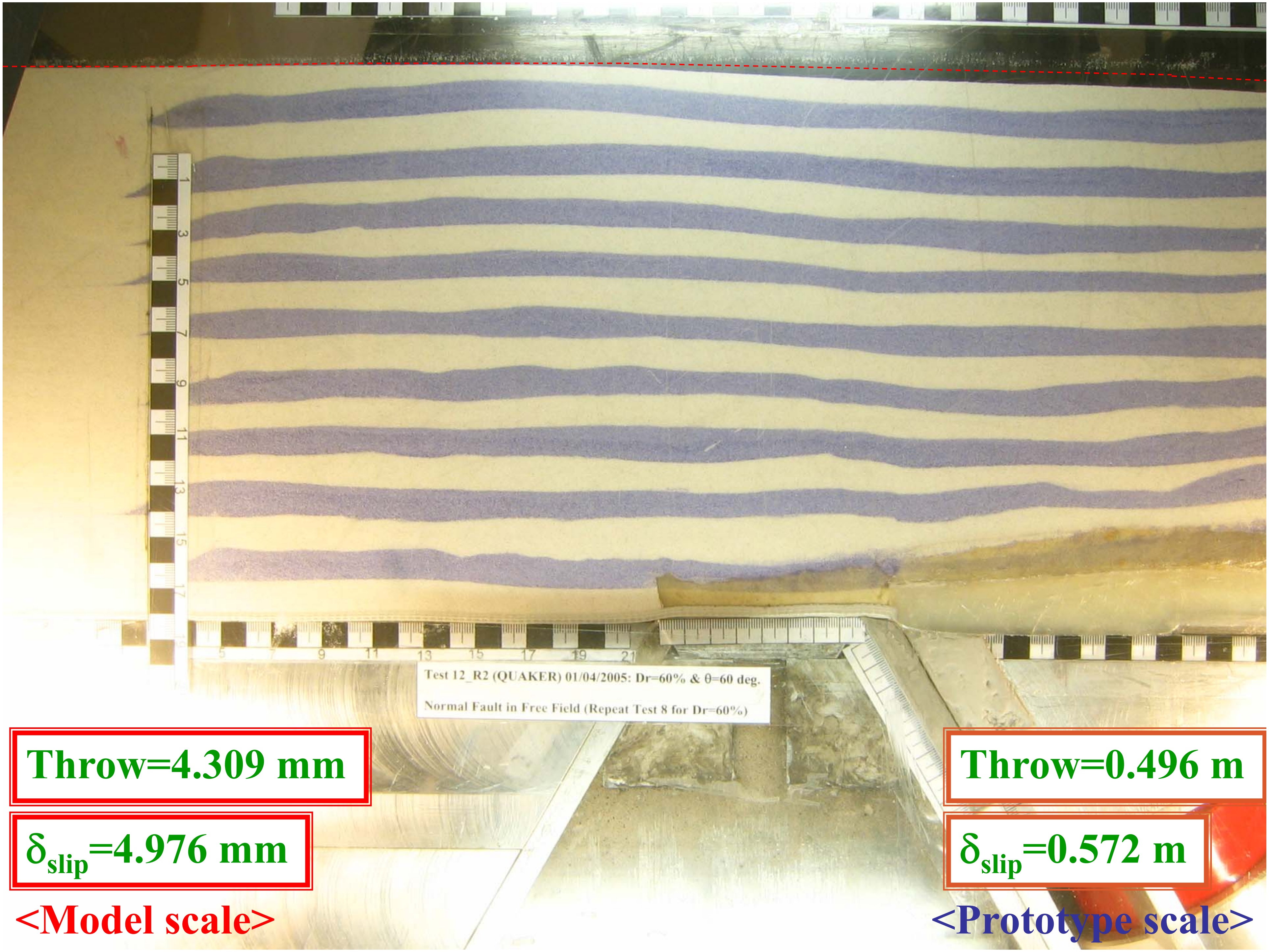
Centrifuge apparatus – normal fault

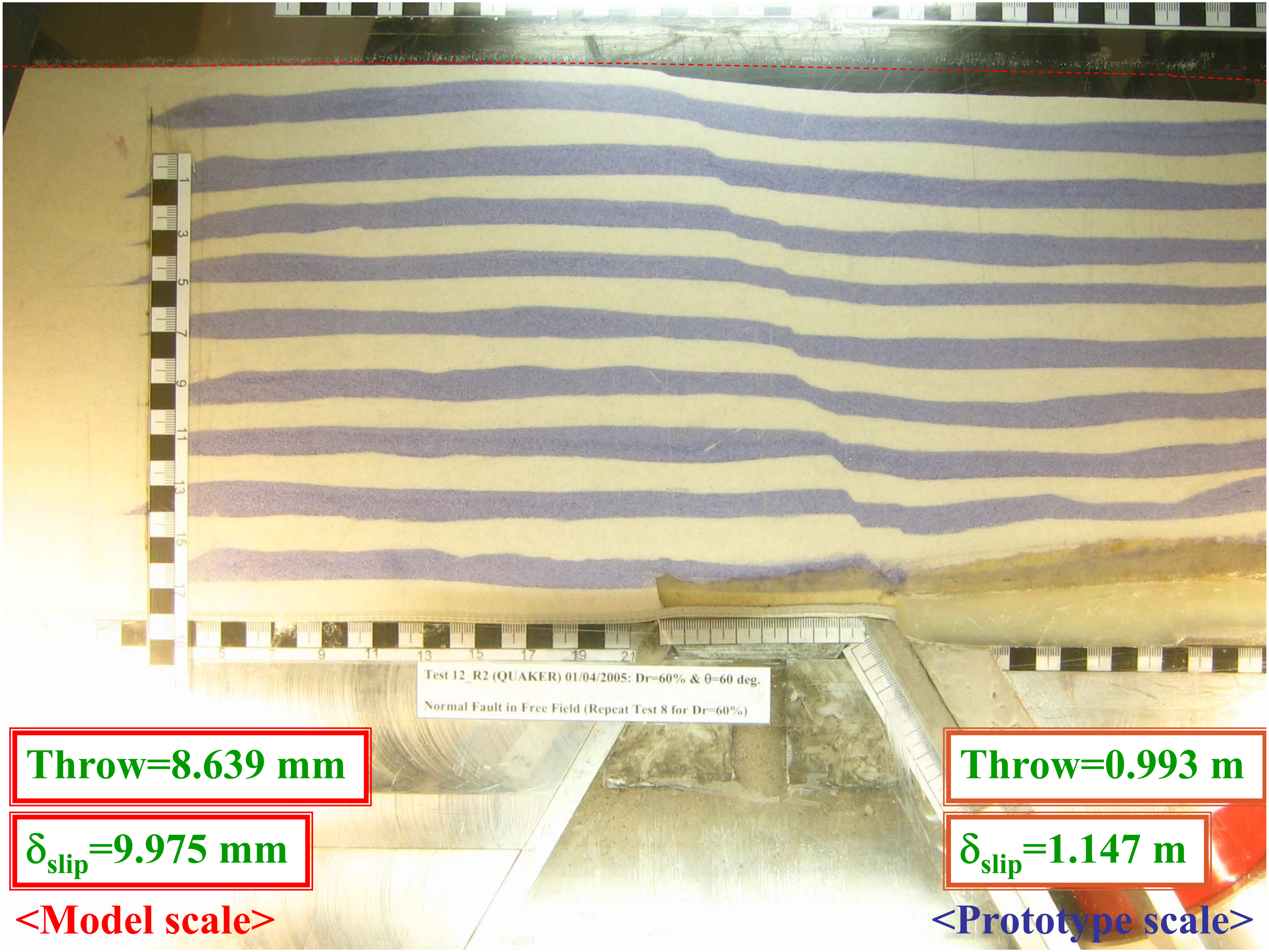



Date: 21 / 10 / 05 Test 22

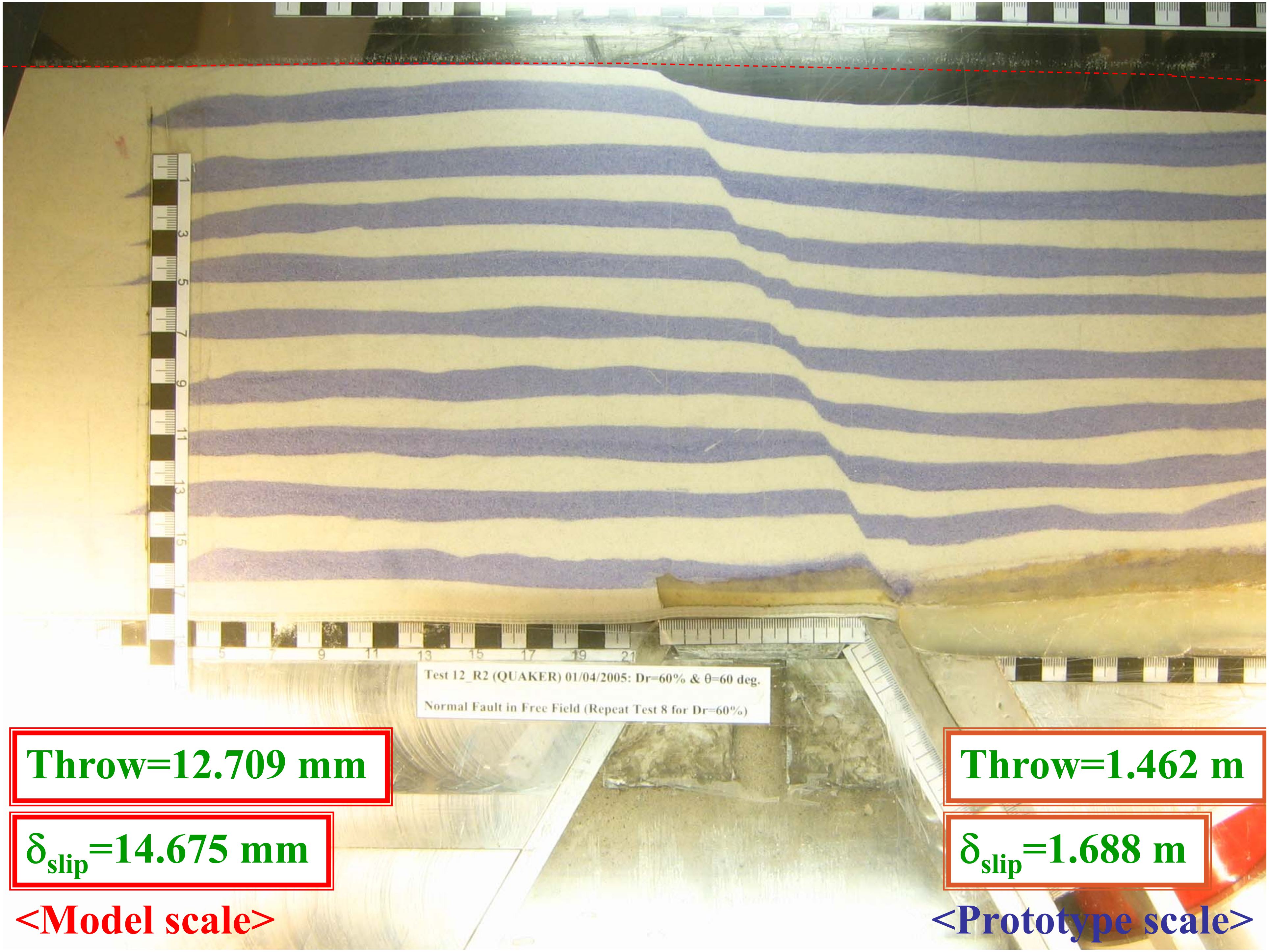


H_{soil}=25.0 m
Test 12_R2 (QUAKER) 01/04/2005: Dr=60% & θ=60 deg.
Normal Fault in Free Field (Repeat Test 8 for Dr=60%)
Throw=0.000 mm
δ_{slip}=0.000 mm
<Model scale>
Throw=0.000 m
δ_{slip}=0.000 m
<Prototype scale>


Test 12_R2 (QUAKER) 01/04/2005: Dr=60% & θ=60 deg.
Normal Fault in Free Field (Repeat Test 8 for Dr=60%)
Throw=4.309 mm
δ_{slip}=4.976 mm
<Model scale>
Throw=0.496 m
δ_{slip}=0.572 m
<Prototype scale>



Test 12_R2 (QUAKER) 01/04/2005: Dr=60% & θ=60 deg.
Normal Fault in Free Field (Repeat Test 8 for Dr=60%)
Throw=8.639 mm
δslip=9.975 mm
<Model scale>
Throw=0.993 m
δslip=1.147 m
<Prototype scale>


Test 12_R2 (QUAKER) 01/04/2005: Dr=60% & θ=60 deg.
Normal Fault in Free Field (Repeat Test 8 for Dr=60%)
Throw=12.709 mm
δ_{slip}=14.675 mm
<Model scale>
Throw=1.462 m
δ_{slip}=1.688 m
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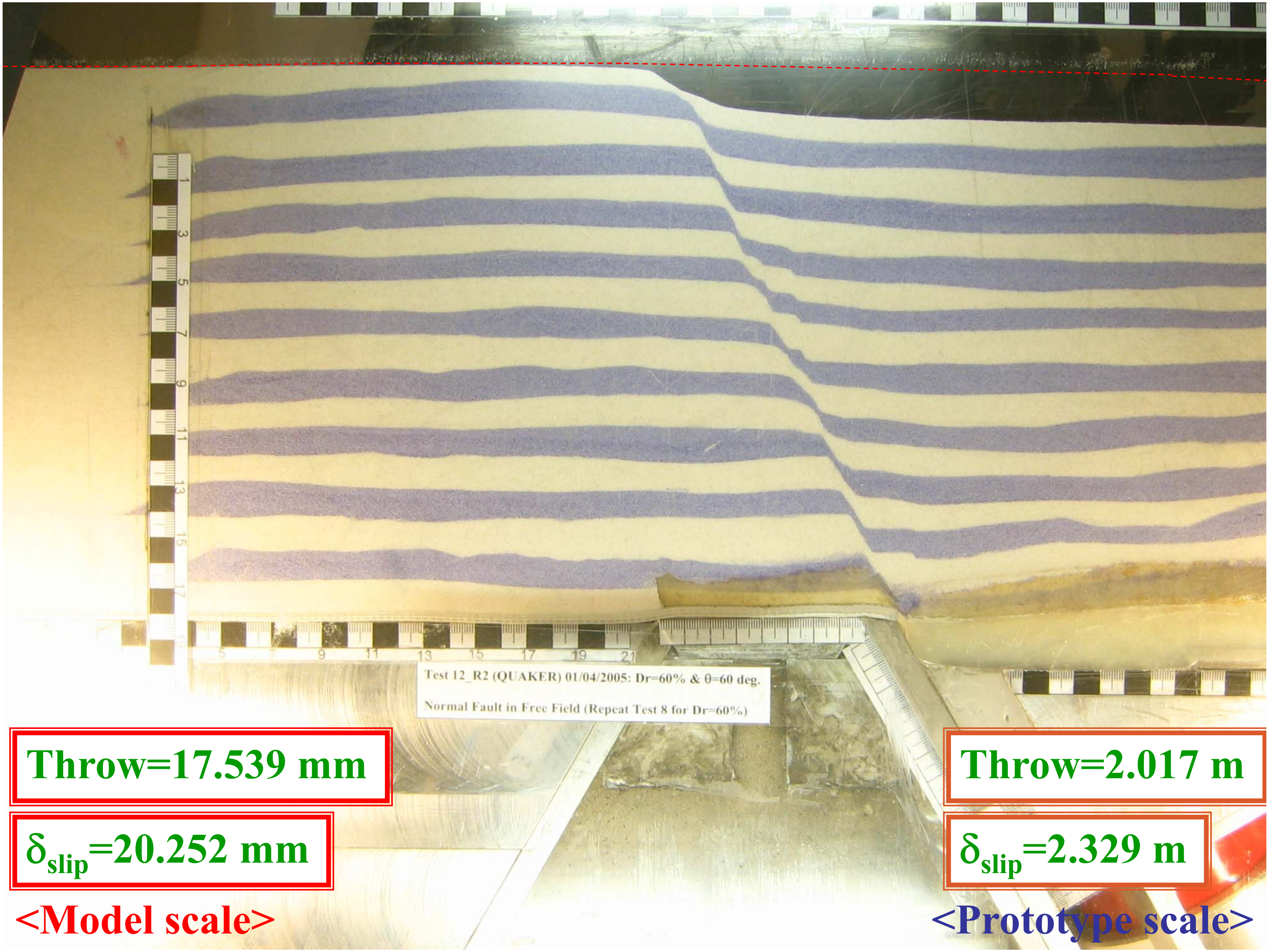
Test 12_R2 (QUAKER) 01/04/2005: Dr=60% & θ=60 deg.
Normal Fault in Free Field (Repeat Test 8 for Dr=60%)
Throw=17.539 mm
δslip=20.252 mm
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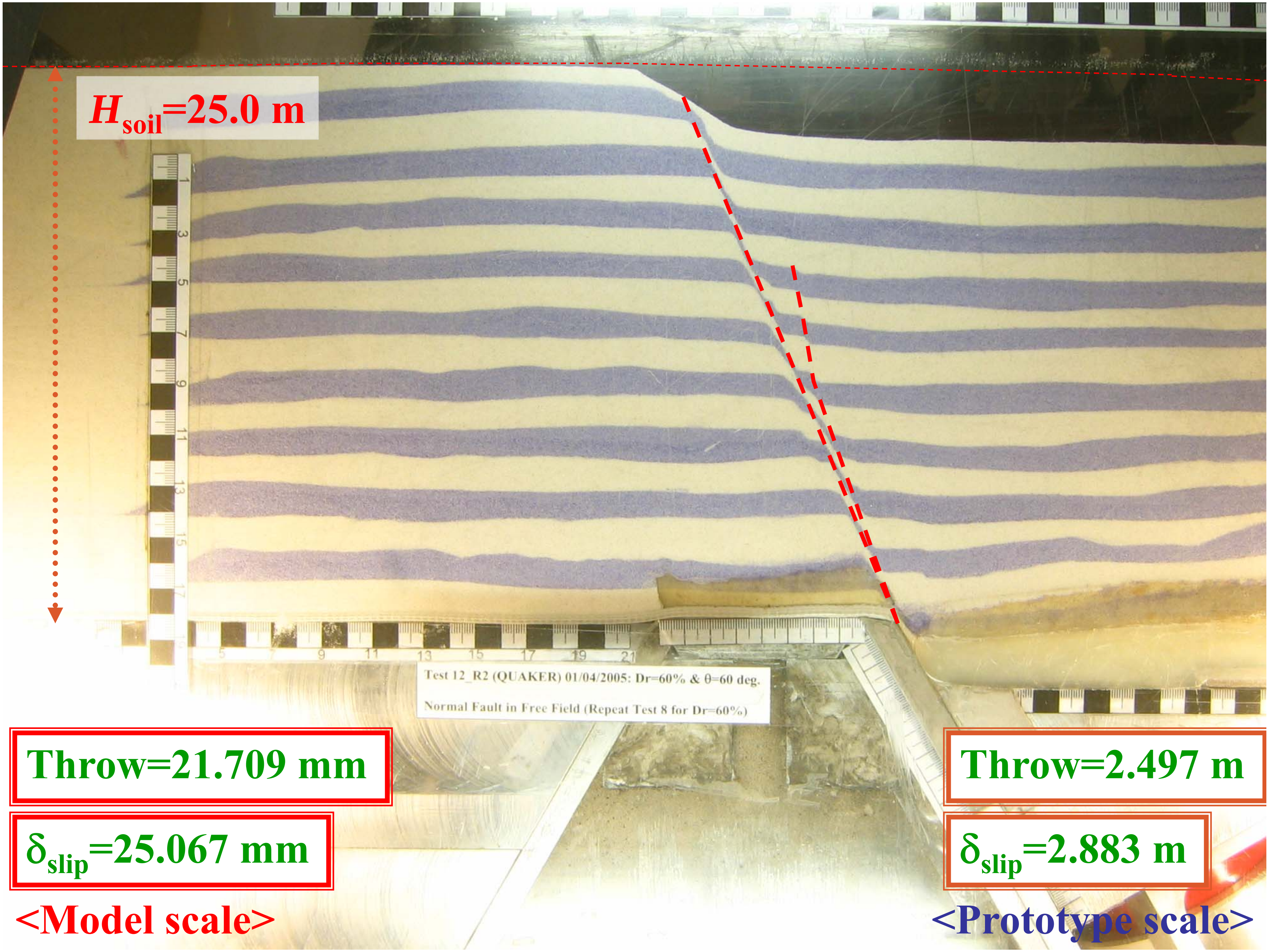
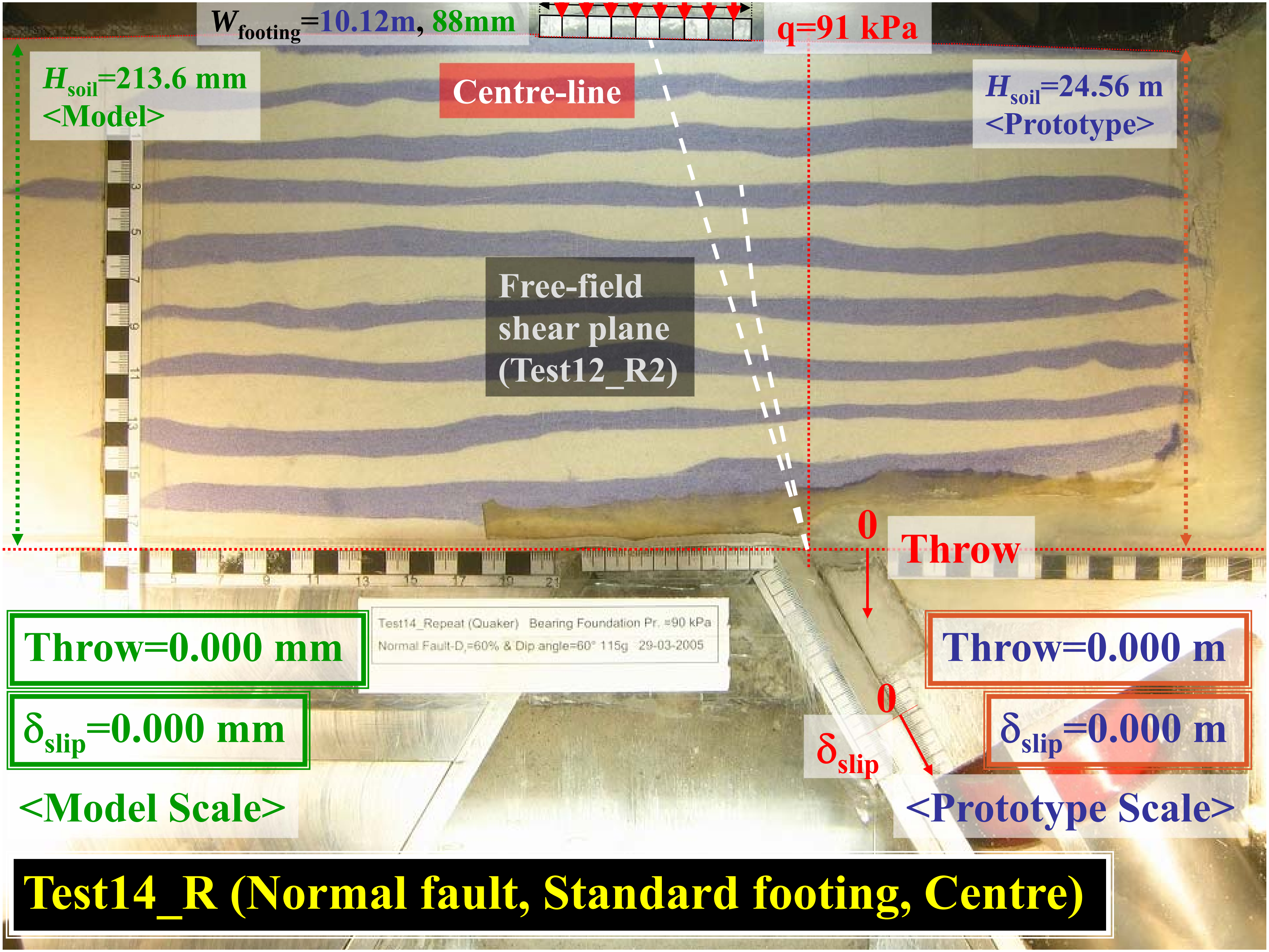
Throw=2.017 m
δslip=2.329 m
<Prototype scale>

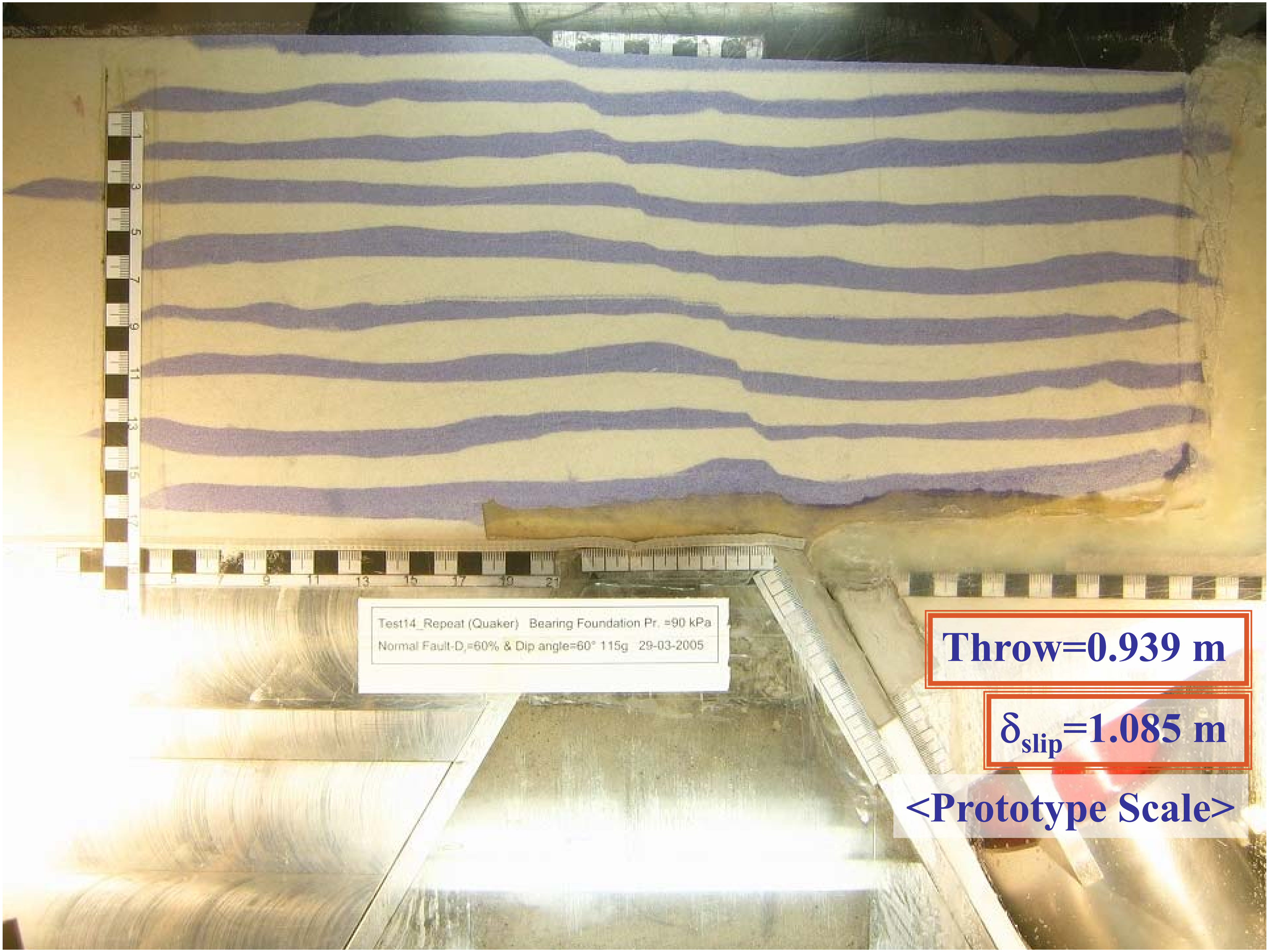


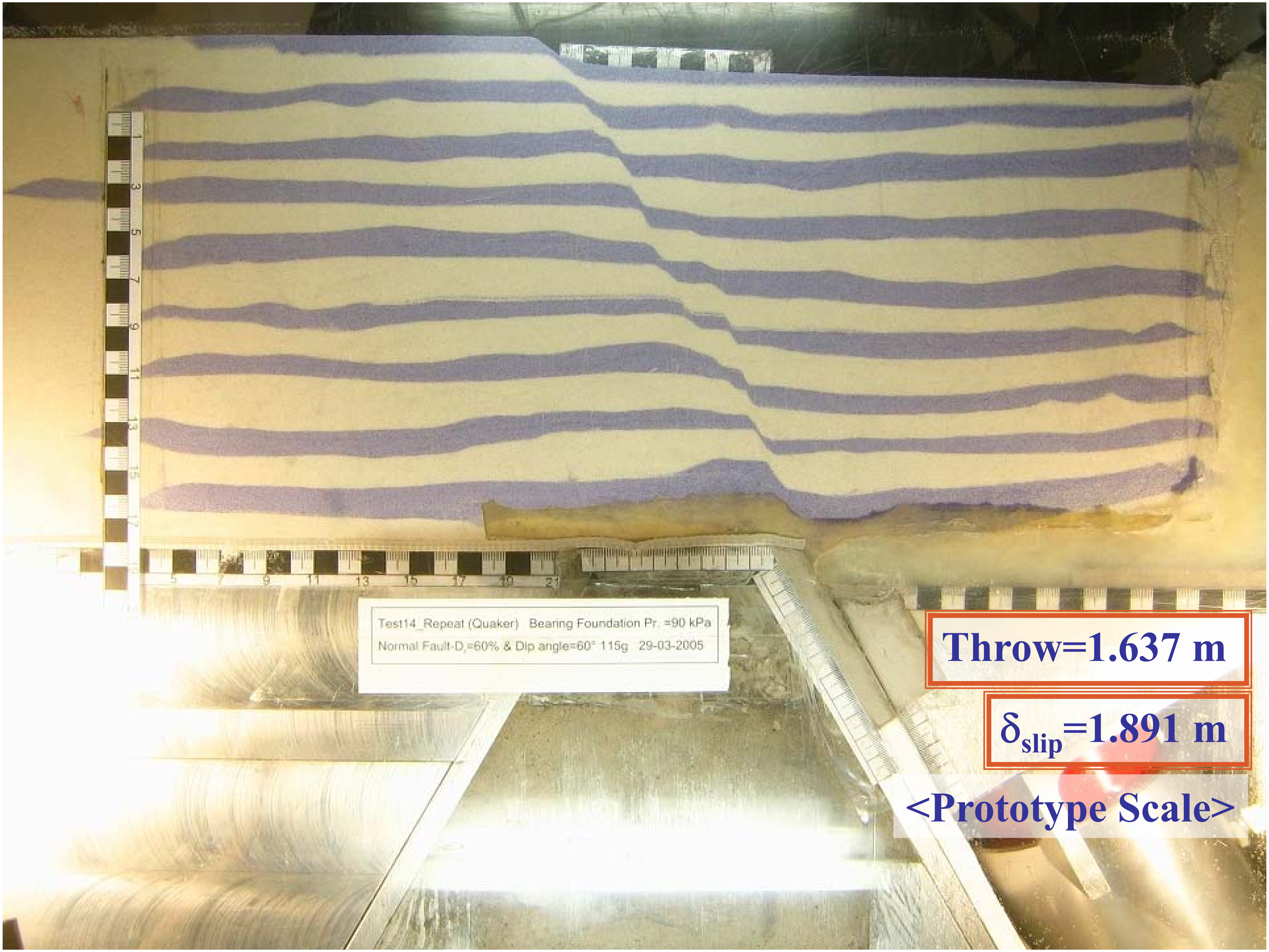
H_soil=25.0 m
Test 12_R2 (QUAKER) 01/04/2005: Dr=60% & θ=60 deg.
Normal Fault in Free Field (Repeat Test 8 for Dr=60%)
Throw=21.709 mm
δ_slip=25.067 mm
<Model scale>
Throw=2.497 m
δ_slip=2.883 m
<Prototype scale>



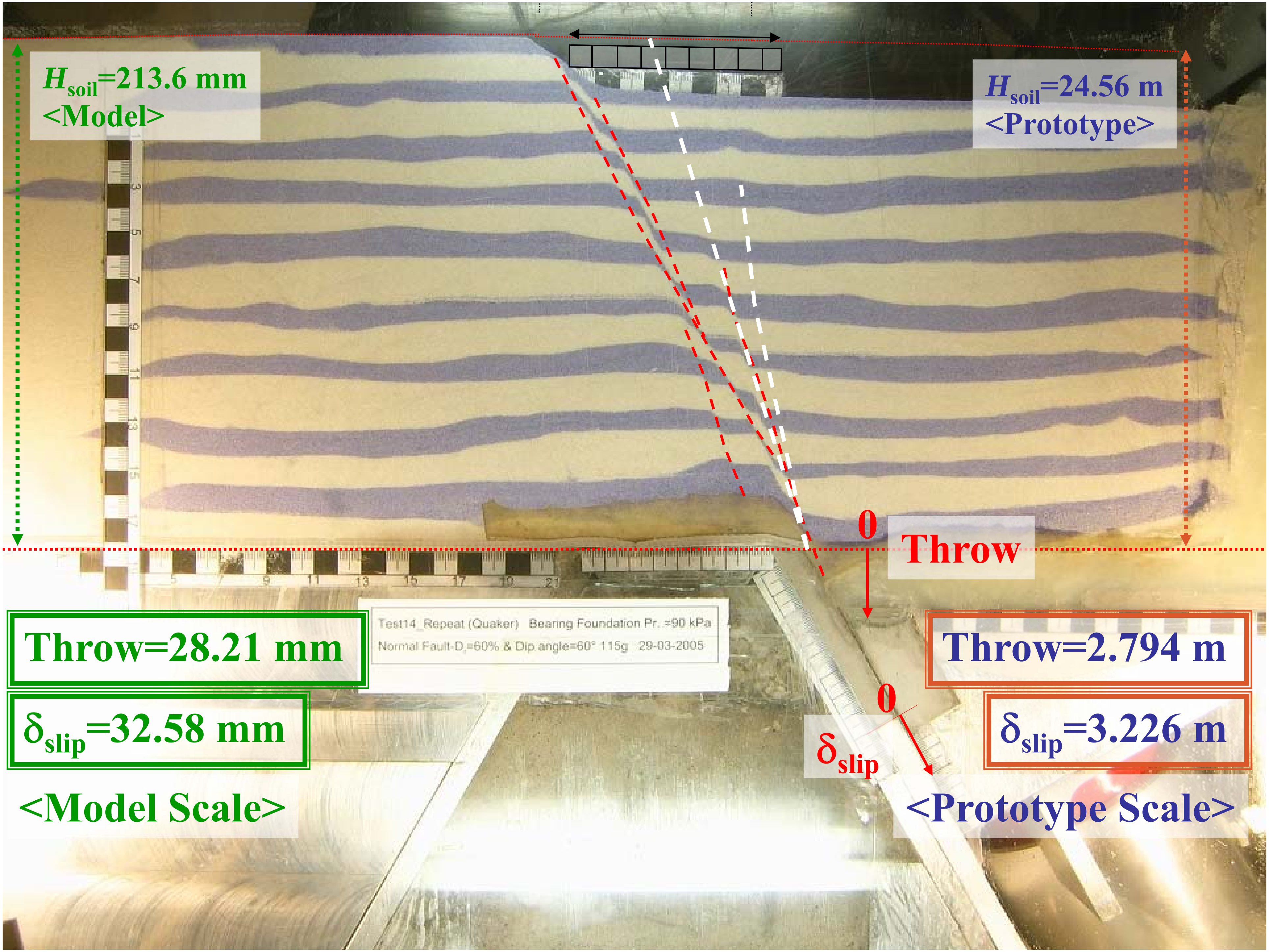
W_footing=10.12m, 88mm
q=91 kPa
H_soil=213.6 mm
<Model>
Centre-line
H_soil=24.56 m
<Prototype>
Free-field
shear plane
(Test12_R2)
0
Throw
Test14_Repeat (Quaker) Bearing Foundation Pr. =90 kPa
Normal Fault-D_r=60% & Dip angle=60° 115g 29-03-2005
Throw=0.000 mm
Throw=0.000 m
δ_slip=0.000 mm
0
δ_slip
δ_slip=0.000 m
<Model Scale>
<Prototype Scale>
Test14_R (Normal fault, Standard footing, Centre)


Test14_Repeat (Quaker) Bearing Foundation Pr. =90 kPa
Normal Fault-D_r=60% & Dip angle=60° 115g 29-03-2005
Throw=0.517 m
δ_{slip}=0.597 m
<Prototype Scale>


Test14_Repeat (Quaker) Bearing Foundation Pr. =90 kPa
Normal Fault-D$_r$=60% & Dip angle=60° 115g 29-03-2005
Throw=0.939 m
δ_{slip}=1.085 m
<Prototype Scale>


Test14_Repeat (Quaker)   Bearing Foundation Pr. =90 kPa
Normal Fault-D_r=60% & Dip angle=60° 115g   29-03-2005
Throw=1.637 m
δ_{slip}=1.891 m
<Prototype Scale>

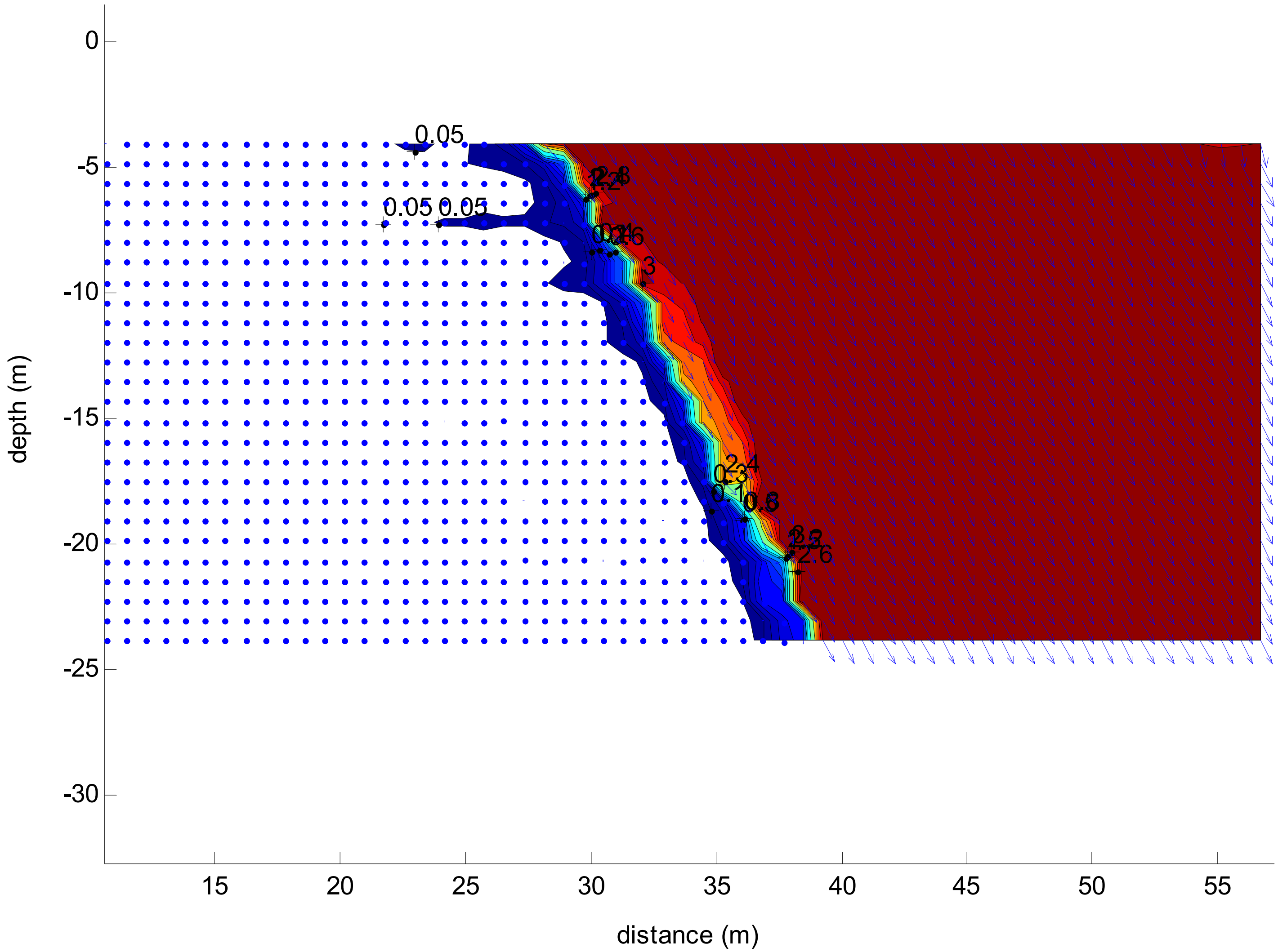

Test14_Repeat (Quaker) Bearing Foundation Pr. =90 kPa
Normal Fault-D$_r$=60% & Dip angle=60° 115g 29-03-2005
Throw=2.019 m
δ_{slip}=2.331 m
<Prototype Scale>



H_soil=213.6 mm
<Model>
H_soil=24.56 m
<Prototype>
0
Throw
Test14_Repeat (Quaker) Bearing Foundation Pr. =90 kPa
Normal Fault-D_r=60% & Dip angle=60° 115g 29-03-2005
Throw=28.21 mm
δ_slip=32.58 mm
Throw=2.794 m
δ_slip=3.226 m
0
δ_slip
<Model Scale>
<Prototype Scale>

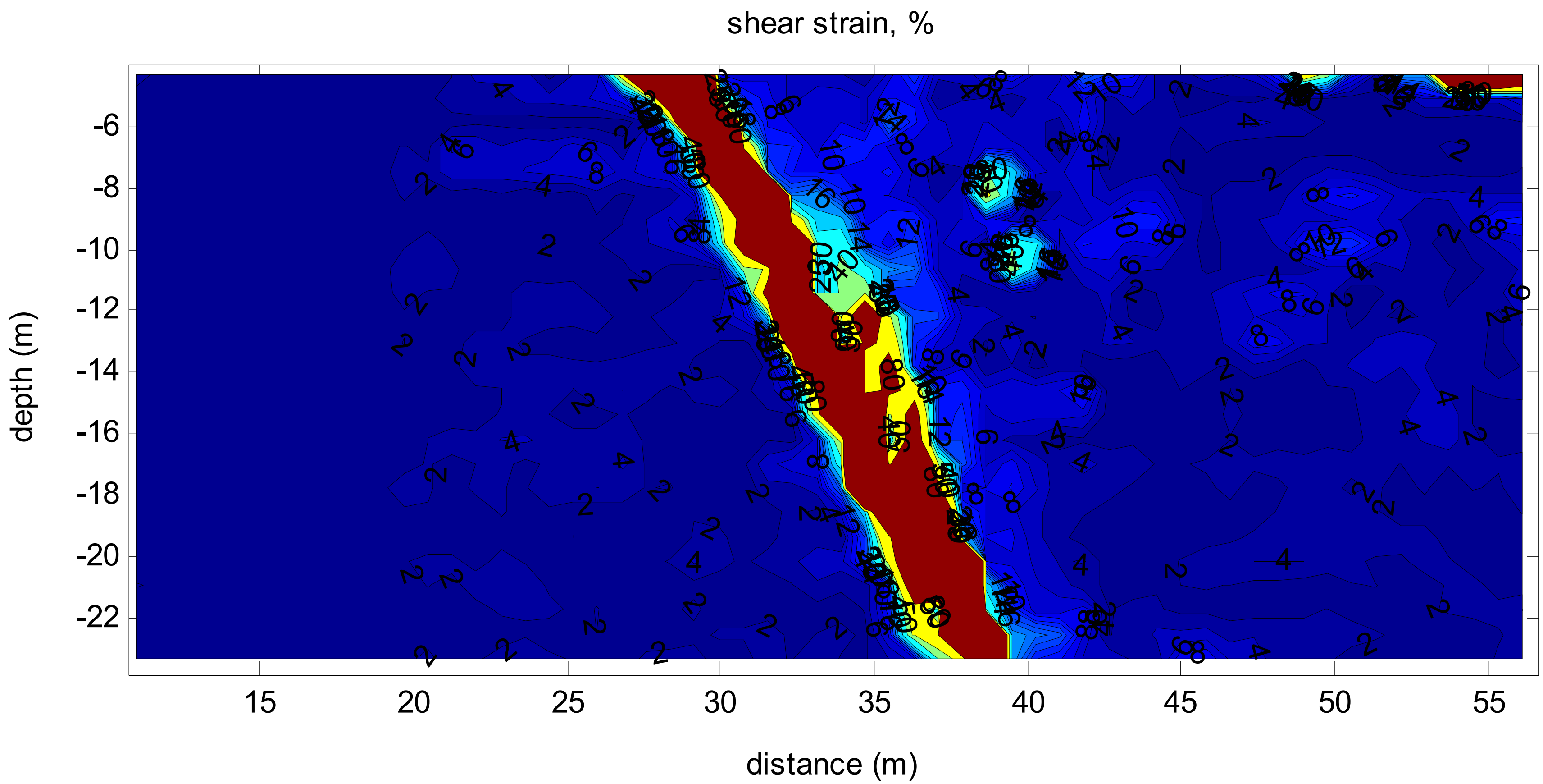
Centrifuge model of normal fault

Displacement vectors



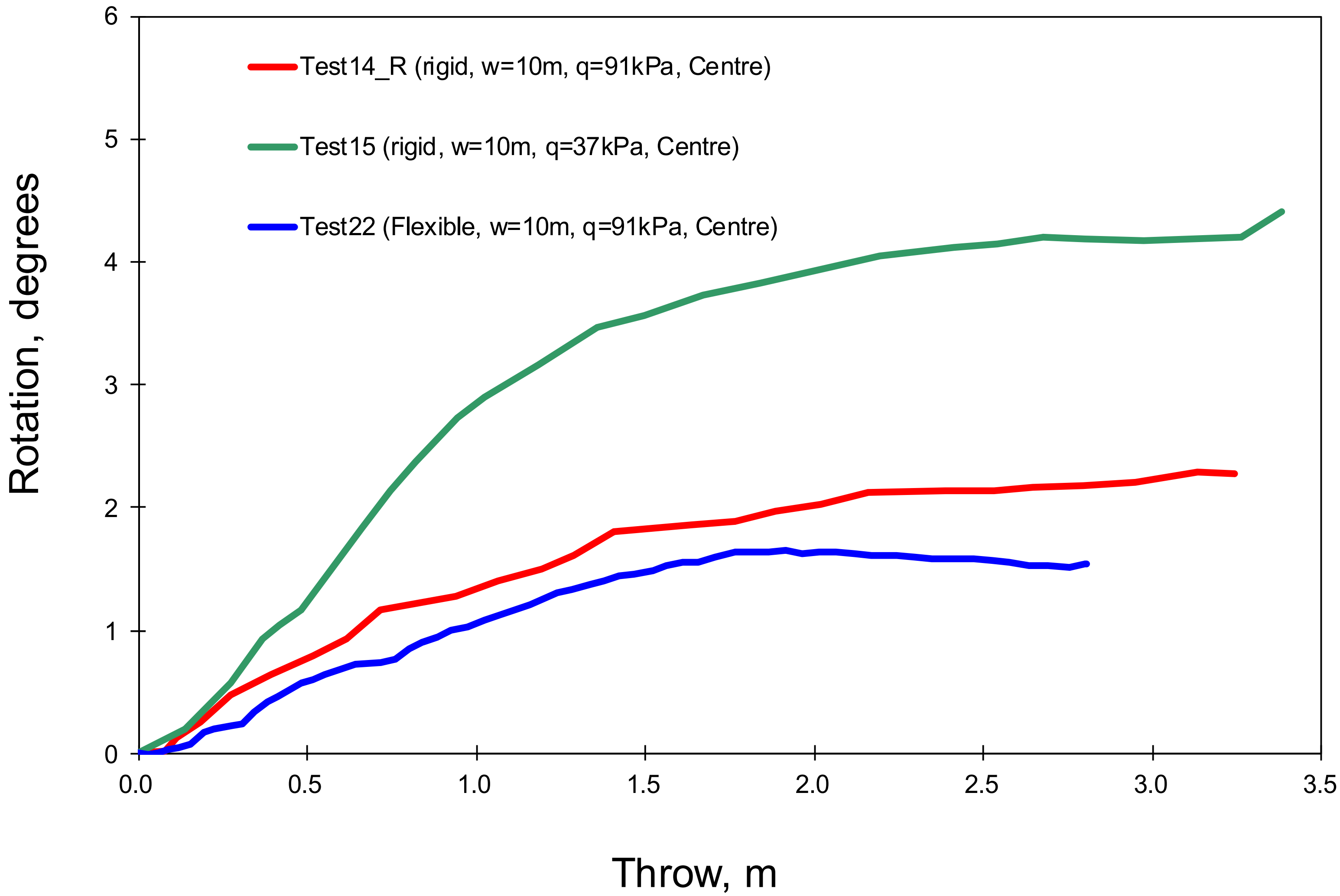
Centrifuge model of normal fault

Shear strains



Centrifuge model of normal fault

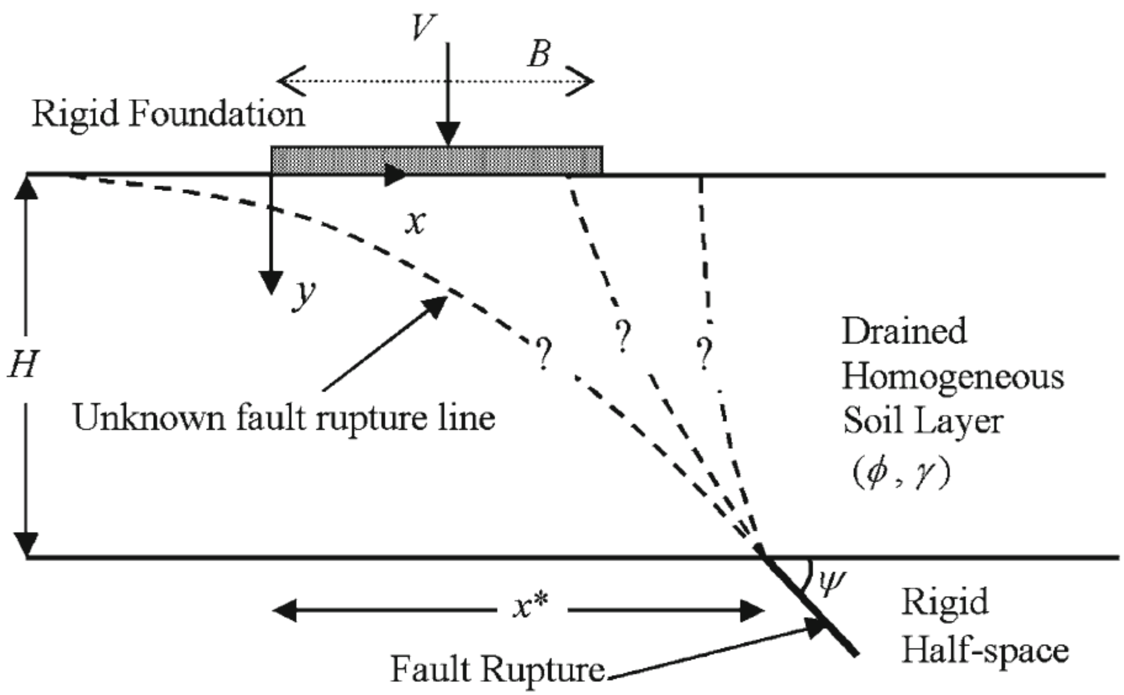
Rotation of foundation

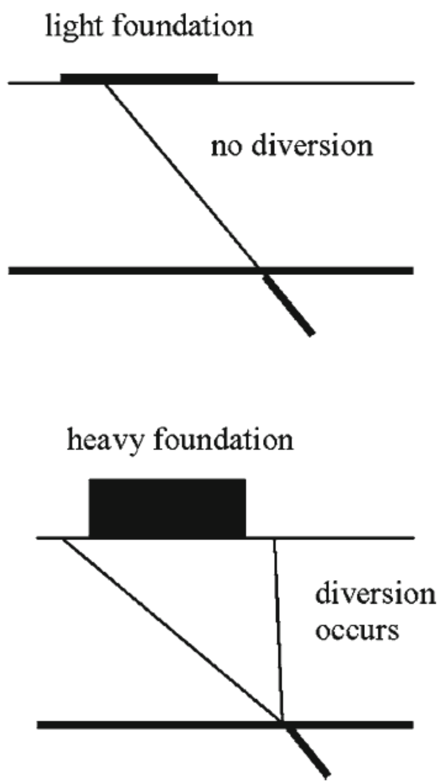


Analysis of fault diversion

Kinematic limit analysis approach after Paolucci and Yilmaz (2008)

Problem statement for a shallow strip foundation resting on drained soil, subject to normal or reverse fault rupture

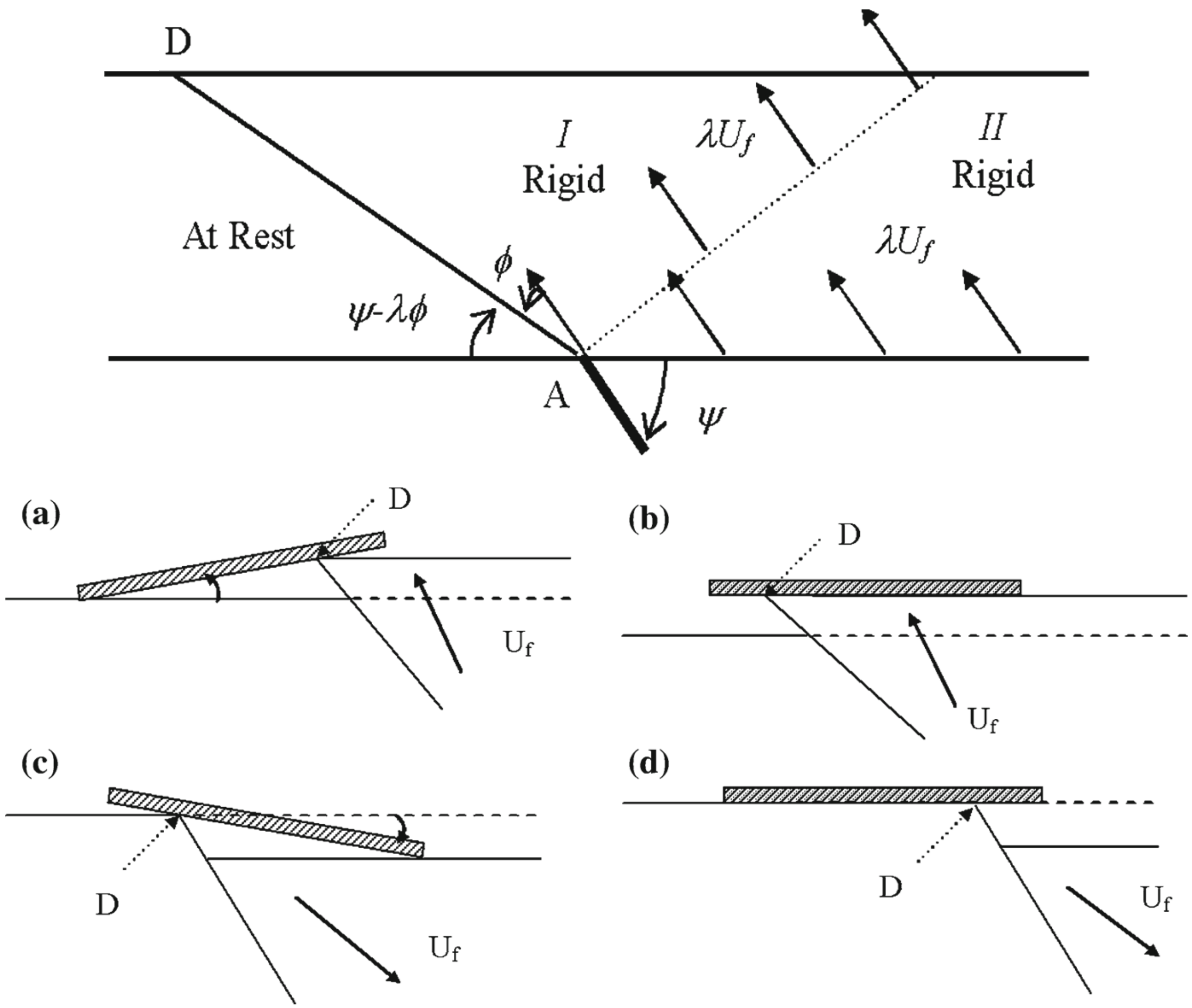




after R. Paolucci and M.T. Yilmaz *Simplified theoretical approaches to earthquake fault rupture–shallow foundation interaction* (2008)

Analysis of fault diversion

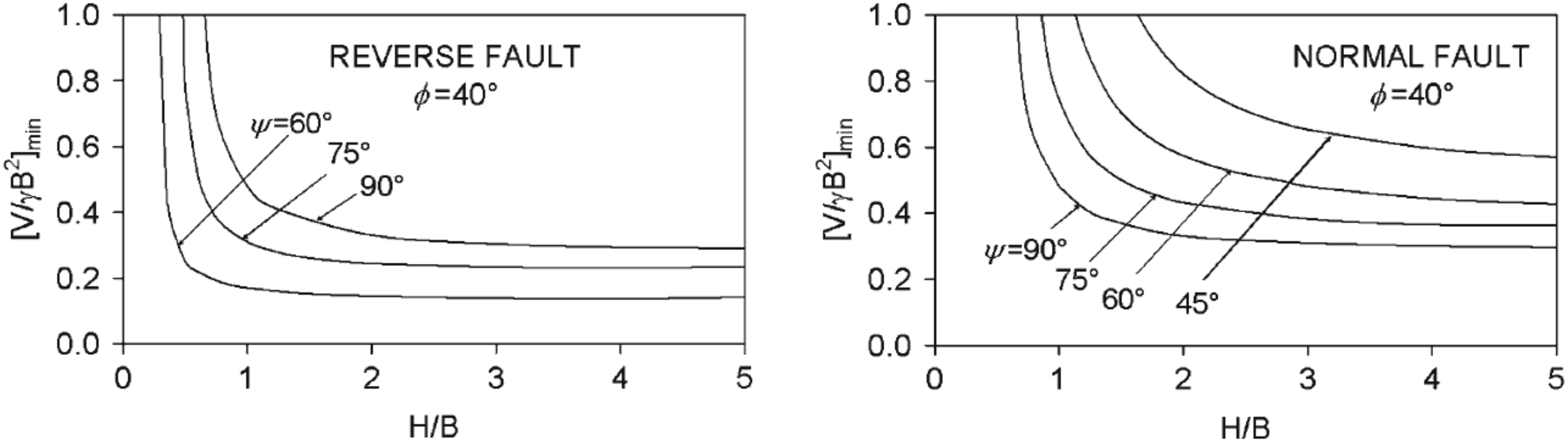
Kinematic limit analysis approach after Paolucci and Yilmaz (2008)



after R. Paolucci and M.T. Yilmaz *Simplified theoretical approaches to earthquake fault rupture–shallow foundation interaction* (2008)

Analysis of fault diversion

Kinematic limit analysis approach after Paolucci and Yilmaz (2008)

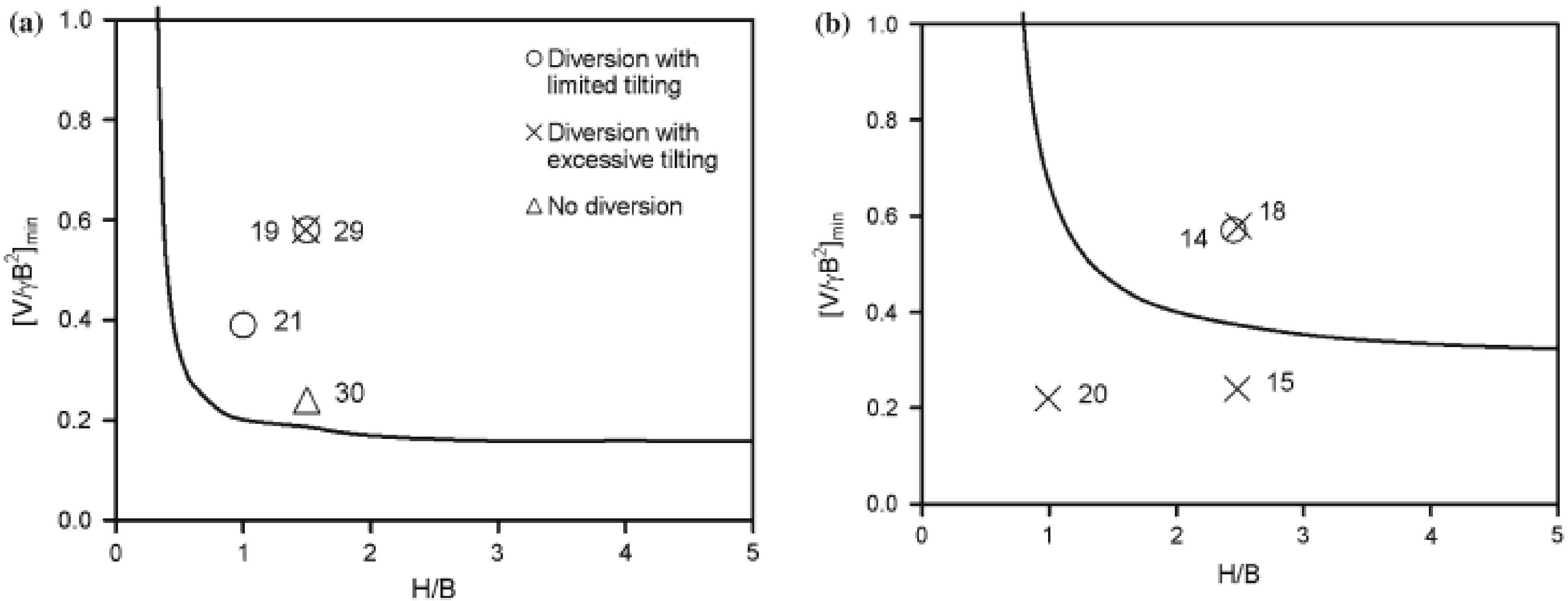


Conditions for the diversion of surface breakage of fault rupture for various dip angles (Ψ) of reverse or normal fault, and different friction angle (φ) of drained soil, obtained by the kinematic approach

after R. Paolucci and M.T. Yilmaz *Simplified theoretical approaches to earthquake fault rupture–shallow foundation interaction* (2008)

Analysis of fault diversion

Kinematic limit analysis approach after Paolucci and Yilmaz (2008)

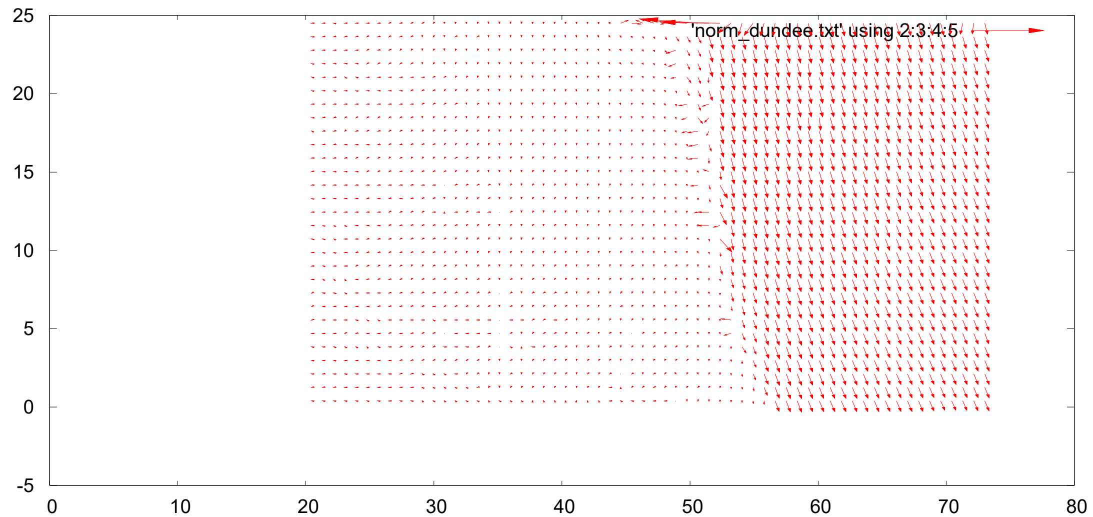


Comparison of centrifuge model tests with diversion criteria (φ = 30° and ψ = 60°)
(a) reverse fault case and (b) normal fault case
N.B. Foundation tilting greater than 3° at 3m fault throw is denoted as excessive

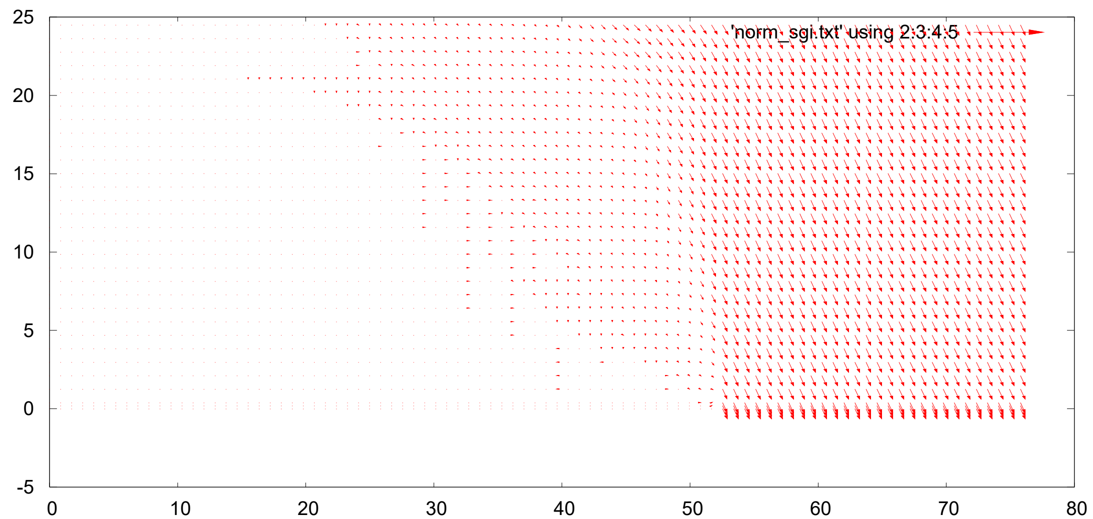
after R. Paolucci and M.T. Yilmaz *Simplified theoretical approaches to earthquake fault rupture–shallow foundation interaction* (2008)

Normal fault – comparison of displacement vectors

Experimental results
(Dundee centrifuge)



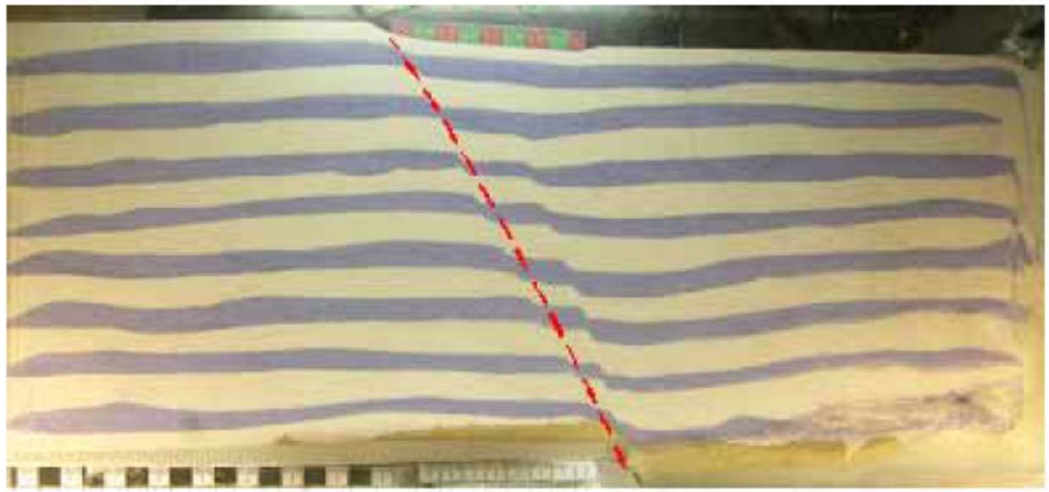
Numerical analysis
(SGI)



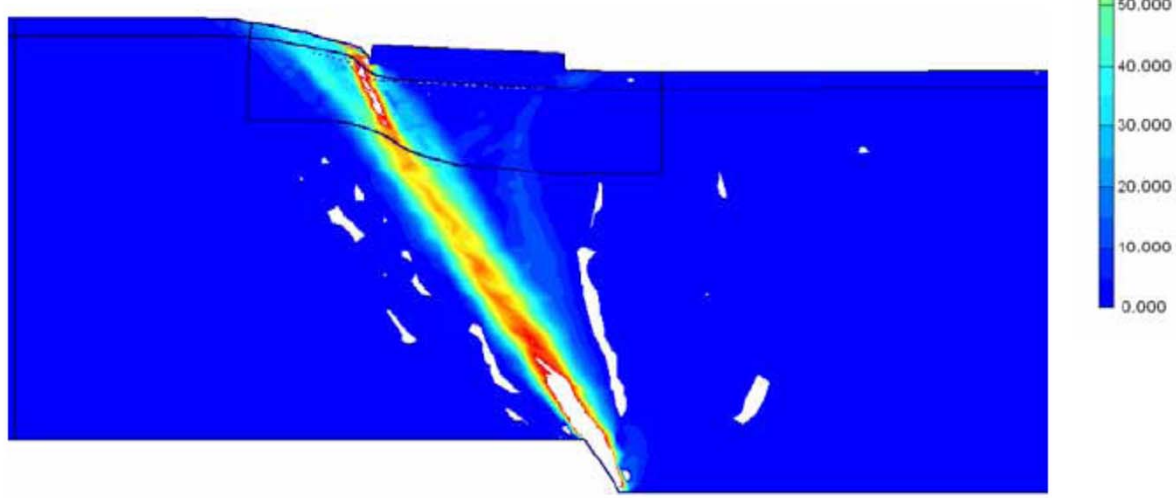
60° normal fault

Normal fault – final imposed dip displacement

Experimental results
(Dundee centrifuge)



Shear strains from
numerical analysis
(NTUA)

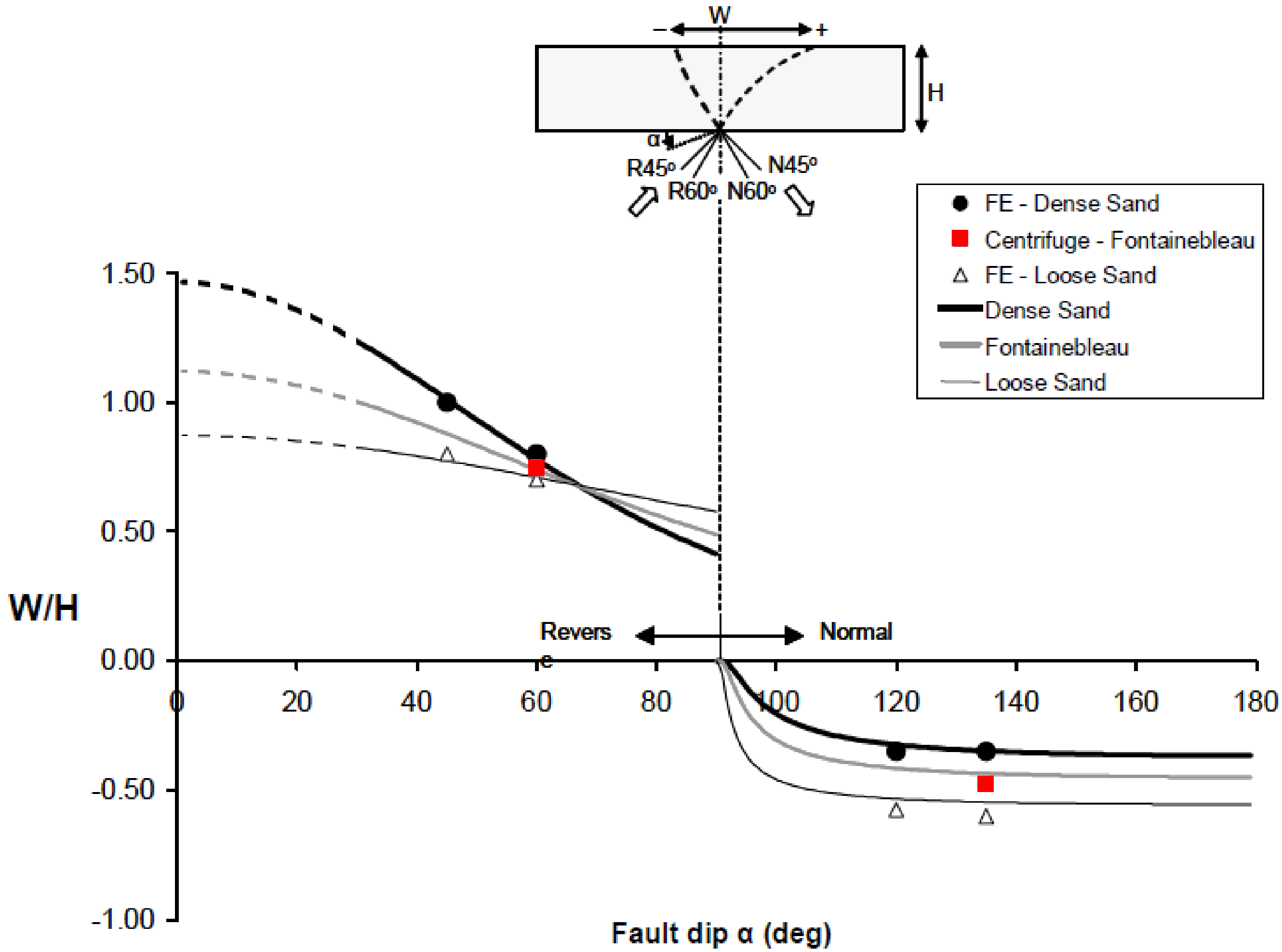


60° normal fault

Analysis of fault diversion

Semi-analytical method approach

after Anastasopoulos, Gerolymos, Gazetas & Bransby (2008)



after Anastasopoulos et al *Simplified approach for design of raft foundations against fault rupture. Part I : Free-field* (2008)

Scope of Presentation

- Introduction
  - Capturing complexity in analytical models
  - Centrifuge modelling to capture complexity
  - Geotechnical research process
- Examples
  - Soil nailing
  - Root reinforcement of slopes
  - Earthquake soil-foundation-structure interaction (SFSI)
- Conclusions

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Conclusions

- Geotechnical centrifuge modelling permits repeatability associated with laboratory testing combined with the ability to conduct parametric studies.
- Correctly scaled centrifuge models capture the complexities of prototype systems.
- Centrifuge models allow the observation of mechanisms and the capture of qualitative data that can be used both to understand mechanisms and inform the development of analytical solutions.
- Centrifuge models provide quantitative data for developing and validating analytical solutions.

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- **Professor S. Mickovski**, Glasgow Caledonian University (formerly University of Dundee)

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