Bio-engineering for erosion control and slope stabilization in Thailand: research and practice

Apiniti Jotisankasa

PhD DIC

Geotechnical Innovation Laboratory, Department of Civil Engineering, Kasetsart University

4th ICRMCE International Conference on Rehabilitation and Maintenance in Civil Engineering

12 July 2018

Outline of presentation

- Introduction - Slope failure and erosion problems – Typical field response of slope
- Influence of suction & root concentration on root cohesion & root properties
- Field monitoring of change in root concentrations in bio-engineered structures and its potential use
- Conclusions

Landslide and erosion in Thailand

Petchaboon, 2001

Nakonsri-Thammarat, 1988

Uttaradit, 2006

Widespread shallow slides to debris flow in a large area: This type of failure can be prevented and remediated using vegetation and bioengineering

Vetiver grass system for erosion prevention and shallow stabilization

- *Chrysopogon zizanioides* or formerly known as *Vetiveria zizanioides*
- Traditionally planted as hedgerows parallel to the slope contour
- Of very dense fine vertical root system that penetrates as deep as 3-4 meter in some applications
- Effective for shallow slope stabilization, reduction of runoff erosive energy and sediment trap

(Hengchaovanich, 1998, Truong et al., 2008)

Source: Department of Highways


Implemented for erosion control and slope stabilization along highways
อ.ทองผาภูมิ จ.กาญจนบุรี
Photo Courtesy of Dr. Weerachai Na-Nakorn

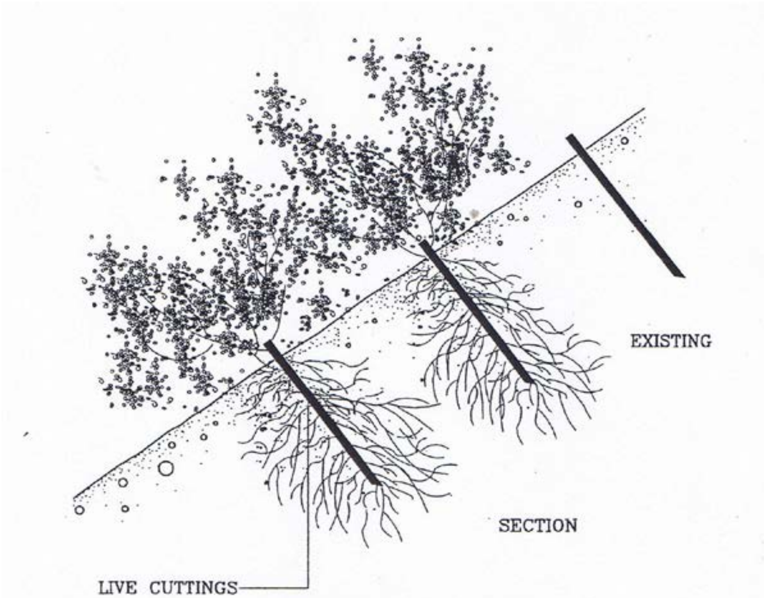

Implemented for erosion control and
slope stabilization along highways
อ.ทองผาภูมิ จ.กาญจนบุรี
Photo Courtesy of Dr. Weerachai Na-Nakorn


Photo Courtesy of Dr. Weerachai Na-Nakorn


Photo Courtesy of Dr. Weerachai Na-Nakorn

Live stake & Live pole

- The technique involves inserting and tamping of easily rootable woody cuttings (usually 12 to 38mm in diameter and 0.6 to 0.9m long) relatively deep into the ground (about 80% of its length)
- Live pole is the term used to describe a bigger version of a live stake, normally 50mm in diameter, and installed to a depth of about 1 meter vertically in a pre-drilled hole.
- Normally considered to act as a small reinforcing pile when installed.
- Standards and various practical handbooks available (ASTM: D 6765 – 02; Coppin et al. 1990; Gray and Sotir 1996; Eubanks and Meadows 2002; Goldsmith et al. 2014).



Live staking. Robbin Sotir & Associates

Source. Lewis, 2000

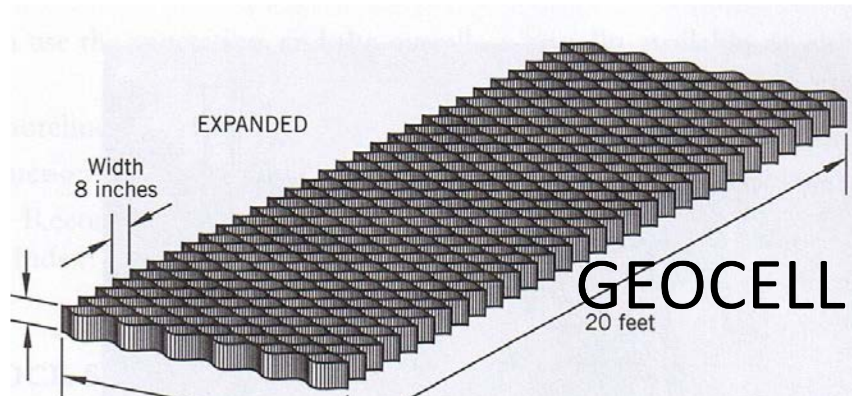
Erosion control cover system

- **Different Soil cover systems/**Soil blanket (natural fibre)/Soil log/Erosion control mat/Geocell)/ *what are the relative performance??*

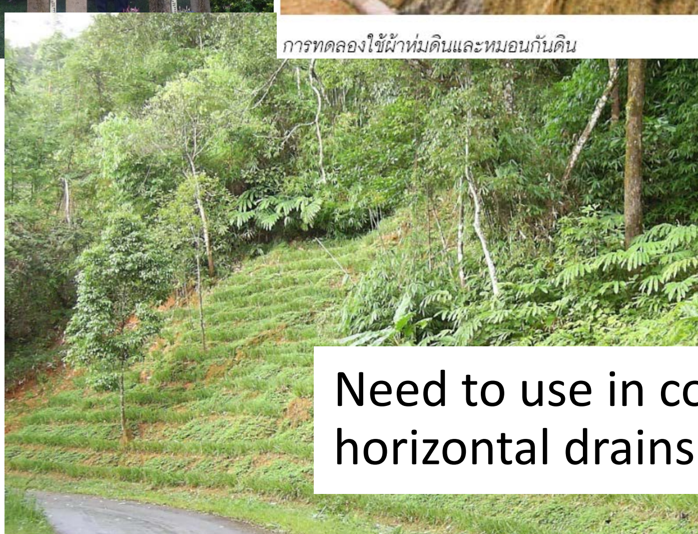
Sawangsuriya, A., Jotisankasa, A., Sukolrat, J., Dechasakulsom, M., Mahatumrongchai, V., Milindalekha, P. and Anuvechsirikiat, S (2013) Comparison of Erosion Susceptibility and Slope Stability of Repaired Highway Embankment. Geo-Congress: Stability and Performance of Slopes and Embankments III Geotechnical Special Publication, Vol 231

Soil blanket&
Soil log

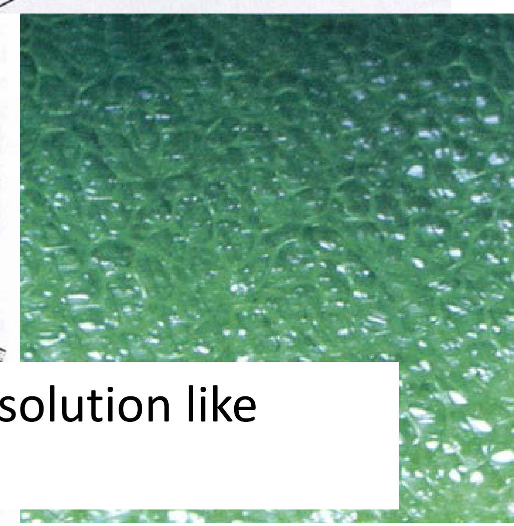
การทดลองใช้ผ้าห่มดินและหมอนกันดิน



GEOCELL



Erosion control
mat

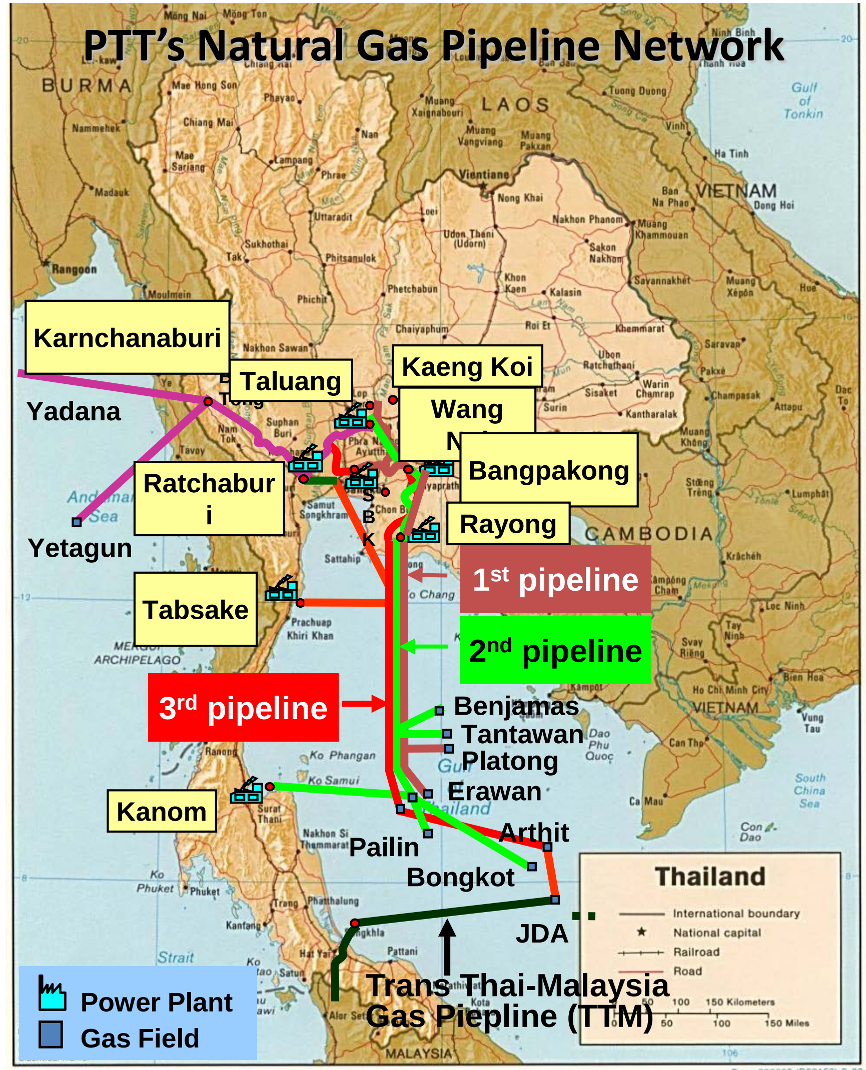


Need to use in conjunction with engineering solution like horizontal drains or reinforced soil slope

Figure 16.20 Turf reinforcement mat used to foster development of plant roots (after Gray & Sotir, 1996).

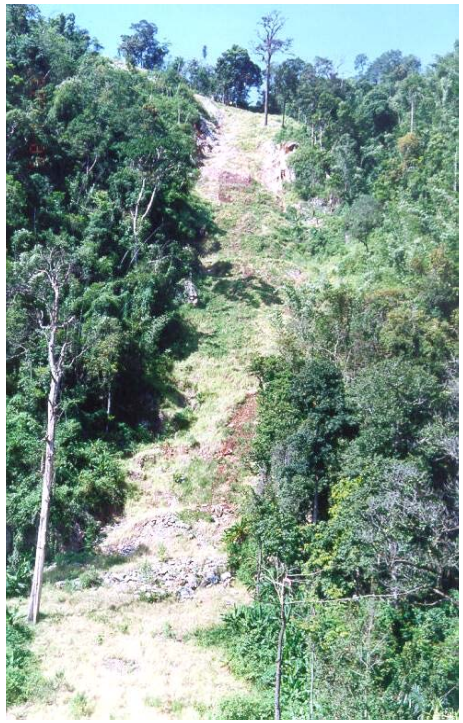
PTT's Natural Gas Pipeline Network
Thailand-Myanmar

NATURAL GAS TRANSMISSION PIPELINE SYSTEM AND FUTURE PROJECTS

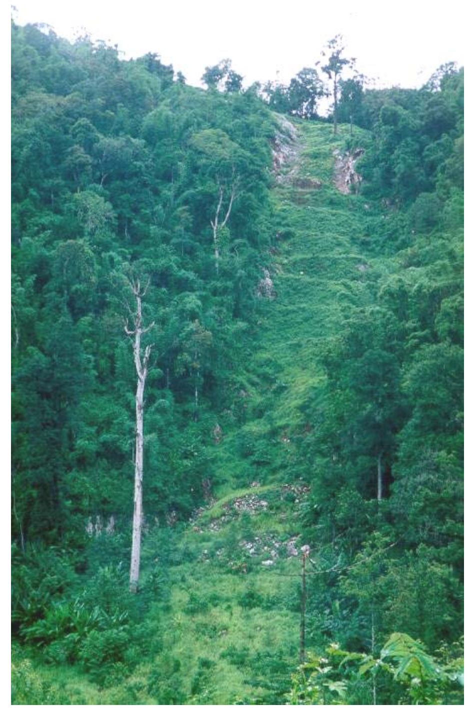


Nature restoration
PTT's Natural Gas Pipeline Network
Thailand-Myanmar

KP 19+900 : มิถุนายน 2541



KP 19+900 : มีนาคม 2542



KP 19+900 : ตุลาคม 2543

KP 19+900 :พฤศจิกายน 2544

Nature restoration
PTT's Natural Gas Pipeline Network
Thailand-Myanmar

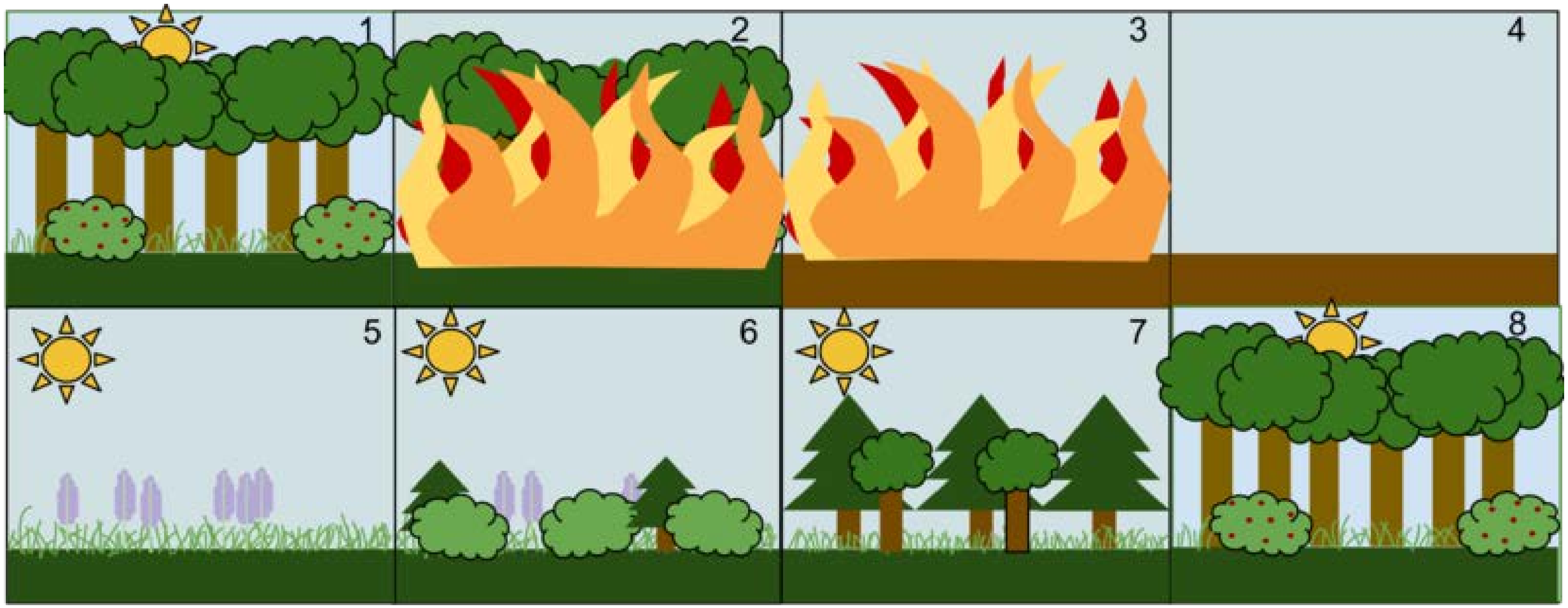
A total of 5,000 live stakes of 7 native plants were used to peg into the jute sacks.

1. *Garuga pinnata Roxb.*
2. *Choerospondias axillaris (Roxb.) B.L.Burtt & Hill*
3. *Pterocarpus indicus Hasm.*
4. *Lagerstroemia tomentosa Presl*
5. *Erythrina subumbrans (Hassk.)*
6. *Cephalanthus tetrandra (Roxb.) Ridsdale & Bakhf.*
7. *Elaeocarpus hygrophilus Kurz.*

Live stake + Jute sack + Vetiver grass and horizontal drains

Plant selection based on Plant succession

- Plant succession



AS ALL LIVING THINGS, PLANTS ALWAYS IN A CONTINUALLY CHANGING STATE
Usually suitable plants for bio-engineering purposes are "pioneer plants"

http://en.wikipedia.org/wiki/Ecological_succession

Important research questions and practical needs

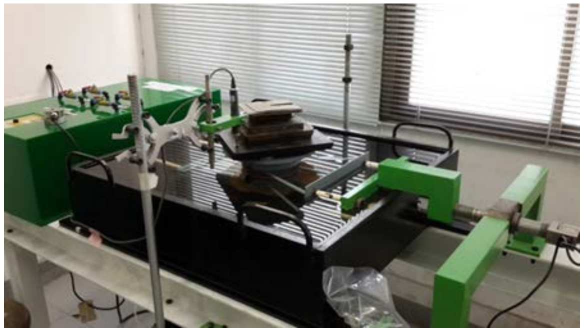
- **How to quantify the vegetation effects on slope stability in the field and lab?? Root cohesion, Suction induced from evapotranpiration, root effects on soil/pore structure etc.**

- **Vegetation changes with time according to plant succession principle/maintenance. How would these changes in plant (in root reinforcement?) affect on slope stability in the longer term??**

- Vadose zone normally subject to large variation in suction/moisture. How would this affect the root reinforcement?

- How to maximize benefit of plants used in combination with engineering techniques such as soil bags/geotextiles/cover system???

Research approach



FIELD

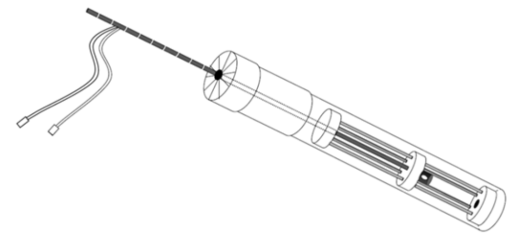
Field observation

Actual root distribution

(Root area ratio)

Pullout-capacity/Field

direct shear test



Empirical knowledge/ experience from practitioners

EMPIRICAL EXPERIENCE

LAB

Laboratory investigation

Root cohesion,

Soil permeability,

Soil-water retention curve,

of root-reinforced sample

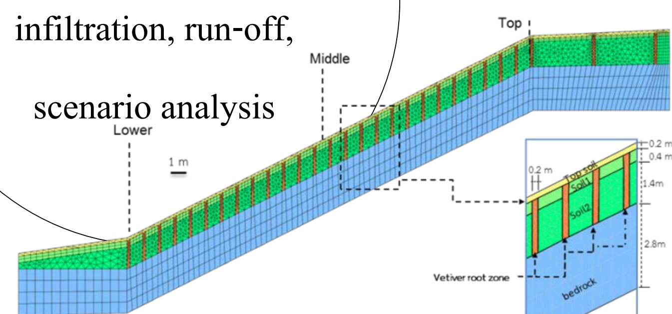
Numerical modelling

slope stability, rainfall-

infiltration, run-off,

scenario analysis

NUMERCIAL SIMULATION



Root-soil mechanics

- As soils in root zones are normally of air and water. Unsaturated soil mechanics are needed.
- Unsaturated seepage- permeability and moisture are function of positive & negative pore water pressure

$$\frac{\partial}{\partial x}\left[k_x \frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y \frac{\partial h}{\partial y}\right] + Q = m_w \left[\frac{\partial u_w}{\partial t}\right]$$

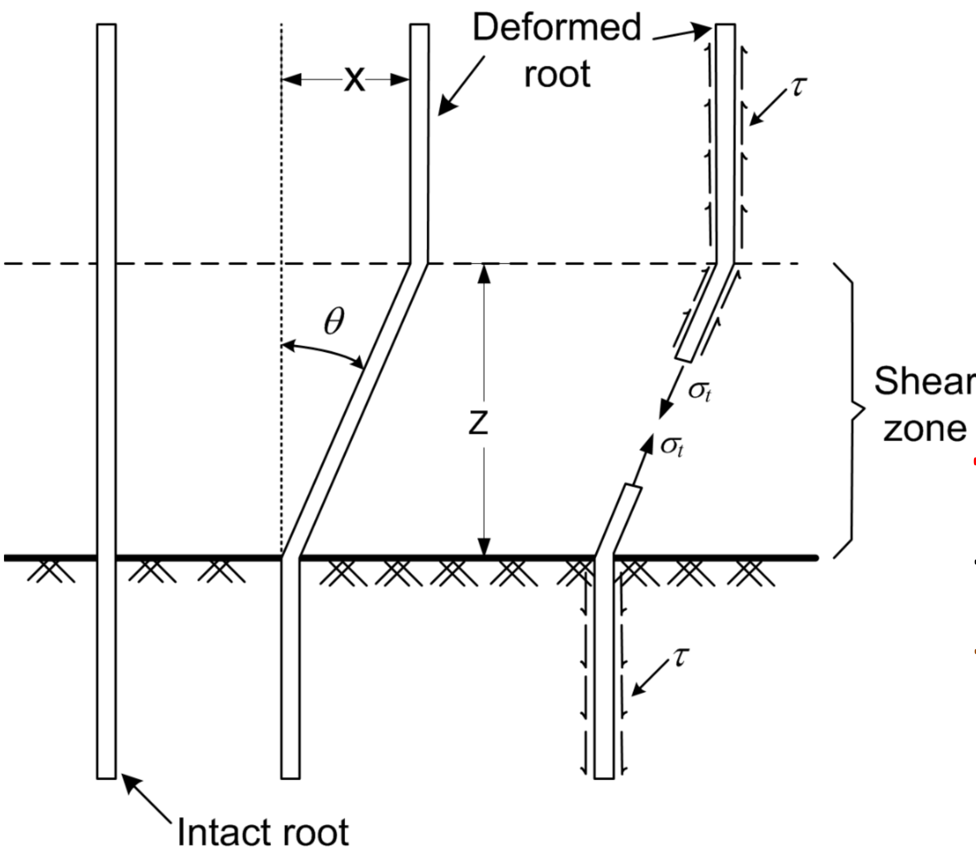
- Shear strength (considering root reinforcement and suction)) -

$$\tau = c^r + c' + \sigma_n \tan\phi' - u_w \tan\phi^b$$

Root reinforcement (c^r)

Affected by infiltration (not considering transpiration) (u_w)

- Program used – Finite Element Modelling – Seepage; Limit Equilibrium – Stability analysis (Geo-studio)



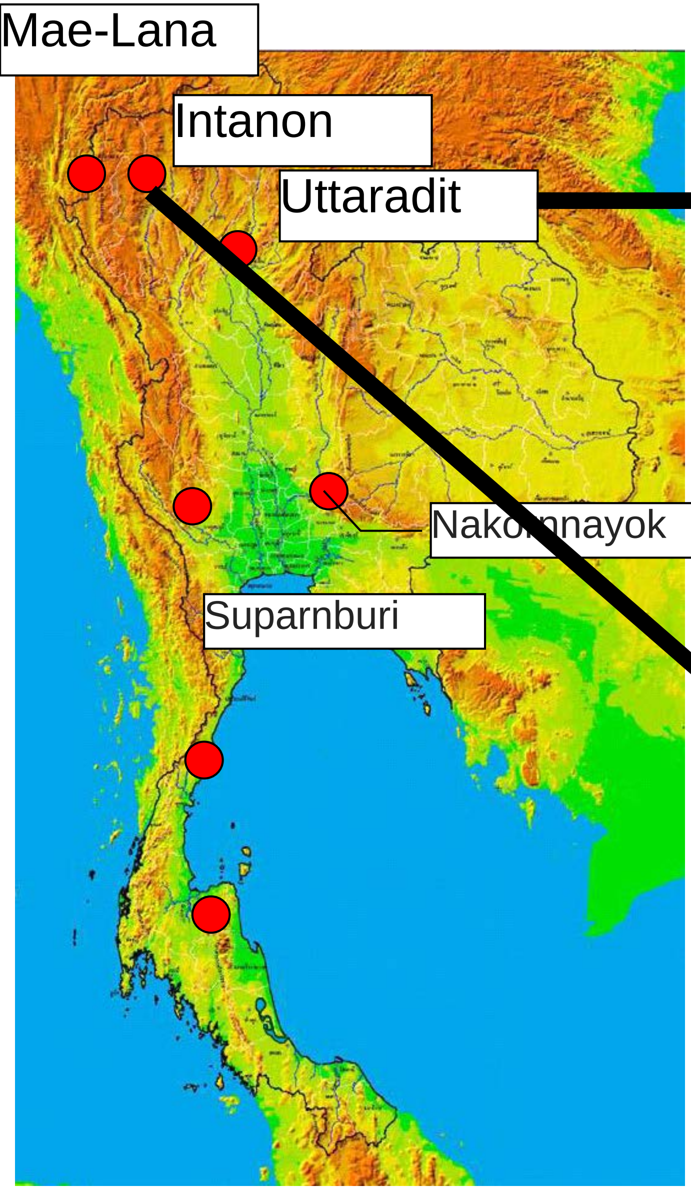
A simple mechanistic model for root reinforcement
(Wu et al. 1979)

Three modes of root-soil failure mode: fiber breaks, fiber stretch and fiber pull-out, all depends on moisture condition, plant growth stage etc

$$c_r = \sigma_t(\frac{A_R}{A})[\sin\theta + \cos\theta \tan\phi]$$

ϕ = the angle of internal friction of the soil; θ = the angle of shear distortion in the shear zone; σ_t = the mobilized tensile stress of root fibers developed at the shear plane; $\frac{A_R}{A}$ = the root area ratio: A_R is the root area and A = total area of soil.

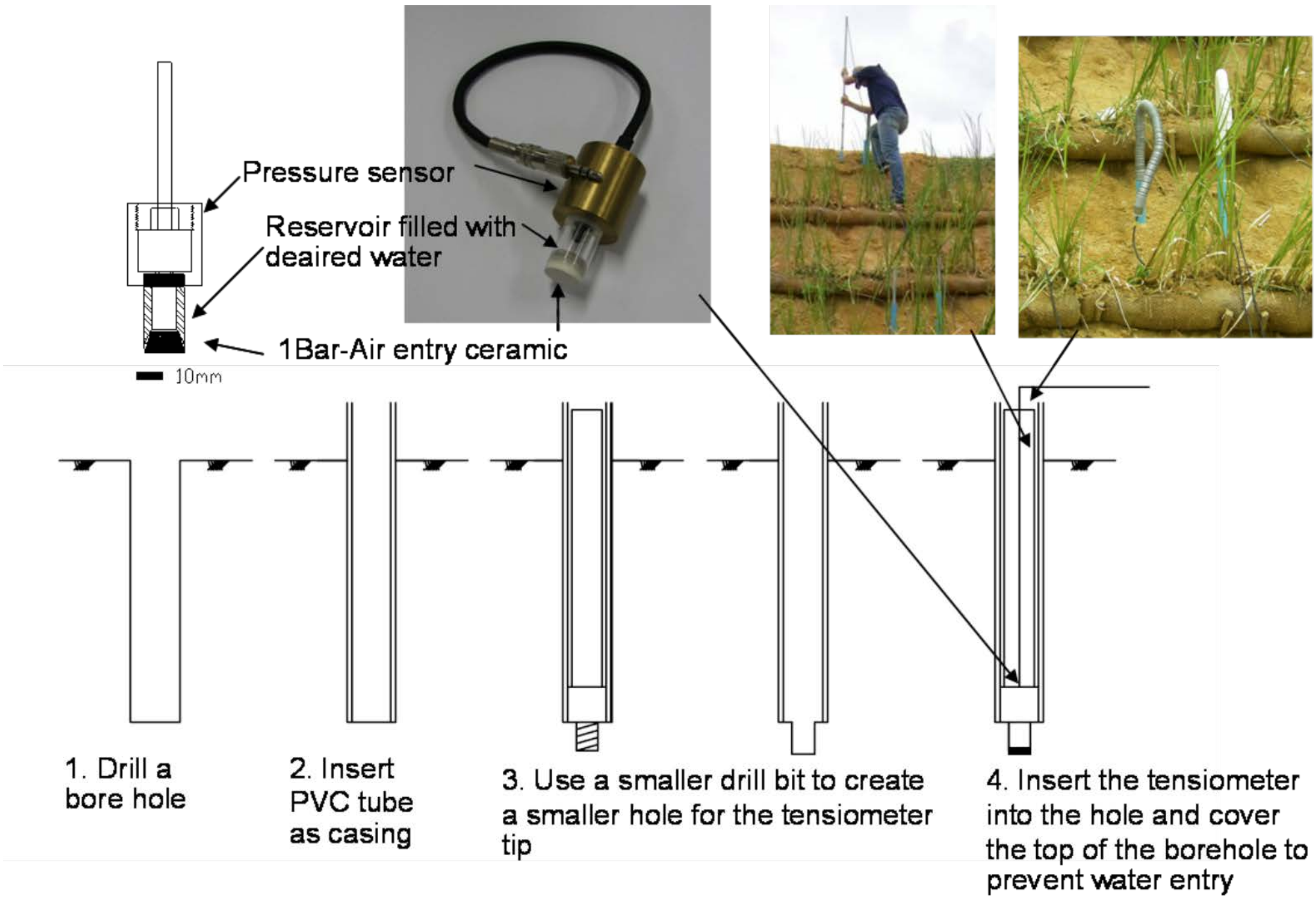
Pore-water pressure/suction response of slope
Some selected instrumented sites
aimed at understanding hydrological regime in slopes:



Large-area shallow failure

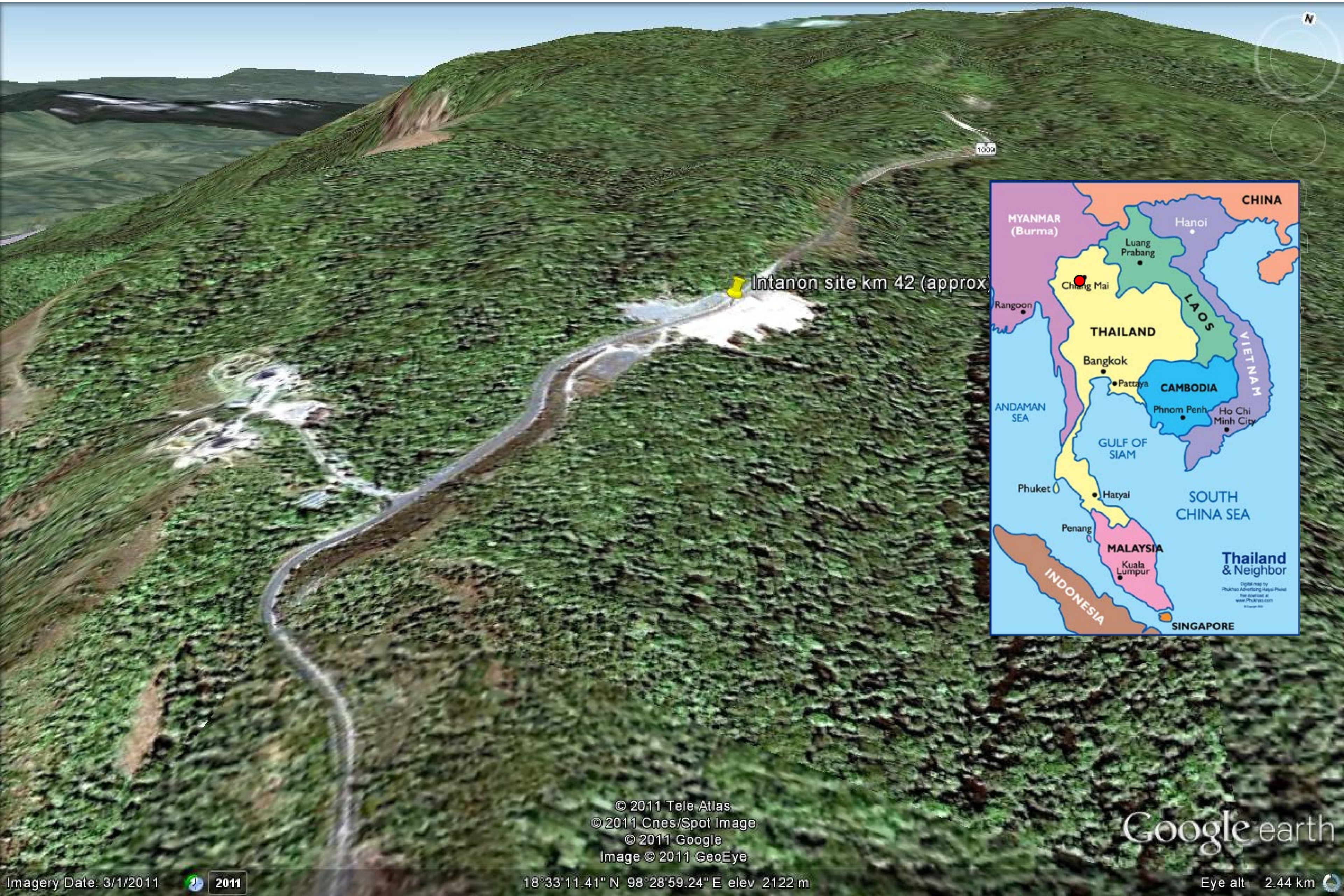
Localised slope failure
(highway slope)

Field measurement of pore water pressure and suction using KU tensiometers



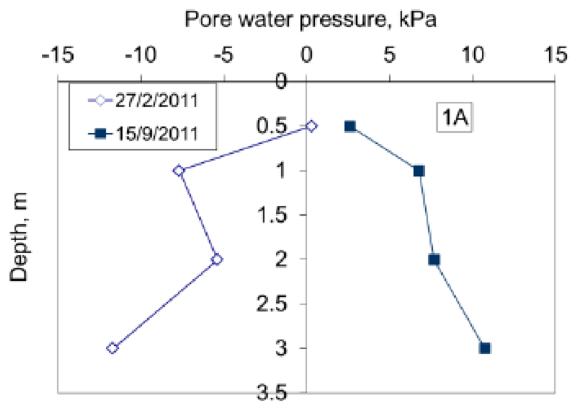
Doi-intanon test site km -42

- Highway no. 1009 - 108 (Jomtong) – intanon km.41+945 – km.42+715 shallow failure during surface erosion and internal erosion during heavy rainfall (high altitude: around 2500 m MSL)– Highway to highest peak of Thailand

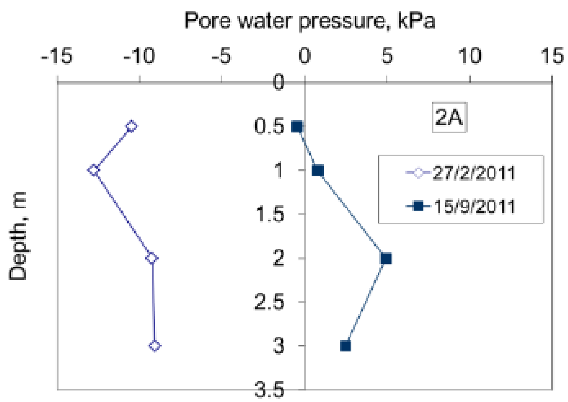


Intanon site km 42 (approx)
1009
MYANMAR (Burma)
CHINA
Hanoi
Luang Prabang
Chiang Mai
Rangoon
LAOS
THAILAND
VIETNAM
Bangkok
Pattaya
CAMBODIA
ANDAMAN SEA
Phnom Penh
Ho Chi Minh City
GULF OF SIAM
Phuket
Hatyai
SOUTH CHINA SEA
Penang
MALAYSIA
Kuala Lumpur
INDONESIA
SINGAPORE
Thailand & Neighbor
© 2011 Tele Atlas
© 2011 Cnes/Spot Image
© 2011 Google
Image © 2011 GeoEye
Google earth
Imagery Date: 3/1/2011
2011
18°33'11.41" N 98°28'59.24" E elev 2122 m
Eye alt 2.44 km

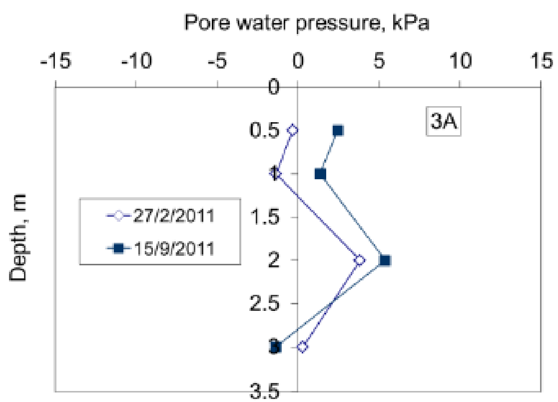
Pore water pressure profile



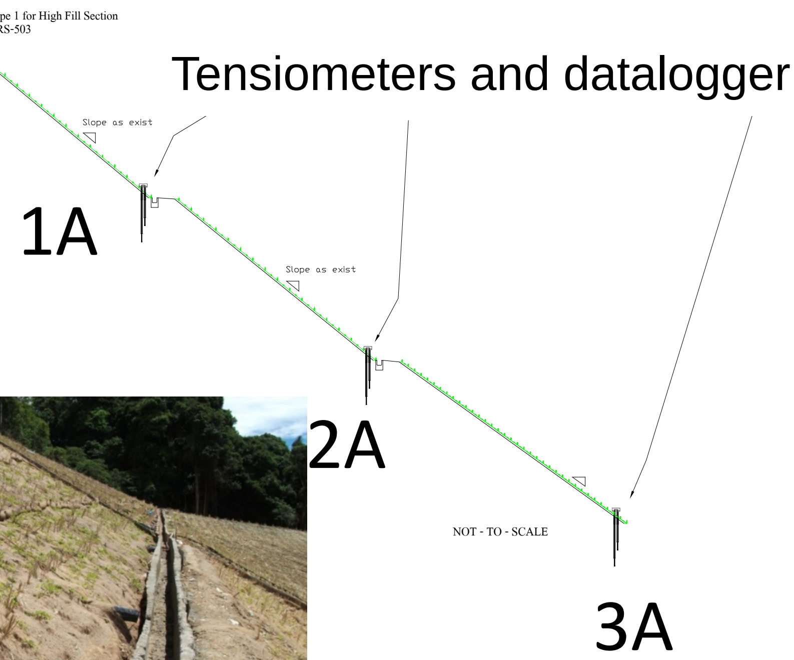
(a)



(b)

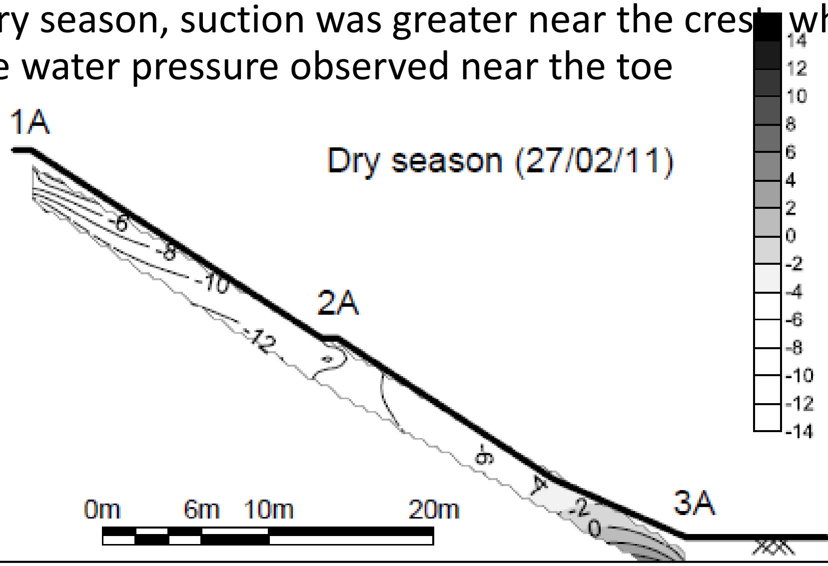


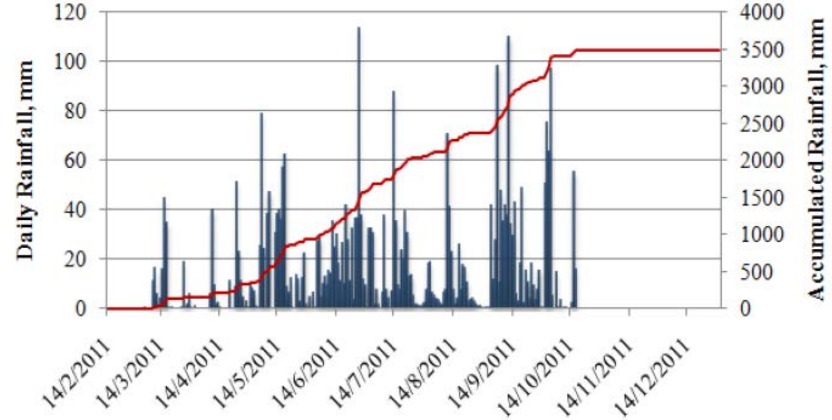
(c)

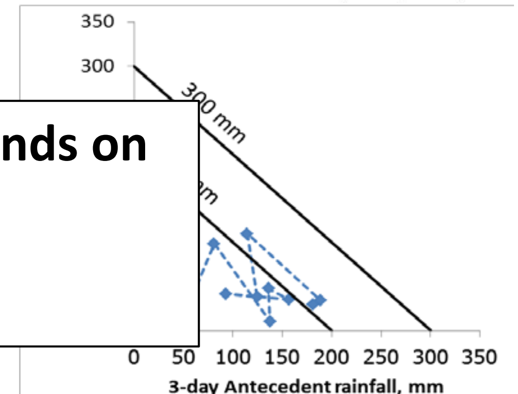


Pore water pressure, kPa

In dry season, suction was greater near the crest while positive pore water pressure observed near the toe

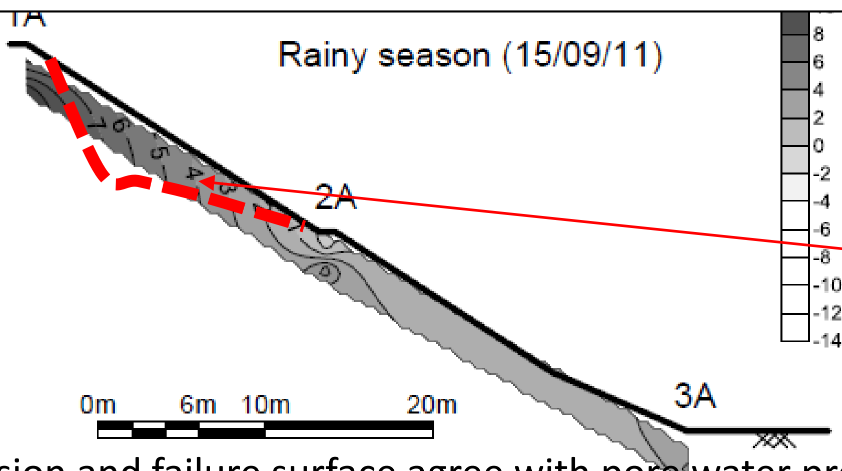






Non-uniformity of pore-water pressure regime, depends on stratigraphy and geology and 3-D effect.

Root zones are in variably saturated condition

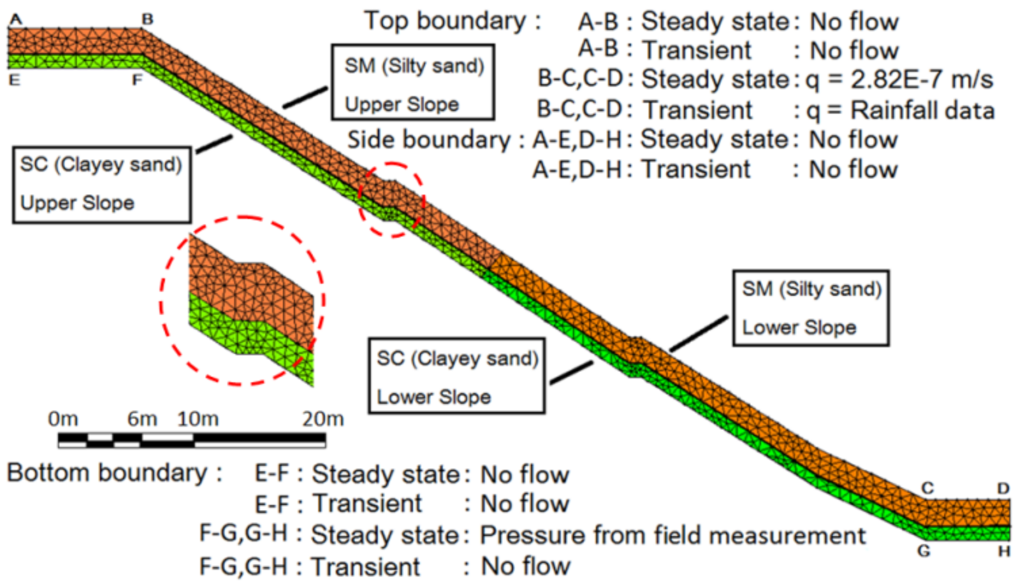


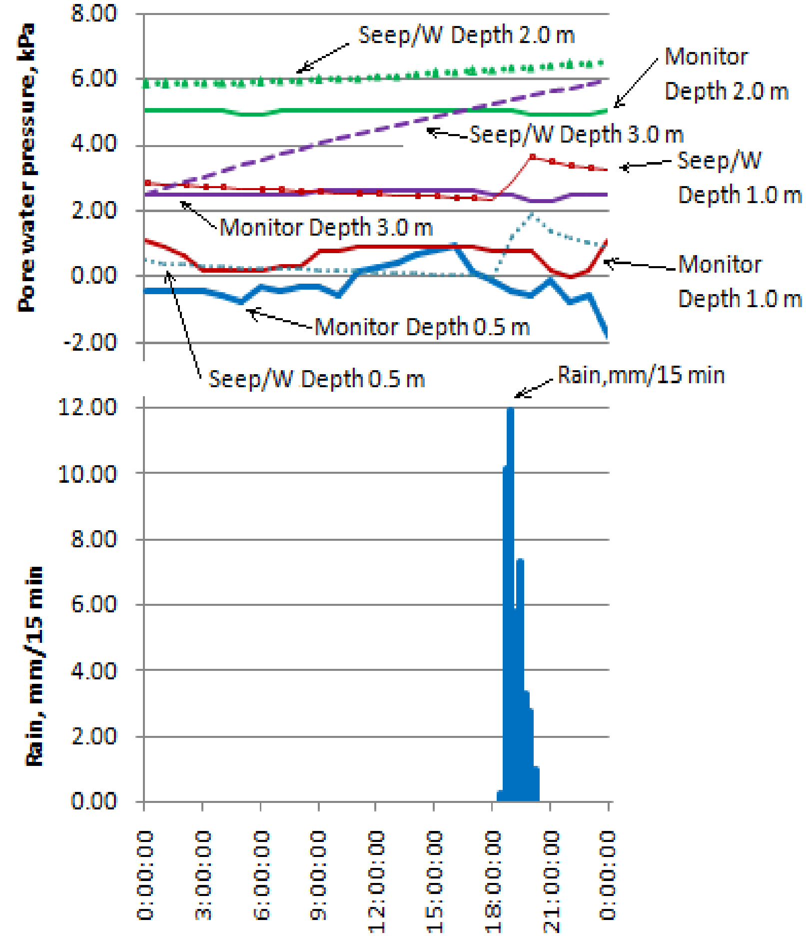
Erosion and failure surface agree with pore water pressure results

(b)

Internal seepage erosion

Numerical seepage analysis





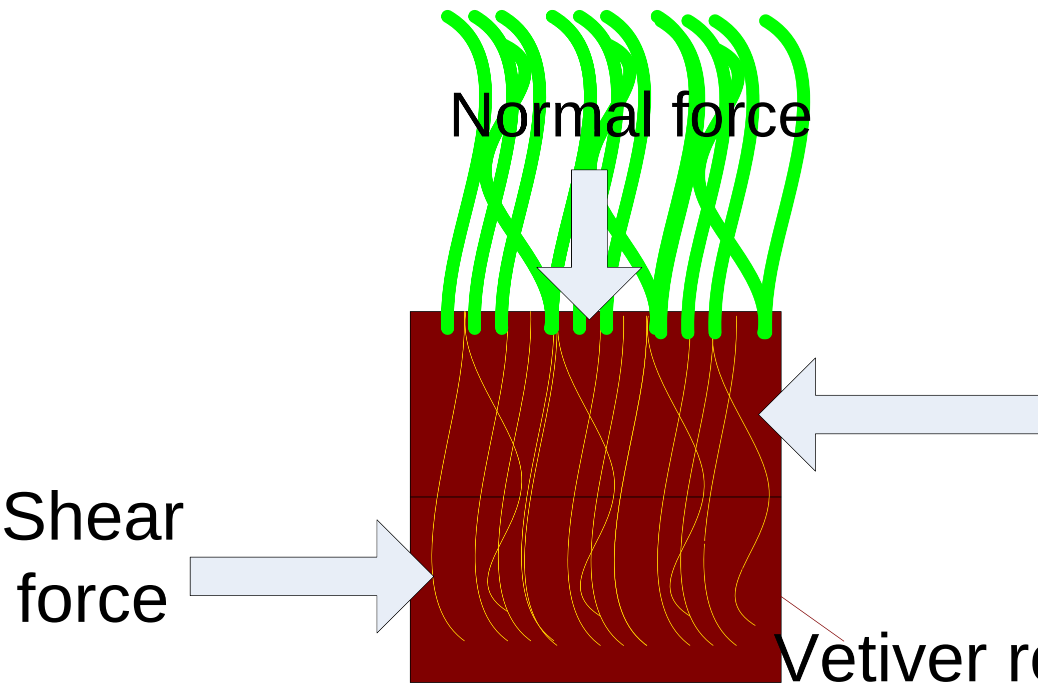
- Comparison between measured and simulated pore water pressure variation with time: good agreement at depth lower than 2 m: less agreement at greater depth due to 3D effect

Influence of suction and root concentration on root reinforcement/hydraulic behavior

Laboratory studies

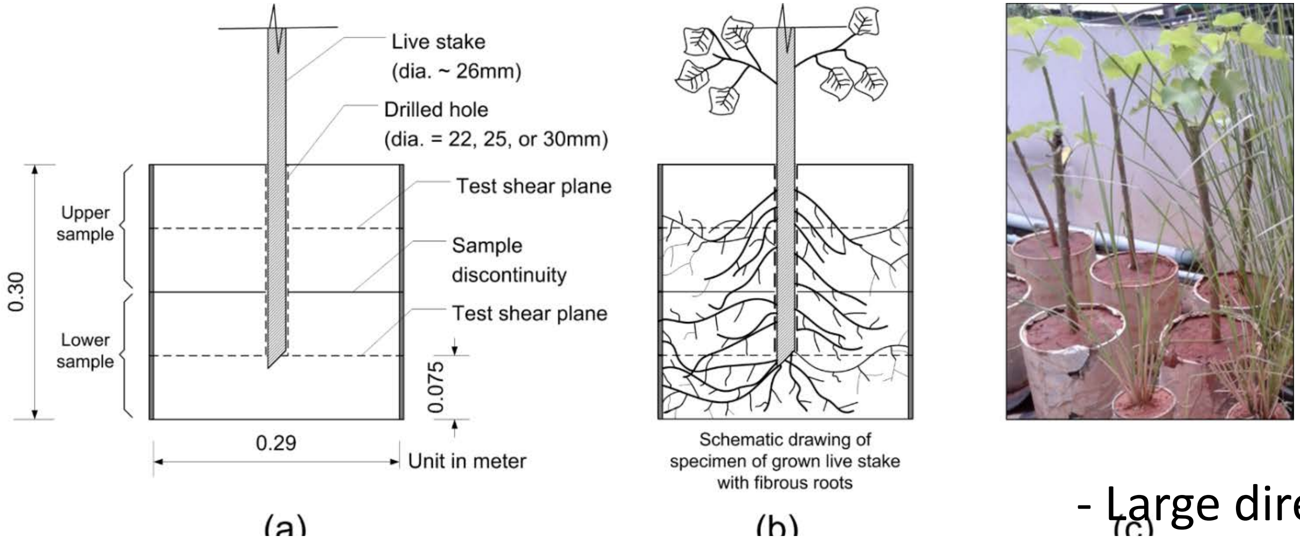
Direct shear tests on vetiver reinforced specimen and live stake specimen

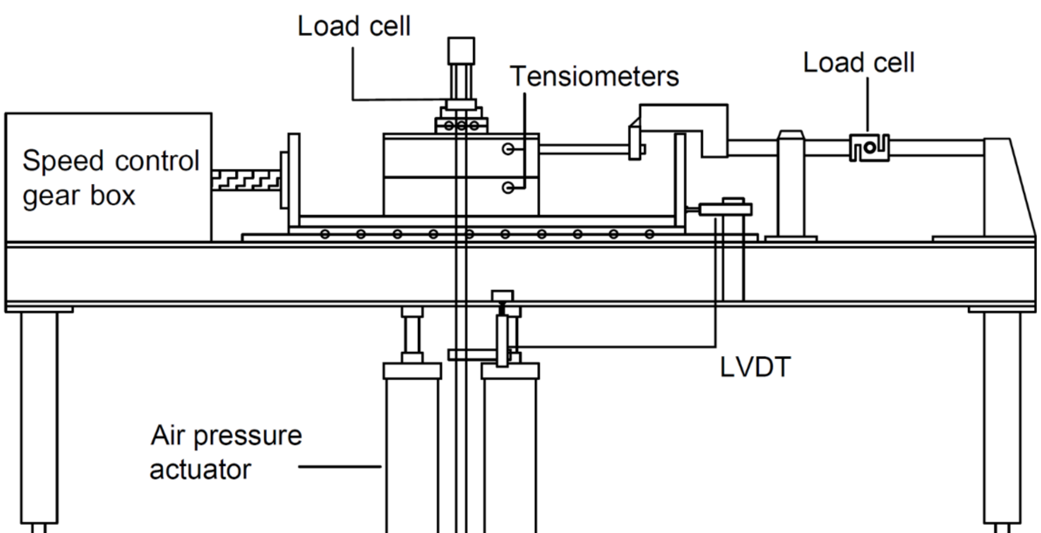
- Large direct shear tests on clayey sand Transparent acrylic tube as sample holder (For investigating the root distribution)
- Test in soaked condition and unsaturated condition



Vetiver roots reinforce specimen

Large direct shear test on live stake sample (*Jatropha*)

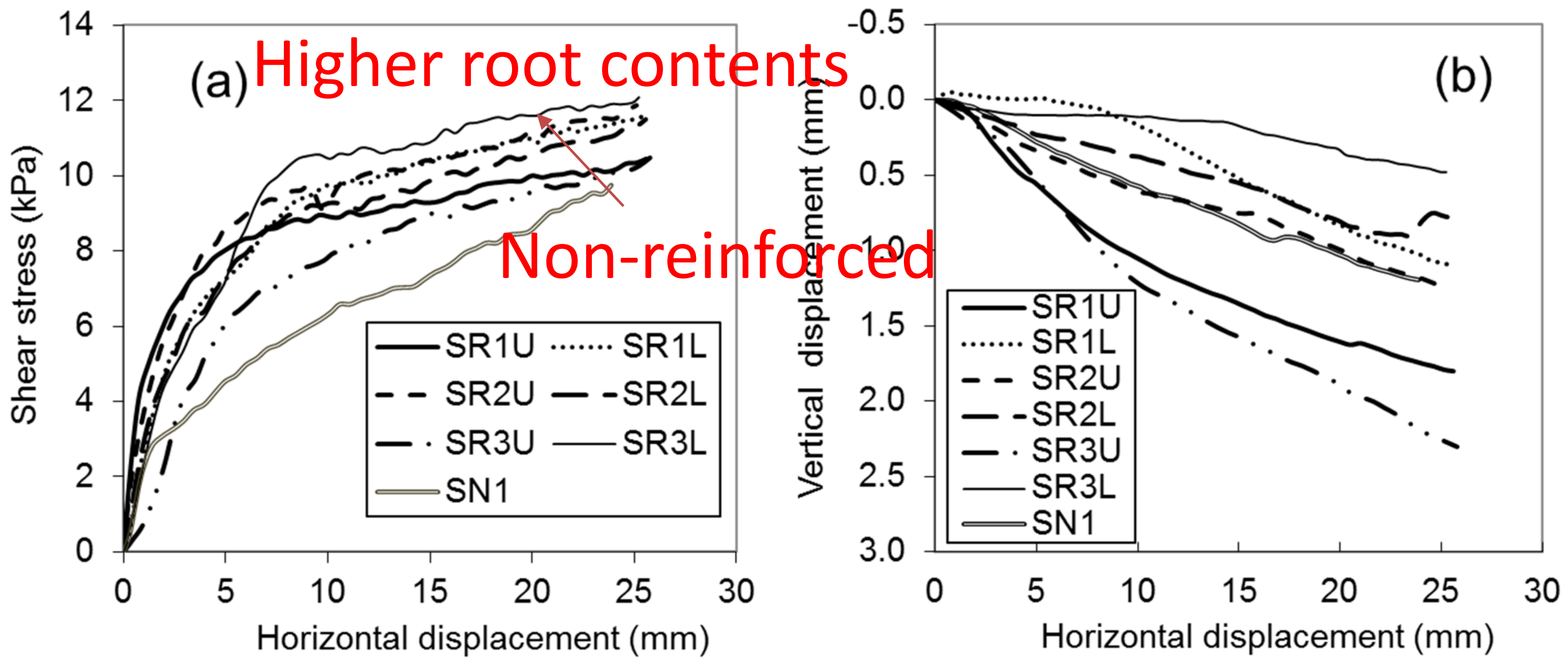




- Large direct shear tests were conducted on compacted clayey sand, reinforced with Jatropha live stakes of various root concentrations in saturated and unsaturated conditions.
- Acrylic molds used to observe root area ratio at the side

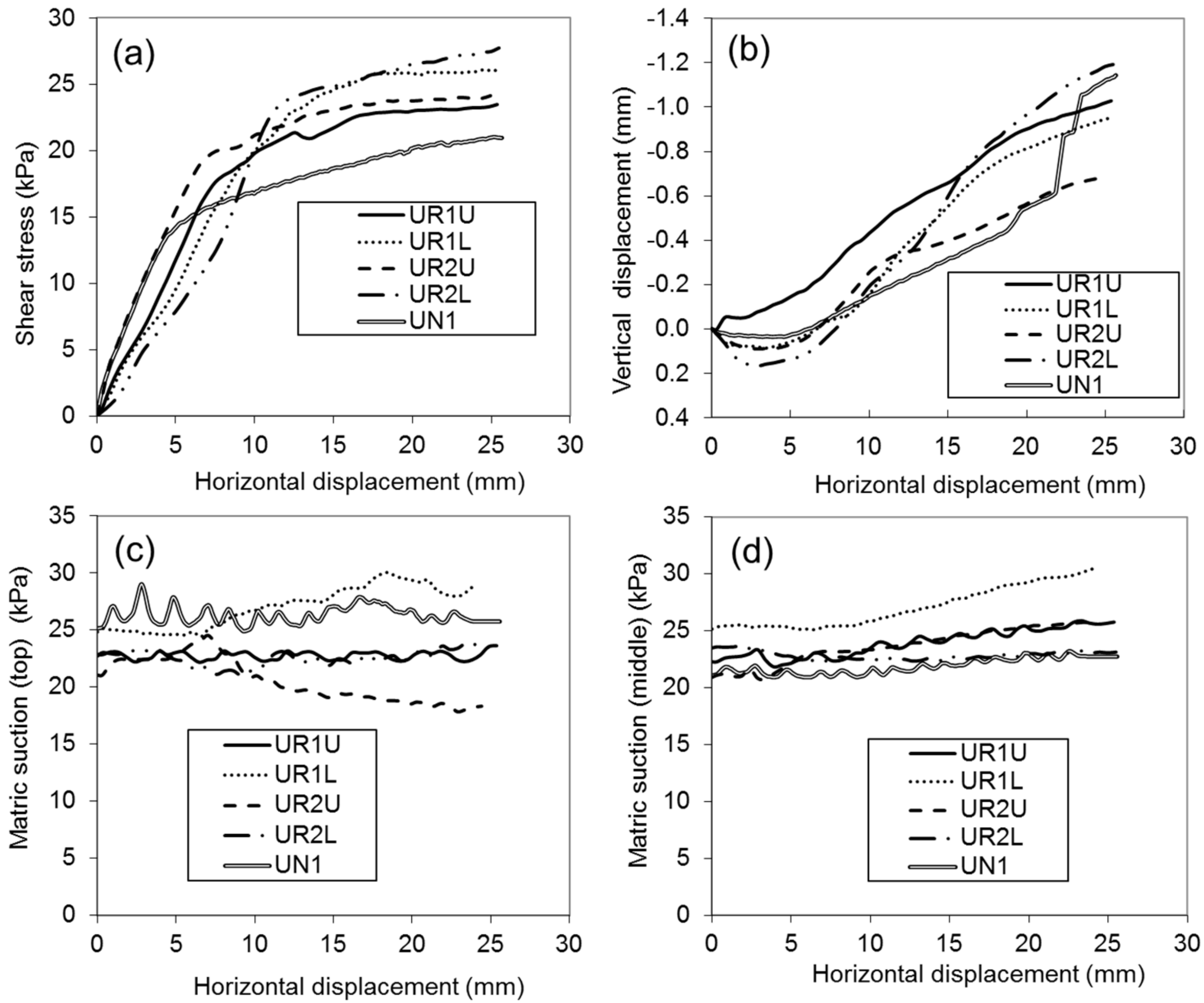
Jotisankasa, A. and Taworn, D. (2016). Direct Shear Testing of Clayey Sand Reinforced with Live Stake. Geotechnical Testing Journal, ASTM, Vol. 39, No.4, July 2016, 608-623.

Saturated shearing

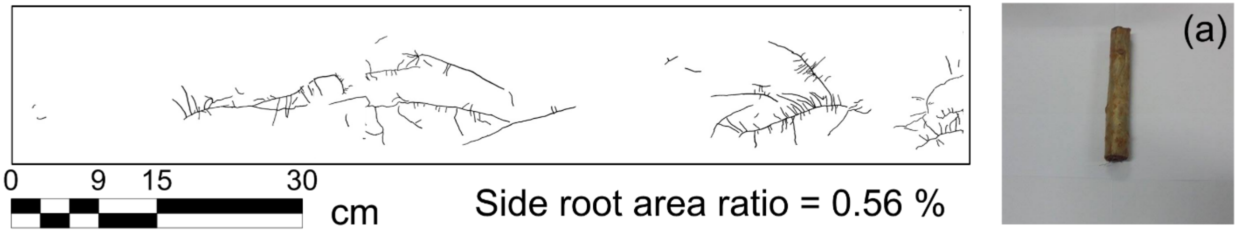


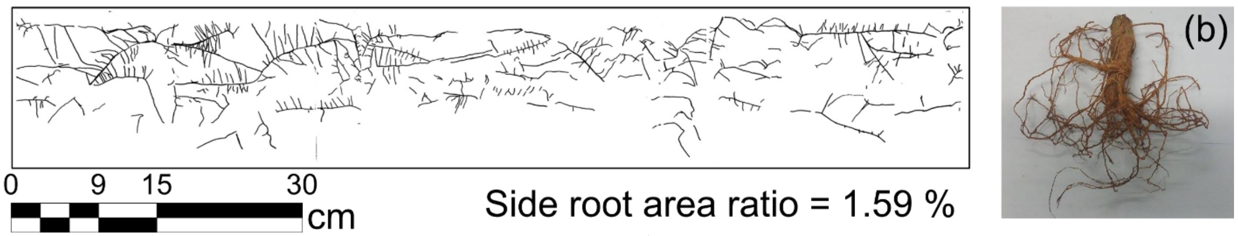
- Live-stake reinforced samples were of higher shear strength than the non-reinforced soil and also possessed a stiffer response.

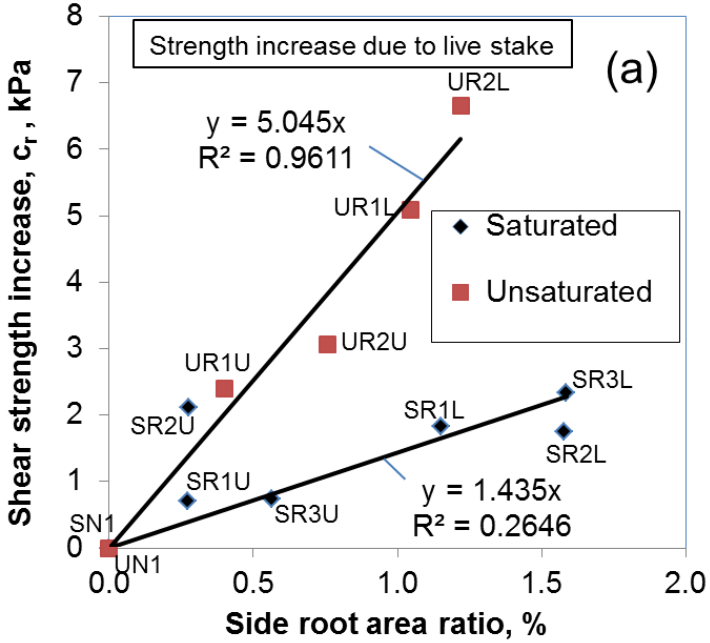
Unsaturated shearing (23 kPa suction)

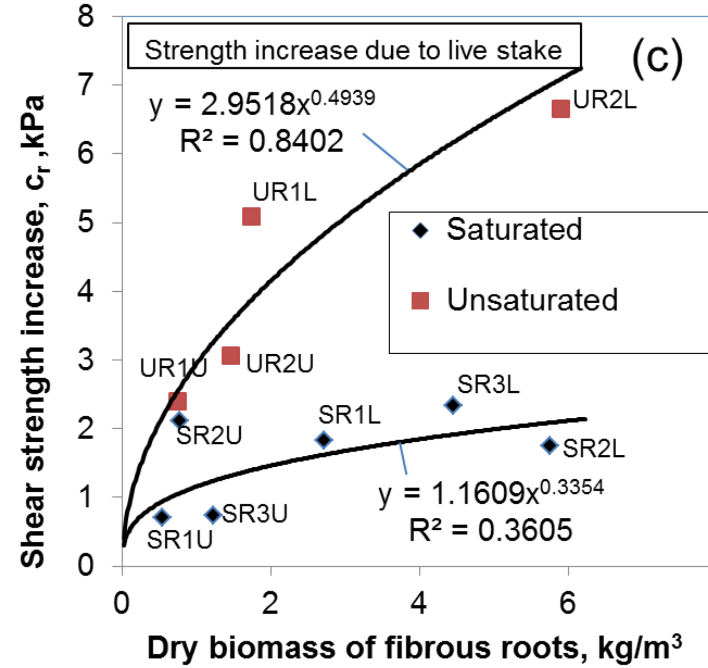


- Samples with higher root contents had higher strength
- at a suction of about 23kPa, both non-reinforced and reinforced samples exhibited some marginal dilation towards the end of shearing.
- All the unsaturated samples exhibited strain-hardening behavior.





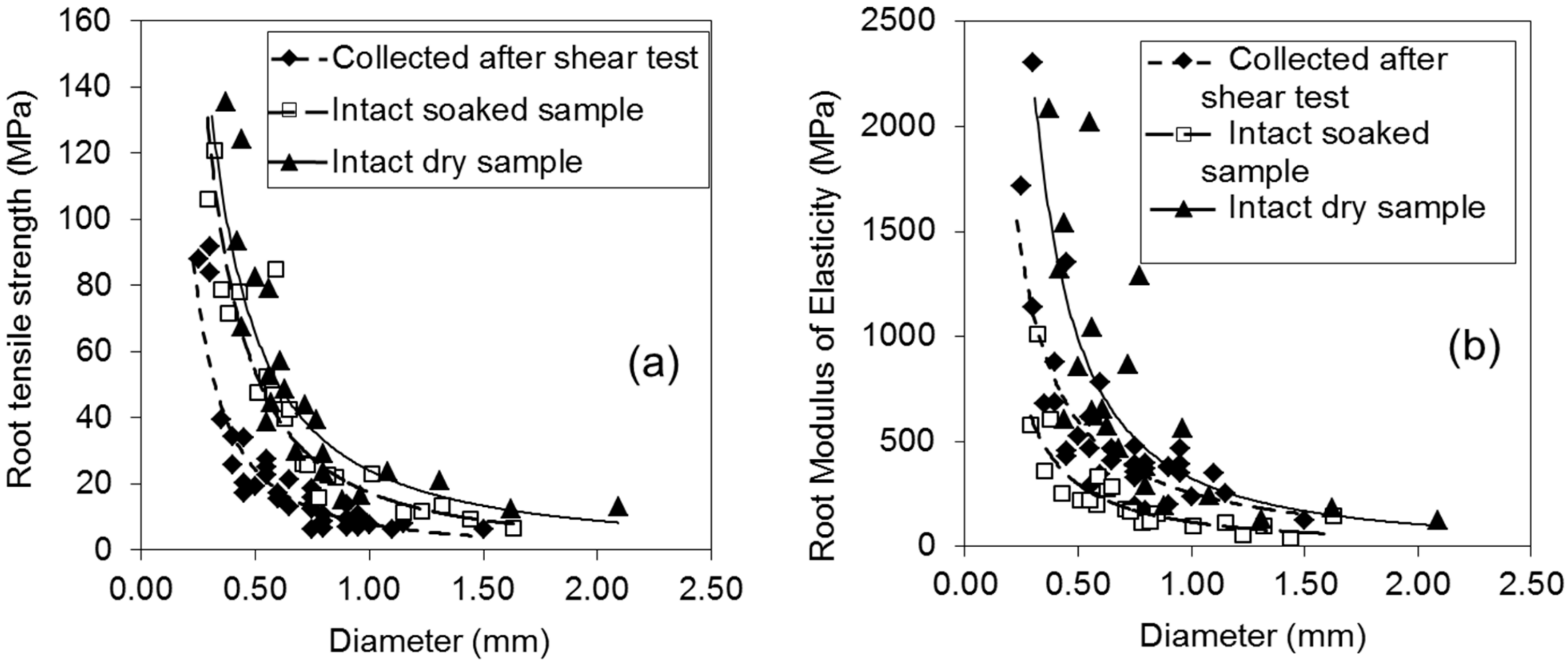




$$c_r = k_1\left(\frac{A_R}{A}\right) + k_2$$

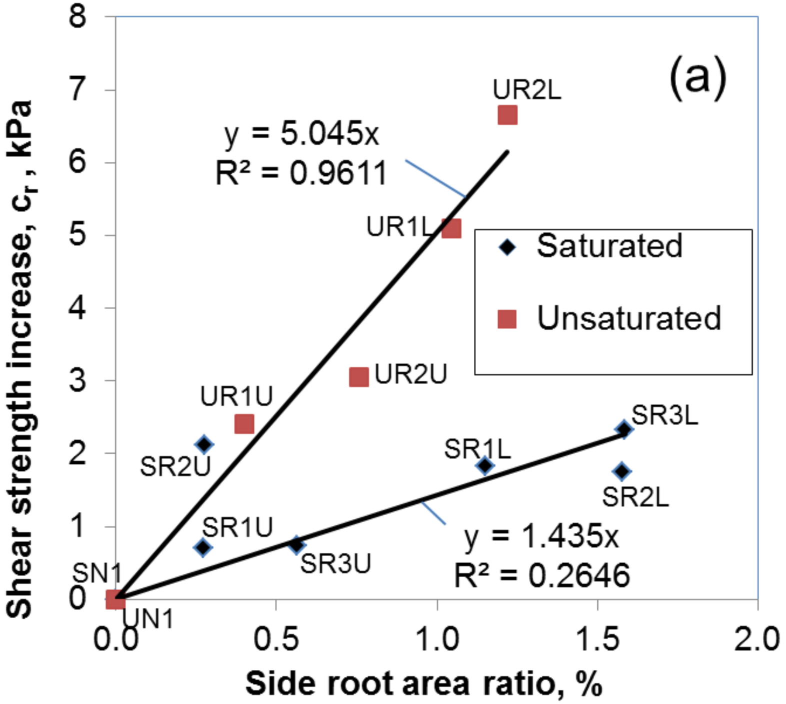
$$c_r = f(\rho_R)$$

Influence of suction on root tensile strength and modulus of *Jatropha*



- Dry roots controlled at a total suction 39,300 kPa using (relative humidity equilibration)
- Tensile strength decreased with increased diameter, a trend commonly observed in previous studies of root tensile strength (e.g. Nilaweera 1994; Nilaweera and Nutalaya 1999).

Effects of soil suction on the rate of strength increase due to root content



$$c_r = k_1(s) \cdot RAR_{side}$$

k_1 is dependent on suction

Normalization procedure is proposed, where

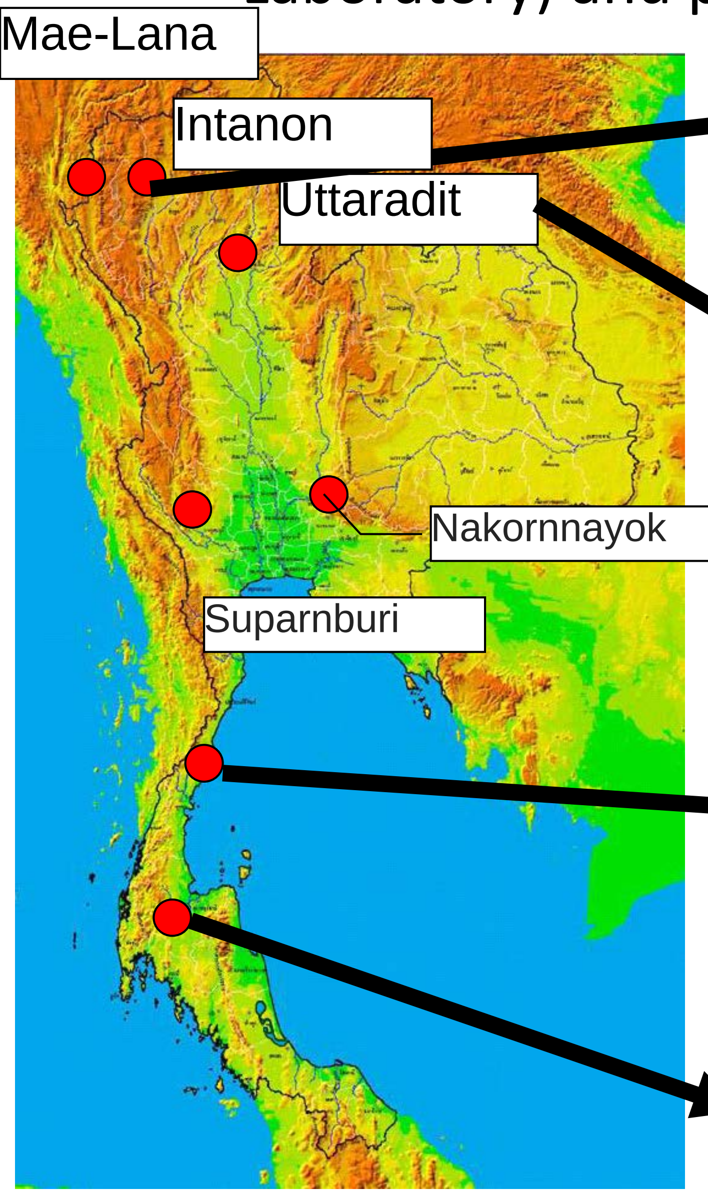
$$k_1(s) = \eta(s) \cdot k_{1-sat}$$

$$\eta(s) = \eta_b \cdot \eta_t \cdot \eta_m \cdot \eta_o$$

Model for correction of root cohesion due to suction effect

η_b is the correction factor for suction effect on bond stress;
η_t is the correction factor for the suction effect on average root tensile strength;
η_m is the correction factor for the suction effect on average root tensile modulus;
η_o is the correction factor for the suction effect on shear zone thickness and root orientation.

Bio-engineering test sections by Kasetsart University (Geotechnical Innovation Laboratory) and partners

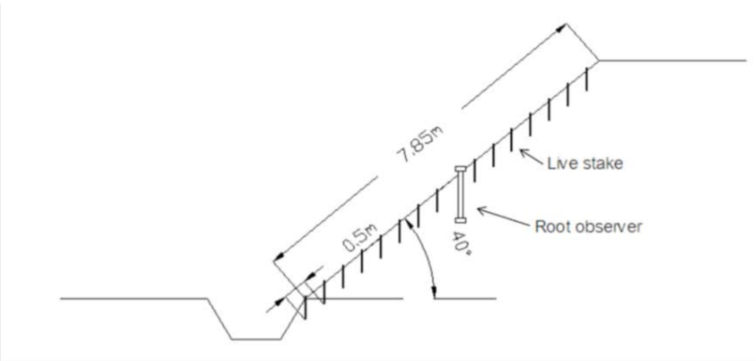


Coastal & river bio engineering at Bangberd

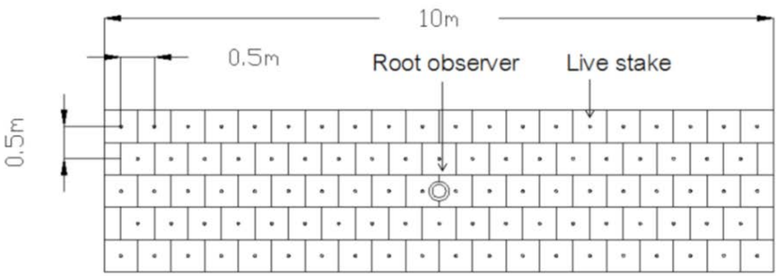
Highway no 44. Krabi

Field evaluation of time-dependent root contents and root reinforcement

A bioengineered test slope along a Highway no 44 in Krabi province, Southern Thailand using Jatropha live stakes   A mini-rhizotron was installed in the middle of the slope to a depth of 0.9m in order to monitor the changing root content with time.



a)



b)

a)

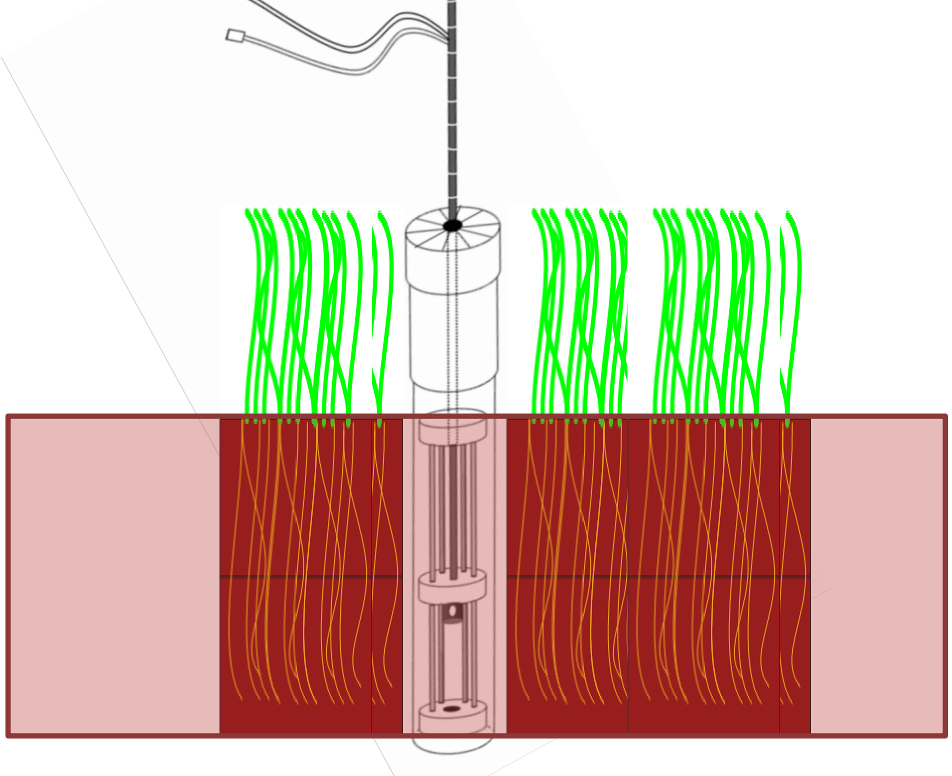
27/03/2013

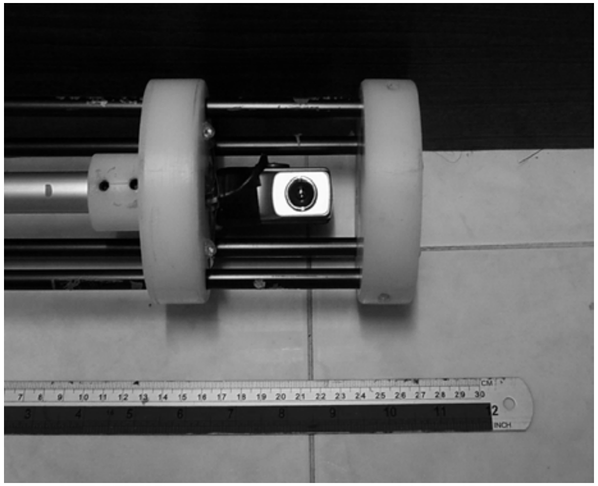
b)

16/08/2013

Field observation of root concentrations

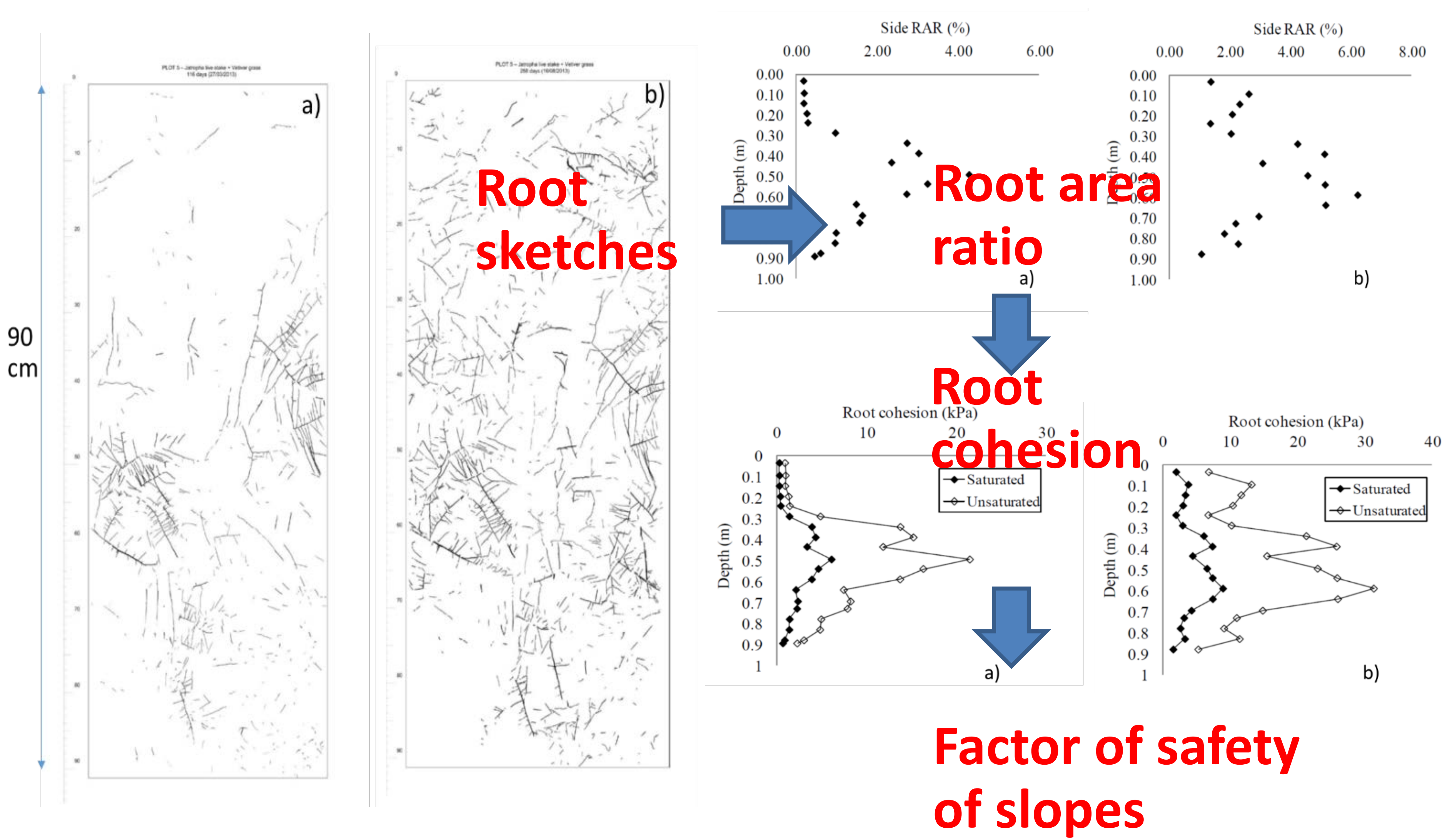
- Minirhizotron system has been used for observing fine roots intersecting the surface of a transparent tube buried in the soil (a non-destructive method)
- Useful for studying changing conditions of roots



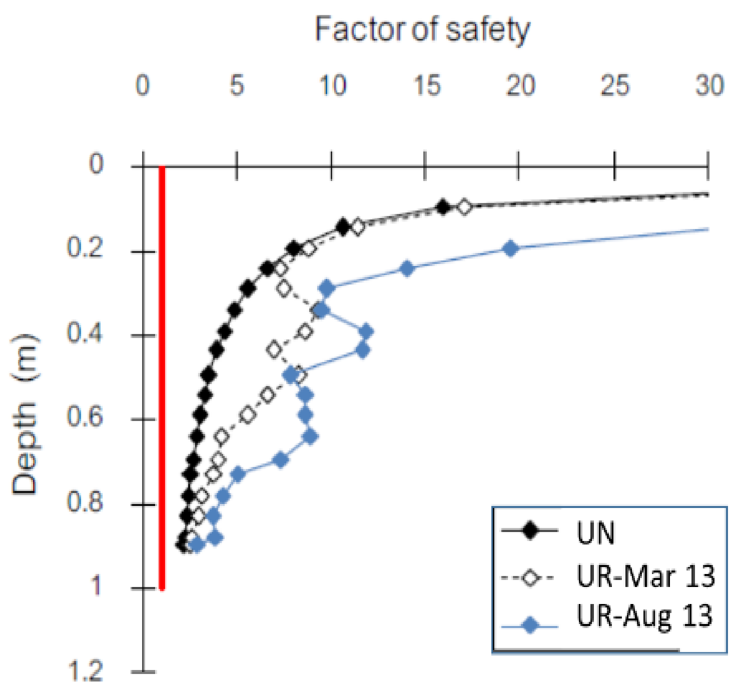


$$RAR_{side} = \frac{A_R}{A} = \frac{Number\ of\ root\ pixels}{Total\ number\ of\ pixels}$$

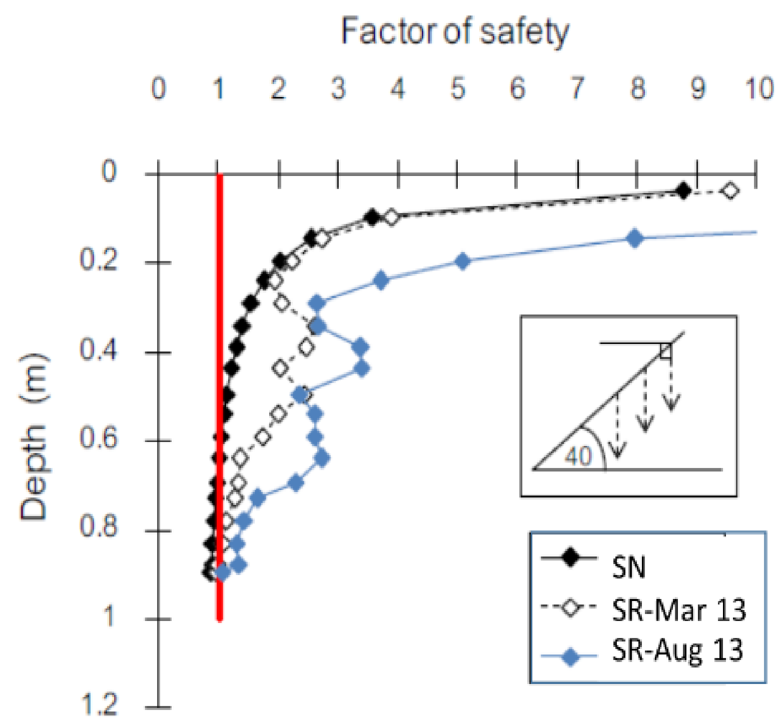
- Sketches of roots in a minirhizotron for the bioengineered test slope a) 27/03/2013, b) 16/08/2013



Estimated factor of safety for the test slope a) Unsaturated slope b) Saturated slope, for non-reinforced condition (UN & SN) and for reinforced



a)



b)

- in unsaturated condition (assuming 23 kPa suction), both non-reinforced and reinforced slope appeared to be stable (FS >1.5).
- in saturated condition (assuming zero pore water pressure or seepage flow angle being vertical), the roots were only effective in improving the factor of safety around the depth of 0.5 meter, where the root content was the highest.

Field observation of vetiver roots (decaying case)

- Field site on top of 45° degree slope in Surathani, South Thailand, (Sandy soil)
- Before and after photos of vetiver grass that disappeared from the slope due to invasion from native species

Minirhizotron

Before

After

March. 2013 - Measurement near Vetiver grass

Oct. 2014 Measurement at same location, Vetiver disappeared due to invasión by native species

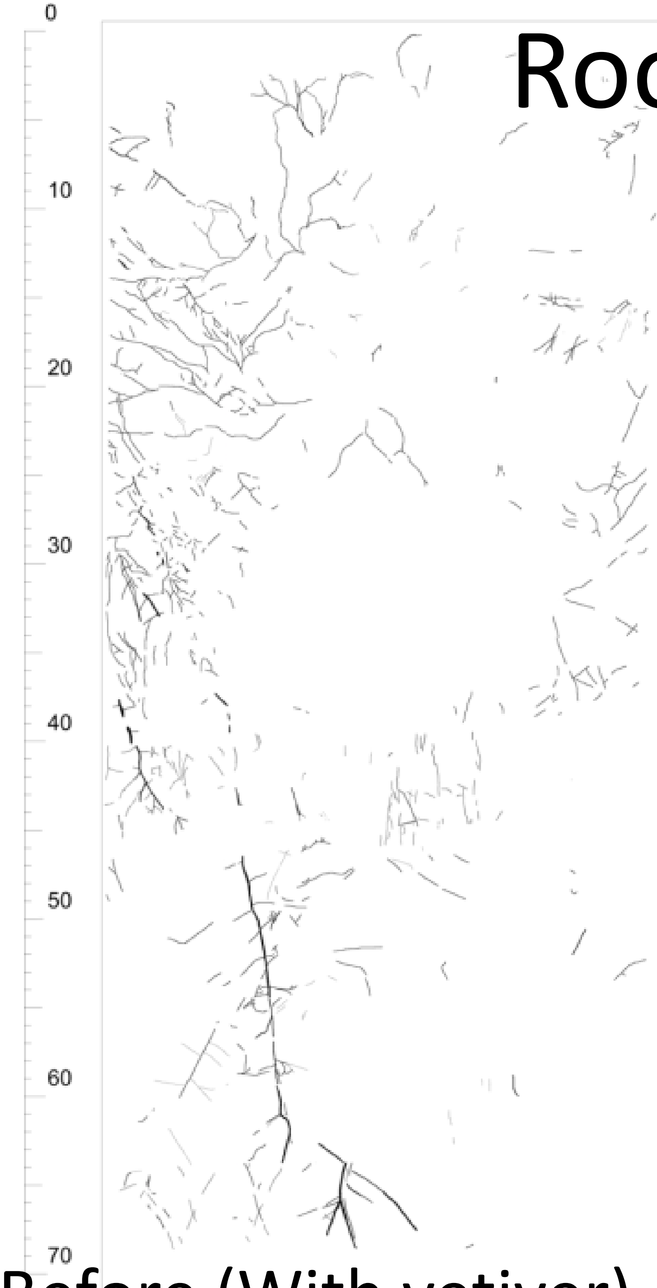
Mar. 2013

Oct 2014

New roots of native species

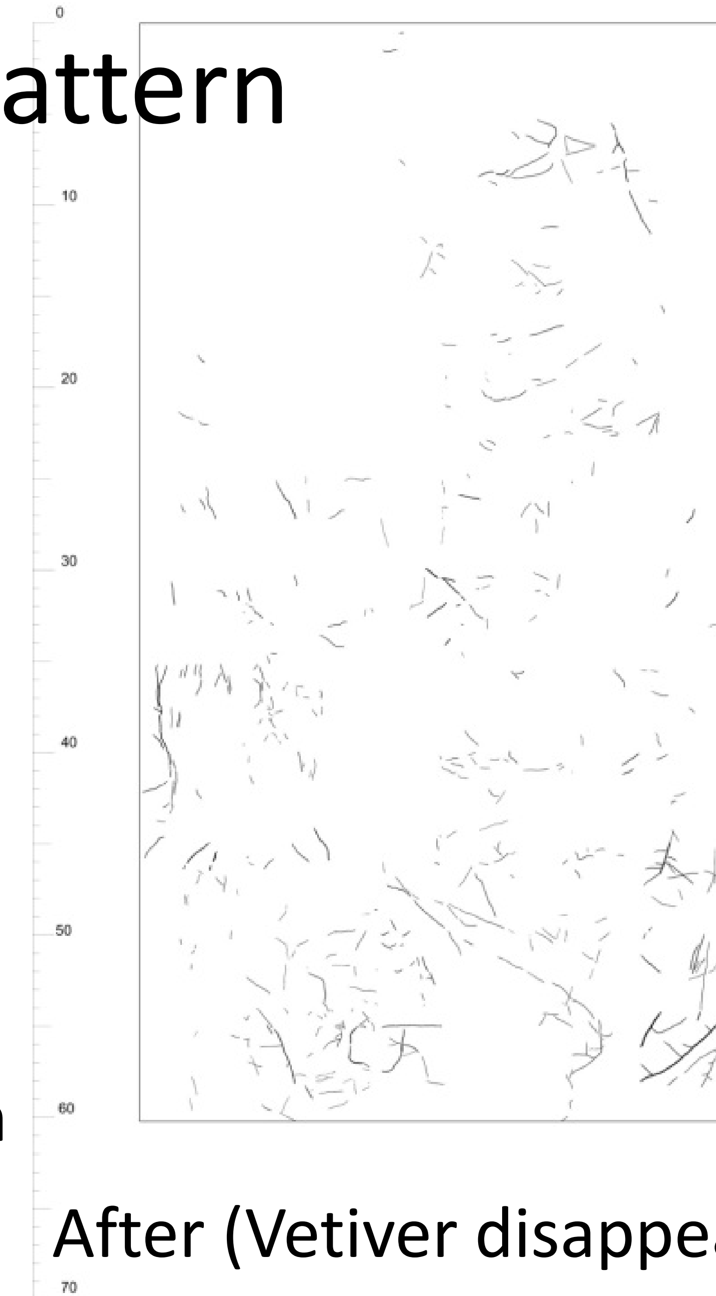
New voids generated around degraded roots

Root pattern



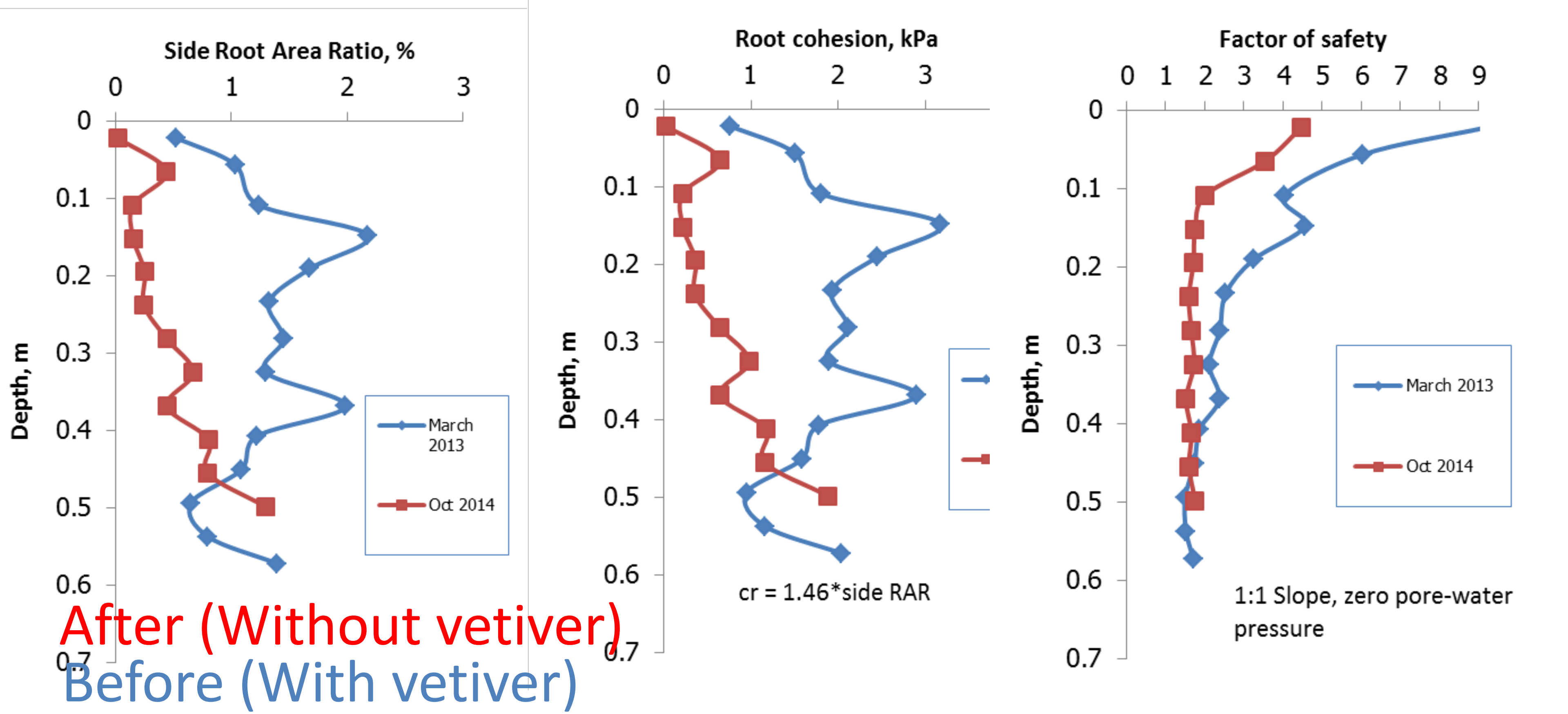
cm

Before (With vetiver)



cm

After (Vetiver disappeared)



- After the Vetiver disappeared and its roots decayed, the root area ratio decreased significantly leading to loss in root cohesion and decreased factor of safety.
- This emphasizes the **importance of frequent maintenance of the VS in practice in order to sustain long-term** slope stability.

Numerical analysis of rain infiltration into slope with/without vetiver

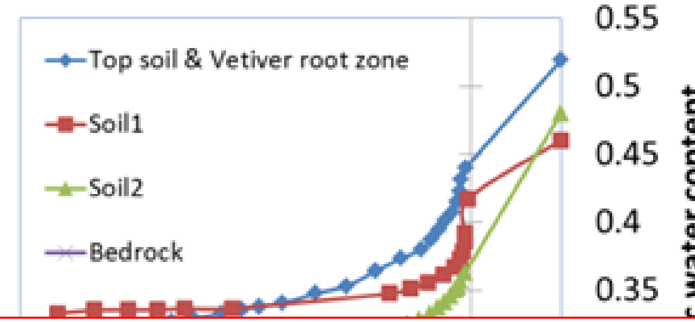
Objectives

- To explore both advantage and potential risk of vetiver grass on slopes by way of numerical modeling.
- The Finite Element Method was used to analyze infiltration of rain into slope
- Limit-equilibrium method for slope stability calculation
- 2 hypothetical slopes with gradient of about 27^o and 60^o. For both cases, the slopes were modelled with and without vetiver row in order to compare the effects of vetiver on stability.

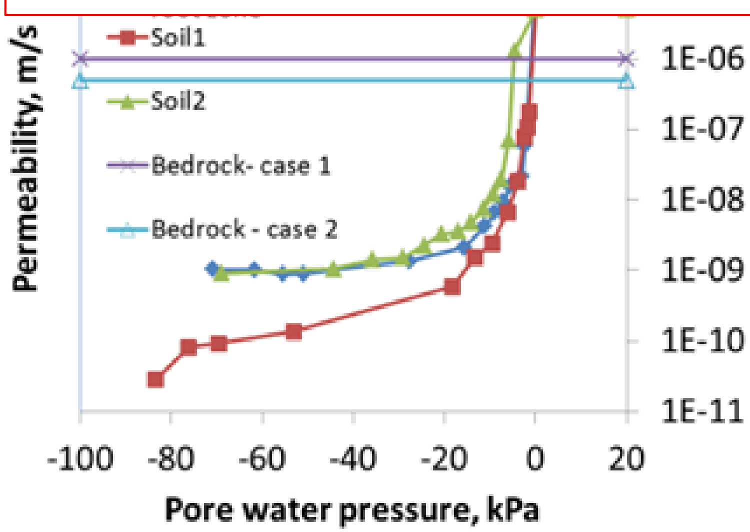
Soil properties in the analysis

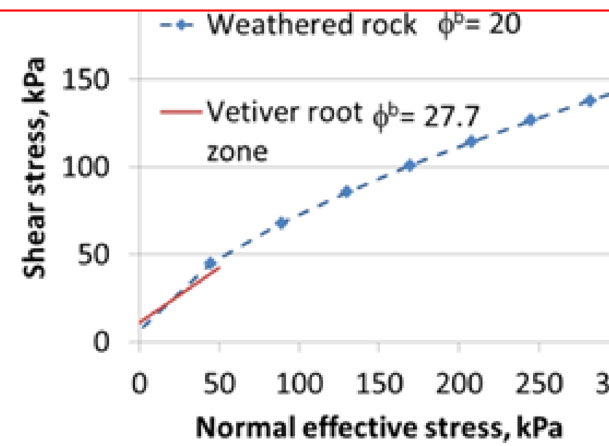
Material	γ_{sat} kN/m^3	$c'+c^r$ kPa	ϕ' deg.	ϕ^b deg	γ_{moist} kN/m^3	
Top soil	17	22.8	17.6	13.9	16.5	*
Soil 1	18.5	2	32	27.7	18	*
Soil 2	18.7	2	32	27.7	18	*
Veti[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	**

Sou[illegible]
(201[illegible]

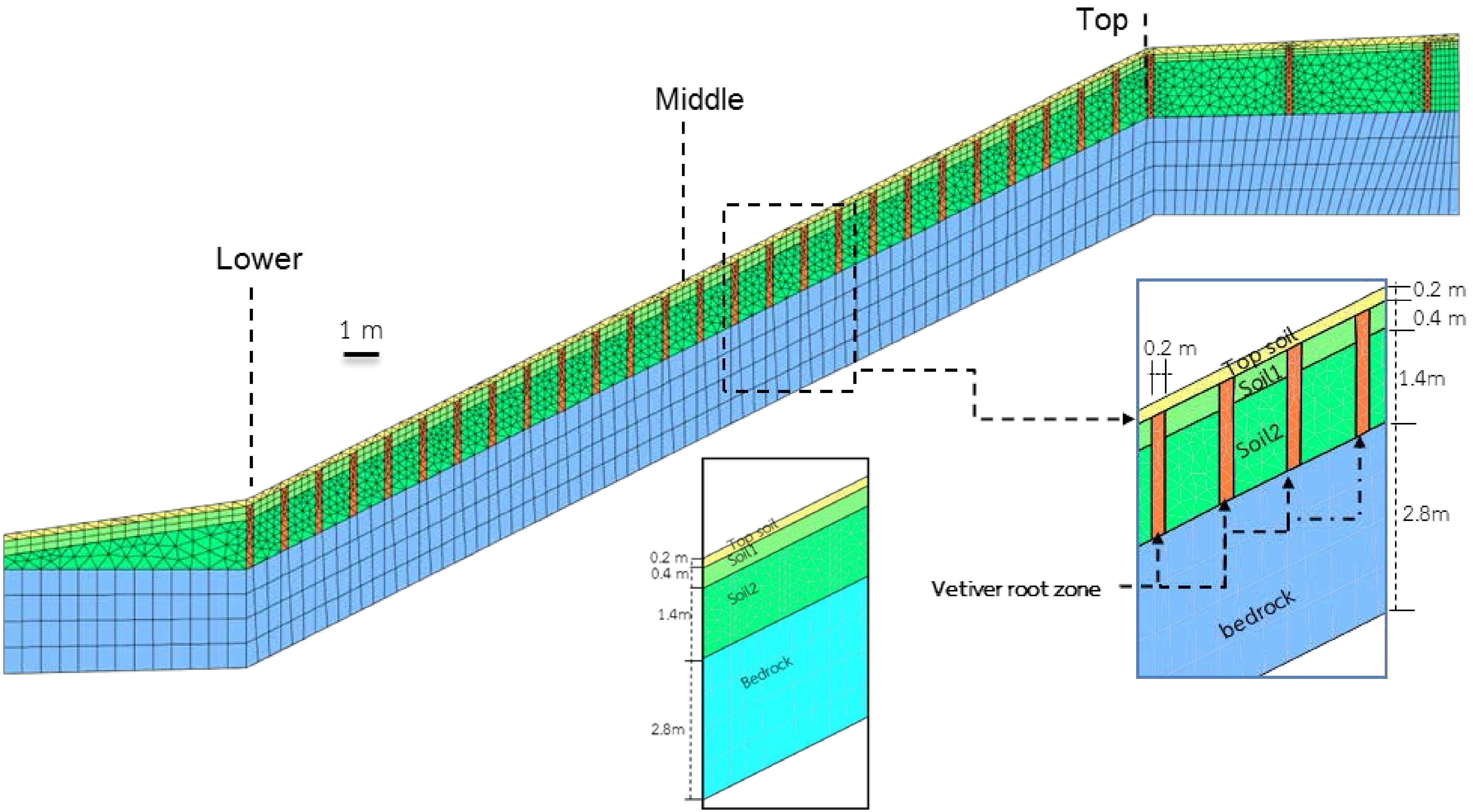


Permeability of root zone is assumed to be 2 times permeability of no-root zone (more permeability root zone or effect of decayed roots considered)
Root cohesion,Cr, of 20 kPa assumed.



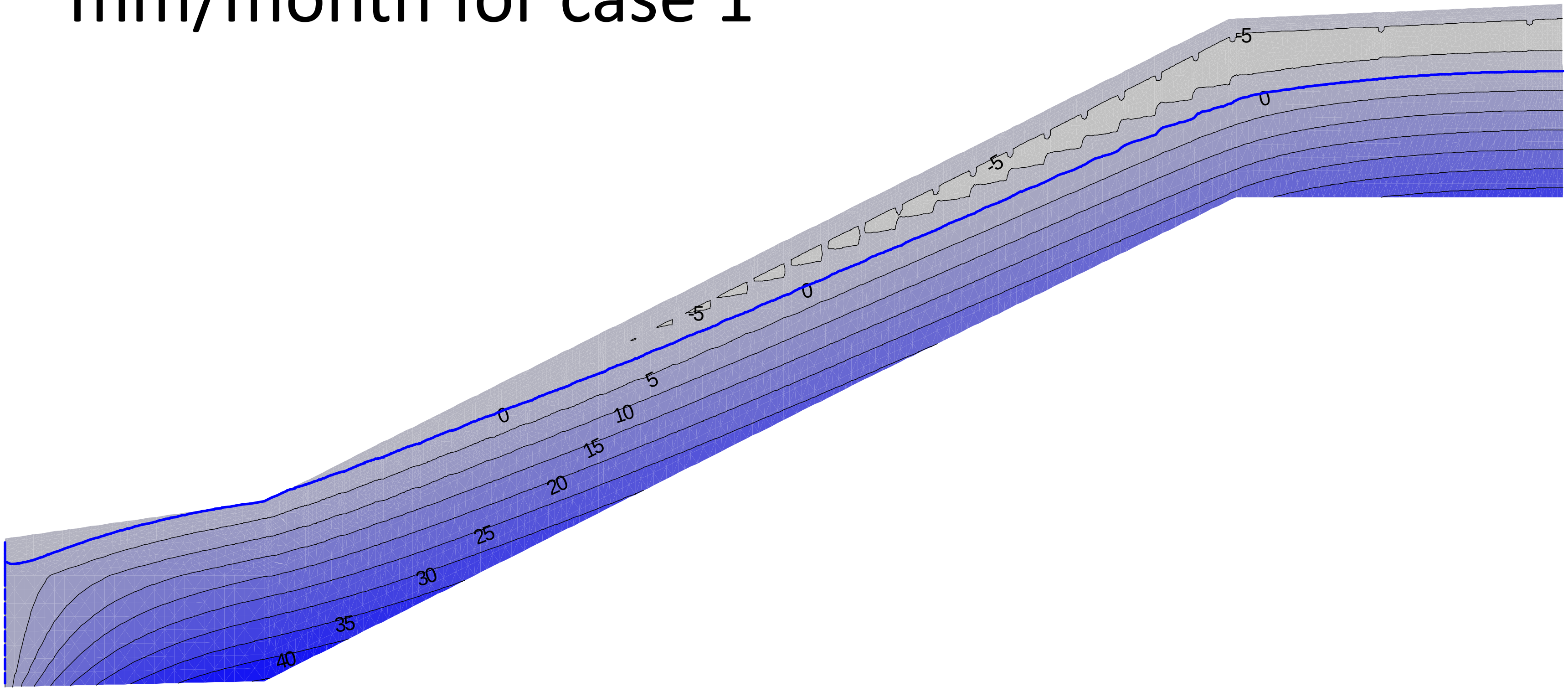


Natural slopes (26 degree) with/without rows of vetiver grass

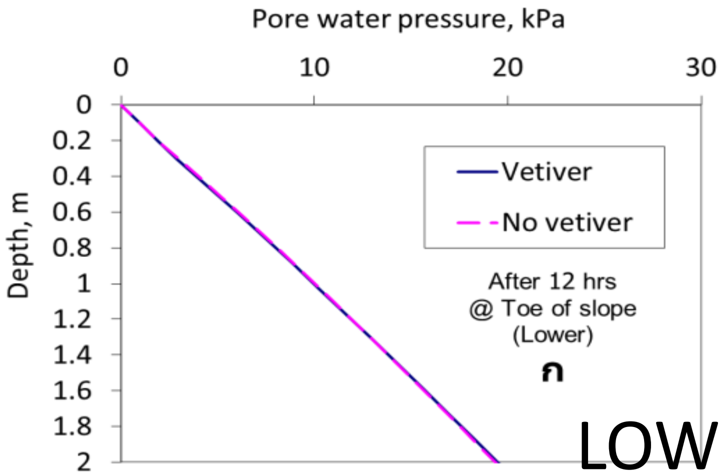


Initial condition from steady state analysis

- Contour of pore water pressure (kPa)
- (time= 0 hr) Average infiltration of 300 mm/month for case 1

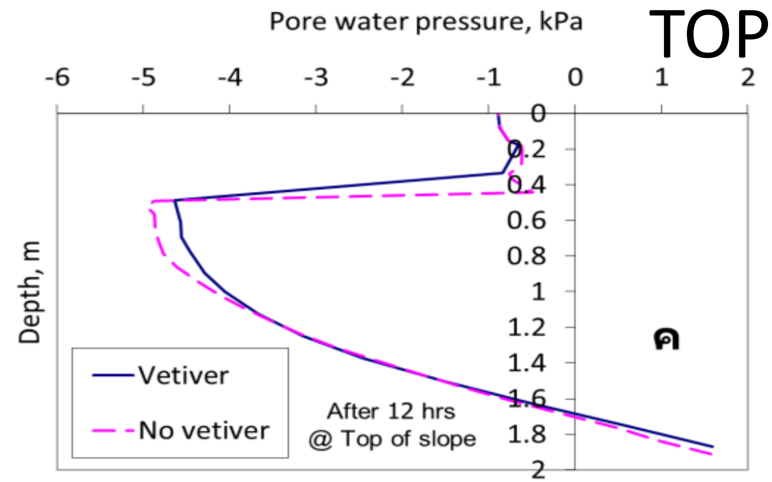


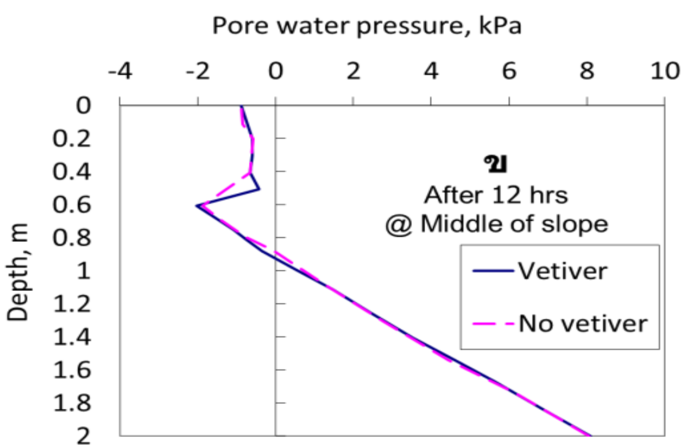
Comparison between pore waterpressure in slopes with vetiver rows and without vetiver rows (at 12 hours time = 43 mm of rain)



LOWER

TOP

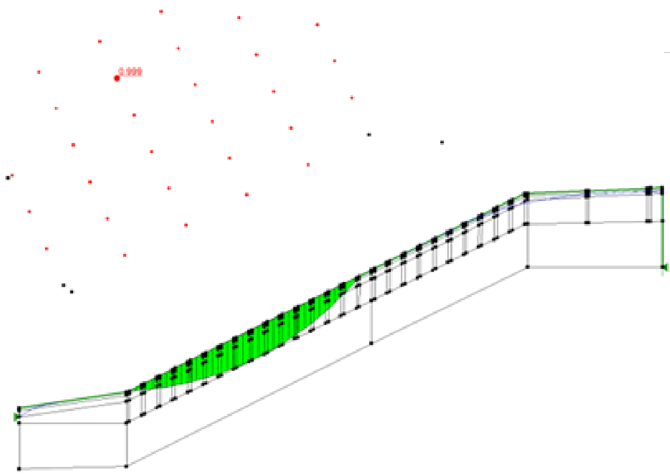


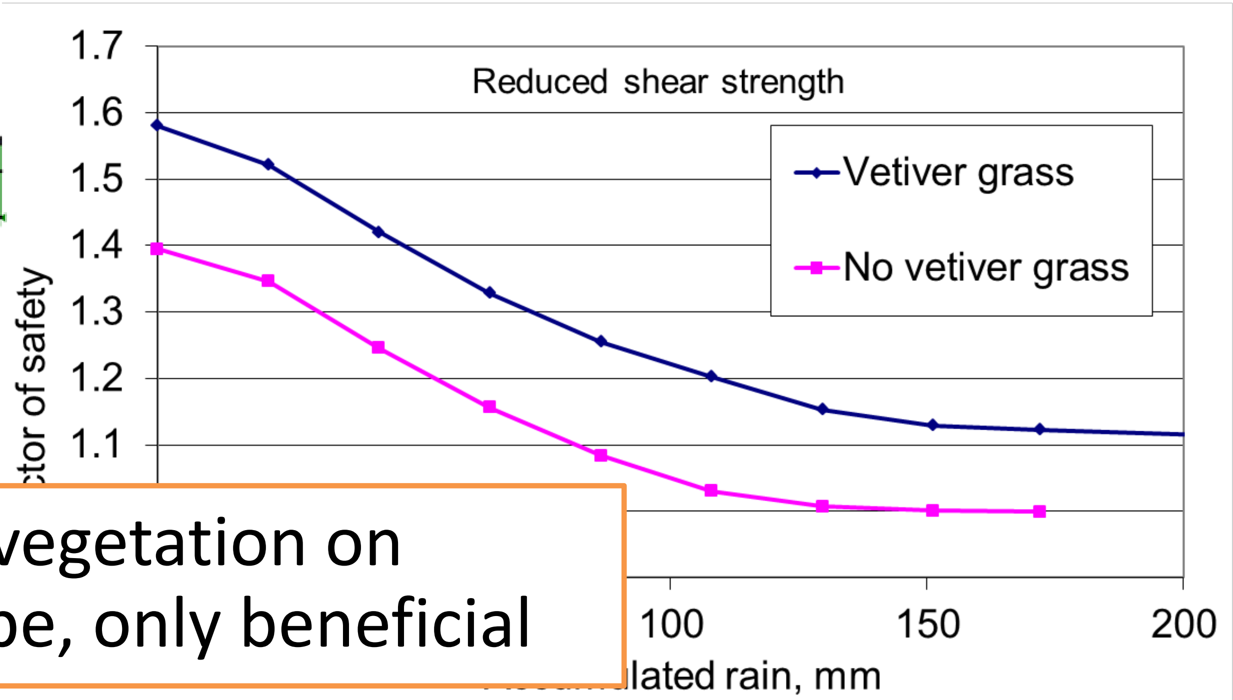


MIDDLE

- There was **<u>only very slight difference</u>** between the two cases.
- Except at the top part of slope, for slope with vetiver rows, the root zone appeared to conduct some water to a greater depth
- All in all, there is not much significant difference between the pore water pressure of 26o slopes with or without vetiver.

Natural slope 26 degree



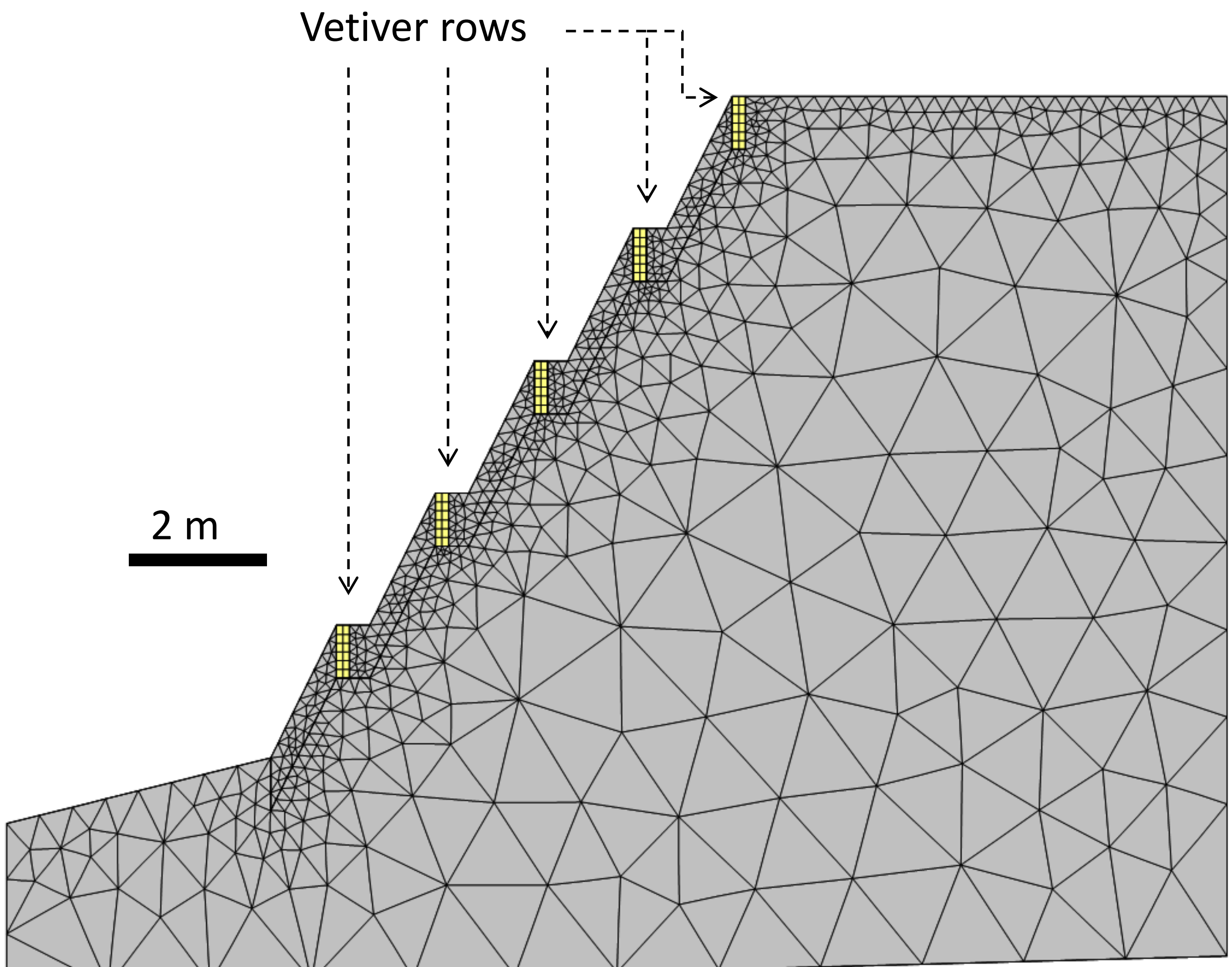


No adverse effect of vegetation on stability for 26.6° slope, only beneficial

- Limit Equilibrium slope stability analysis carried out based on pwp from transient seepage analysis
- The slope without vetiver grass appeared to fail (FS=1) when the total rainfall reached about 120-170 mm
- The increased cohesion due to roots (c_r) more than offsets the higher permeability of root zone that induce greater infiltration into slopes, for the case of 26.6° slope

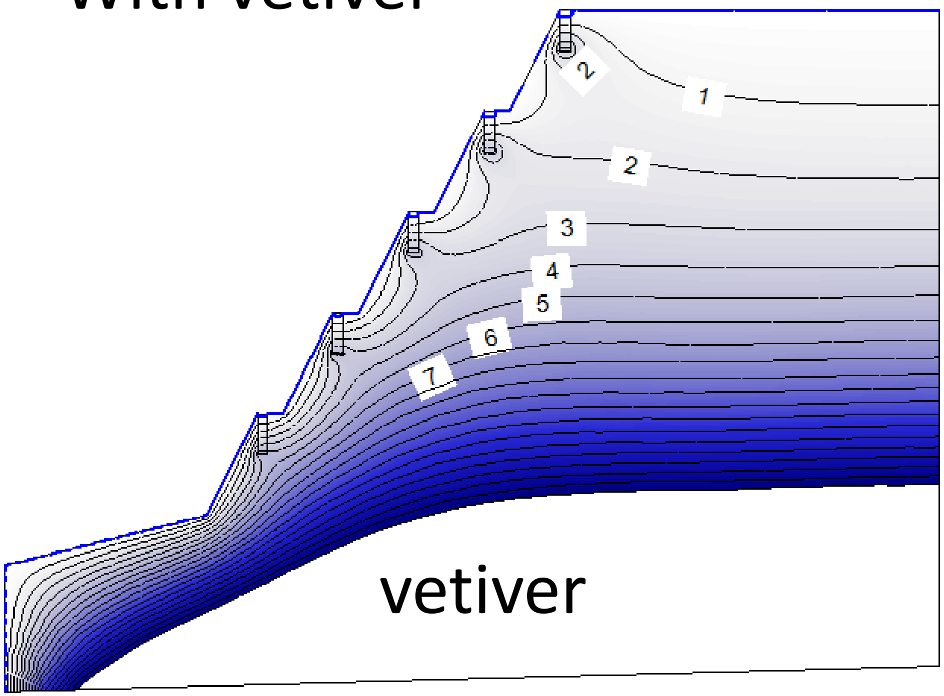
Rock cut slope (60 degree) with/without rows of vetiver grass

- 10 m high slope (2 m high step) vetiver planted on each bench

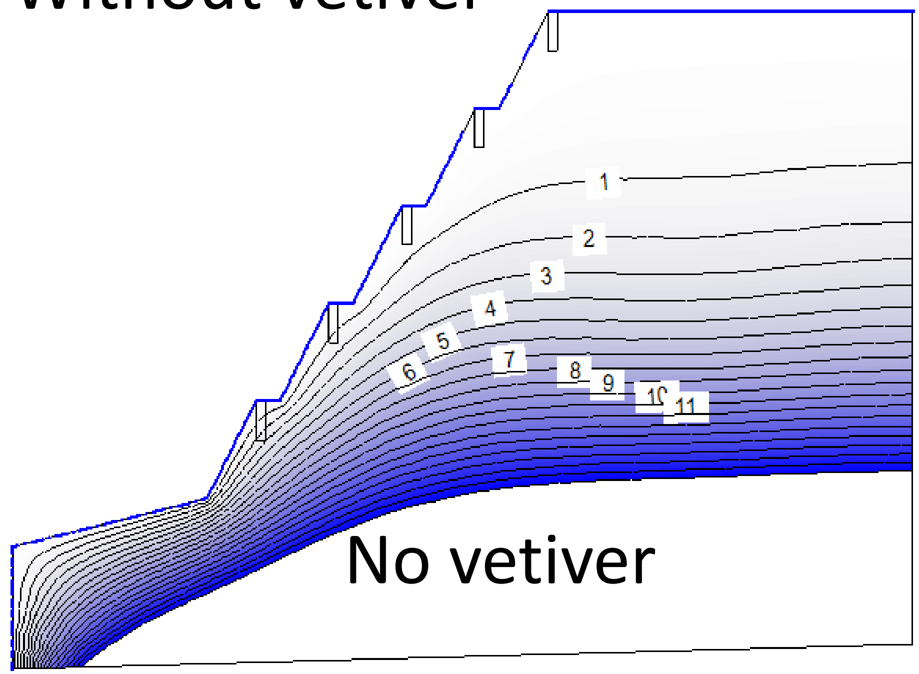


Pore water pressure variation
After 24 hours = 84 mm

With vetiver

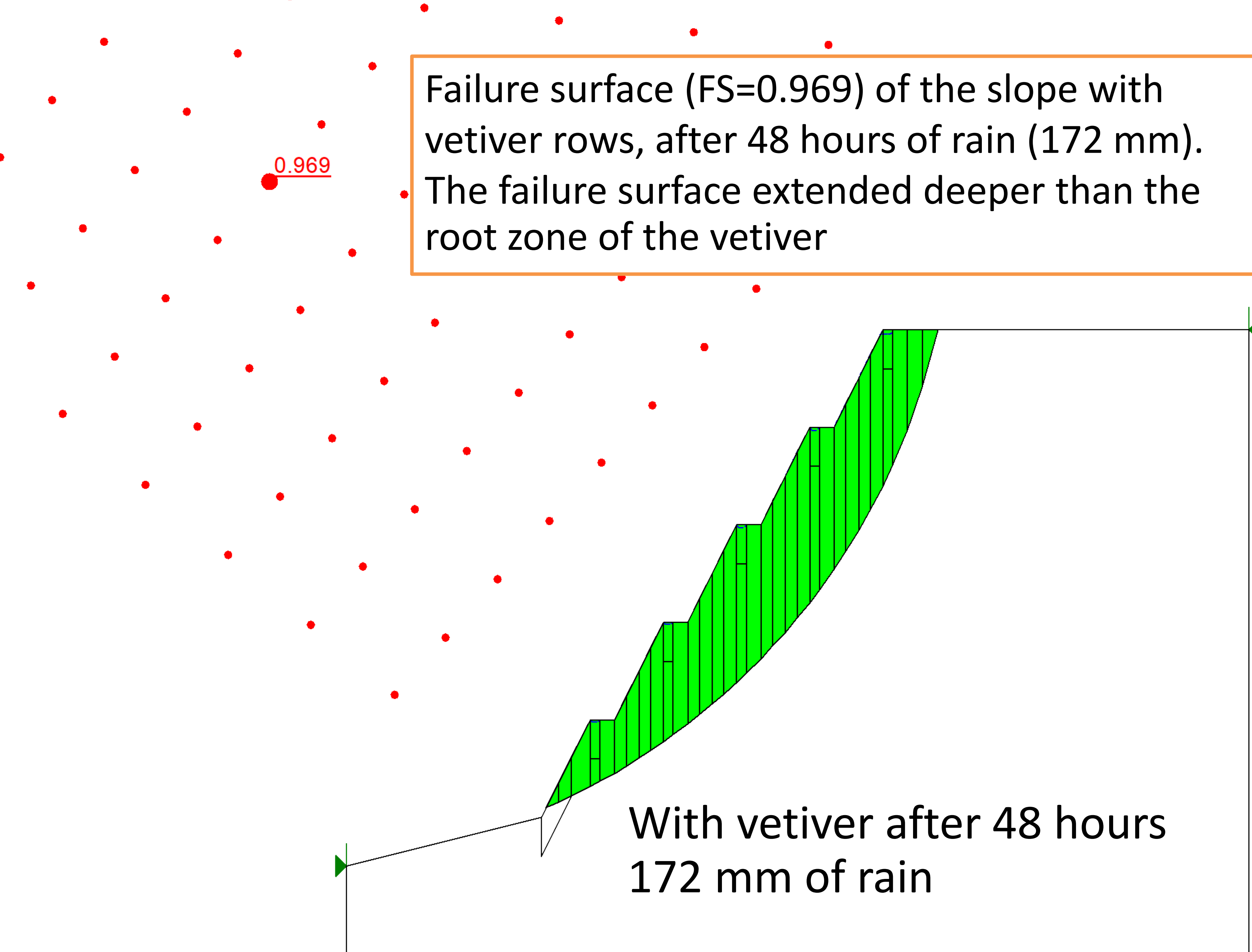


Without vetiver



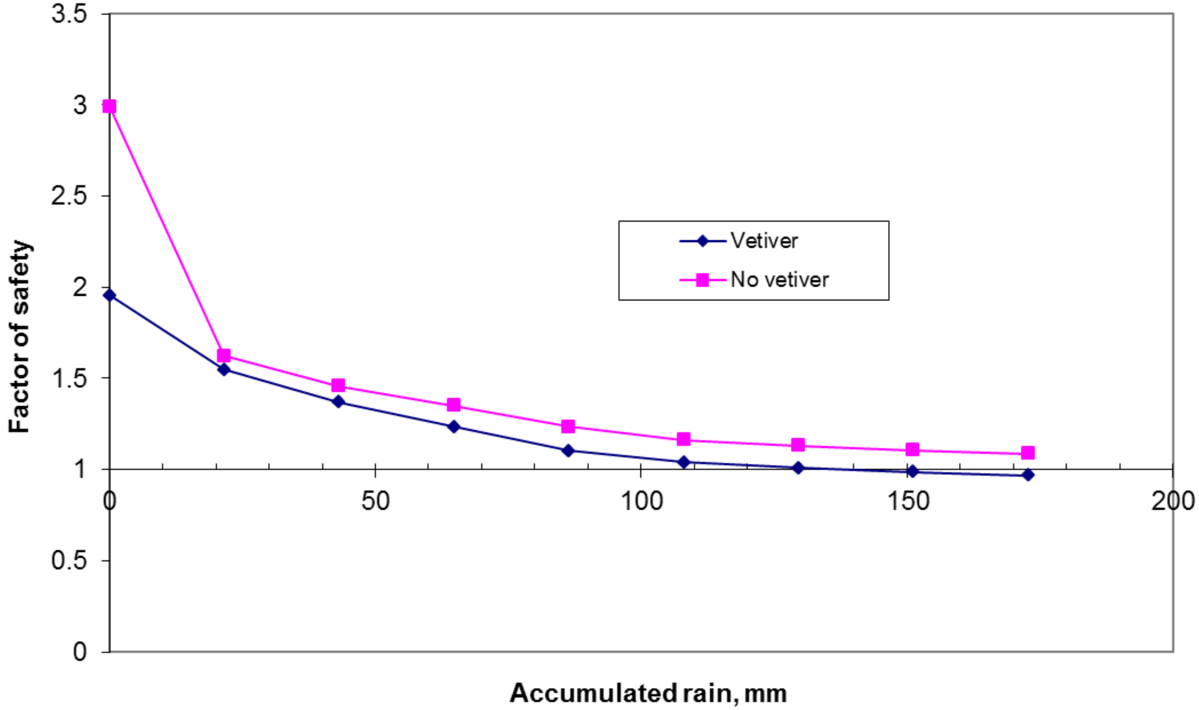
- With vetiver hedgerows on slope, groundwater can infiltrate to a greater depth through the **assumed more permeable root zone**, resulting in **higher pore water pressure in the slope**.
- Without the vetiver rows, part of the rainfall would not permeate the ground and tend to become runoff.

Failure surface (FS=0.969) of the slope with vetiver rows, after 48 hours of rain (172 mm). The failure surface extended deeper than the root zone of the vetiver



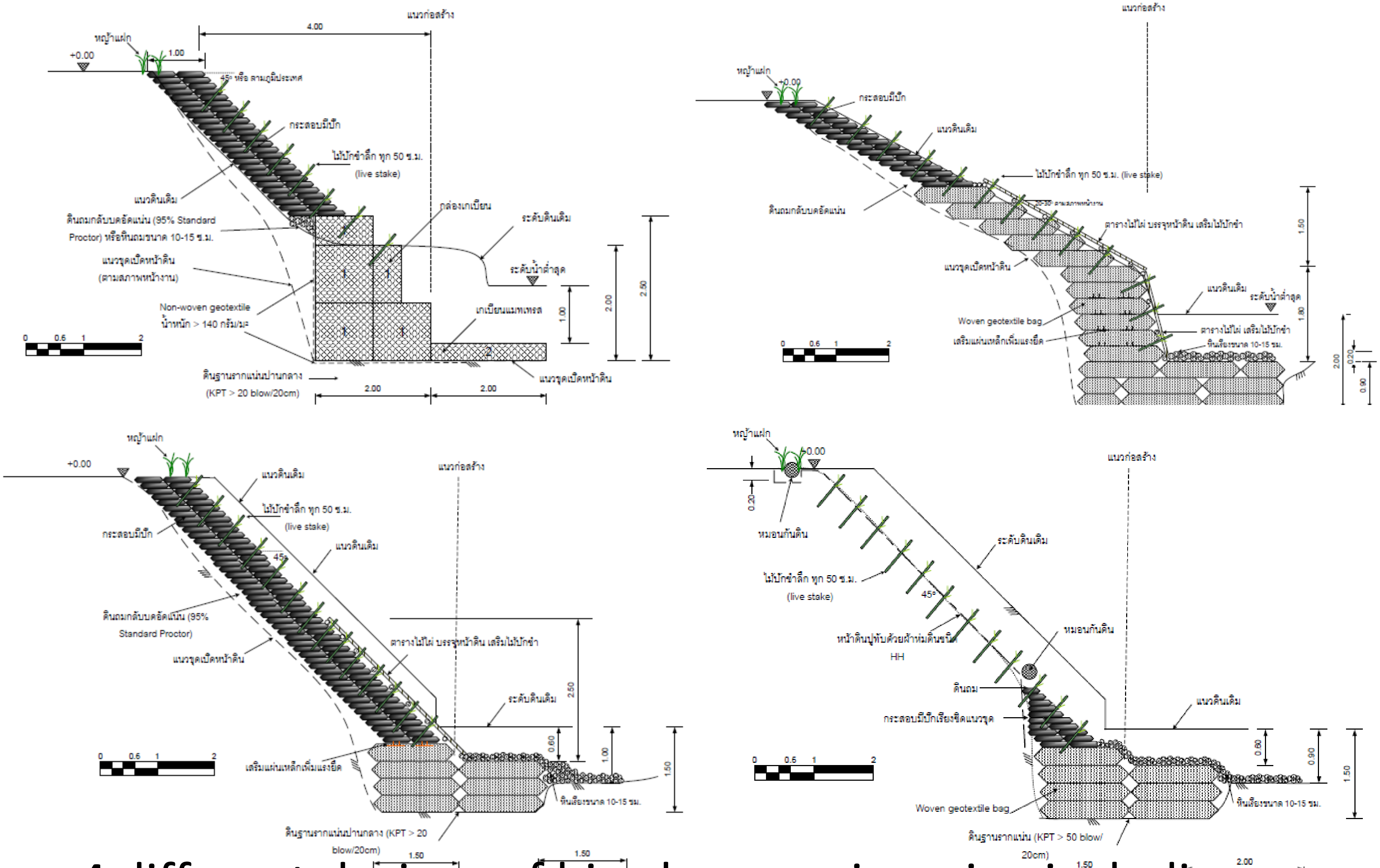
With vetiver after 48 hours 172 mm of rain

Weathered rock slope 60 degree



- Factor of safety for the 60°slope **with permeable root zone** is about **10% lower than the slope without root zone** due to **the increased pore water pressure** induced from **increased infiltration** through the root zone.

Pa-moob river bank bioengineering- Uttaradit province- funded by the royal initiative project of Chaipattana foundation

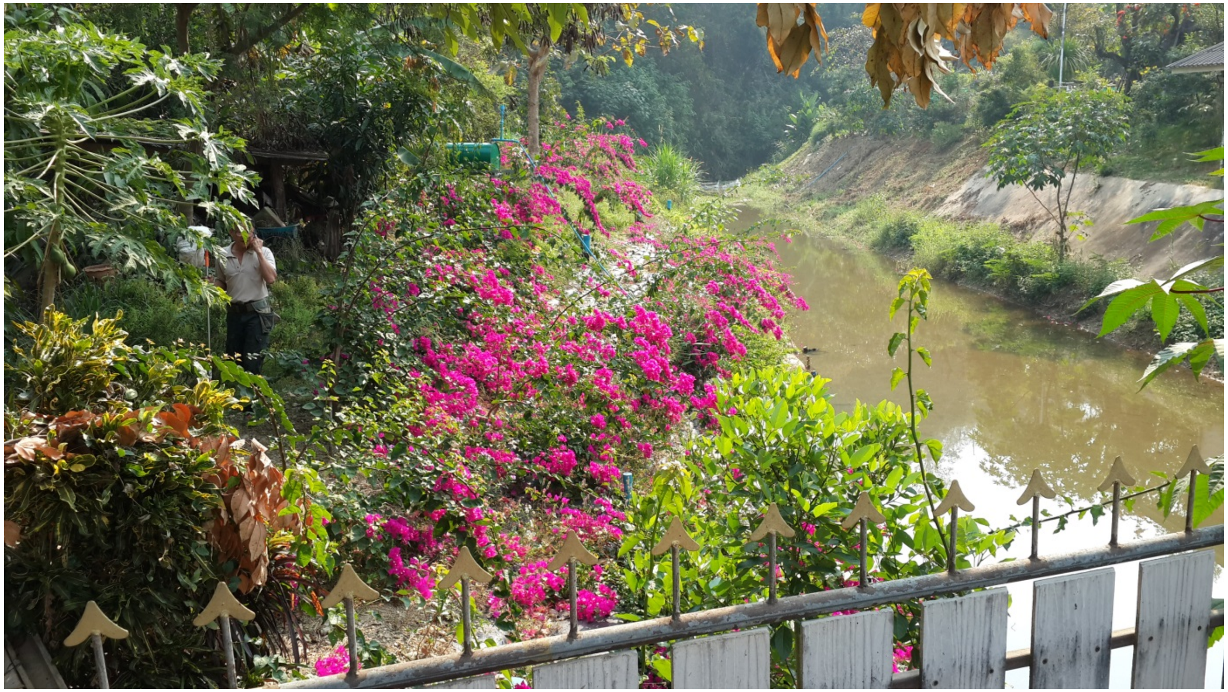


4 different designs of bio slope engineering including green gabion, geotextile bags, vegetated flapped soil bags, erosion control mat, erosion control logs

Construction

Flapped soil bag (*Do-Now*) with extension wings

Live stake of *Bougainvillea spectabilis*



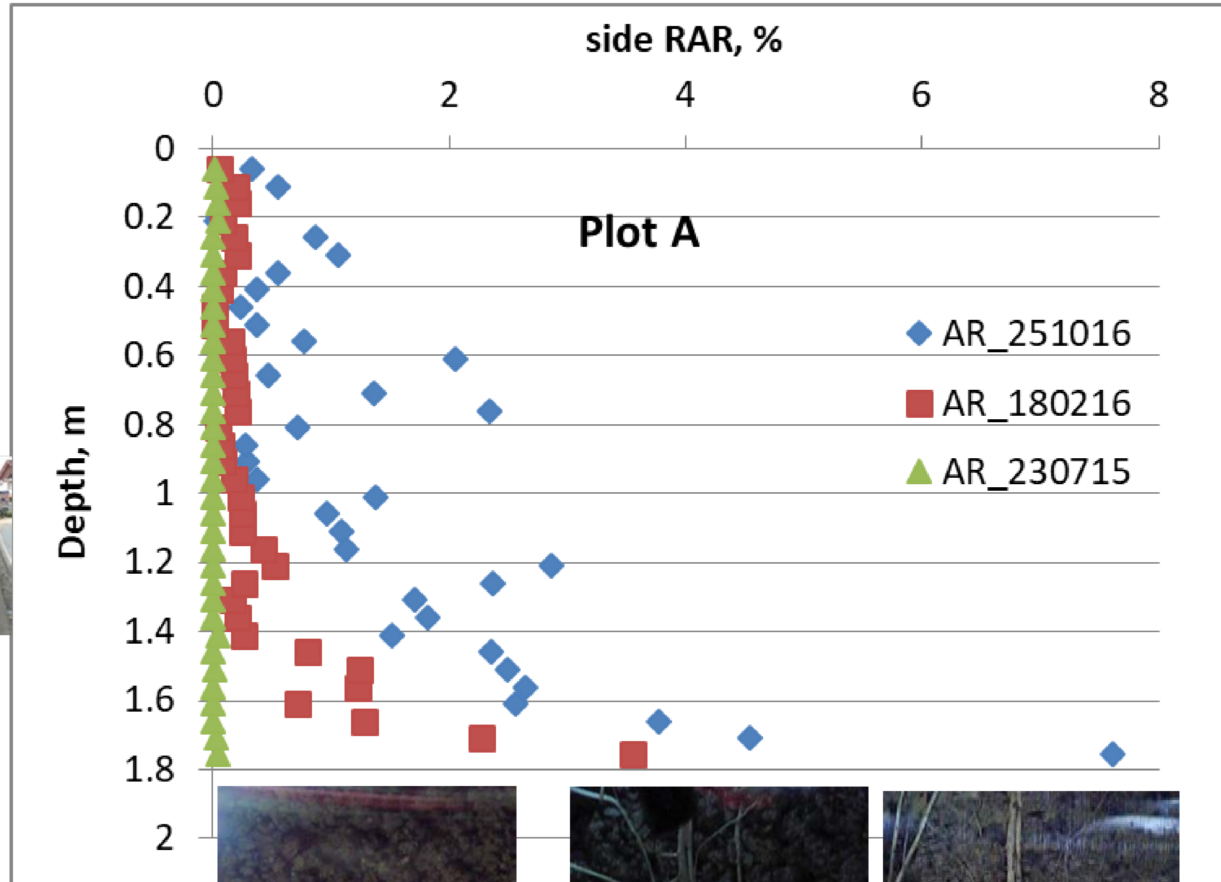
18 Feb
2016

31 มกราคม 2558

28 พฤษภาคม 2558

18 กุมภาพันธ์ 2559

26 ตุลาคม 2559



Root content tends to increase more at the end of live stake therefore providing more reinforcement at a greater depth.

Conclusions

- Minirhizotron can be used to track the change in root area ratio with time in a bio-engineered slope and thus can be used to estimate the root cohesion and factor of safety of the slope at different times based on laboratory-based shear strength. This technique can be used to track the time-dependent change in performance of bio-slope stabilization in the practice
- For the case study of slope along Highway no 44 in Southern Thailand the roots were most effective in improving the factor of safety of slope in saturated condition at the 0.5m depth. (shallow stabilization)
- Field observation showed changing root concentration with time and depth, also dependent on growing technique (Live stake) and maintenance. Vetiver roots may decay when invaded by local species leading to destabilizing effect for steep slope (>60^{o}). Thus the mini-rhizotron can be used for monitoring performance of bio-engineered slope in the long term.

Acknowledgements

The authors gratefully acknowledge the financial support and encouragement by

- Chaipattana Foundation,
- Sustainable Energy Foundation,
- Kasetsart University Research and Development Institute (KURDI), Thailand.
- Office of the Royal Development Projects Board
- Ban-natum & Lablae communities
- Department of Highways

Thank you very much for your attentions

Terima kasih