NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

STATE OF THE ARTS WEBINAR

Unsaturated Soil Mechanics in Singapore

Presented by

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Singapore

Acknowledgement

NTU: Leong Eng Choon, Alfrendo Satyanaga, Vincent Heng, Qin Xiaosheng, Jason Gasmo, Kip Hritzuk, Michael Deutshcer, I Gde Budi Indrawan, Henry Krisdani, Fakhrur Rozy Harnas, Lim Shiyi, Rahimi Arezoo, Zhu Yusi, Yongmin Kim, Nurly Gofar, Vera Hie, Zhai Qian, Sugeng Krisnanto, Arun Prasad, Rayner Wee Jian Dee, Margarit Mircea Nistor, Jason Nong, Li Yangyang, Abdul Halim Hamdany, Jimmy Shen, Saranya Rangarajan

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BCA: Thanabal Kaliannan, Aaron Sham Wai Lun, Poh Teoh Yaw

SLA: Lilian Chua, Wu Hongjun

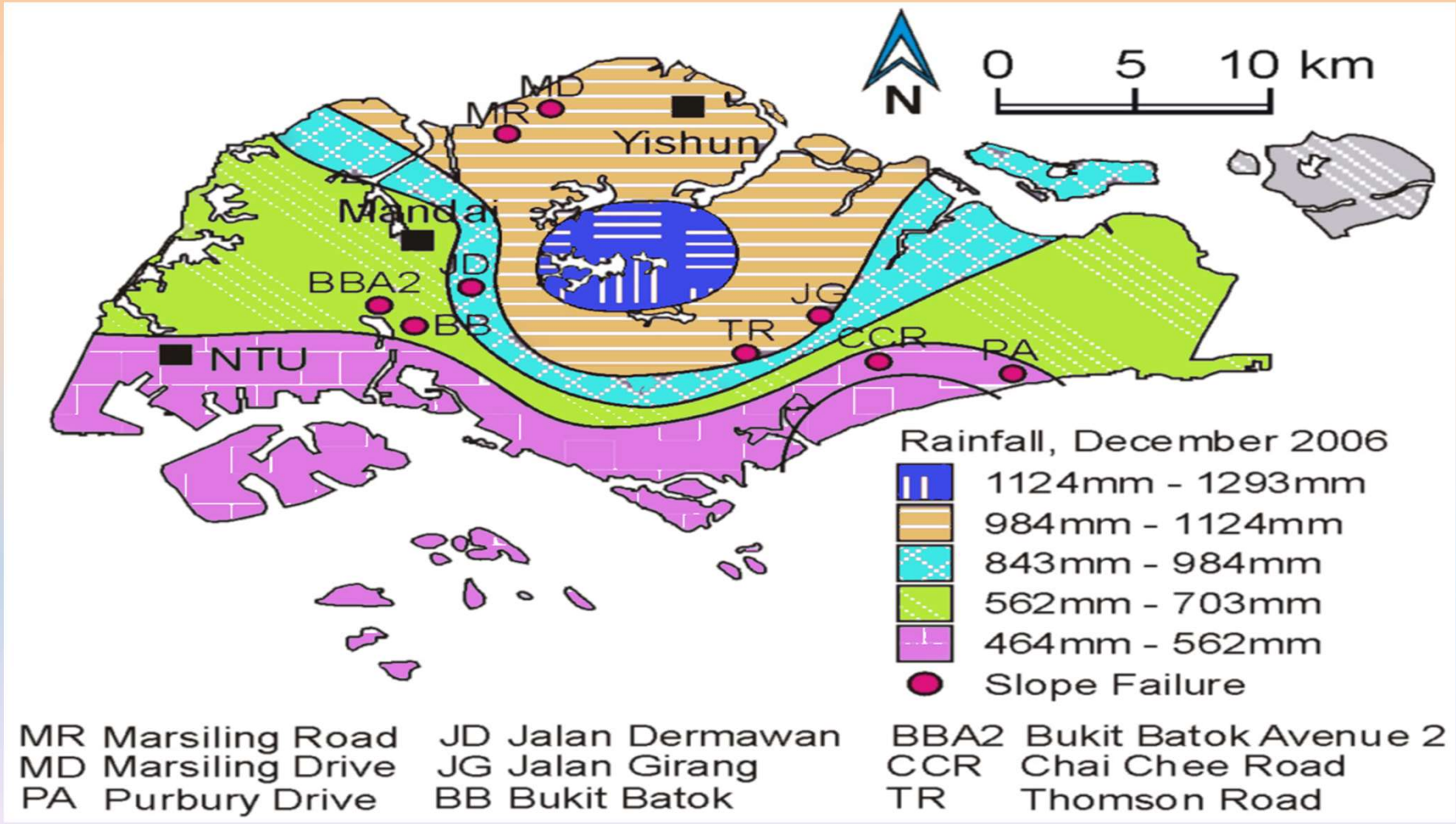
HSR, Switzerland: Hermann Mettler, Hans Schneider

Politenico Di Torino, Italy: Gabriele D'Amore

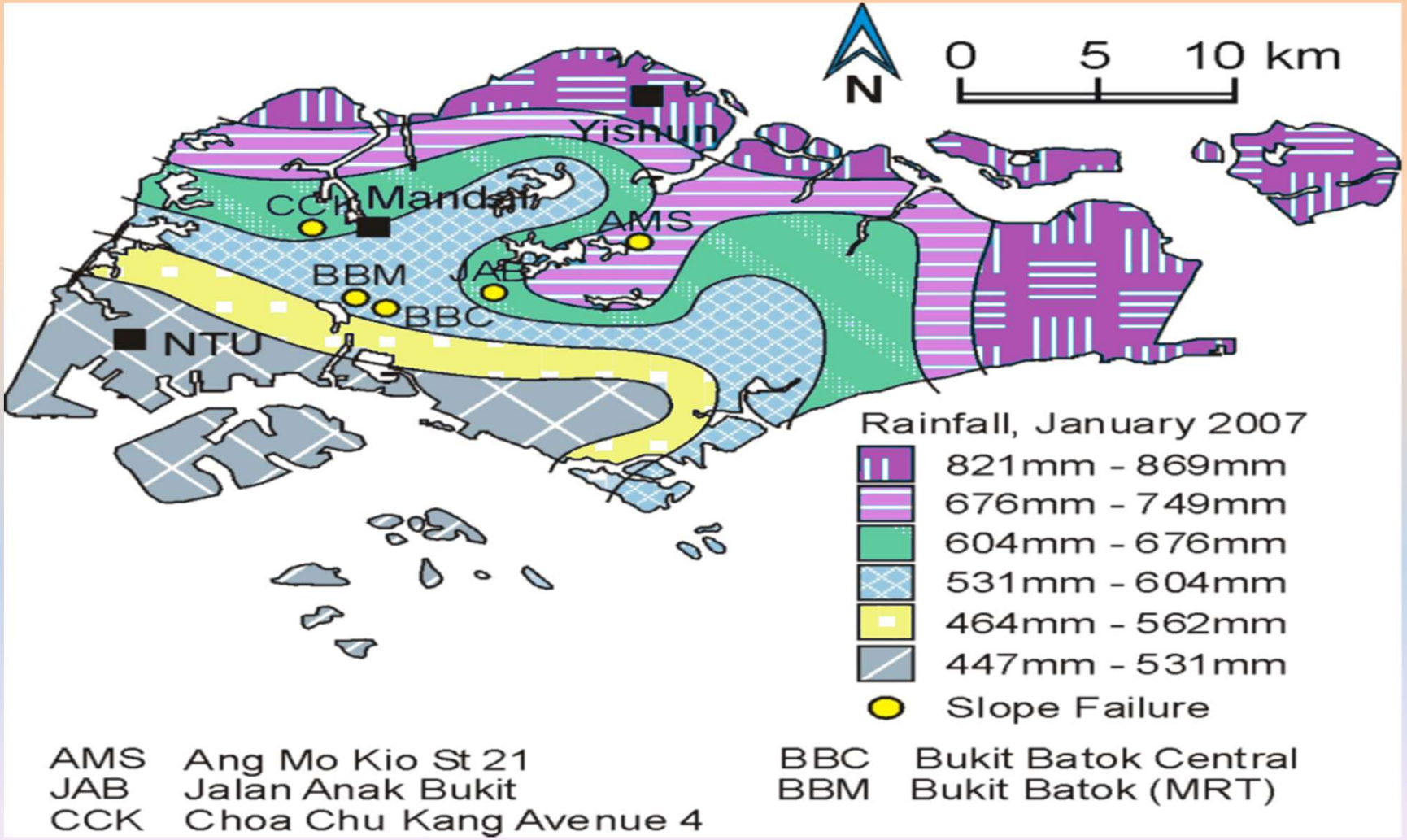
Slope Failure at Bukit Gombak, Singapore (1989)

Slope Failure in Bukit Batok, Singapore (2006)

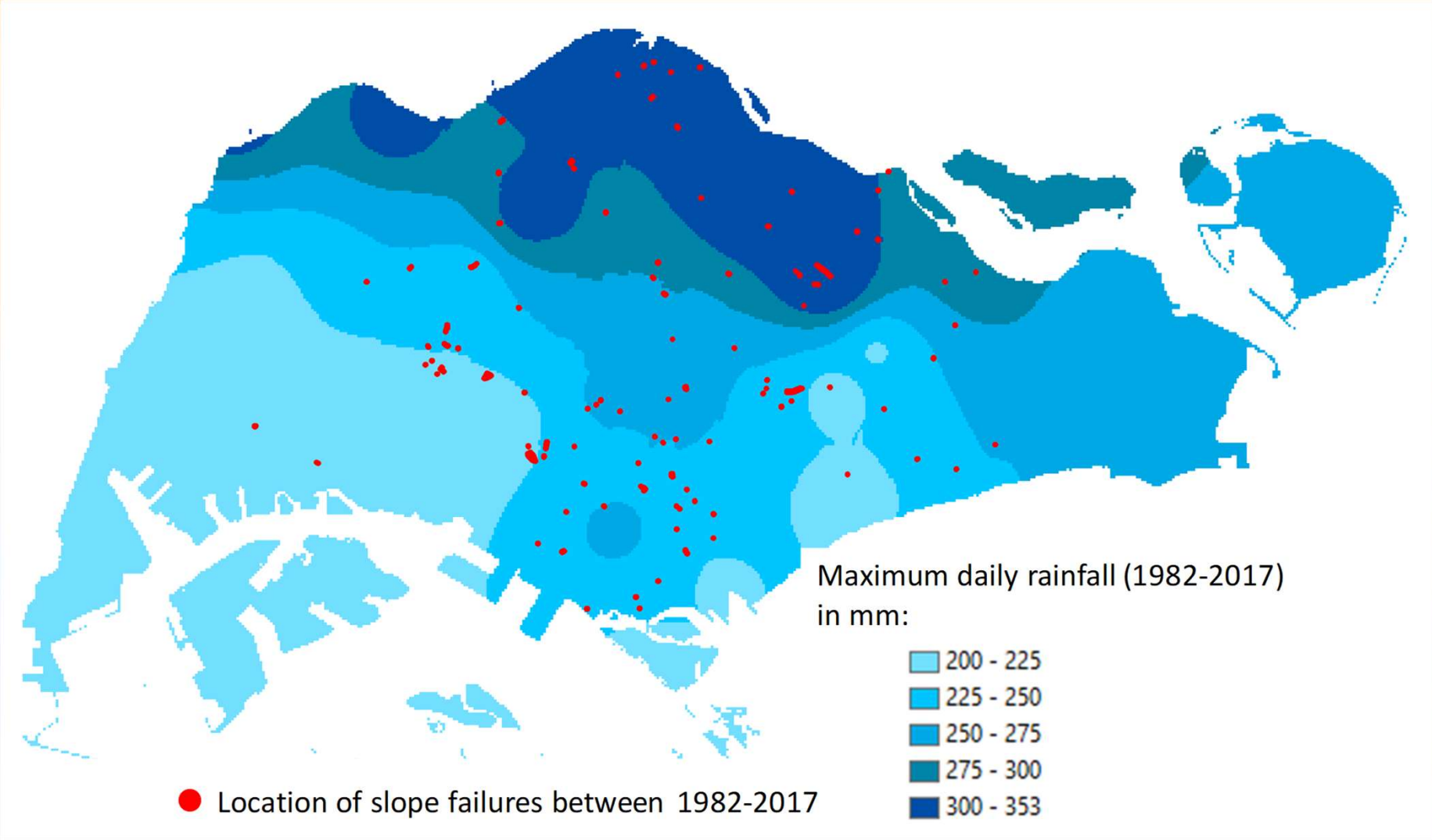
Distribution of Rainfall and Slope Failures during The Month of December 2006 (after National Environmental Agency, 2006)



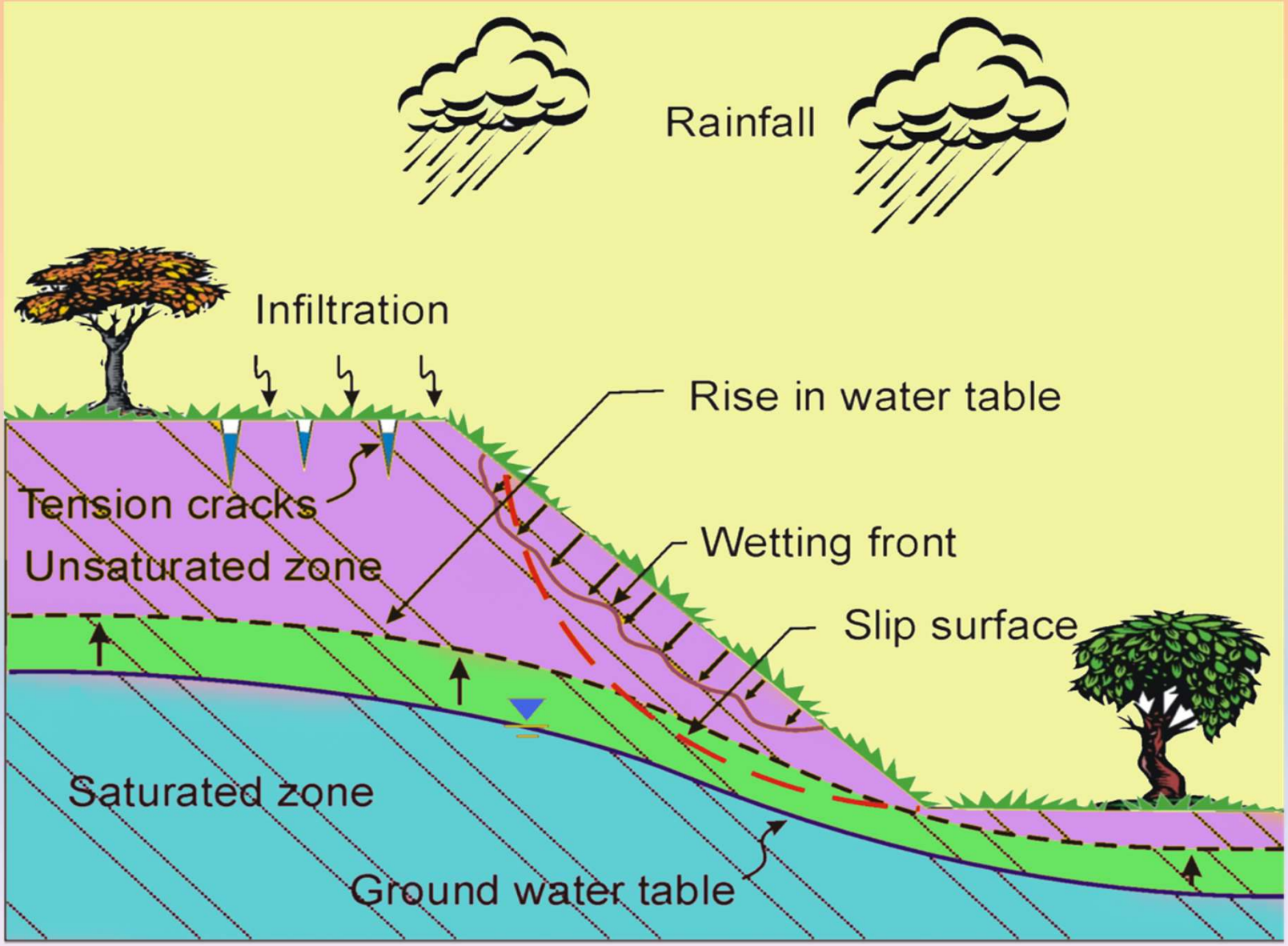
Distribution of Rainfall and Slope Failures during The Month of January 2007 (after National Environmental Agency, 2006)



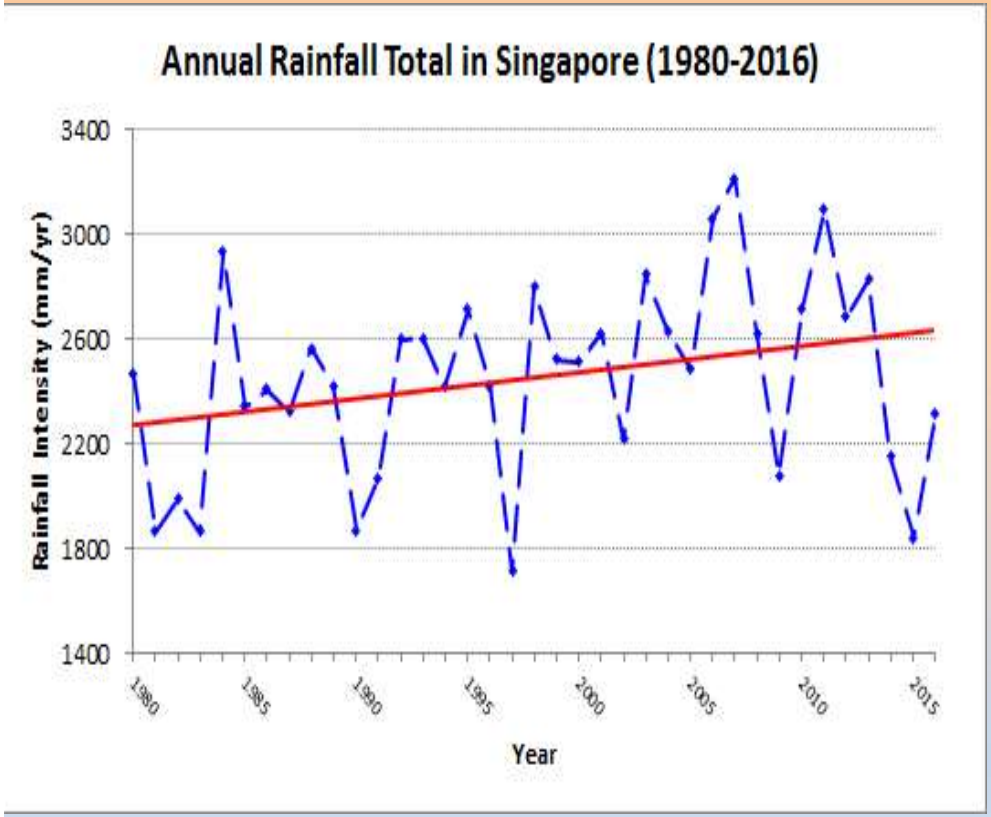
Location of Historical Slope Failures between 1982-2017 in Singapore

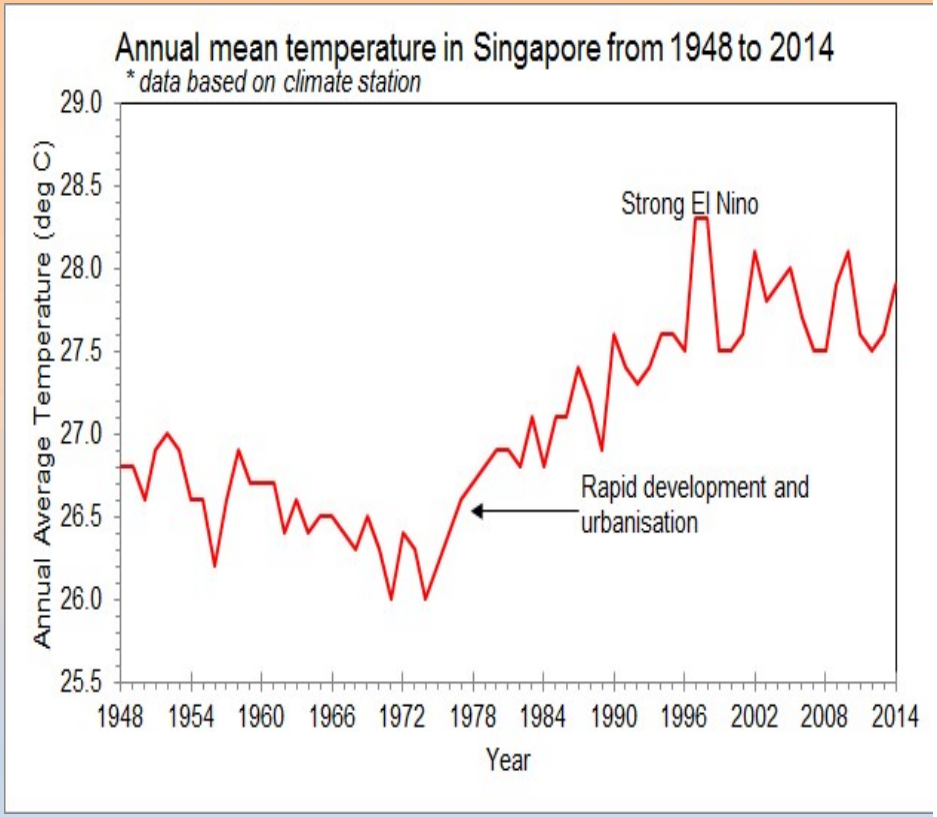


Rainfall-induced Slope Failures



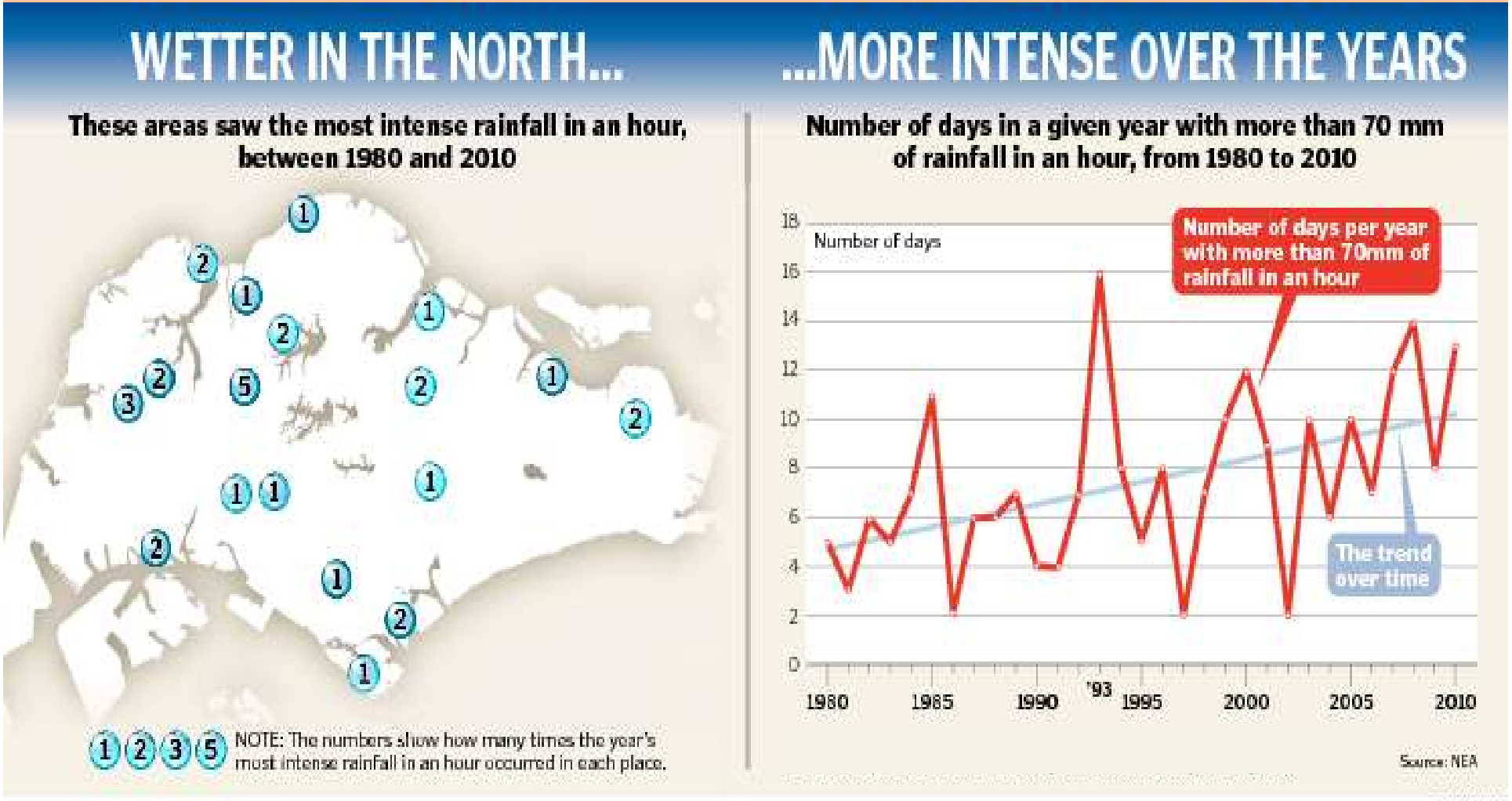
Climate Change in Singapore

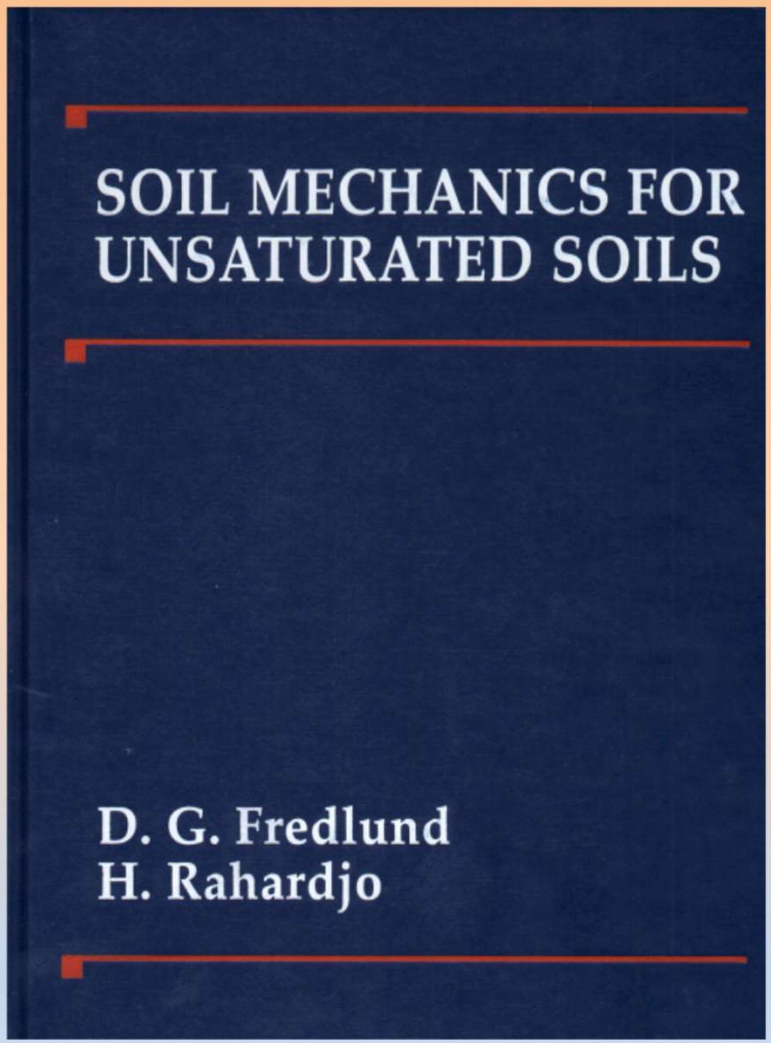




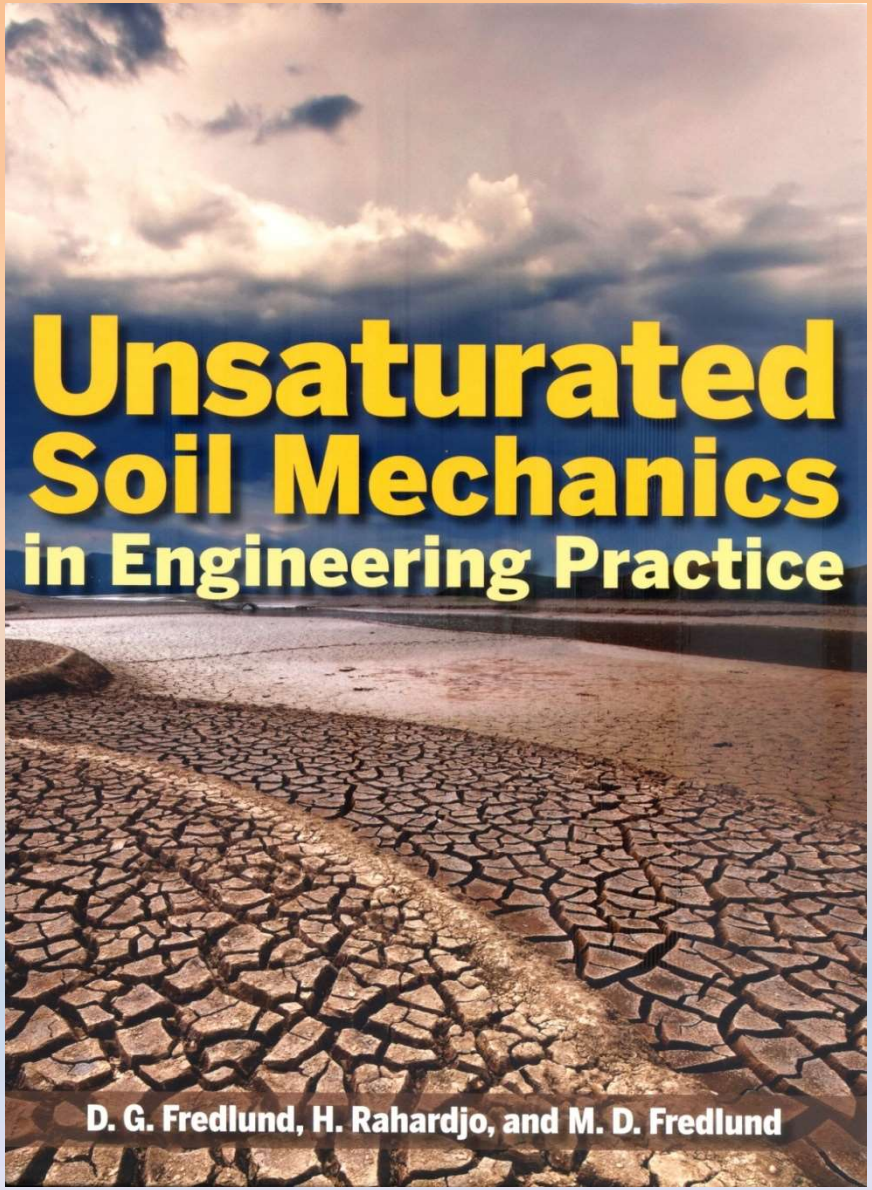
Data taken from http://www.weather.gov.sg/climate-past-climate-trends/

Climate Change in Singapore





First textbook on Unsaturated Soil Mechanics. Published by John Wiley in 1993, translated into Chinese in 1997



ENGINEERING/CIVIL

The definitive guide to unsaturated soil—from the world's experts on the subject

This book builds upon and substantially updates Fredlund and Rahardjo's publication, *Soil Mechanics for Unsaturated Soils*, the current standard in the field of unsaturated soils. It provides readers with more thorough coverage of the state of the art of unsaturated soil behavior and better reflects the manner in which practical unsaturated soil engineering problems are solved. Retaining the fundamental physics of unsaturated soil behavior presented in the earlier book, this new publication places greater emphasis on the importance of the "soil-water characteristic curve" in solving practical engineering problems, as well as the quantification of thermal and moisture boundary conditions based on the use of weather data. Topics covered include:

- Theory to Practice of Unsaturated Soil Mechanics
- Nature and Phase Properties of Unsaturated Soil
- State Variables for Unsaturated Soils
- Measurement and Estimation of State Variables
- Soil-Water Characteristic Curves for Unsaturated Soils
- Ground Surface Moisture Flux Boundary Conditions
- Theory of Water Flow through Unsaturated Soils
- Solving Saturated/Unsaturated Water Flow Problems
- Air Flow through Unsaturated Soils
- Heat Flow Analysis for Unsaturated Soils
- Shear Strength of Unsaturated Soils
- Shear Strength Applications in Plastic and Limit Equilibrium
- Stress-Deformation Analysis for Unsaturated Soils
- Solving Stress-Deformation Problems with Unsaturated Soils
- Compressibility and Pore Pressure Parameters
- Consolidation and Swelling Processes in Unsaturated Soils

Unsaturated Soil Mechanics in Engineering Practice is essential reading for geotechnical engineers, civil engineers, and undergraduate- and graduate-level civil engineering students with a focus on soil mechanics.

D.G. FREDLUND is the author or coauthor of over 460 refereed journal articles, conference proceedings, technical papers, and chapters in edited collections. In 1993, he coauthored *Soil Mechanics for Unsaturated Soils*, the first major text on unsaturated soil mechanics published. He has served as a research consultant to the Government of Hong Kong, U.S. Army Corps of Engineers, and Saskatchewan Highways, and presently is head of the Golder Unsaturated Soils Group, Canada. H. RAHARDJO is head of the Division of Infrastructure Systems and Maritime Studies at the School of Civil and Environmental Engineering at Nanyang Technological University in Singapore. He is the coauthor of *Soil Mechanics for Unsaturated Soils* and over 200 technical publications. M. D. FREDLUND is the President/CEO of SoilVision Systems, Canada, a geotechnical/hydrological software development and numerical modeling company.

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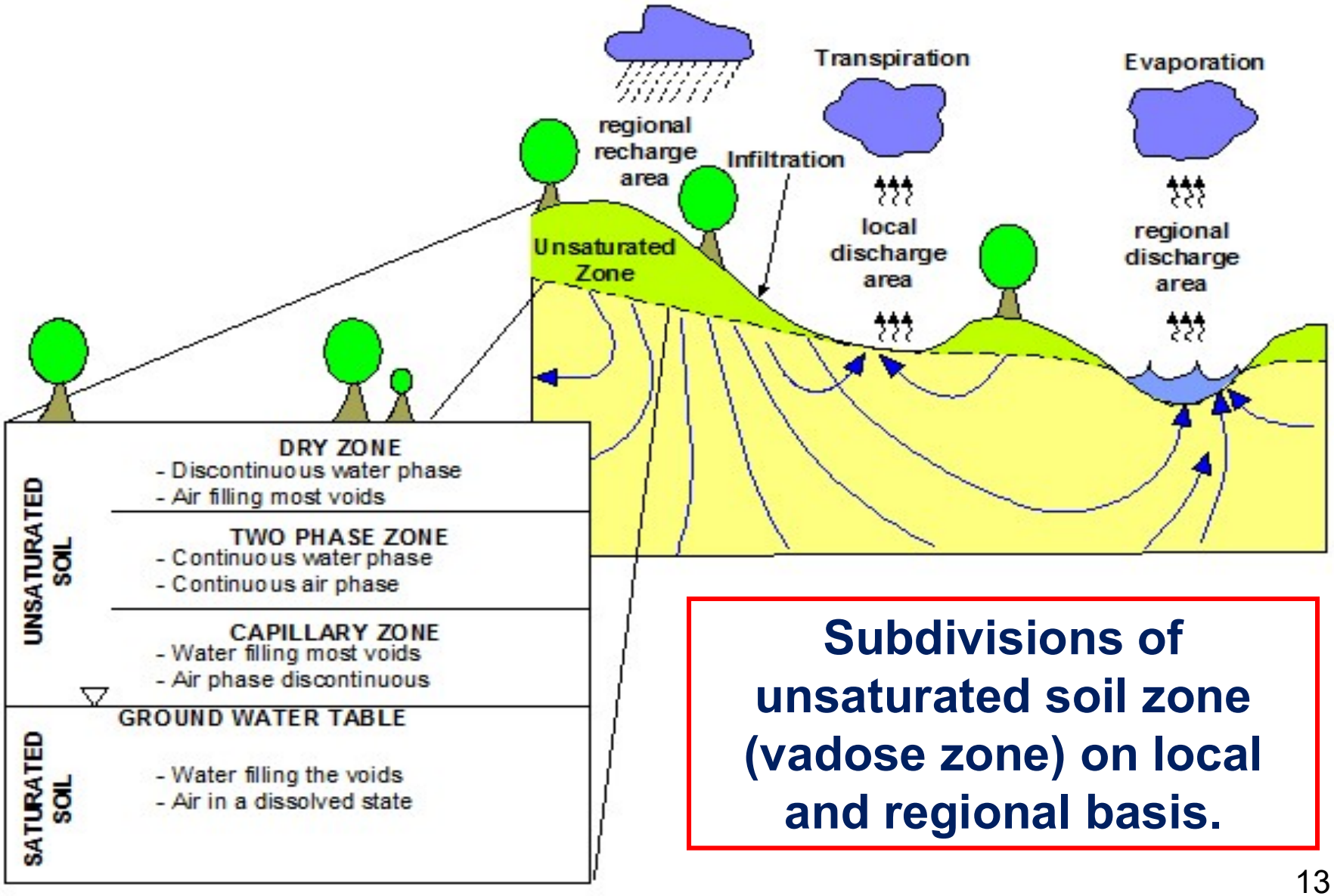
Second Textbook on Unsaturated Soil Mechanics. Published by John Wiley in 2012

Natural Condition of Unsaturated Soils – Soils above Ground Water Table



Subdivisions of unsaturated soil zone (vadose zone) on local and regional basis.

Man made Unsaturated Soils - Compacted Soil

Separation of Saturated and Unsaturated Soil Mechanics

UNSATURATED SOIL MECHANICS

Negative pore-water pressure

Net normal stress $(\sigma - u_a)$ $(u_a - u_w)$ Matric suction

Water table

Effective stress $(\sigma - u_w)$

Positive pore-water pressure

SATURATED SOIL MECHANICS

Unsaturated Soil Mechanics Principle

Two independent stress tensors to represent the stress state of an unsaturated soil:

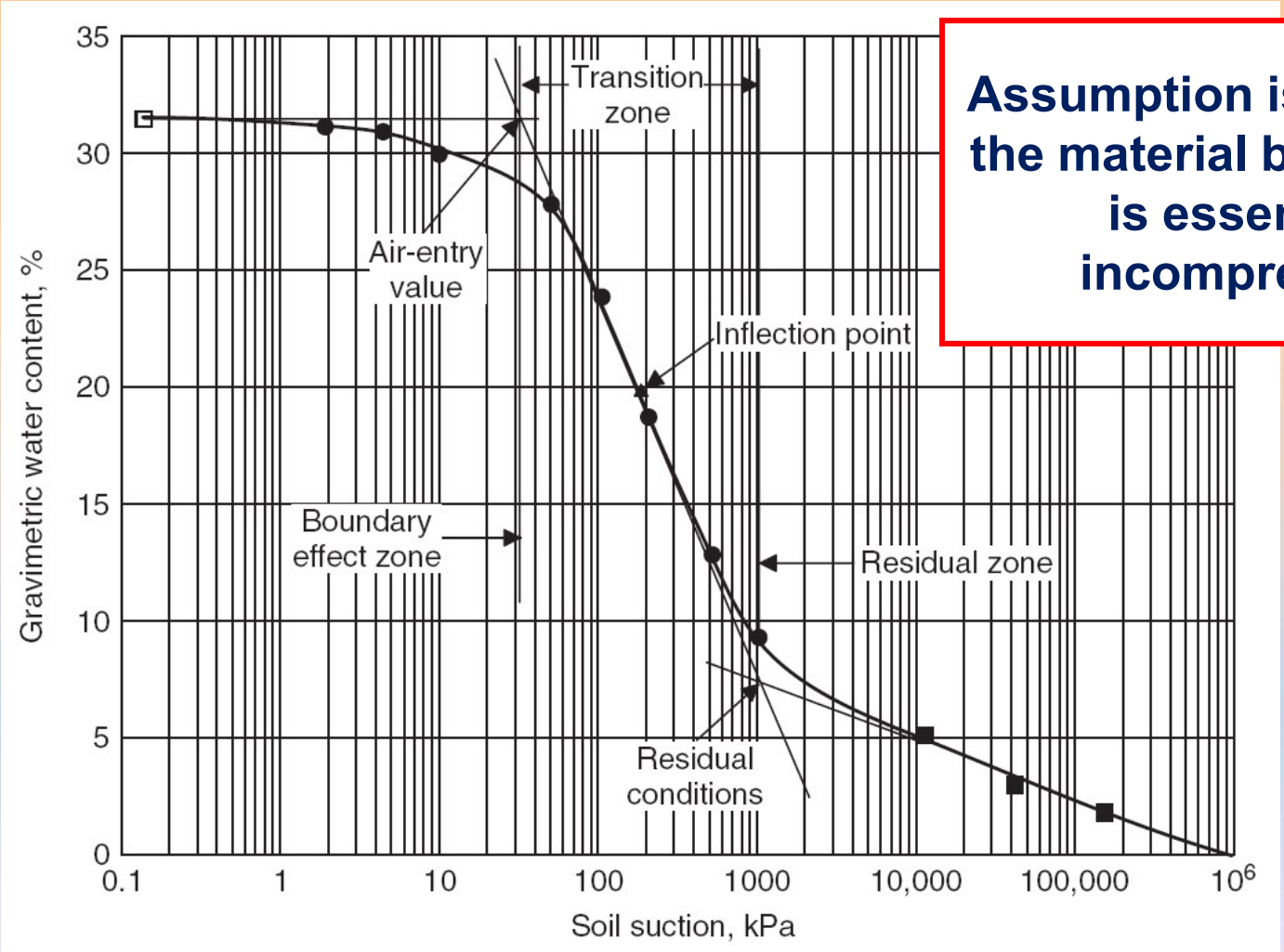
$$\begin{bmatrix} (\sigma_x - u_a) & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & (\sigma_y - u_a) & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & (\sigma_z - u_a) \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} (u_a - u_w) & 0 & 0 \\ 0 & (u_a - u_w) & 0 \\ 0 & 0 & (u_a - u_w) \end{bmatrix} \quad (2)$$

Single stress tensor to represent the stress state of a saturated soil, i.e., effective stress:

$$\begin{bmatrix} (\sigma_x - u_w) & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & (\sigma_y - u_w) & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & (\sigma_z - u_w) \end{bmatrix} \quad (1)$$

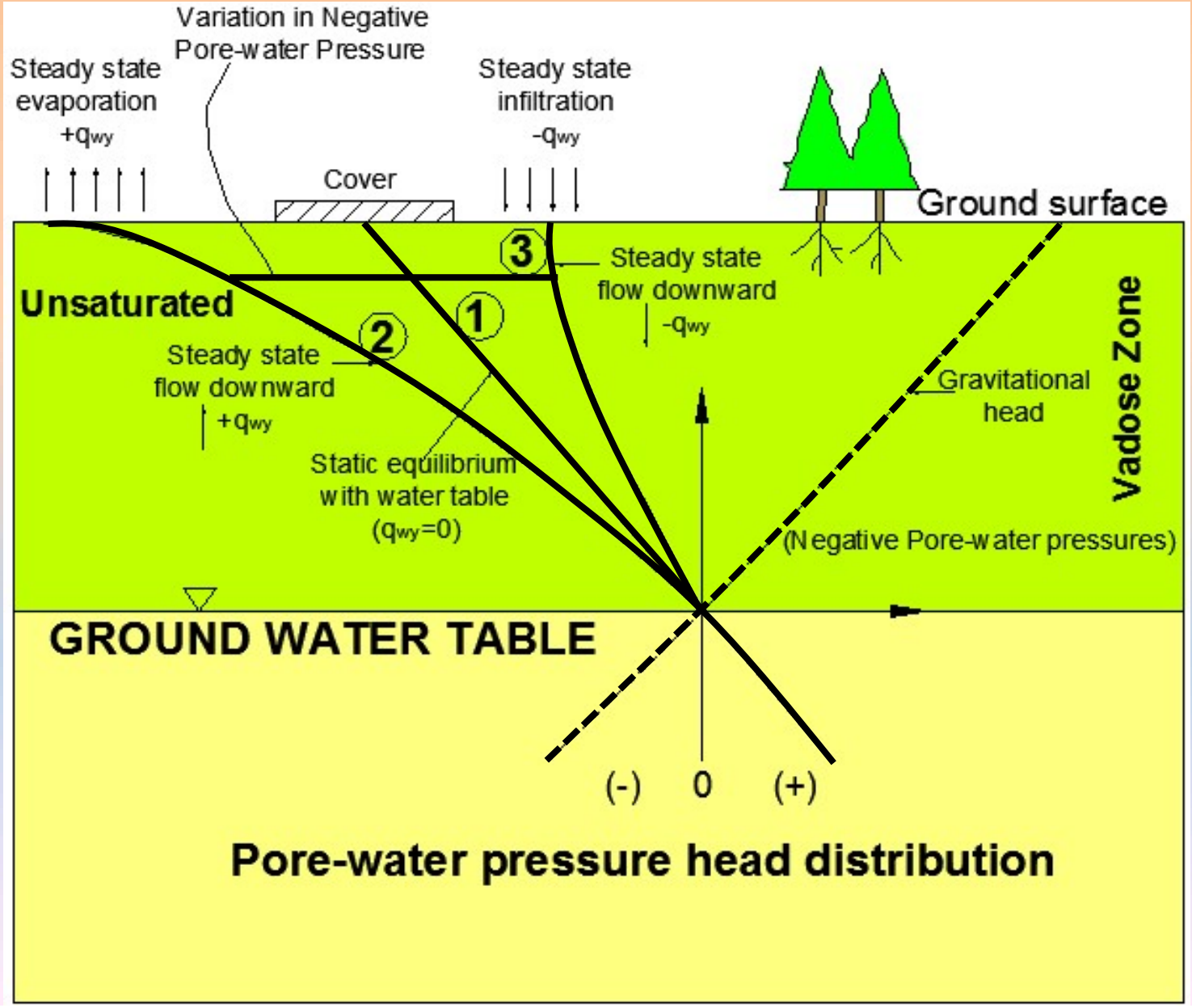
Soil-water Characteristic Curve (SWCC)



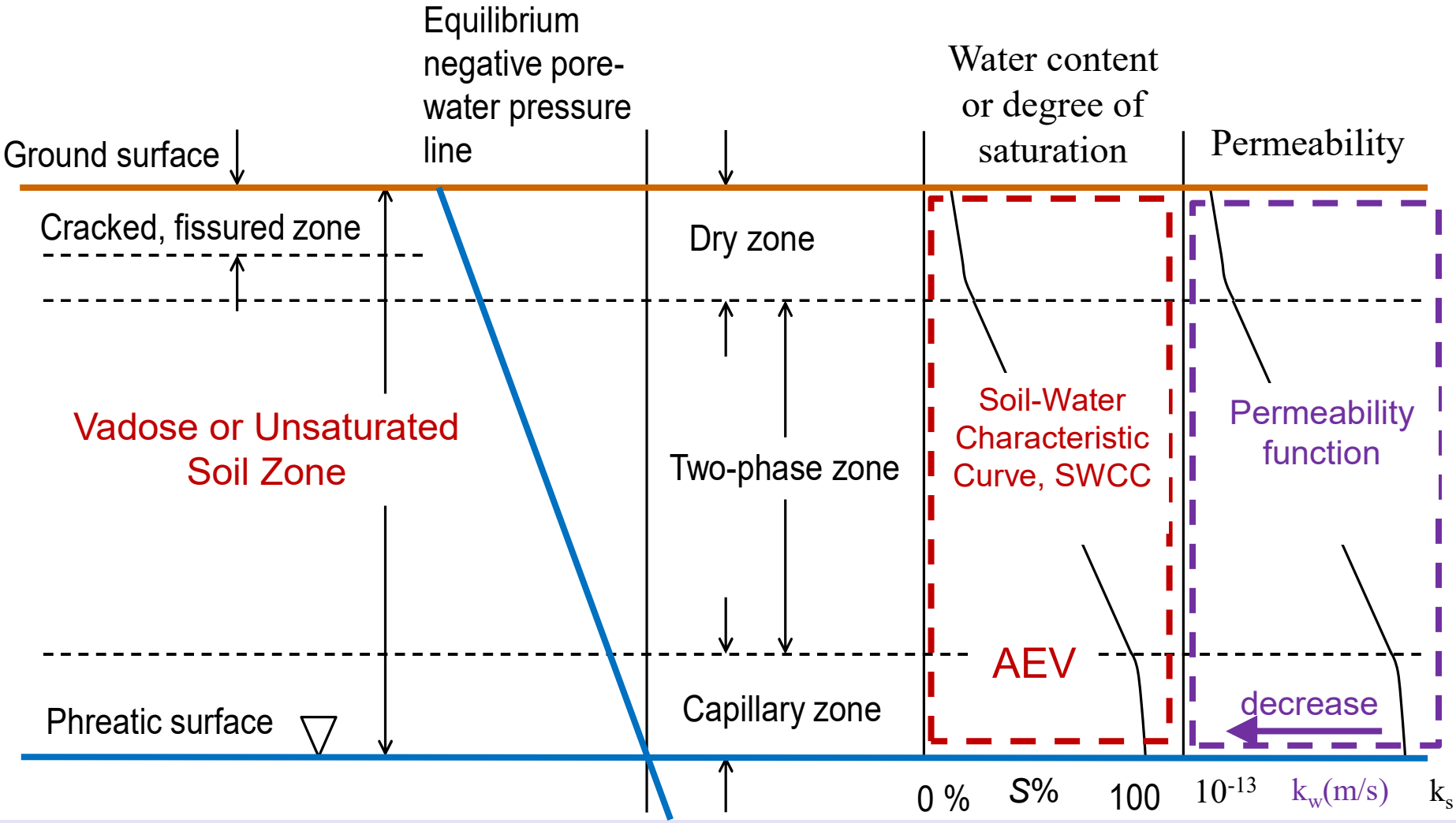
Assumption is made that the material being tested is essentially incompressible

Typical desorption SWCC showing distinct zones of desaturation

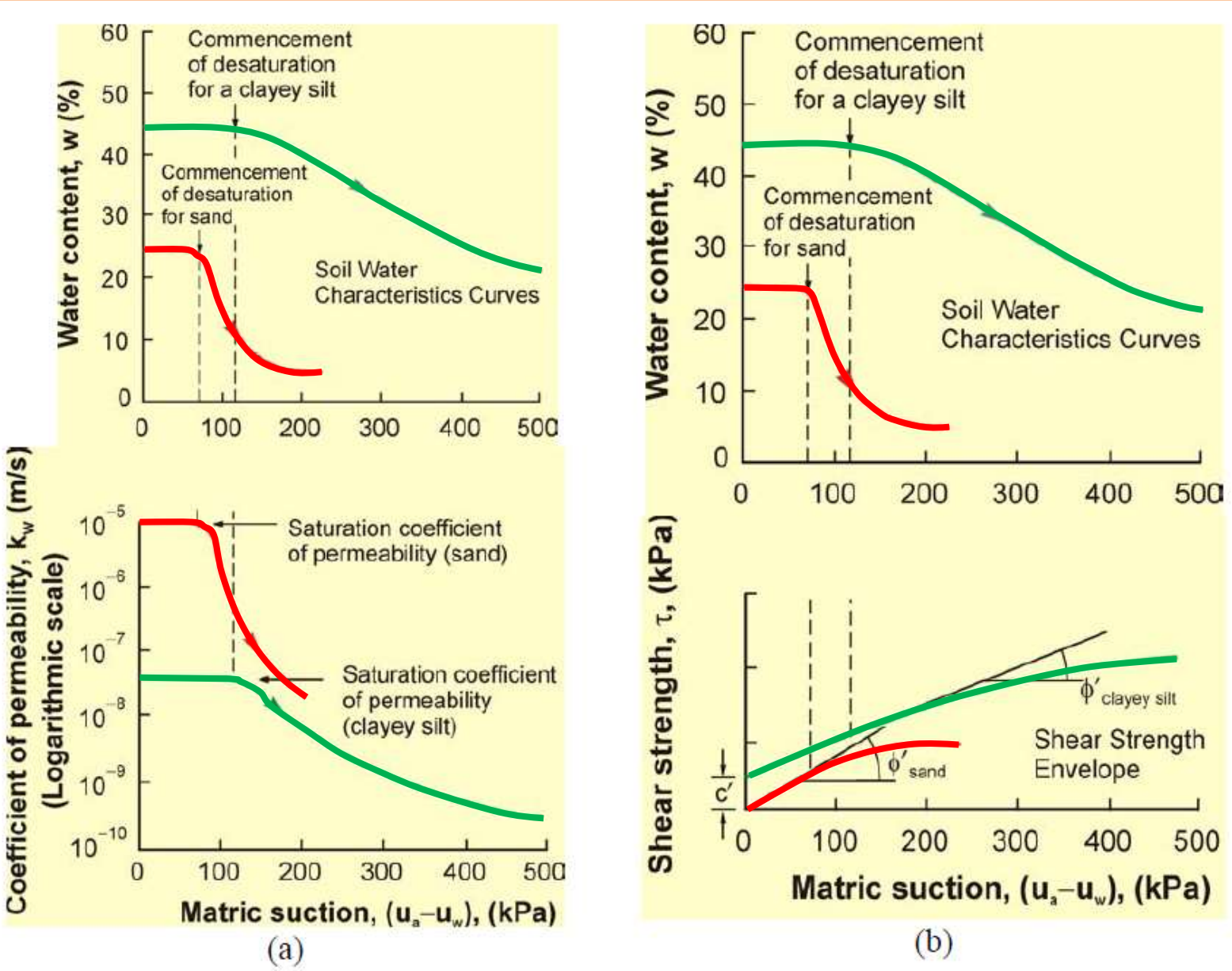
Illustration of The Vadose Zone in Soil Layer (Modified from Fredlund and Rahardjo, 1993)



Water Contents in an Unsaturated Soil?

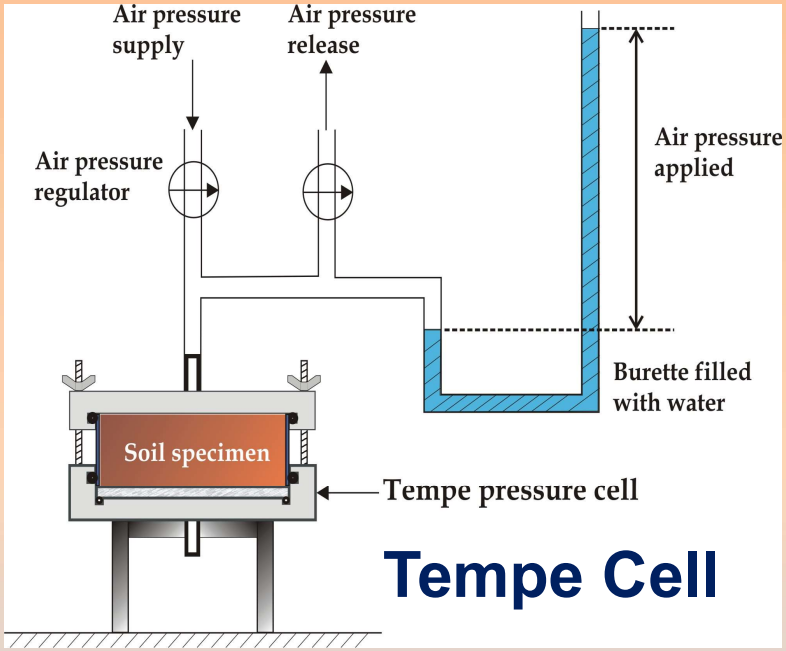


Relationship between SWCC and Permeability Function and Shear Strength

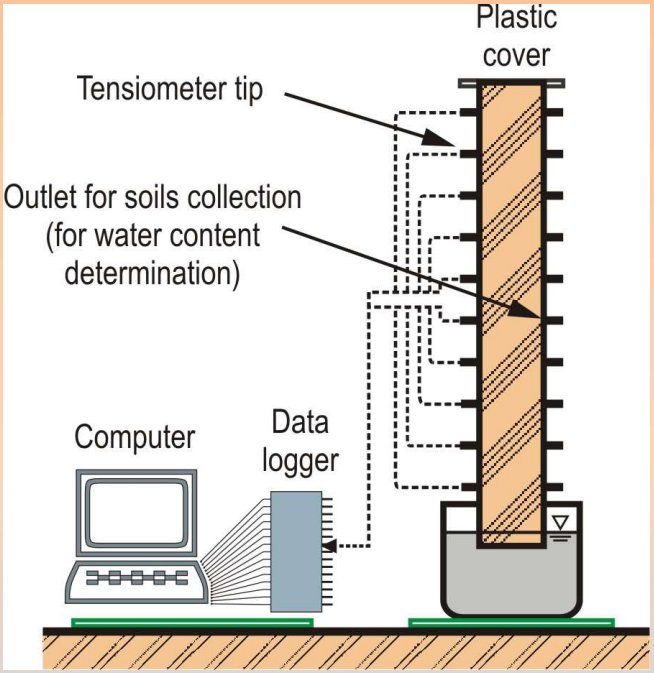


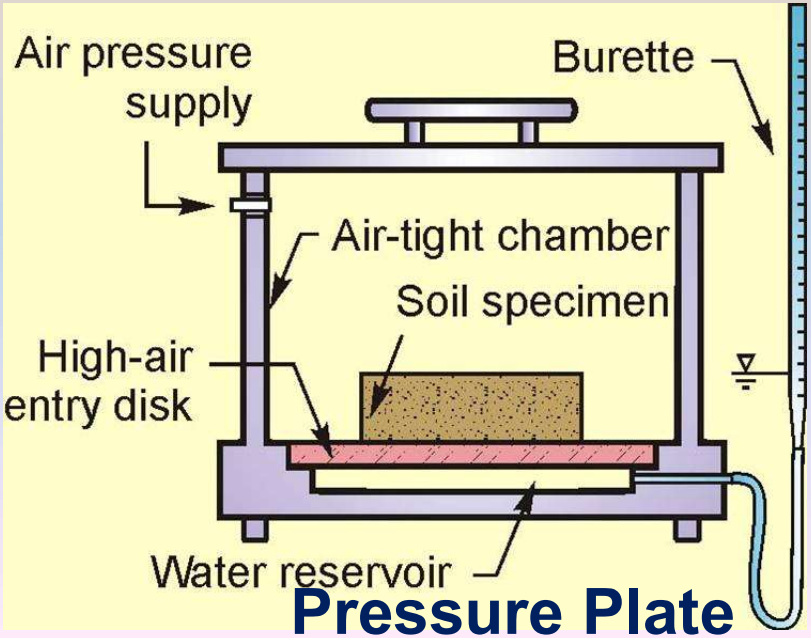
Characterization of Unsaturated and Saturated Properties of Residual Soils in Singapore

Soil-water Characteristic Curve Testing

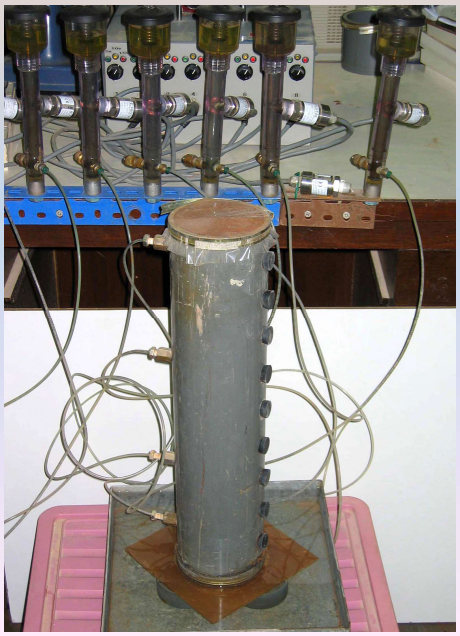


Tempe Cell



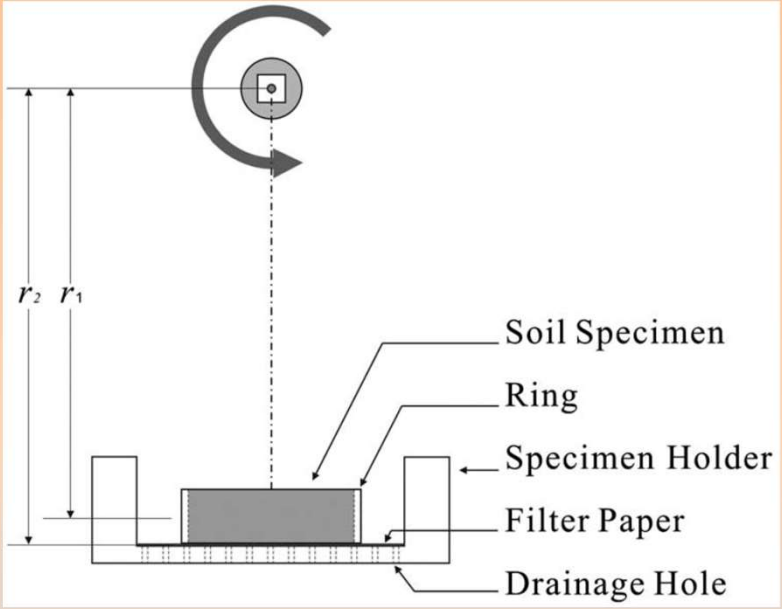


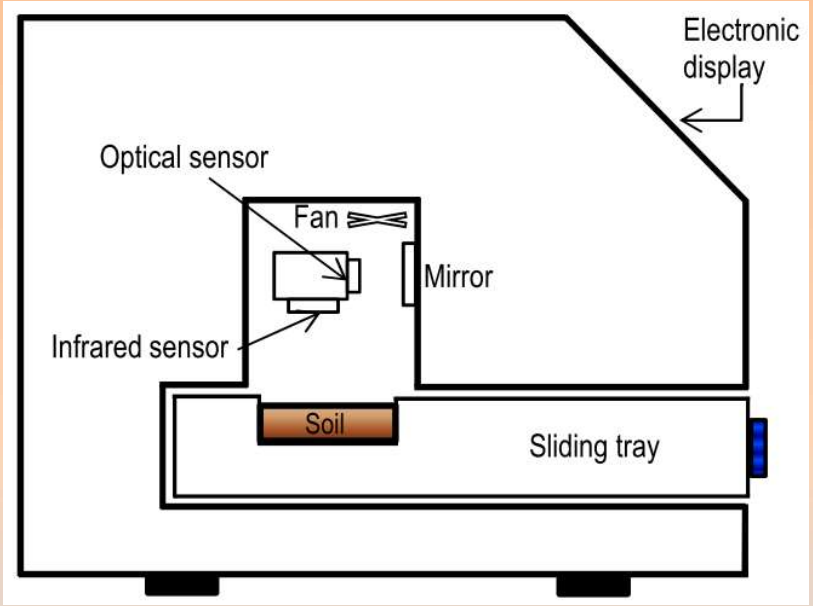
Pressure Plate



Capillary rise test (for the measurement of wetting SWCC)

Rapid Measurement of SWCC

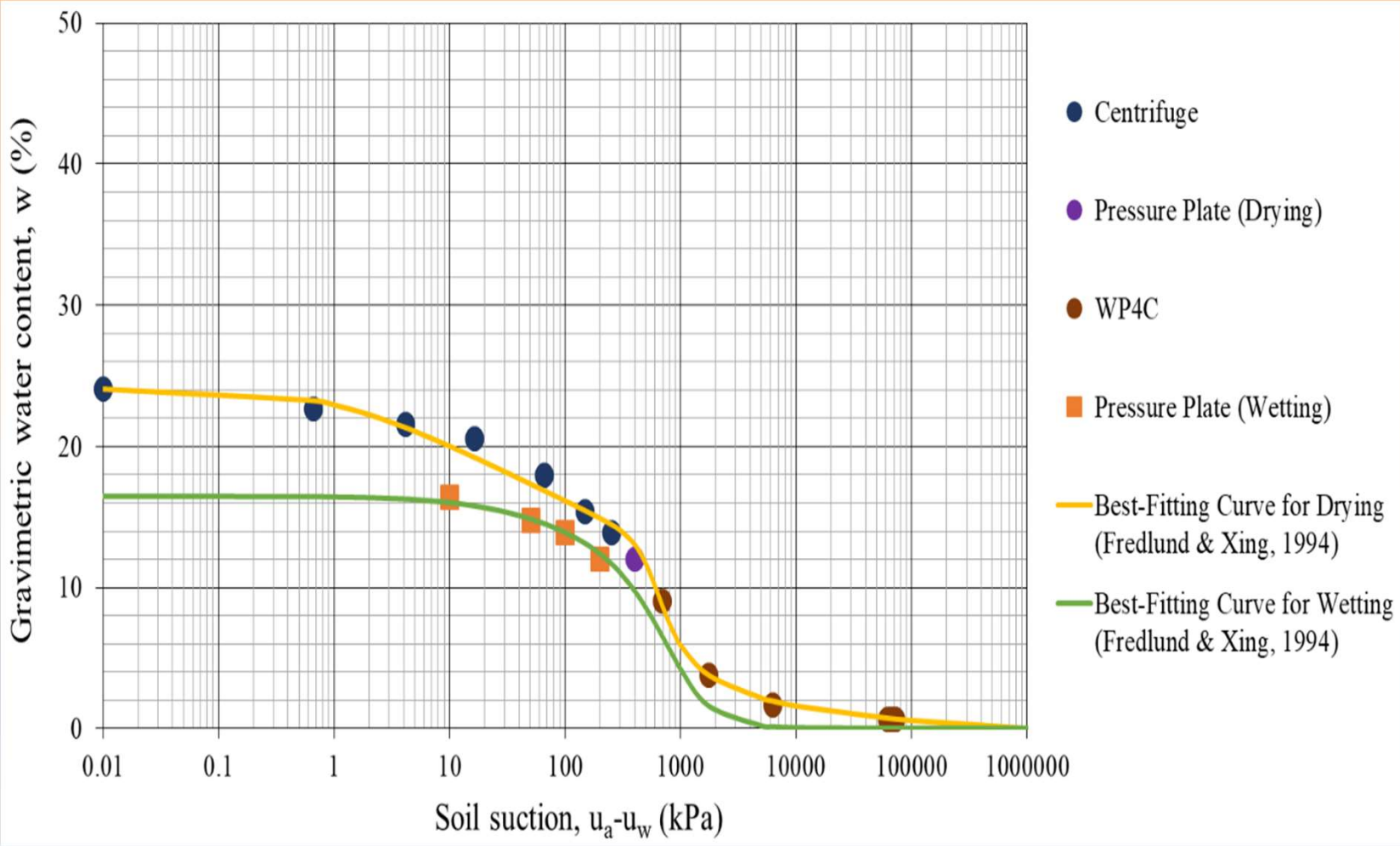




Small-scale centrifuge

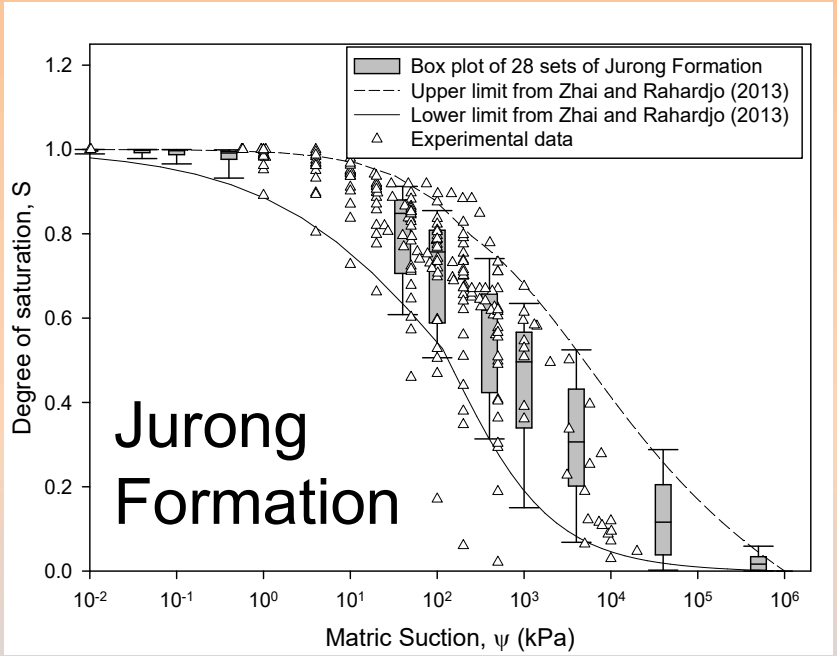
Dew Point Potentiometer

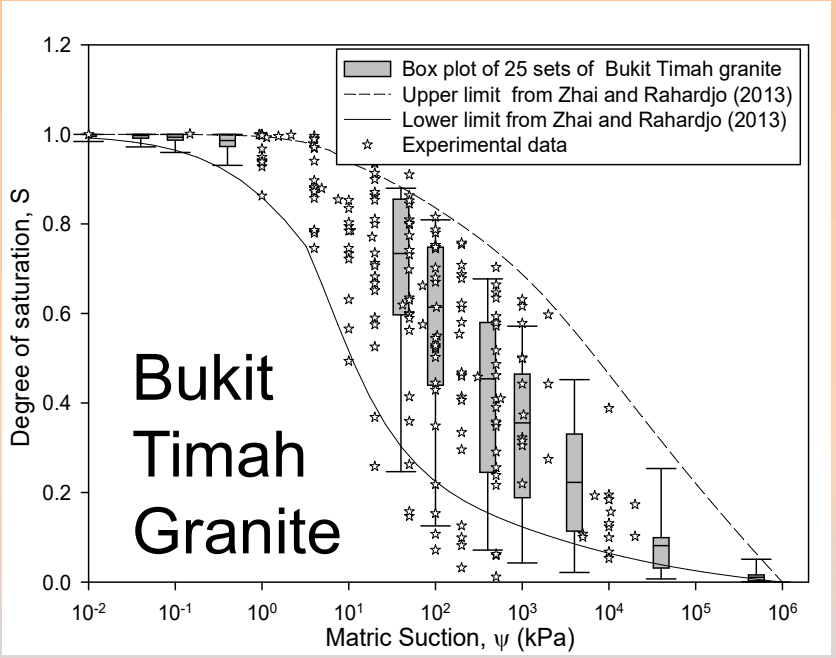
SWCC test from Centrifuge, Pressure Plate and WP4C

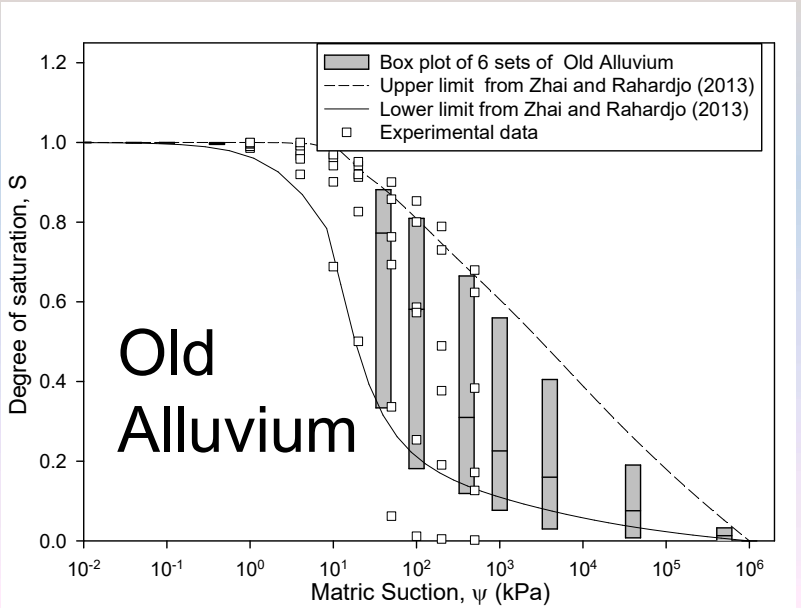


Residual soil from Buangkok Link

SWCC of Residual Soils in Singapore



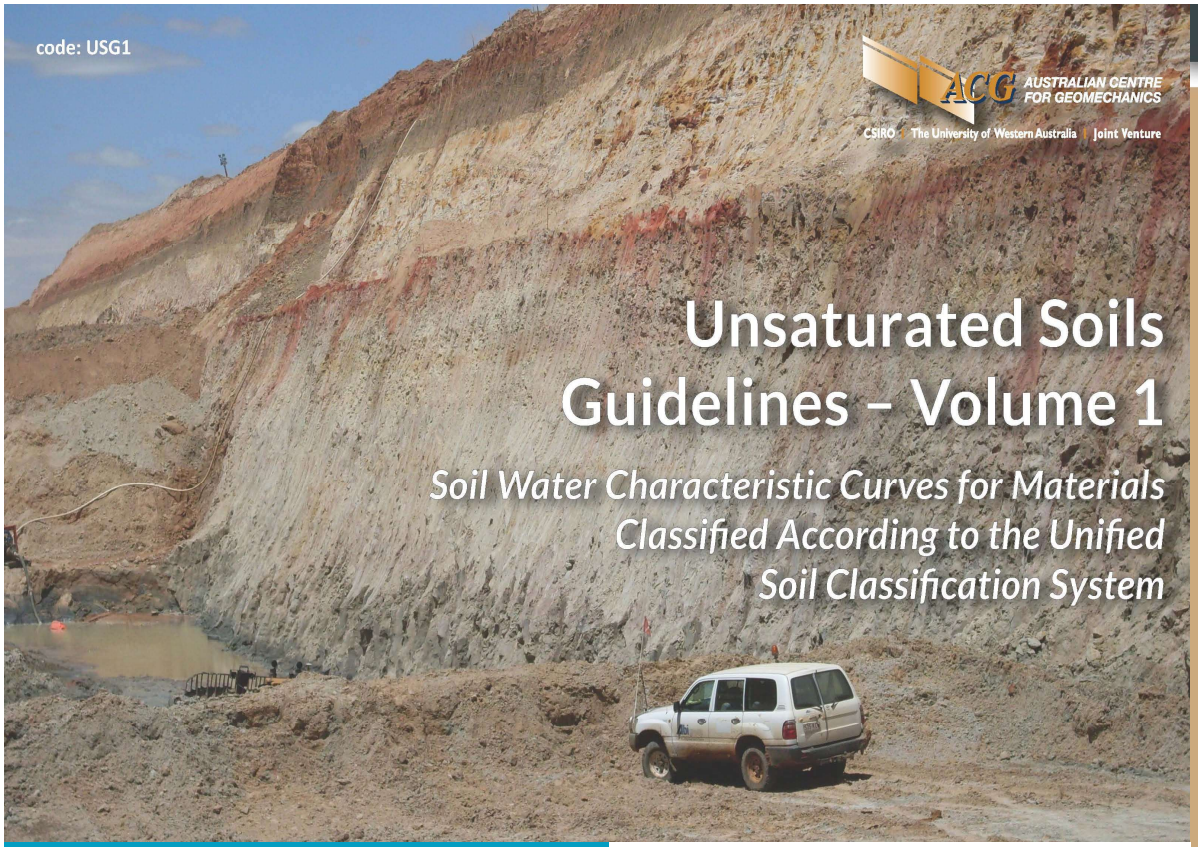




SWCC Parameters of residual soil parameters in Singapore

Soil	Air-entry value (kPa)	Saturated water content	Residual suction (kPa)	Residual water content
Sedimentary Jurong Formation	1 to 116	0.3 to 0.60	1500 to 18000	0.025 to 0.100
Bukit Timah Granite	0.8 to 25	0.21 to 0.61	106 to 12000	0.015 to 0.098
Old Alluvium	5 to 25	0.24 to 0.5	42 to 12000	0.009 to 0.098

code: USG1



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Unsaturated Soils Guidelines – Volume 1

Soil Water Characteristic Curves for Materials Classified According to the Unified Soil Classification System

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Guidelines content

Soil-water characteristic curve (SWCC) defines the relationship between water content and suction (negative pore-water pressure) of the soil. SWCC is used for modelling water flow through saturated-unsaturated system and for estimating the engineering properties of unsaturated soil, such as the permeability and shear strength of unsaturated soil.

The objective of the guidelines is to correlate and present the SWCC statistics categorised according to the ASTM D2487-11 American Standard, the basis of which is the Unified Soil Classification System (USCS).

Unsaturated Soil Guidelines

1) Introduction to the guidelines.
2) An overview of the UCSC classification system and summary of the theory of soil grading, Atterberg Limits and SWCC.
3) Presentation of the maximum, minimum and typical GSD of each of the classified soil groups together with Atterberg Limit ranges.
4) SWCC data and interpretations collected for the different soil classifications providing best-fit equation parameters for unimodal curves.
5) SWCC data and interpretations collected for the different soil classifications providing best-fit equation parameters for bimodal curves.
6) Guidelines for undertaking laboratory testing and interpretation of results.

With a foreword given by Professor Delwyn G. Fredlund, the leading authority on unsaturated soil mechanics:

"The guideline forms a seamless means of embracing the saturated and unsaturated zones of the soil profile into a single analysis."

Flow law for water (Darcy's Law):

Unsaturated soil:

$$v_w = -k_w(u_a - u_w)\left(\frac{\partial h_w}{\partial y}\right)$$

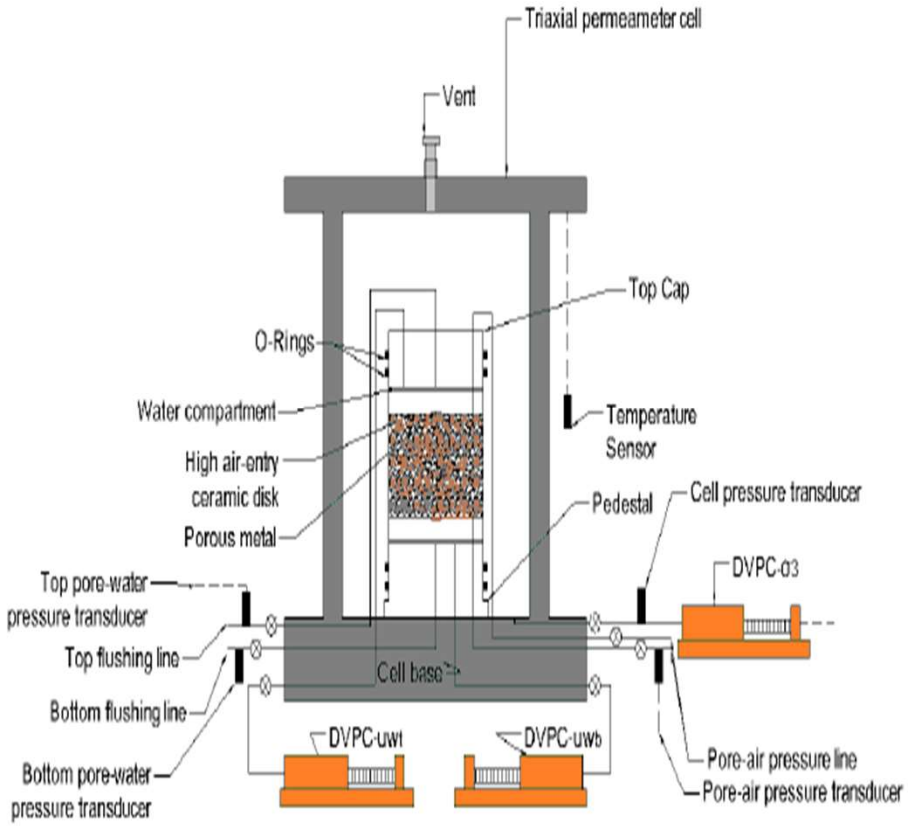
$$h_w = y + \left(\frac{u_w}{\rho_w g}\right)$$

Saturated soil:

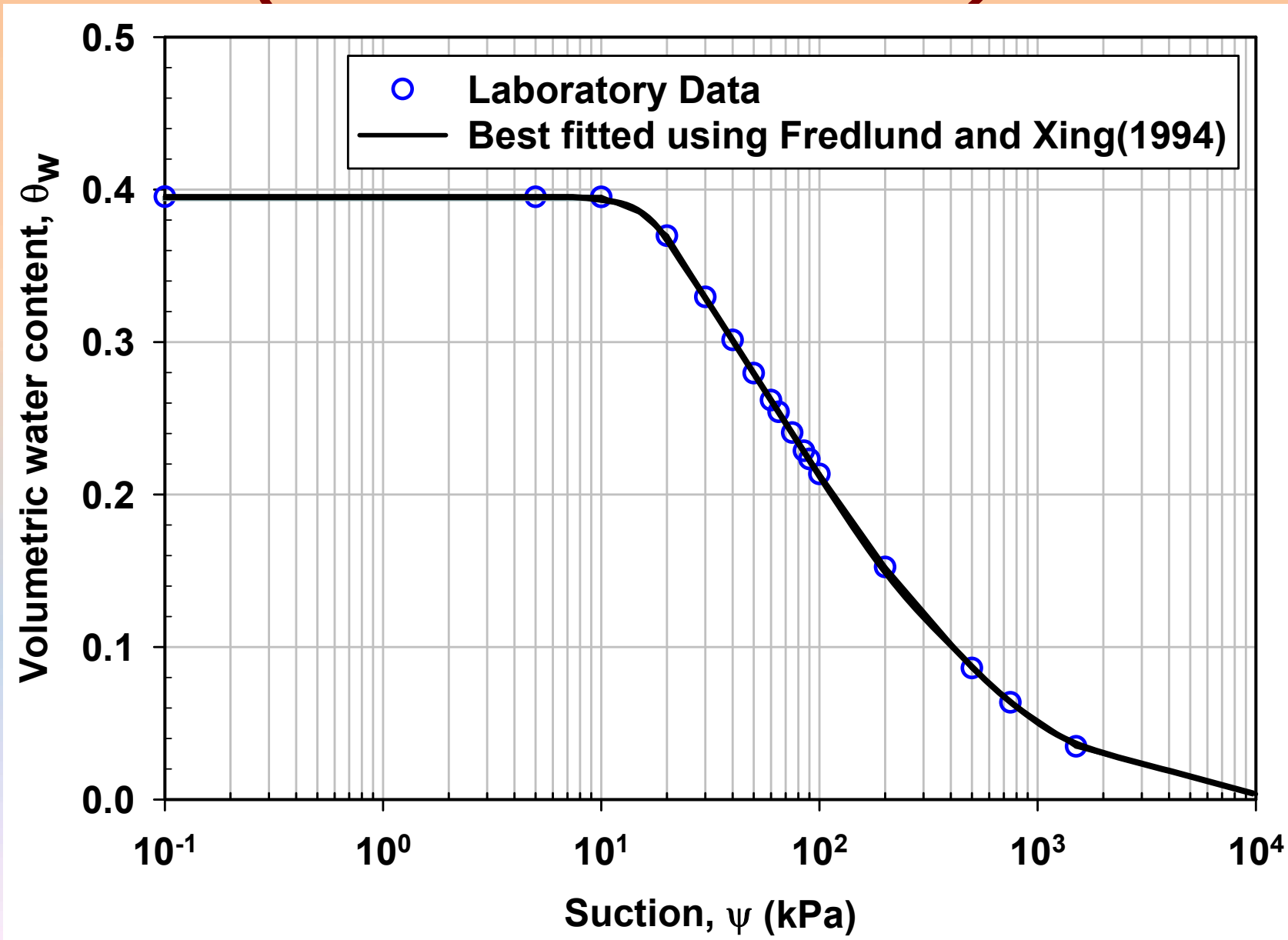
$$v_w = -k_s\left(\frac{\partial h_w}{\partial y}\right)$$

$$h_w = y + \left(\frac{u_w}{\rho_w g}\right)$$

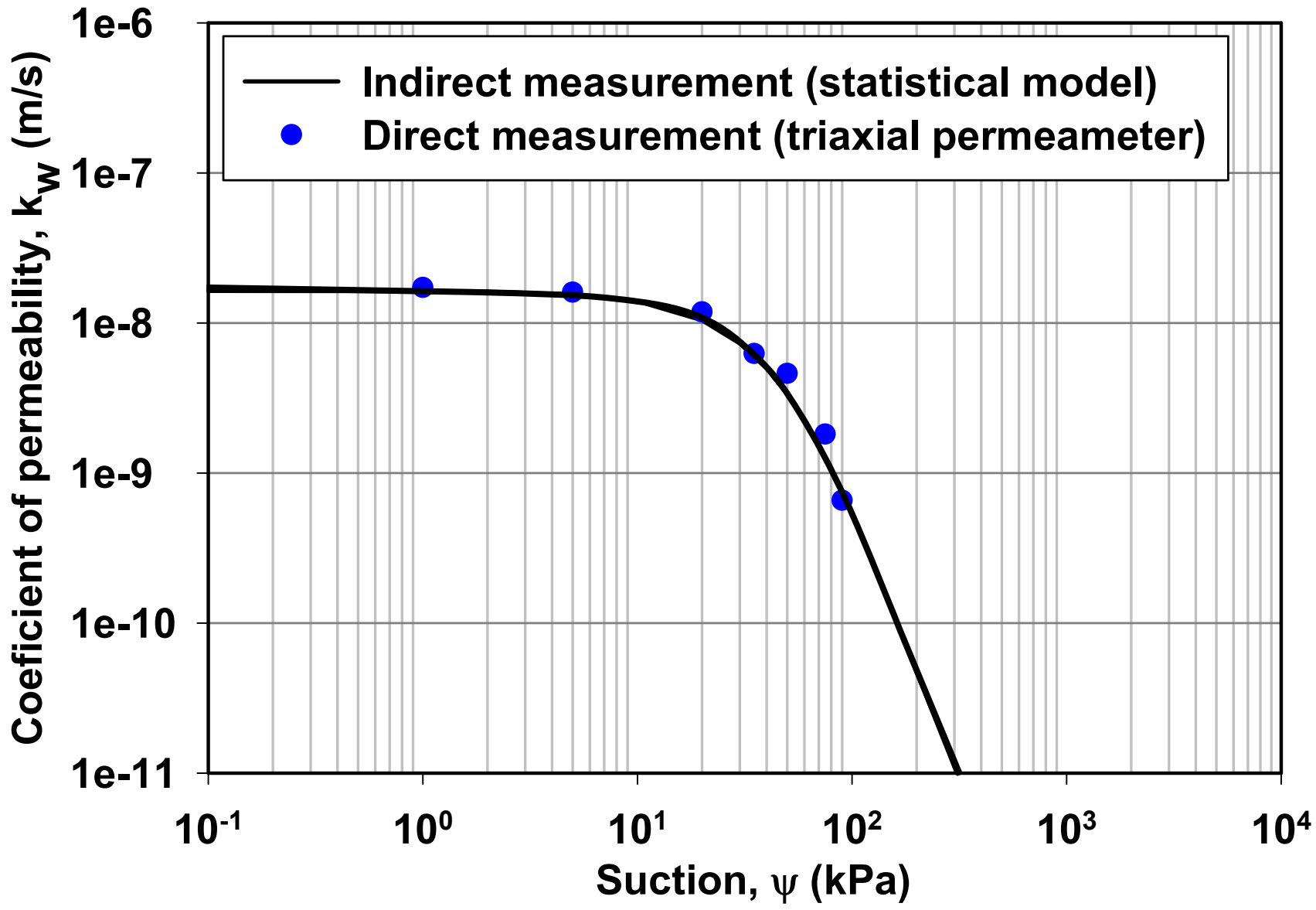
Triaxial Permeameter for Direct Measurement of Unsaturated Permeability



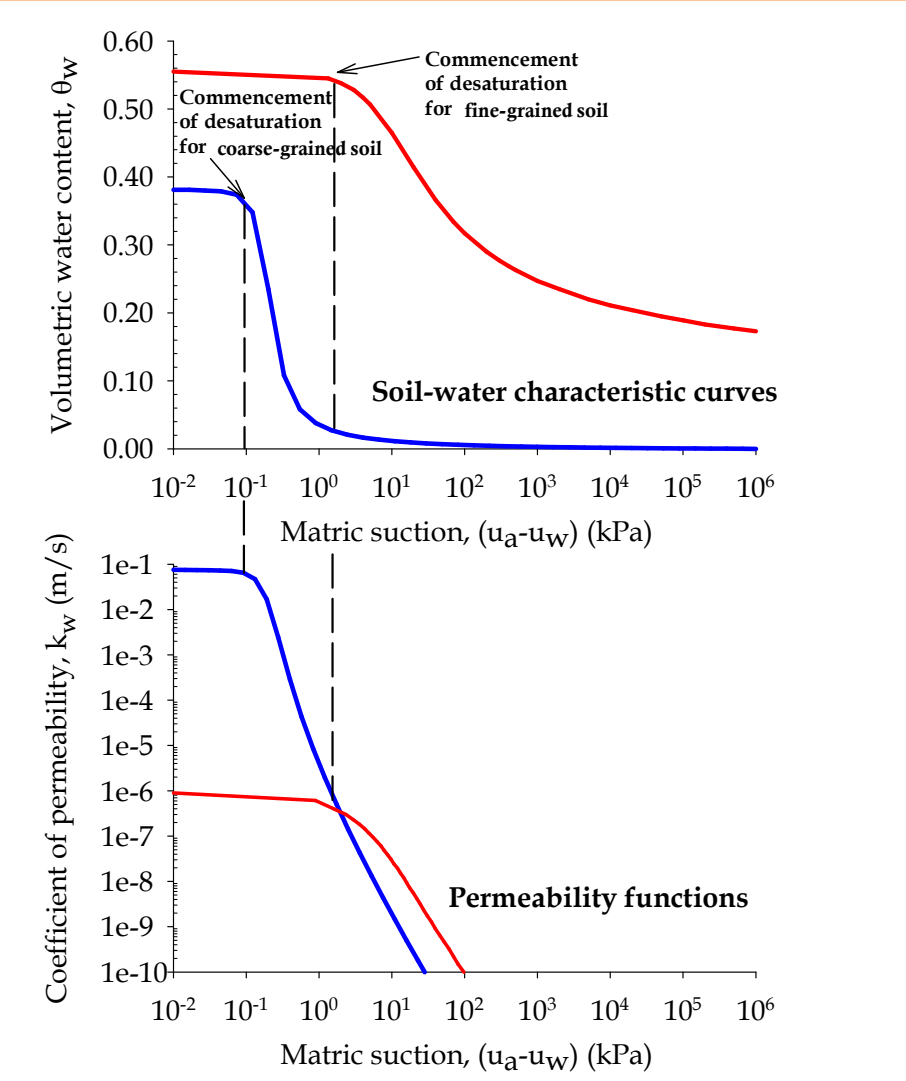
SWCC of Compacted Soil (50%sand-50%kaolin)



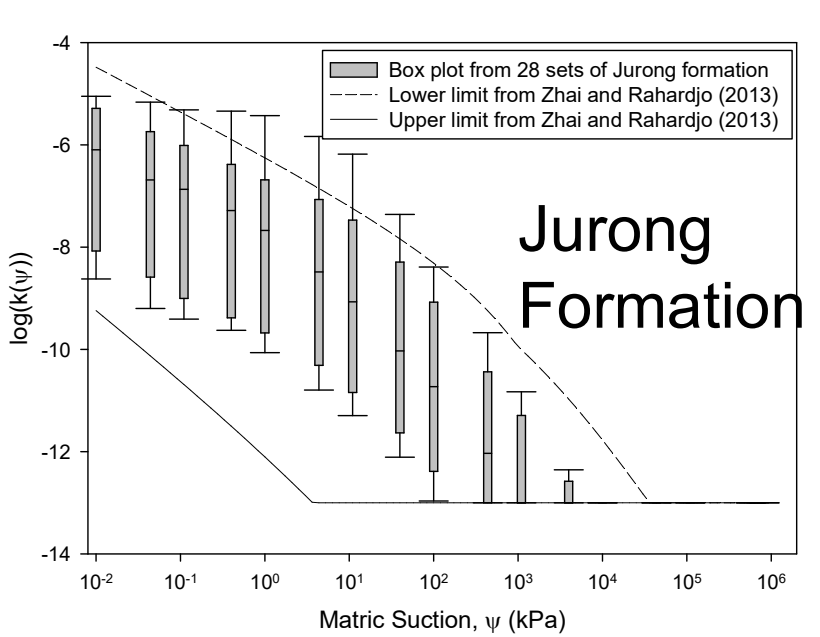
Permeability Function of Compacted Soil (50%sand-50%kaolin)

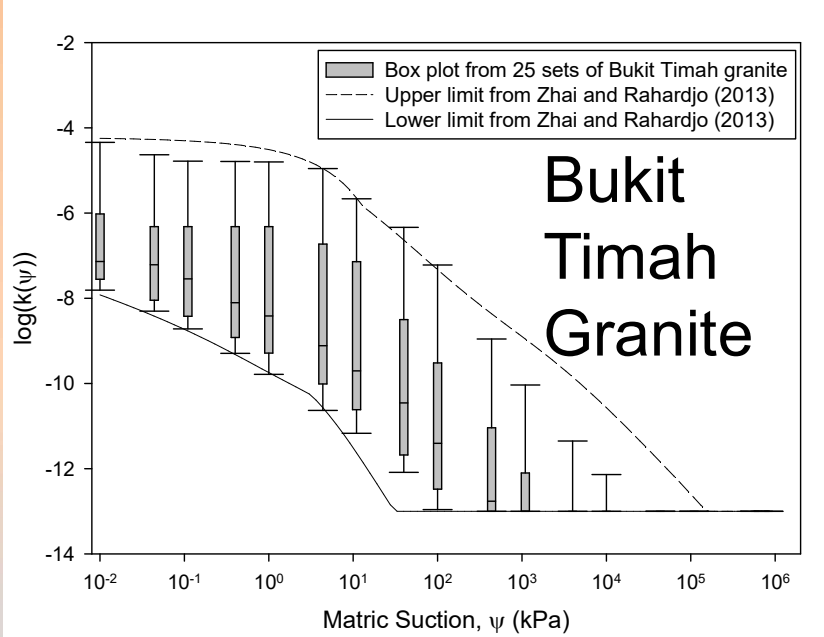


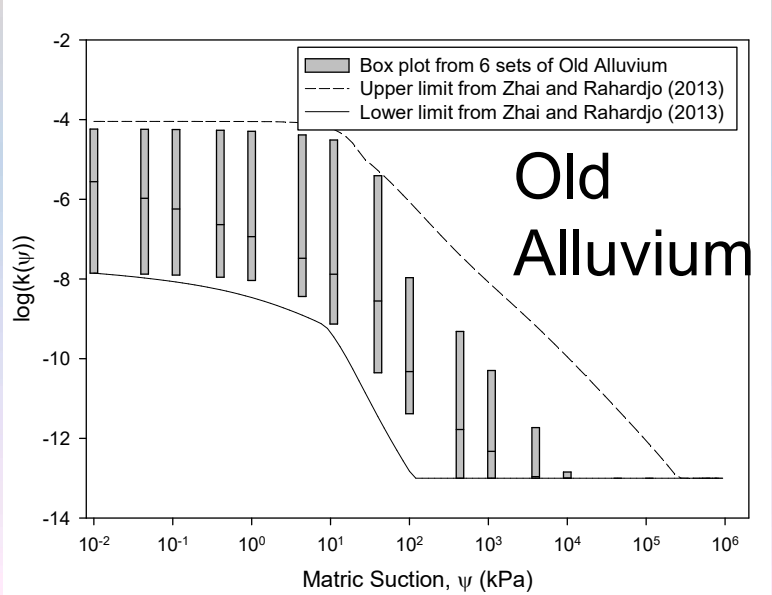
Relationship between SWCC and permeability functions



Permeability Functions of Residual Soils in Singapore







Shear strength:

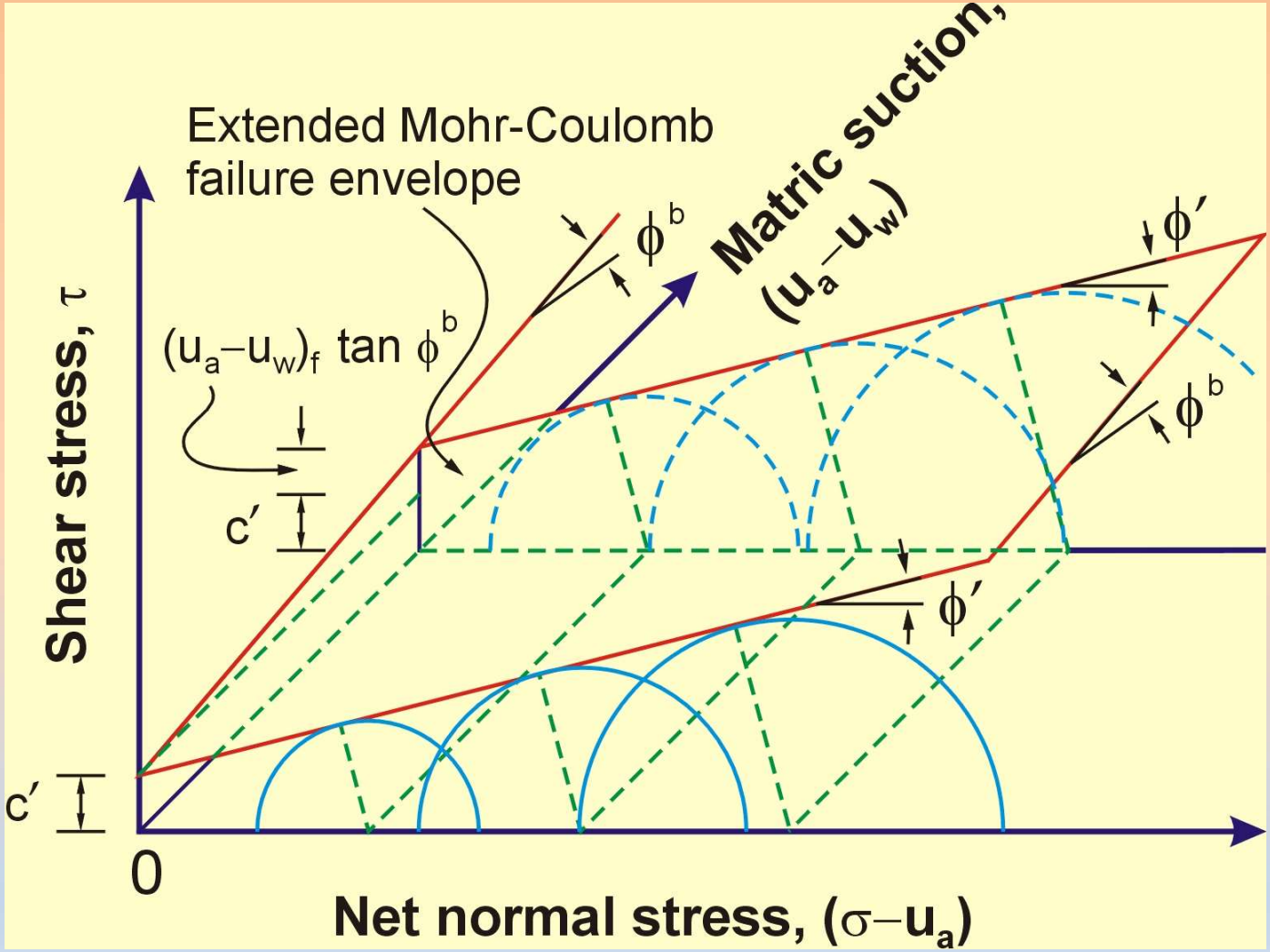
Unsaturated soil:

$$\tau = c' + (u_a - u_w)\tan\phi^b + (\sigma - u_a)_f \tan\phi'$$

$$c = c' + (u_a - u_w)\tan\phi^b$$

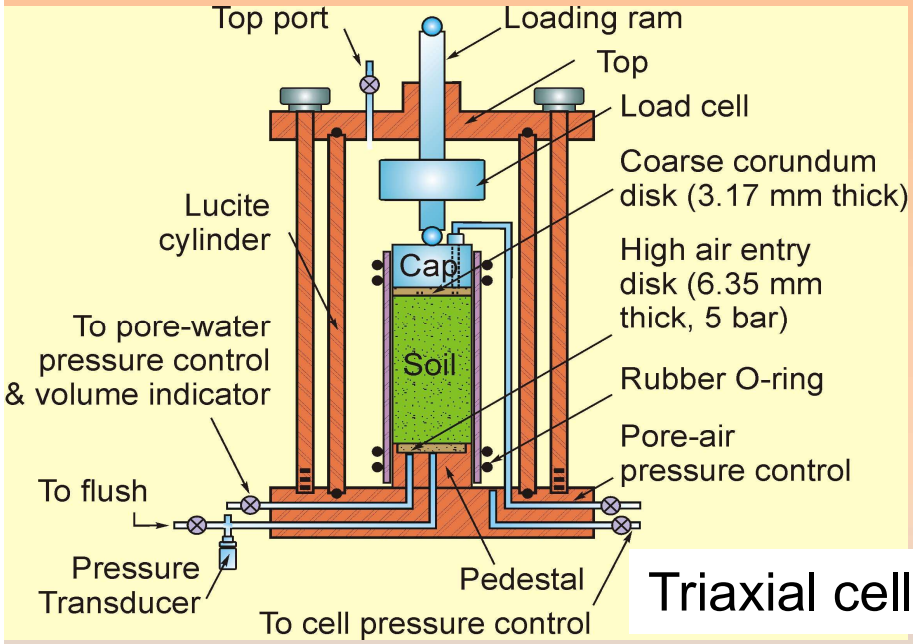
Saturated soil:

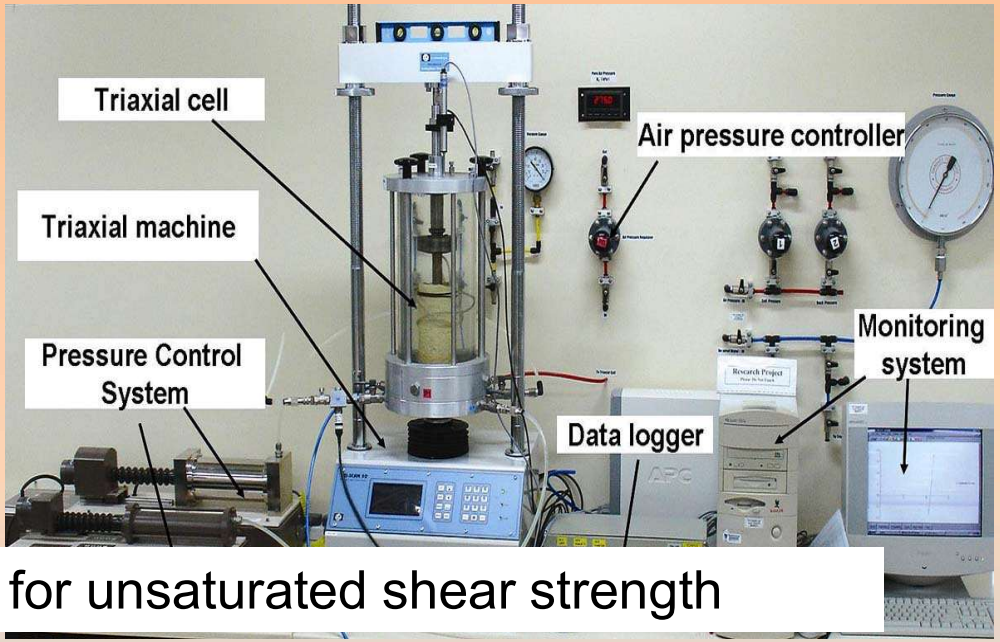
$$\tau = c' + (\sigma - u_w)\tan\phi'$$



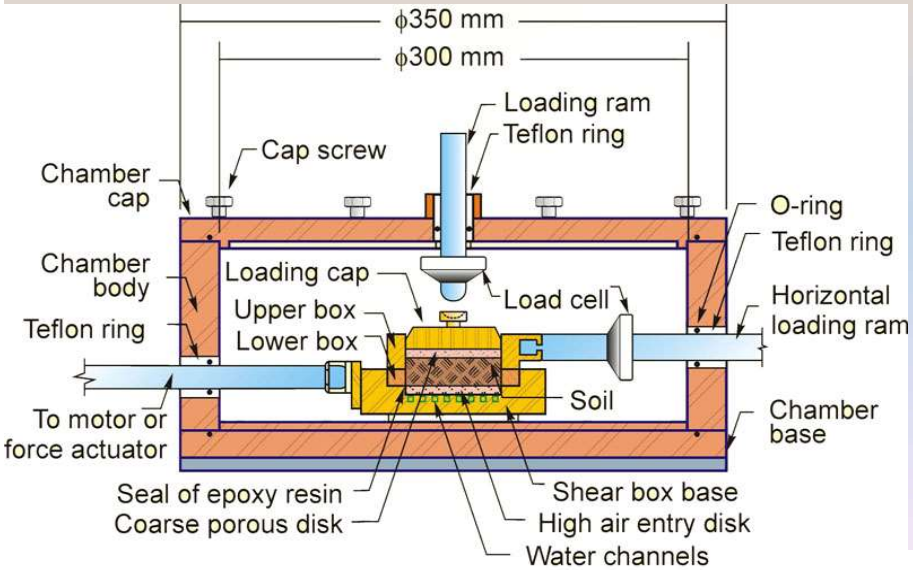
Extended Mohr-Coulomb failure envelope

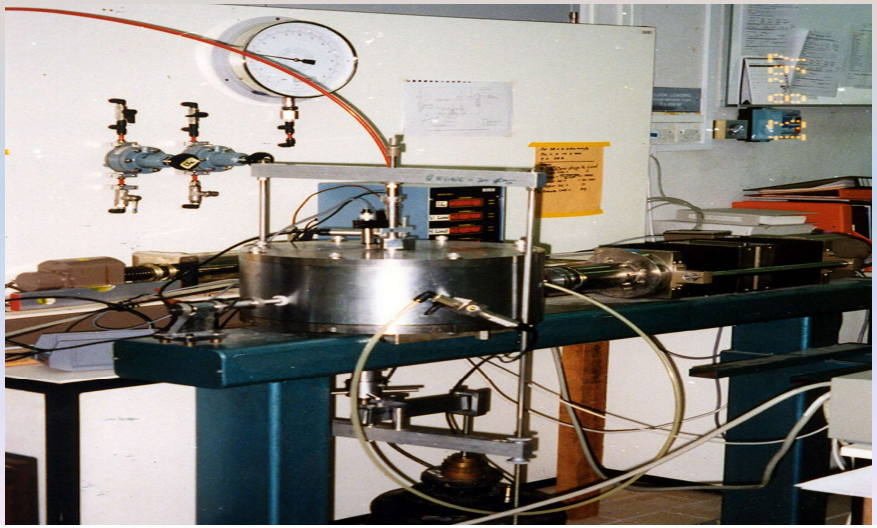
Unsaturated Soil Testing



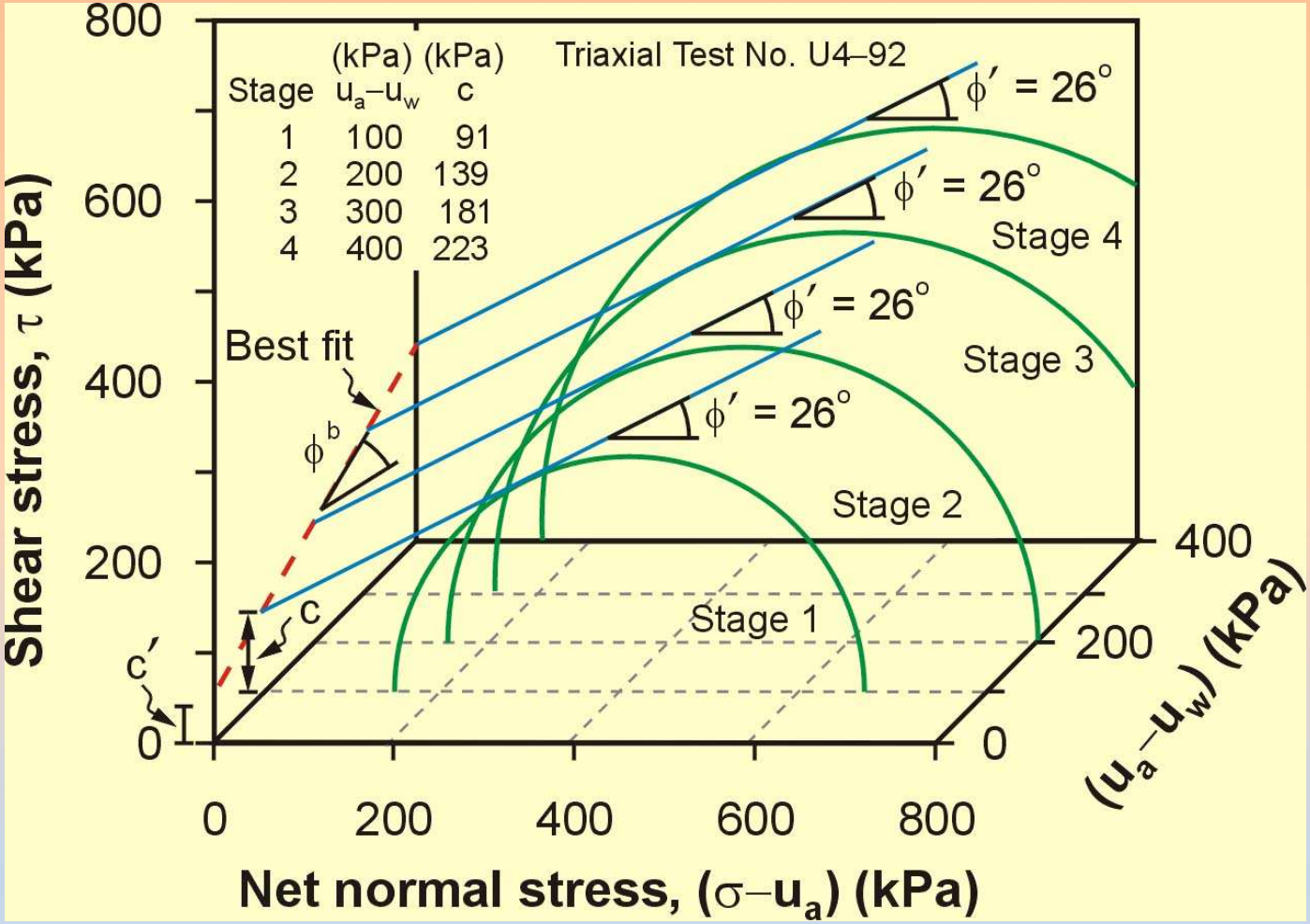


Triaxial cell for unsaturated shear strength

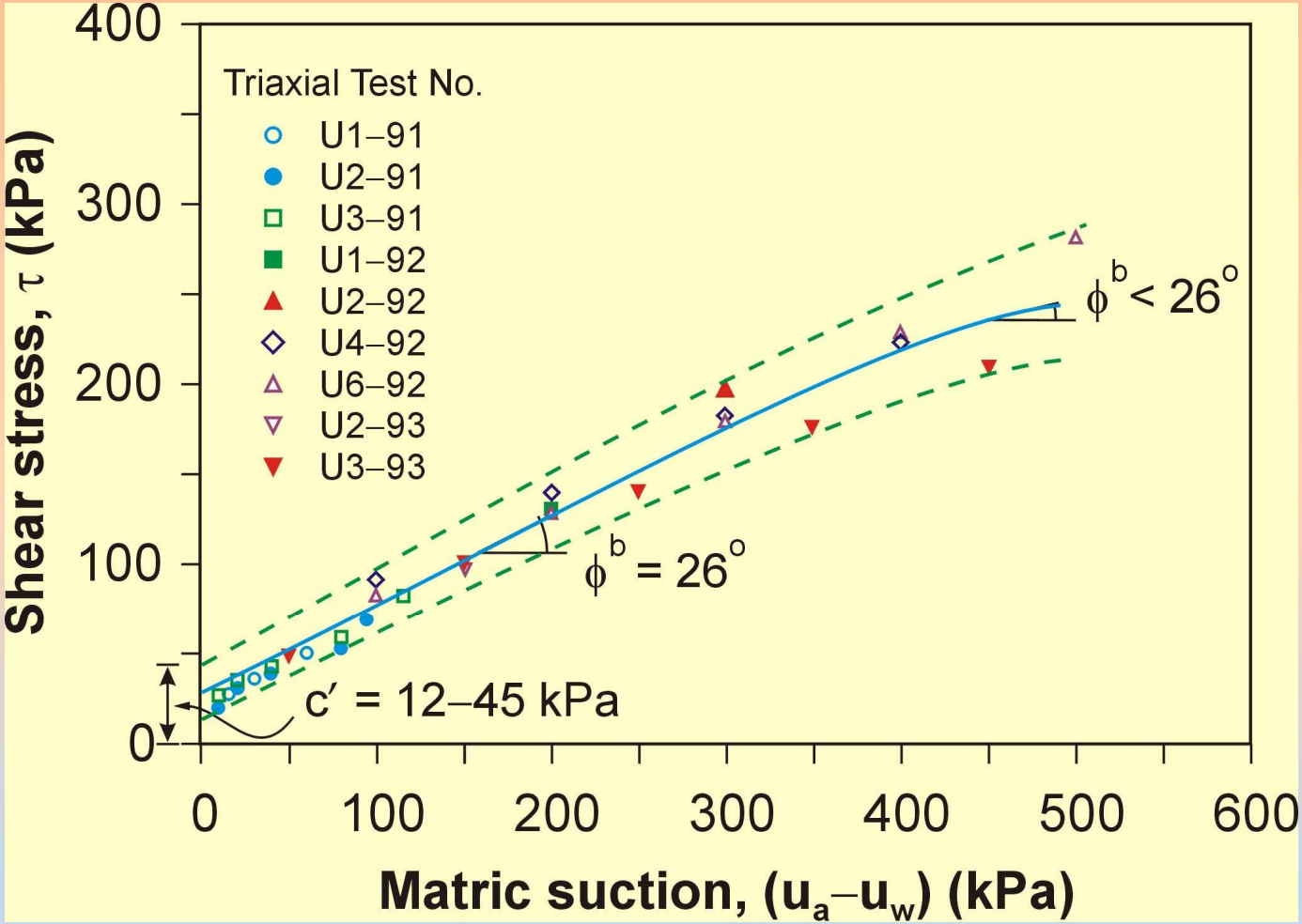




Direct shear for unsaturated shear strength



Interpretation of rate of change of shear strength with respect to matric suction, ϕ^b, from the results of multistage triaxial tests at a constant net confining pressure



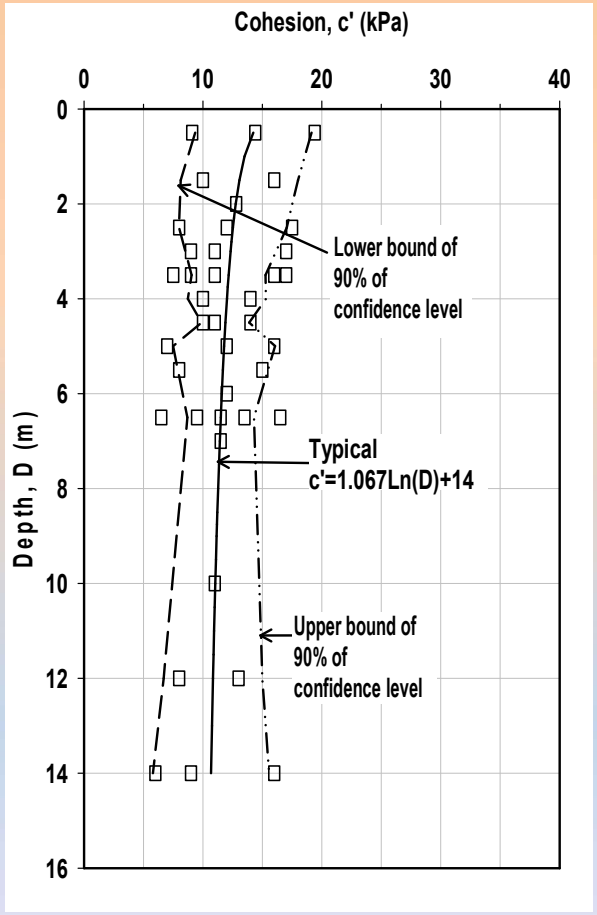
Cohesion intercept at τ versus $(u_a - u_w)$ plane (where $(\sigma - u_a) = 0$) for fine grained residual soils from the Jurong sedimentary formation

Experimental Values Measured for ϕ^b of Residual Soils in Singapore

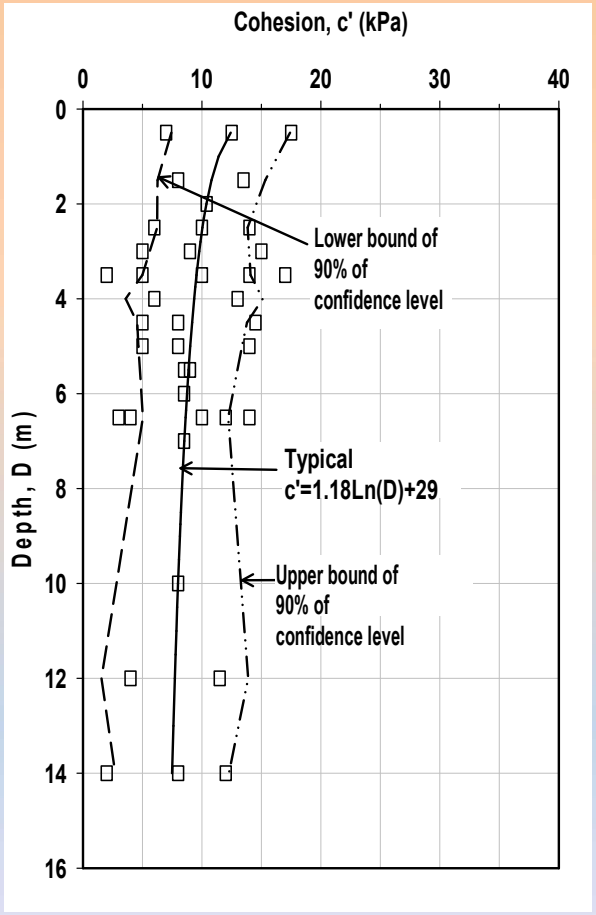
Location	Formation	c' (kPa)	ϕ' (°)	ϕ^b (°)
Bukit Merah	JF	5	30	22
Jalan Kukoh	JF	15	33	25
Havelock Road	JF	14	34	15
Depot Road	JF	12	35	20
Ang Mo Kio	BTG	8	30	18
Thomson Road	BTG	15	33	25
Marsiling Road	BTG	9	30	21
Bukit Batok	BTG	12	37	28
Joo Seng Road	OA	8	35	21
Bedok	OA	3	34	26
Tampines	OA	5	37	20

Note: JF = Jurong Formation; BTG = Bukit Timah Granite; OA = Old Alluvium

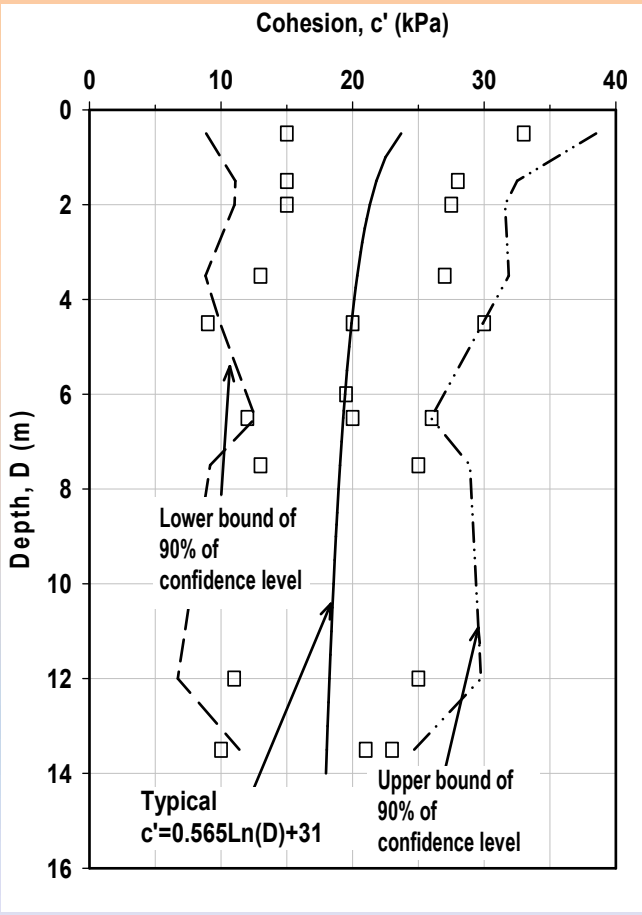
Variations of Effective Cohesion for Residual Soils in Singapore



Jurong Formation

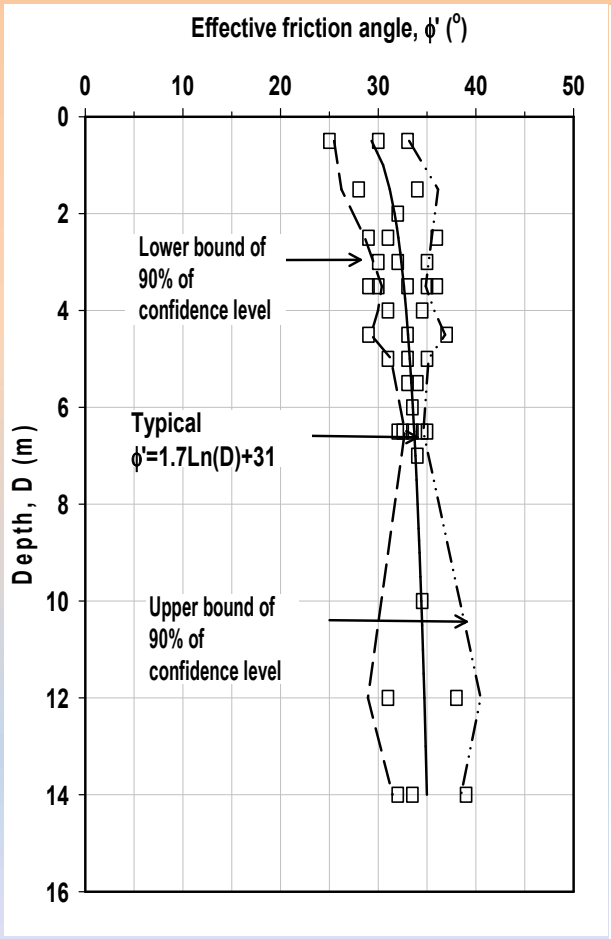


Bukit Timah Granite

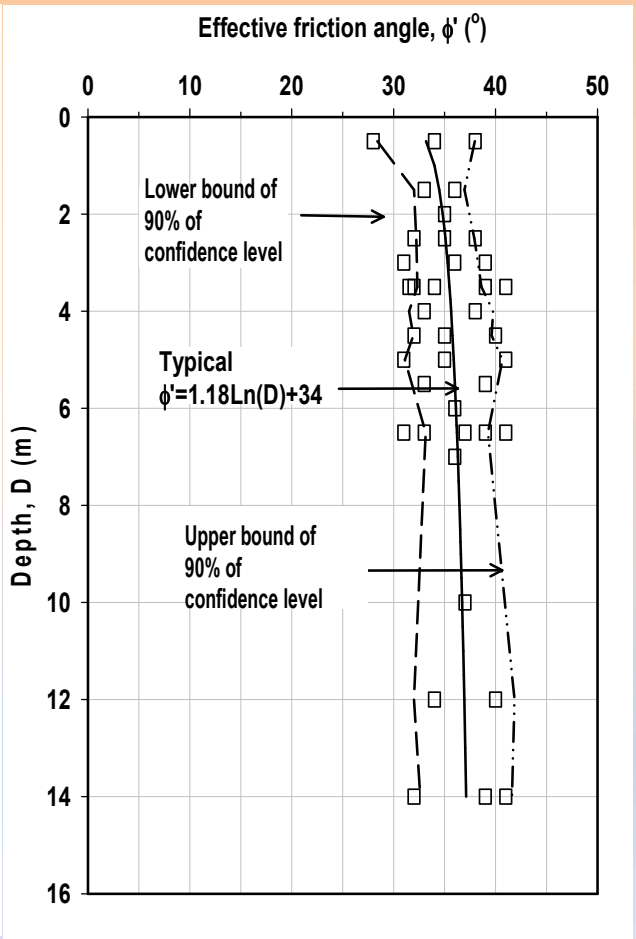


Old Alluvium

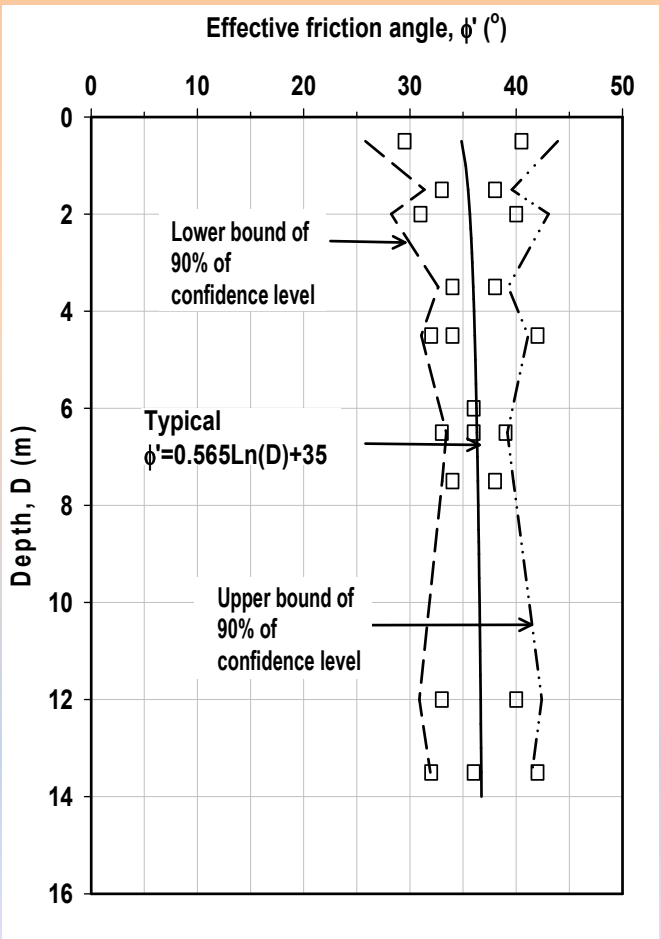
Variations of Effective Friction Angle for Residual Soils in Singapore



Jurong Formation

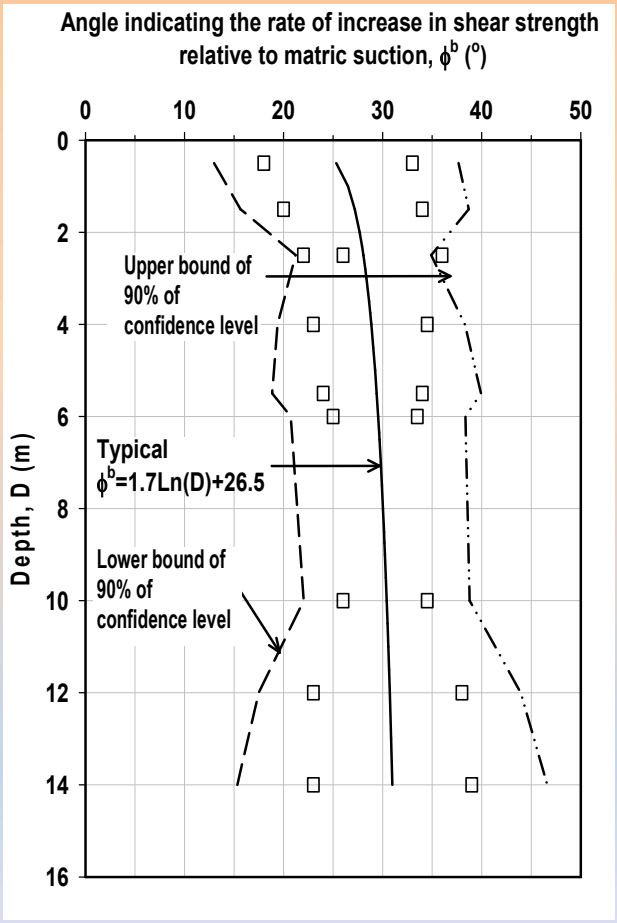


Bukit Timah Granite

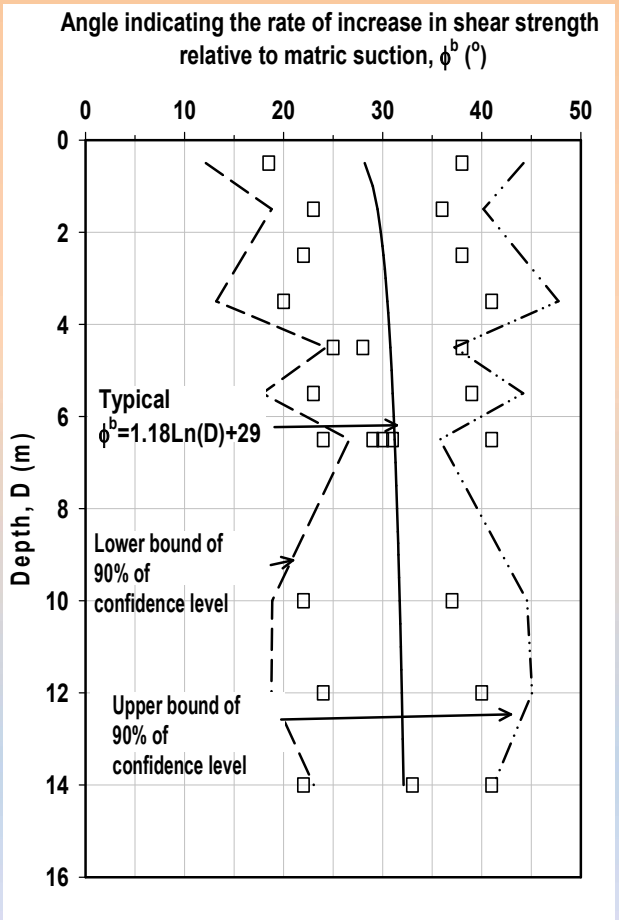


Old Alluvium

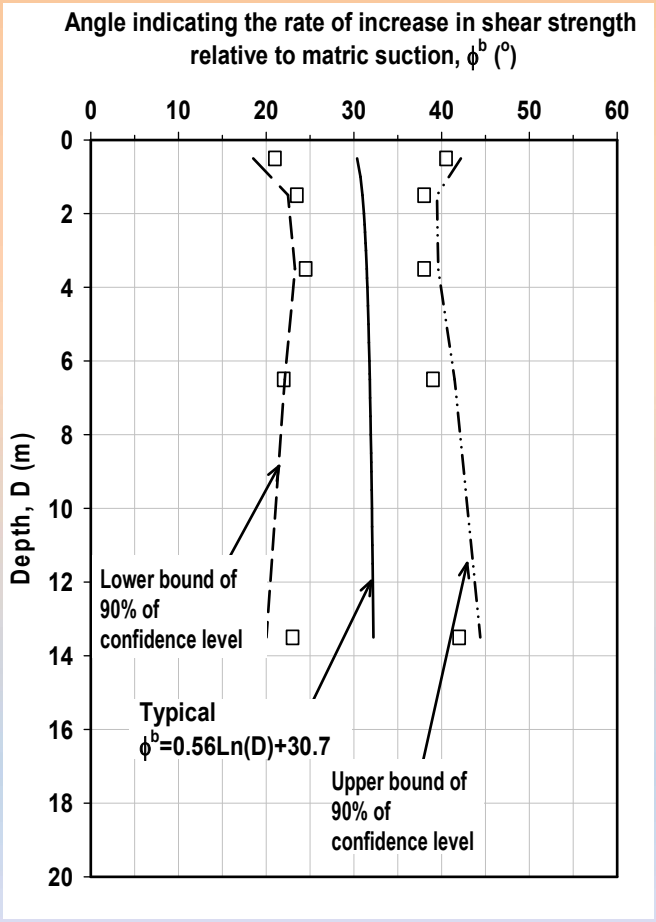
Variations of ϕ^b Angle for Residual Soils in Singapore



Jurong Formation

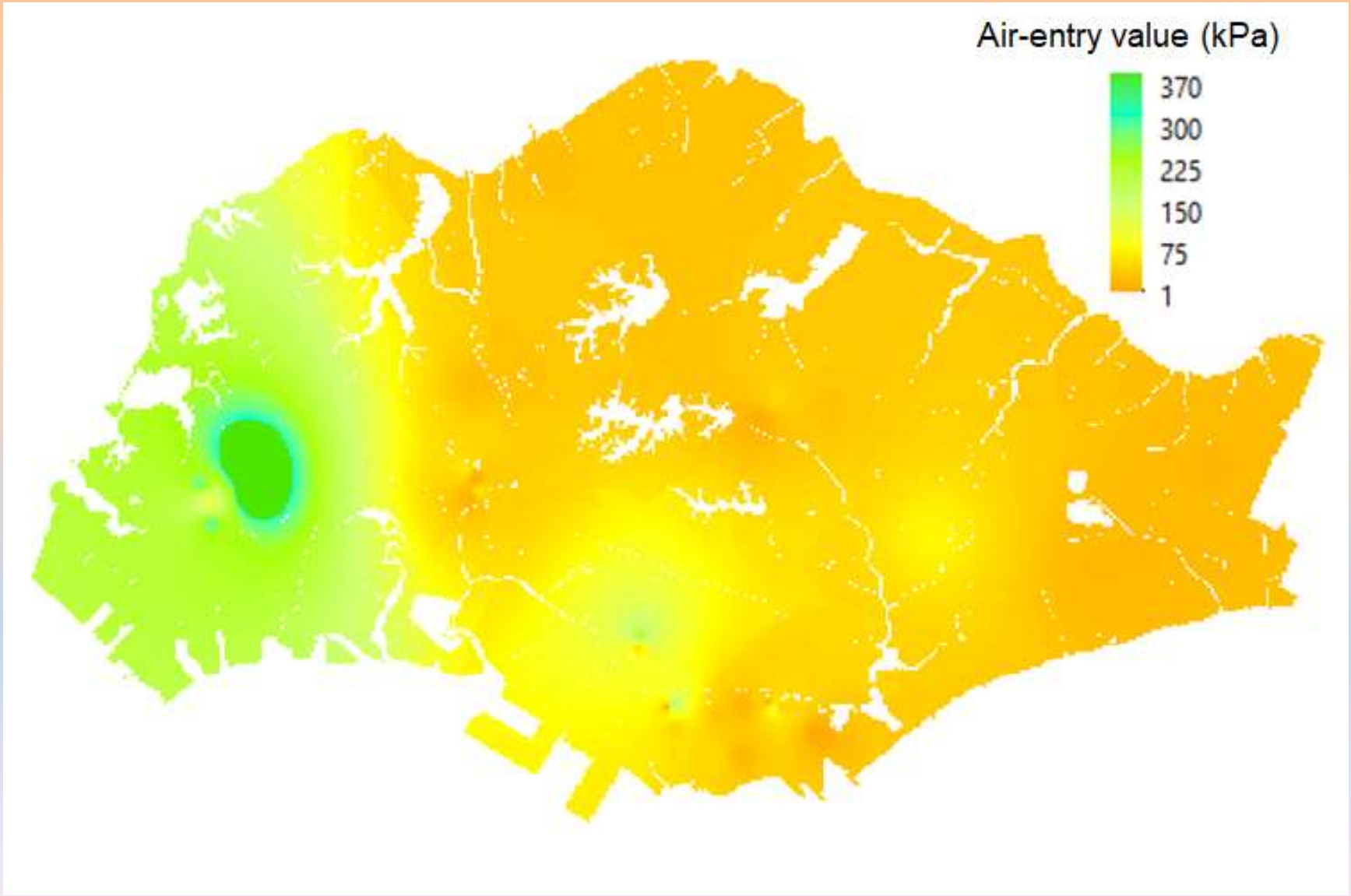


Bukit Timah Granite

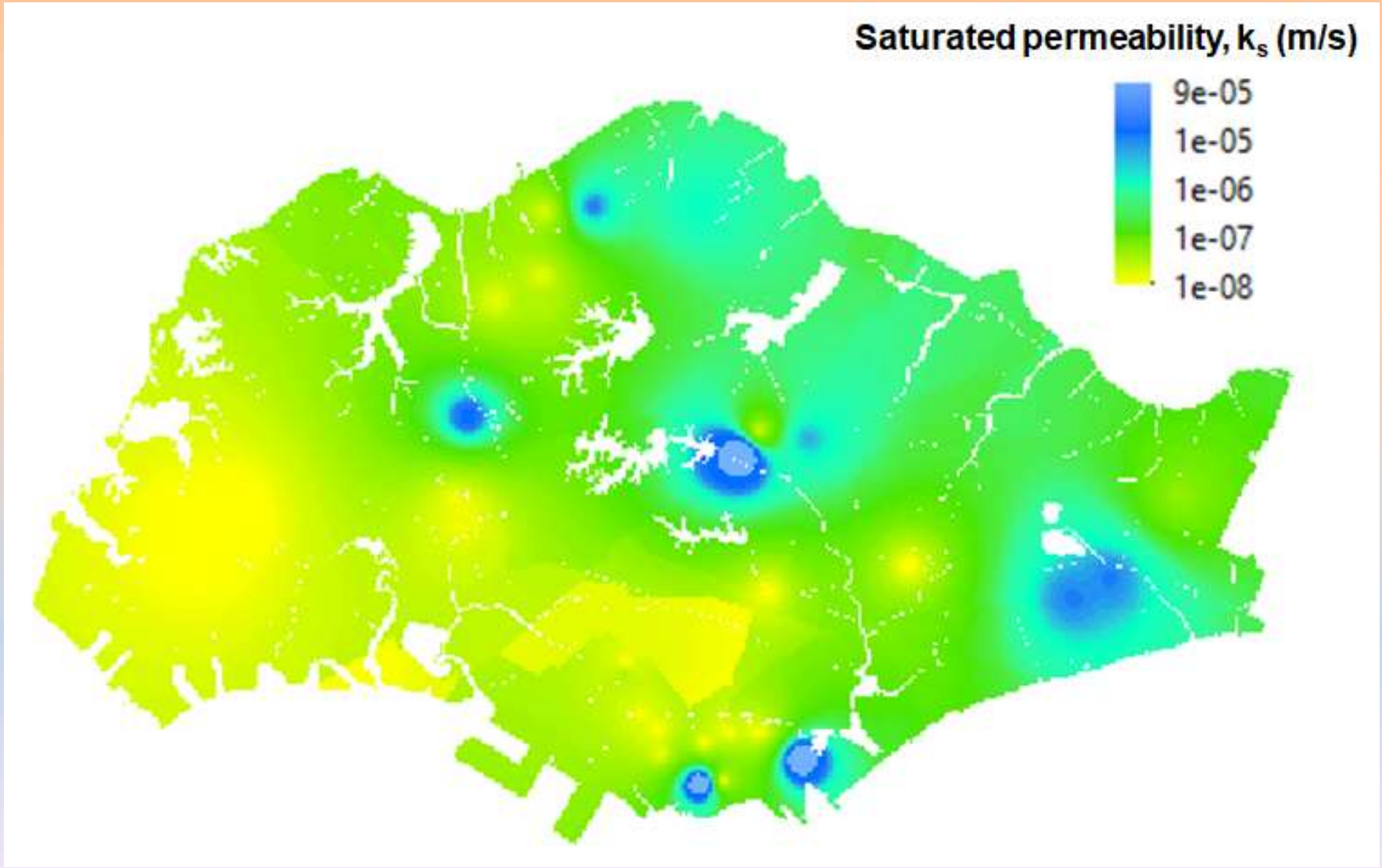


Old Alluvium

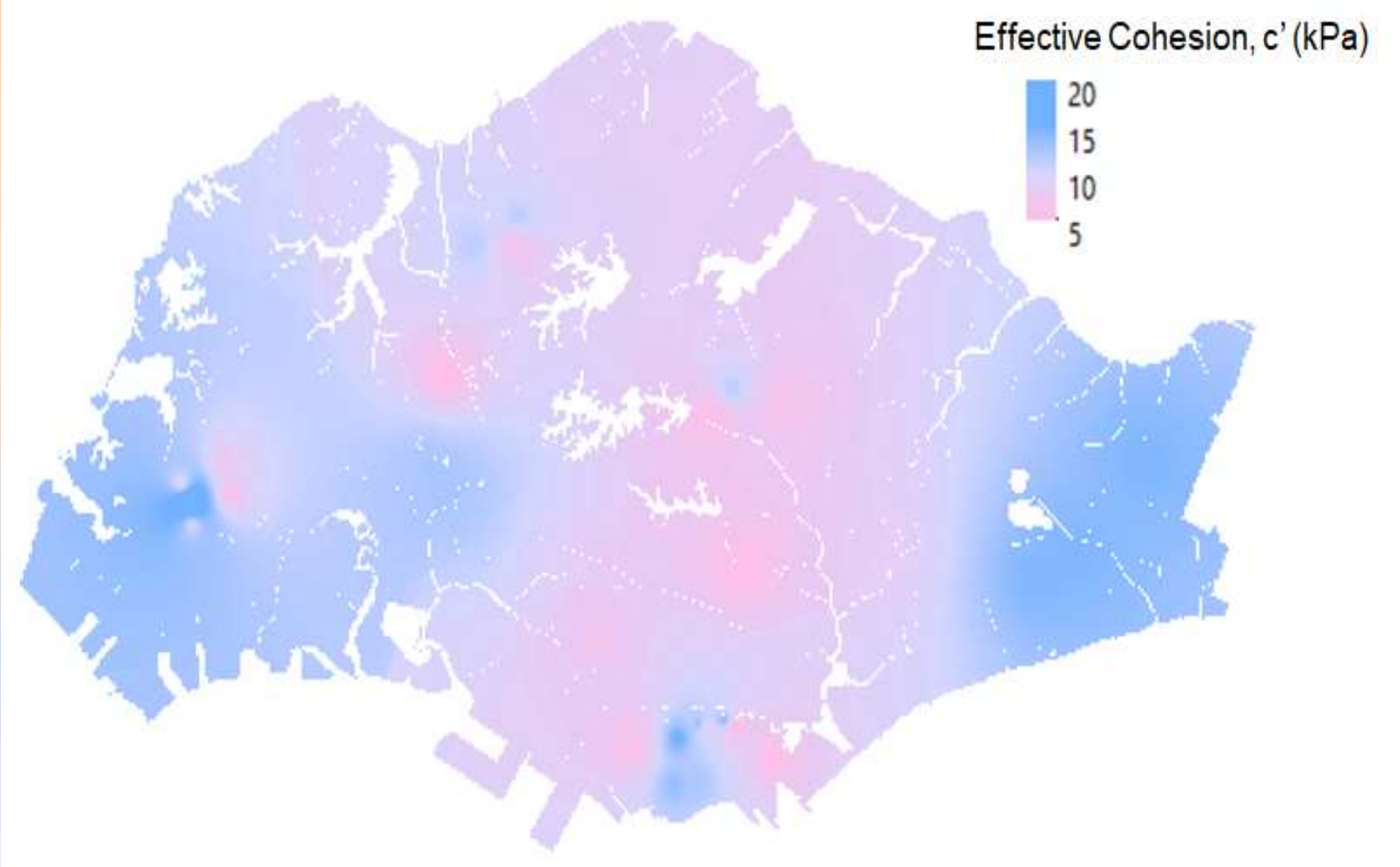
Spatial Distribution of Air-entry Value



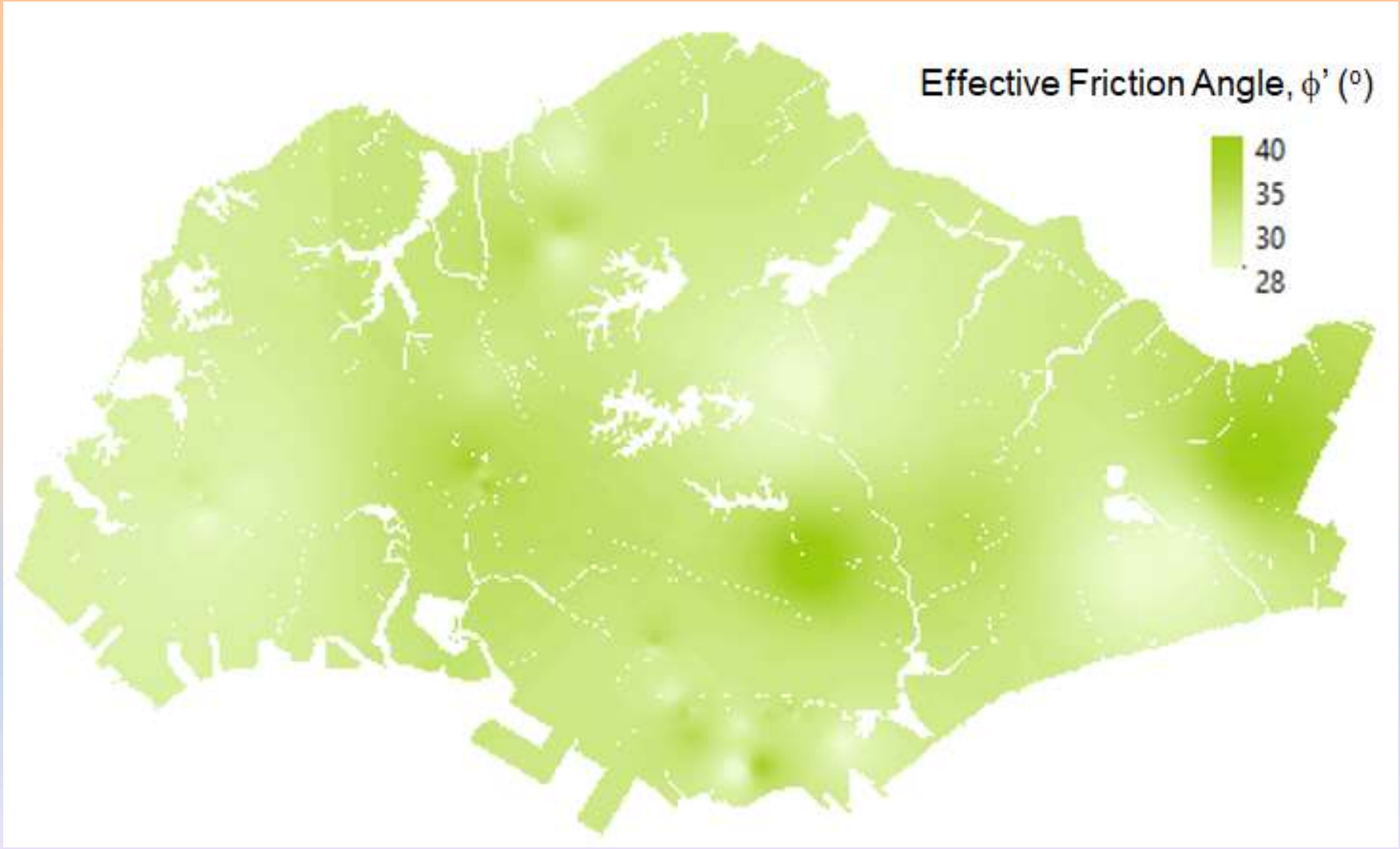
Spatial Distribution of Saturated Permeability



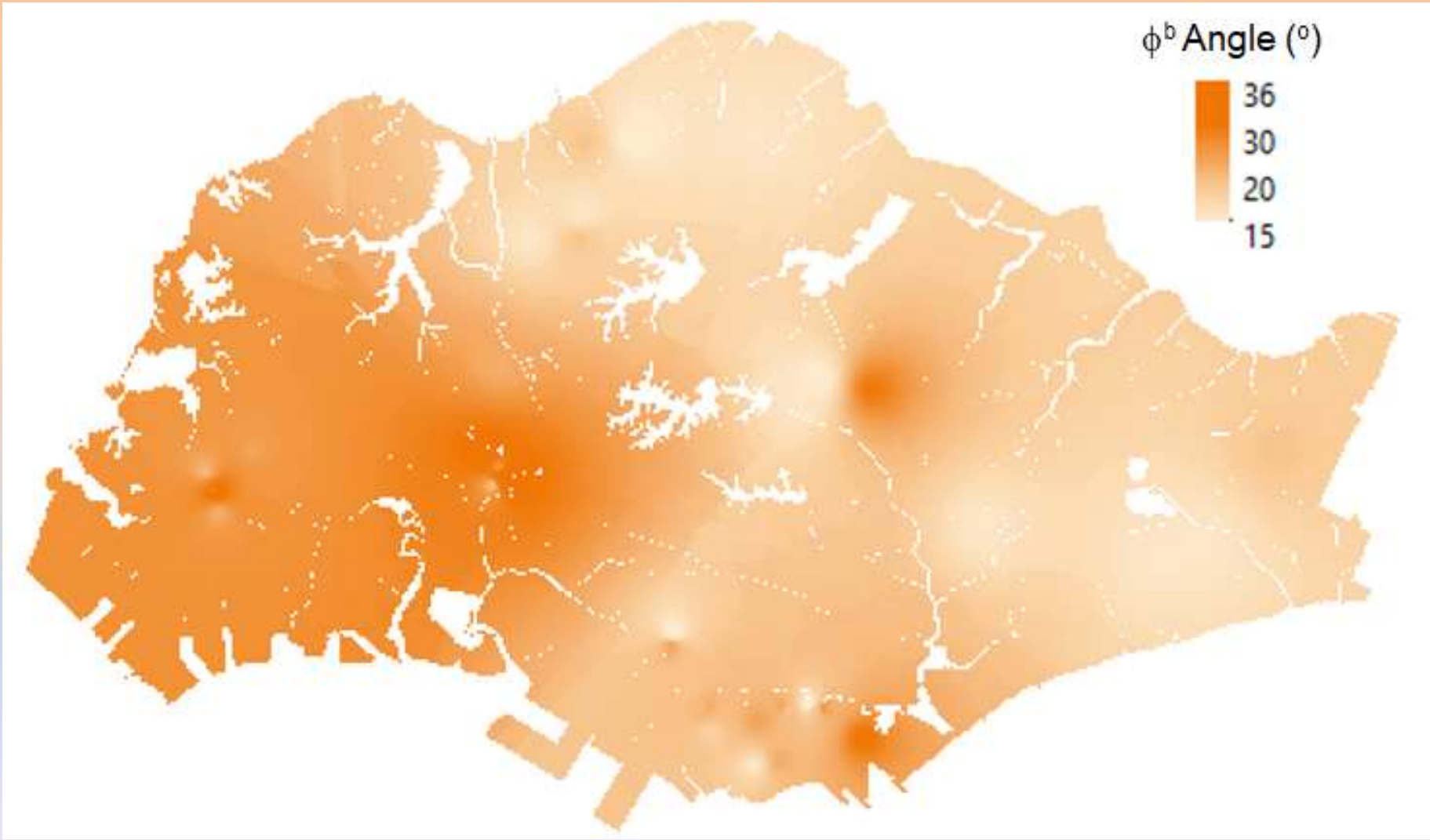
Spatial Distribution of Effective Cohesion



Spatial Distribution of Effective Friction Angle



Spatial Distribution of ϕ^b Angle

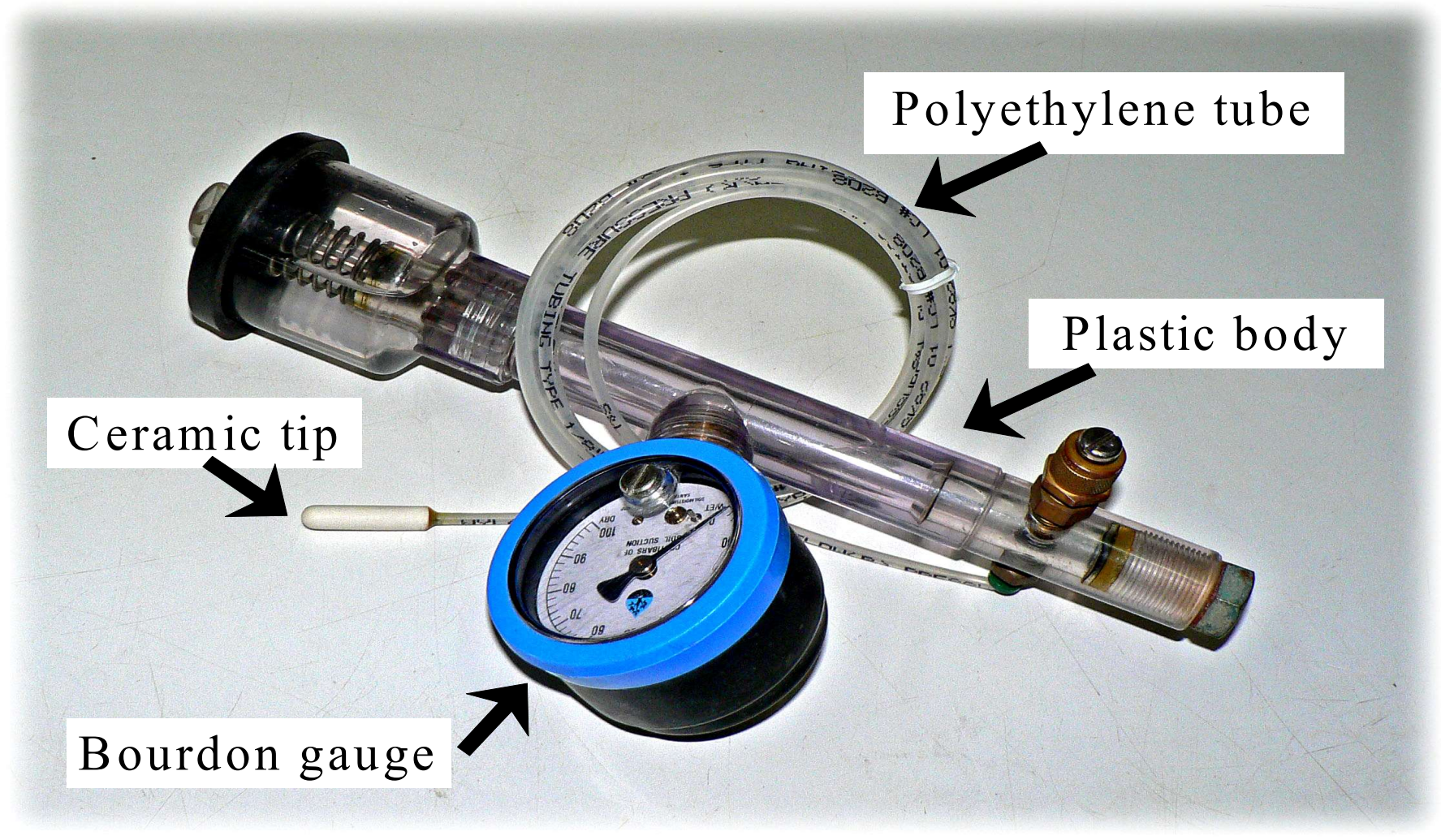


Development of High-range Suction Sensors and Assessment of Role of Unsaturated Soil in Slope Stability during Rainfall

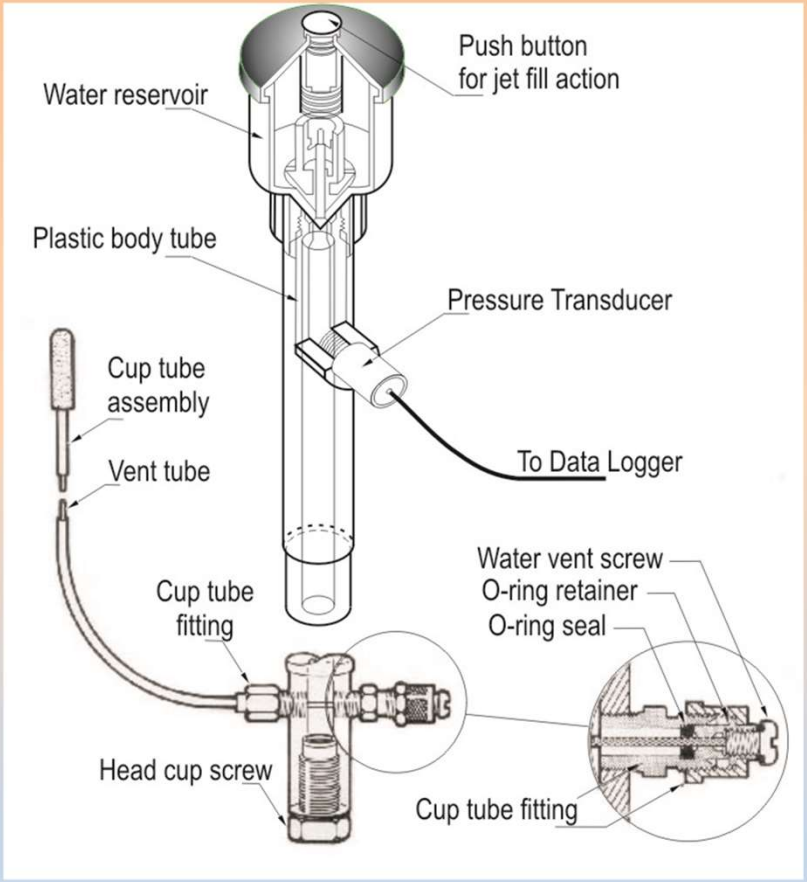
Summary of matric suction measurement devices

Device	Suction component measured	Measurement range (kPa)	Equilibrium time	Manufacturer & relative cost*
Jet fill tensiometer	Matric	0 – 100	Several minutes	Soil Moisture Equipment Skye Instruments Irrometer Co. Dynamax Inc. Cost: $
Small-tip tensiometer	Matric	0 – 100	Several minutes	
Null-type axis translation apparatus	Matric	0 – 1500	Several hours – days	Universities Cost: $$$
Miniature tensiometer	Matric	0 – 1500	Several minutes	Universities Cost: $$
NTU Mini Suction Probe	Matric	0 – 400	Several minutes	Universities Cost: $$
NTU Osmotic Tensiometer	Total	0 – 1500	Several minutes	Universities Cost: $$

Low-Range Suction Measuring Techniques

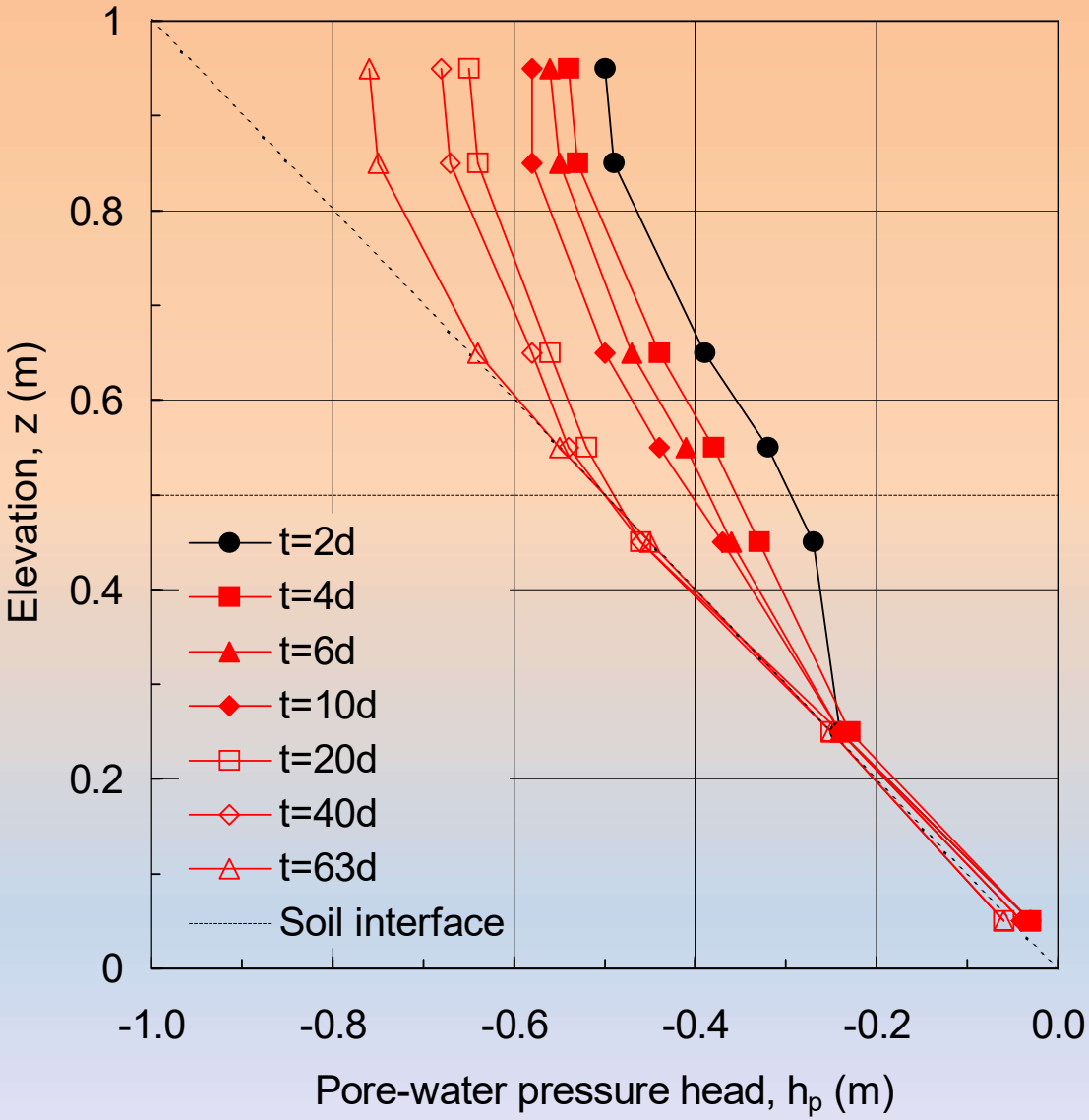


Small tip tensiometer with jet fill cup for flushing



Small tip tensiometer system for measurement in laboratory

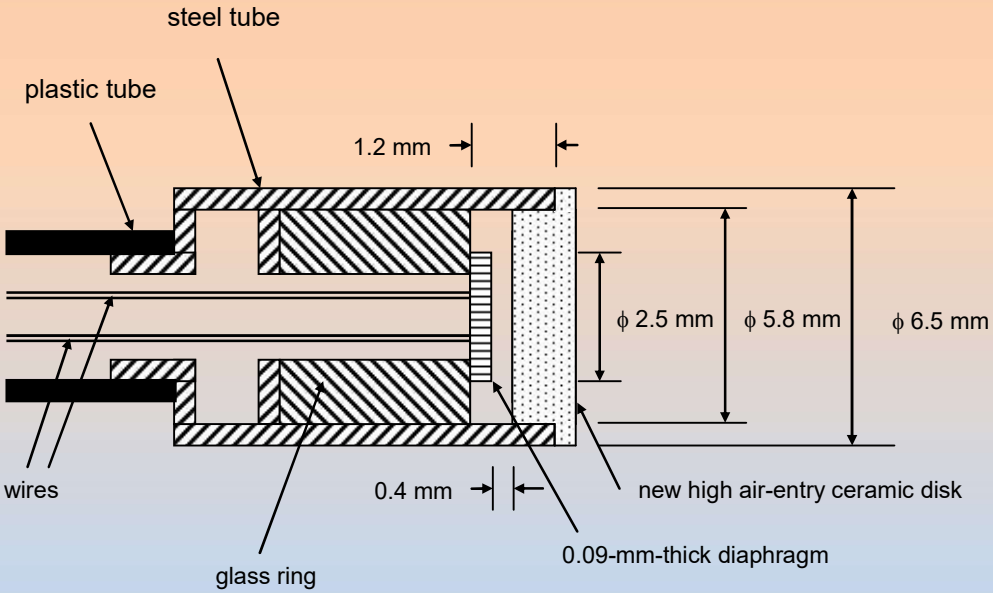
Laboratory set-up of infiltration column



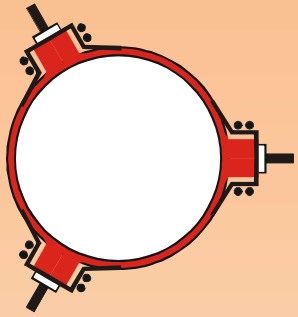
Measurements of pore-water pressure using small-tip tensiometers in an infiltration column of fine sand over medium sand

High - Range Suction Measuring Techniques

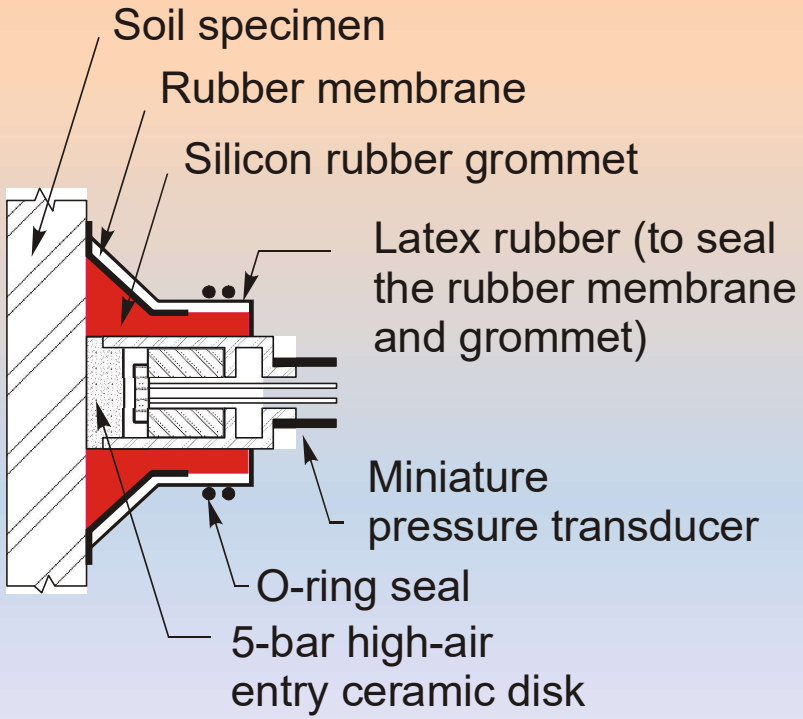
NTU mini suction probe



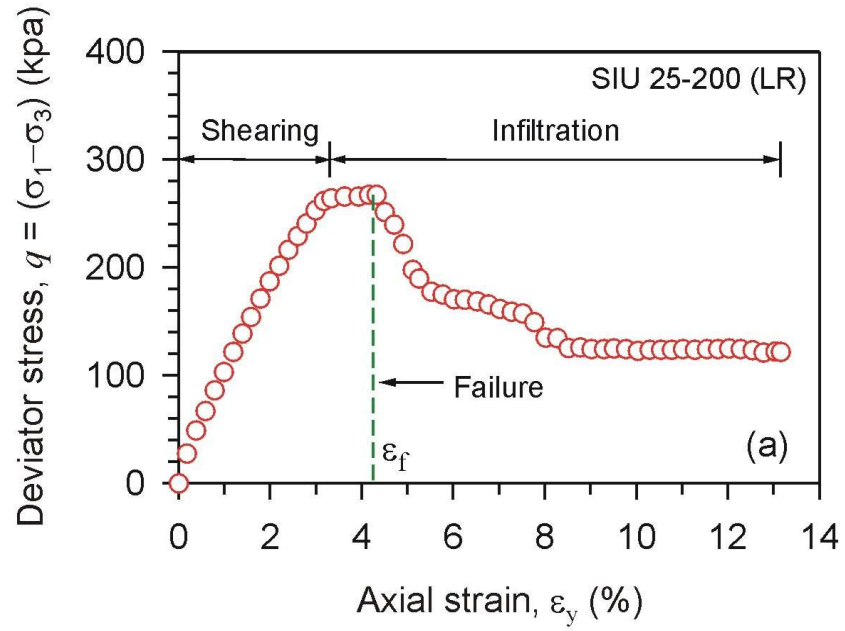
Triaxial equipment for shearing-infiltration test

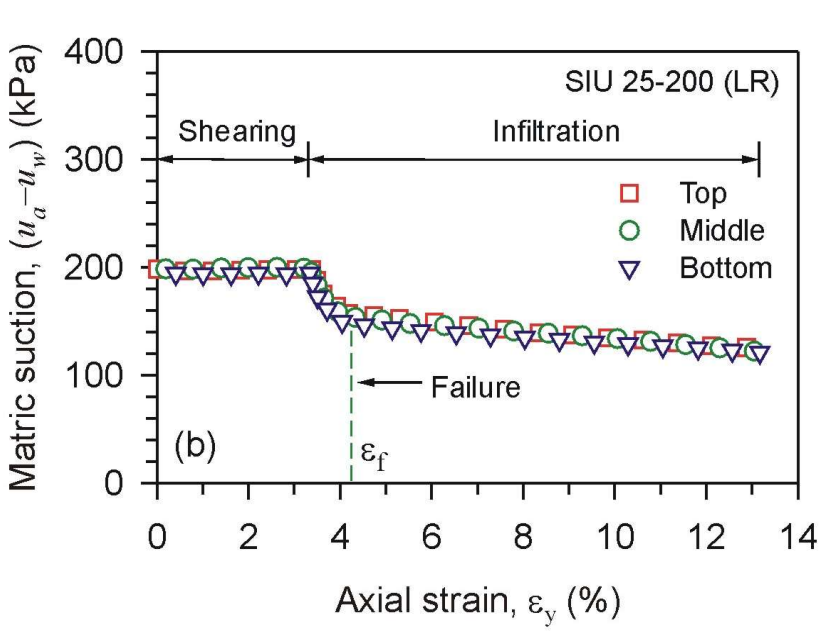


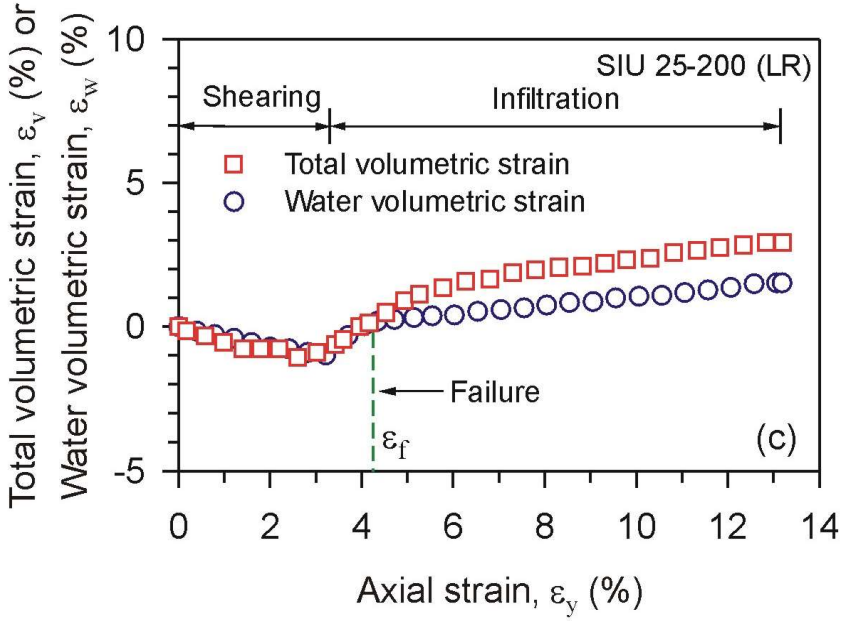
Plan view

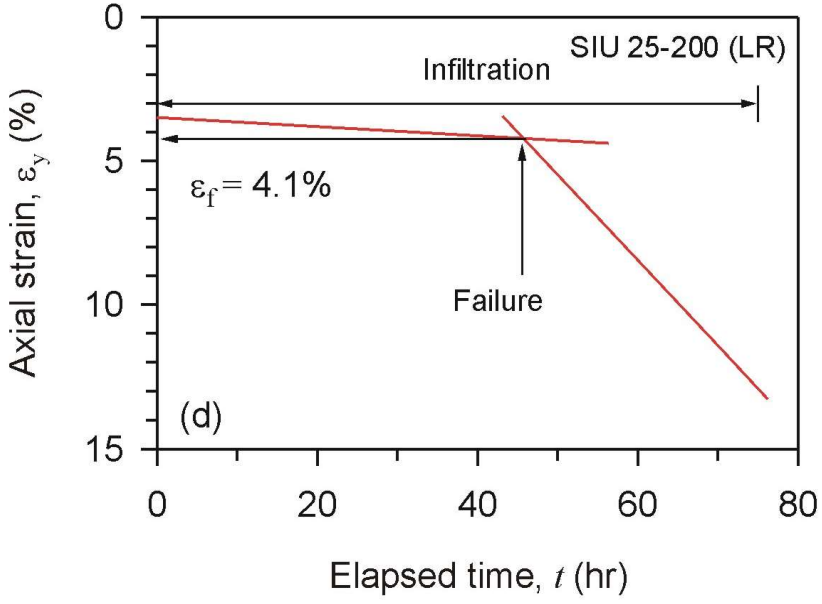


Details of mini probe


SIU 25-200 (LR)
Shearing
Infiltration
Failure
ε_f
(a)
Deviator stress, $q = (\sigma_1 - \sigma_3)$ (kpa)
Axial strain, ε_y (%)

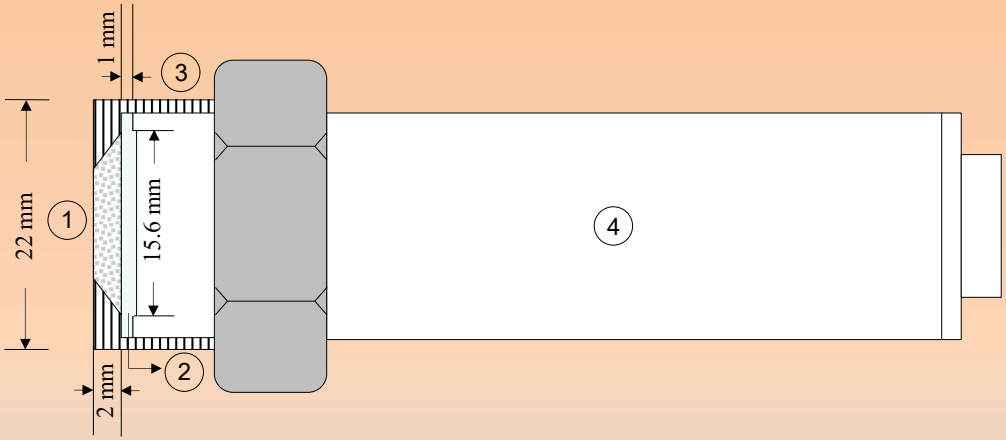

SIU 25-200 (LR)
Shearing
Infiltration
Top
Middle
Bottom
Failure
ε_f
(b)
Matric suction, $(u_a - u_w)$ (kPa)
Axial strain, ε_y (%)


SIU 25-200 (LR)
Shearing
Infiltration
Total volumetric strain
Water volumetric strain
Failure
ε_f
(c)
Total volumetric strain, ε_v (%) or Water volumetric strain, ε_w (%)
Axial strain, ε_y (%)


SIU 25-200 (LR)
Infiltration
ε_f = 4.1%
Failure
(d)
Axial strain, ε_y (%)
Elapsed time, t (hr)

NTU Osmotic Tensiometer Development

Sensor Design and Configurations



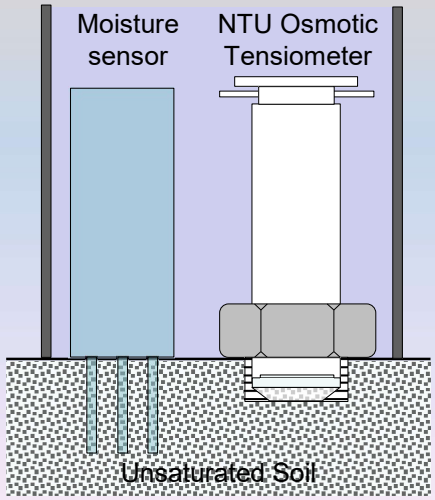
Schematic drawing of NTU osmotic tensiometer design with (1) slope-shaped ceramic disc; (2) polymer chamber; (3) threaded stainless steel cup; and (4) a piezo-resistive transmitter.

Laboratory Calibrations

Centrifuge
Suction range 0 ~ 250 kPa

WP4C Potentiometer
Suction range 0 ~ 100 MPa

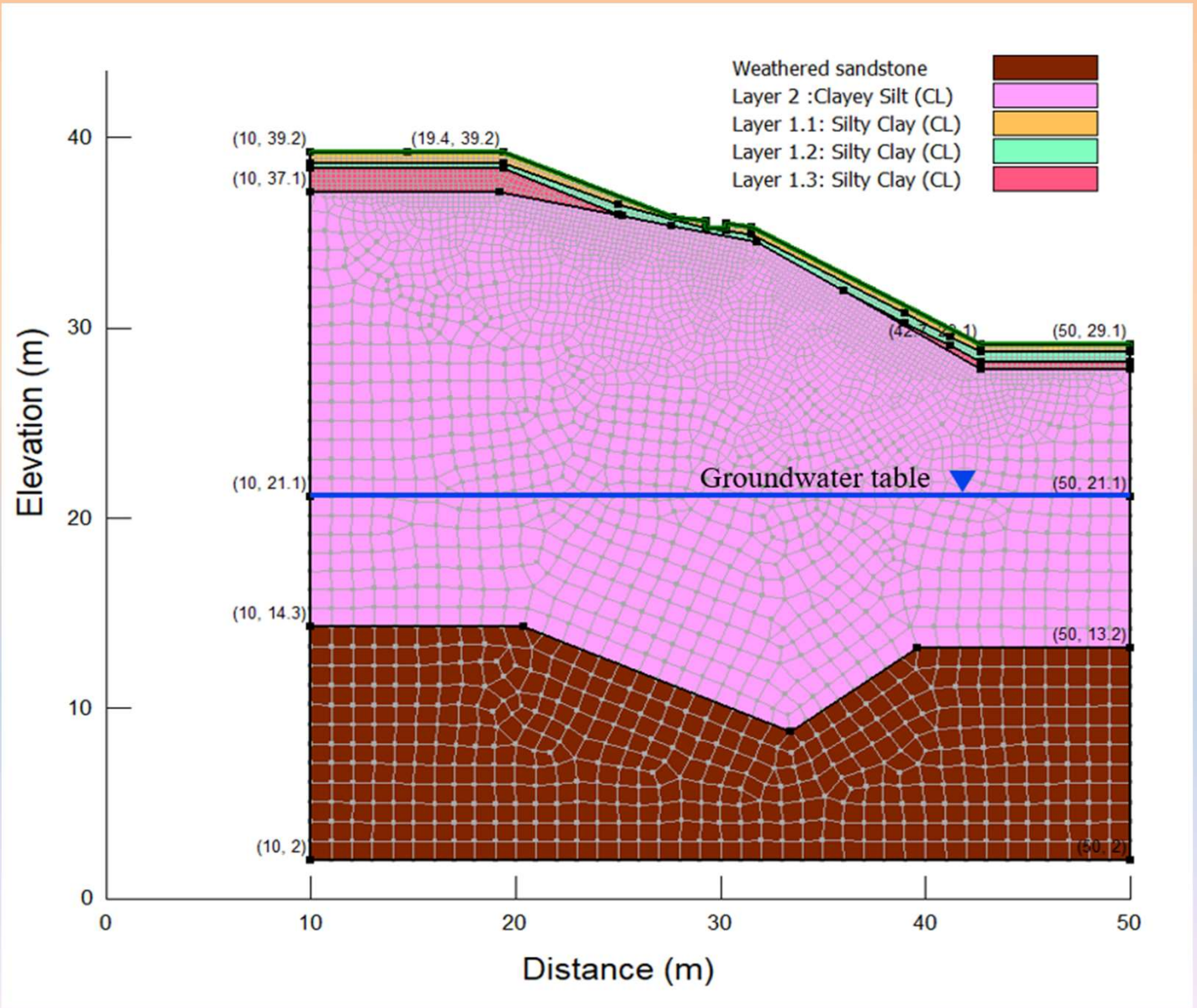
Field Installation



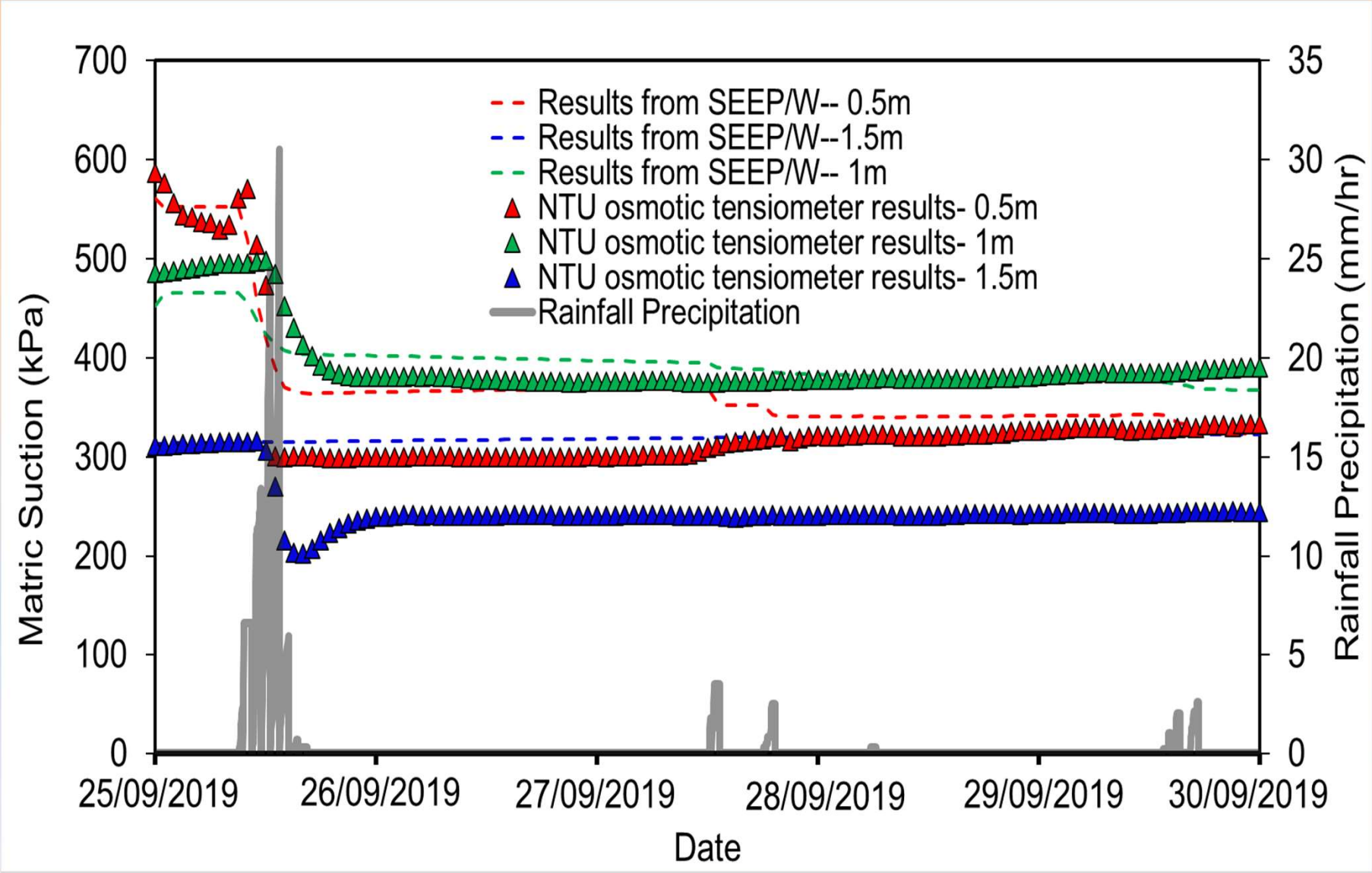
Depths

0.15m (near surface)
0.5m
1.0m
1.5m

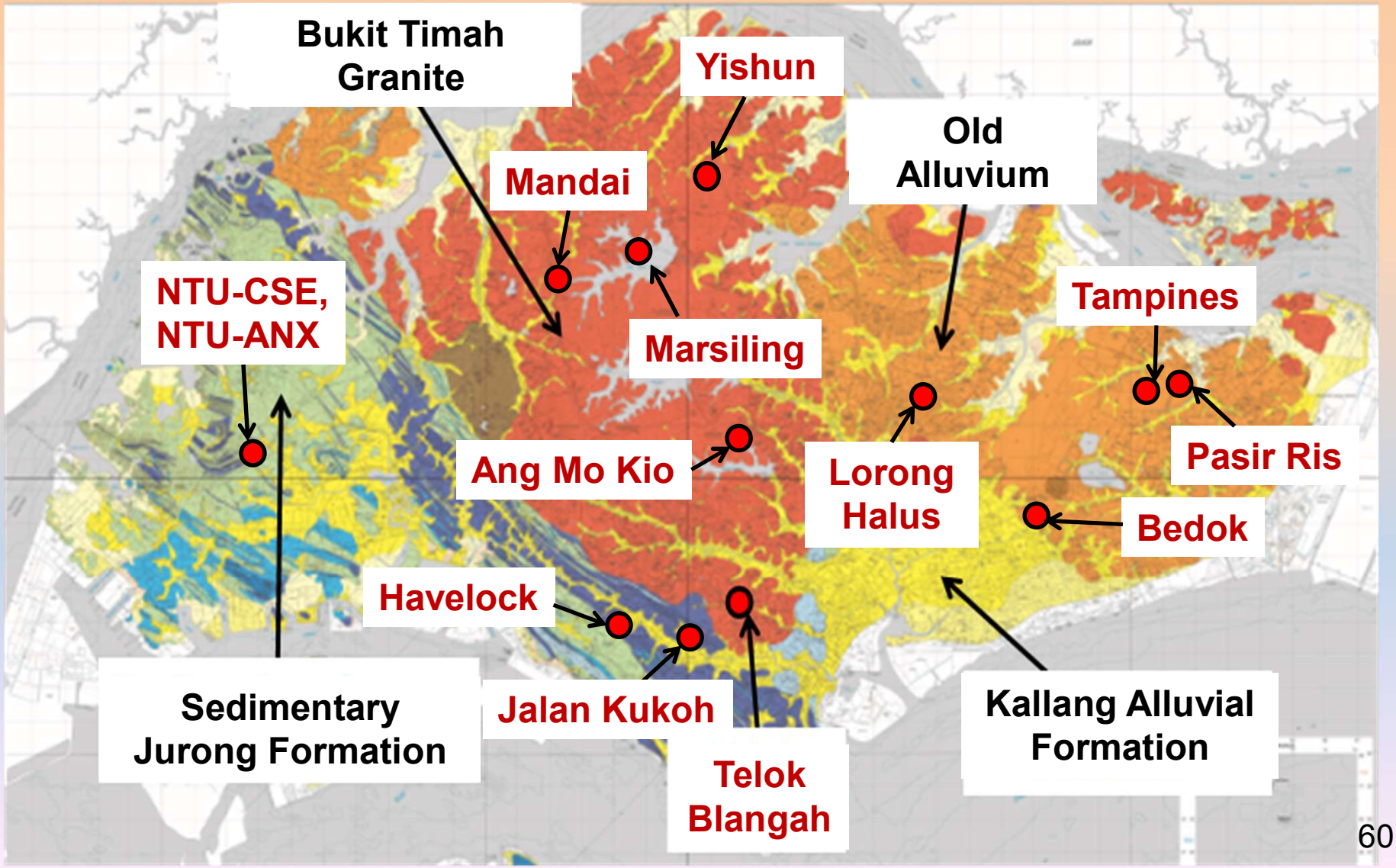
Instrumented Slope



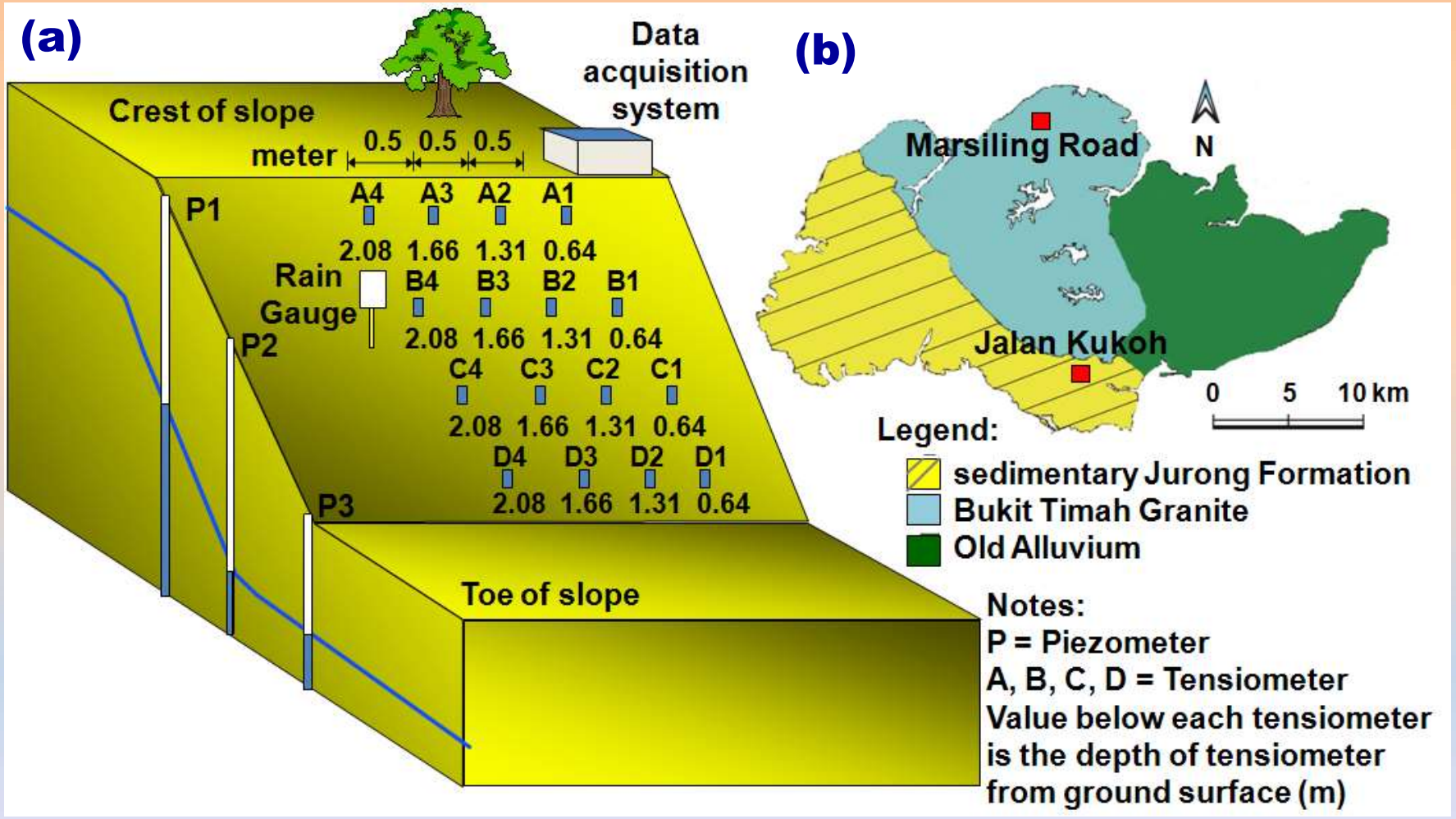
Field Measurements and Numerical Modelling Results



Locations of Instrumented Residual Soil Slopes in Singapore (Research Collaboration between HDB and NTU)



Case Studies for Unsaturated Soil



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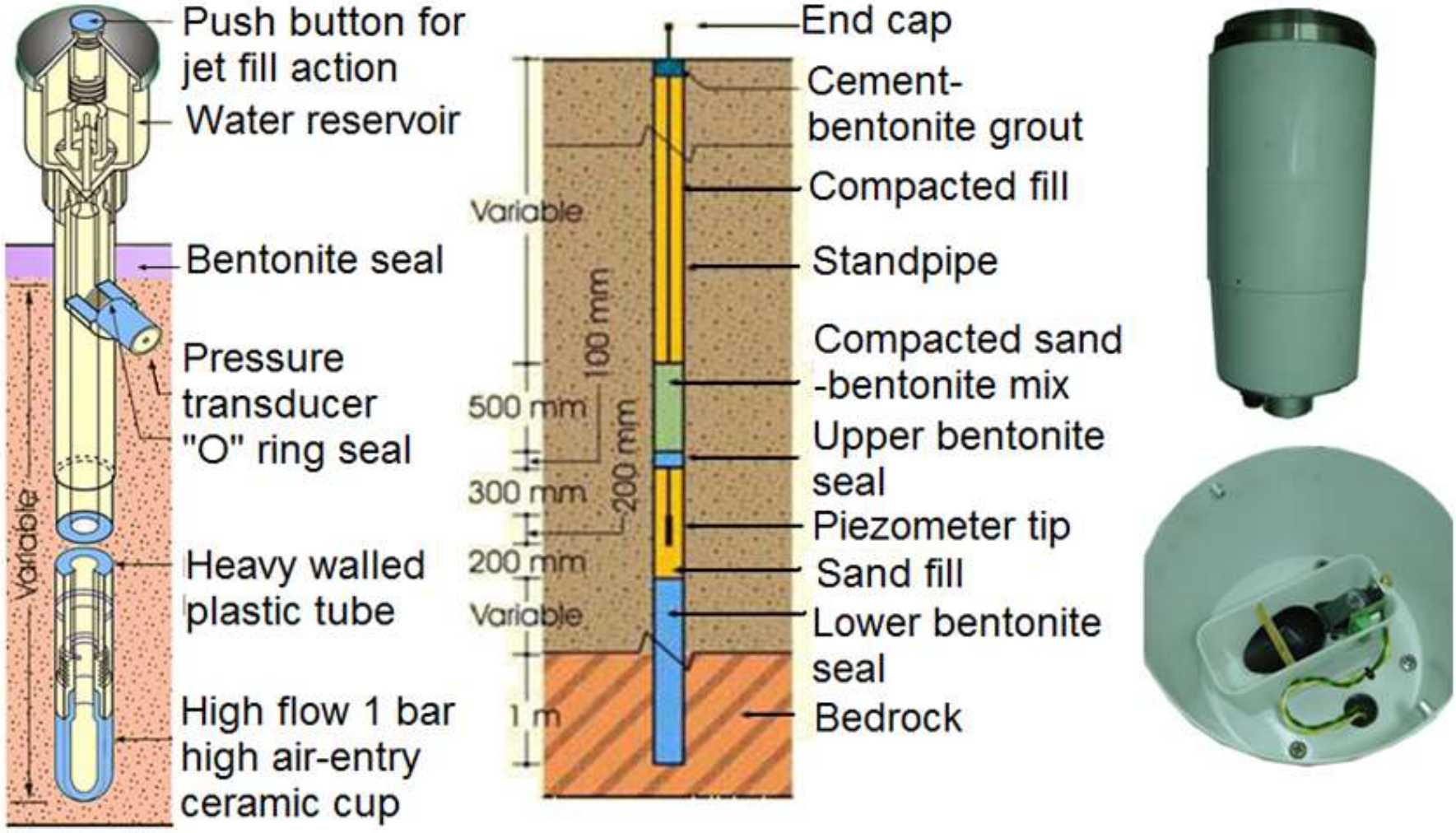
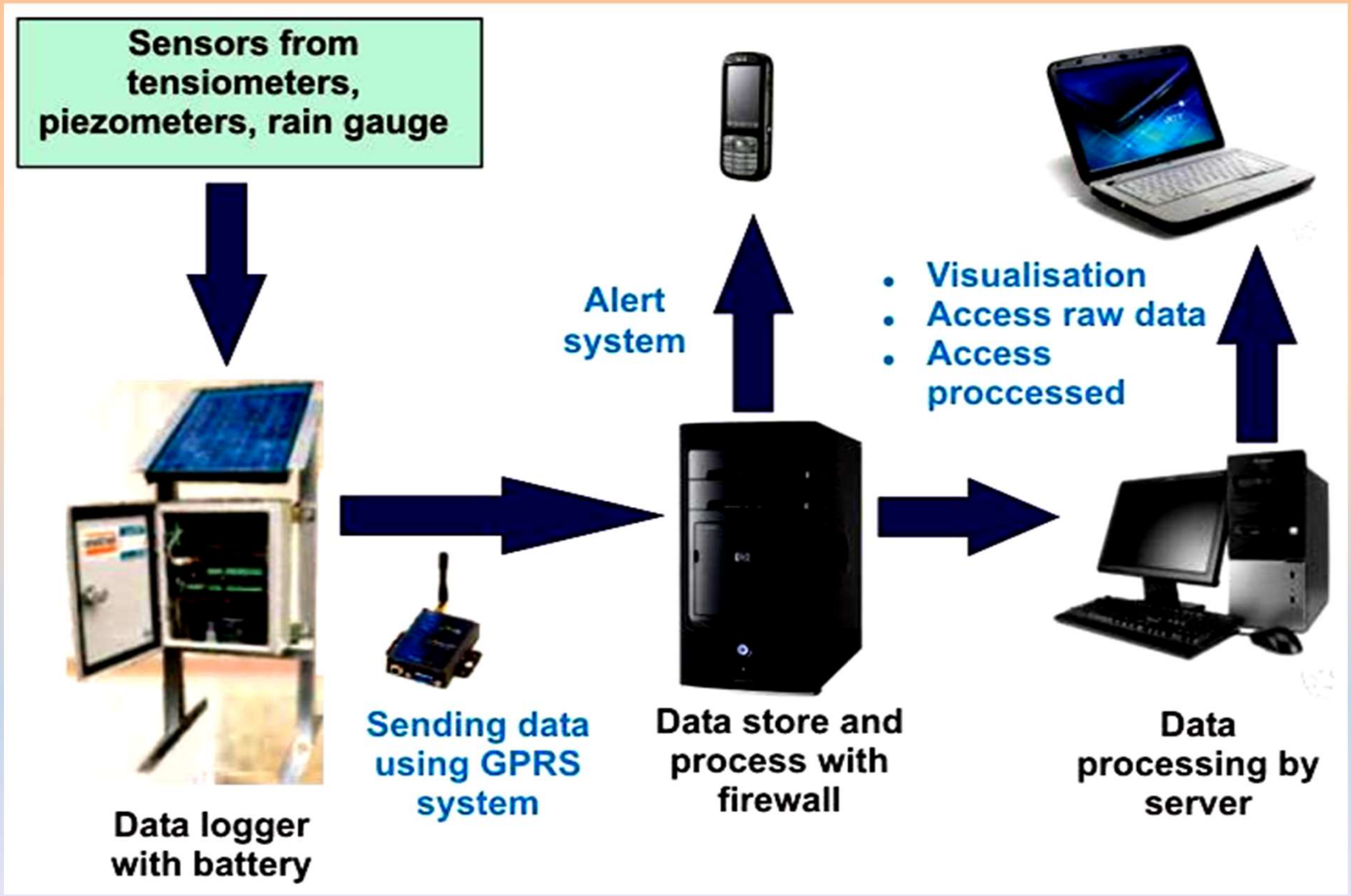
(a) Schematic diagram of relative position and arrangement of on-line monitoring system for Jalan Kukoh and Marsiling Road slopes, (b) generalized geological map of Singapore

Field Instrumentations



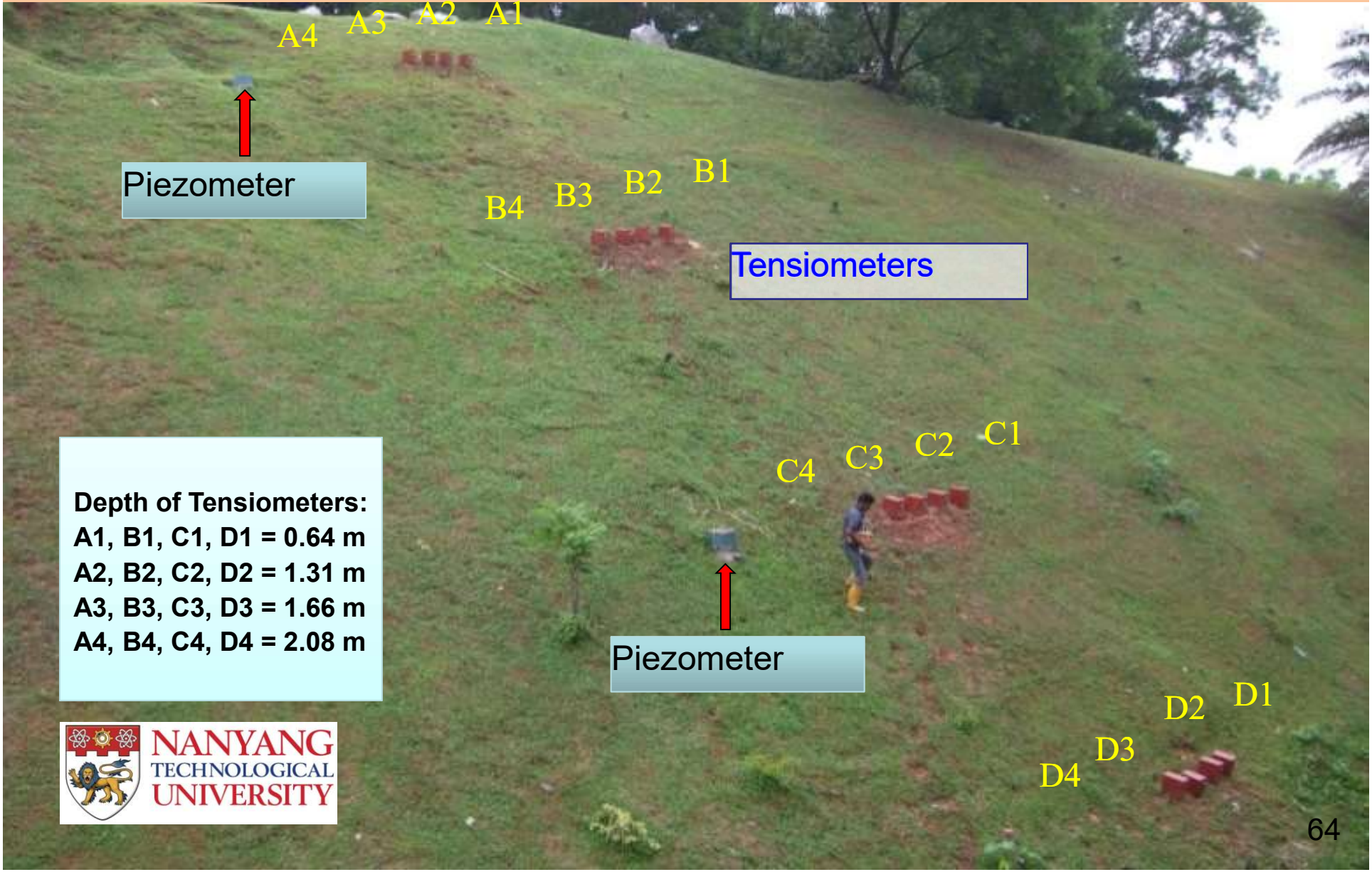
(a) Jet-fill tensiometer **(b) Piezometer** **(c) Rain gauge**

Field Instrumentations



Typical layout of on-line monitoring system

Locations of Instruments for On-line Monitoring in Marsiling Road



Depth of Tensiometers:
A1, B1, C1, D1 = 0.64 m
A2, B2, C2, D2 = 1.31 m
A3, B3, C3, D3 = 1.66 m
A4, B4, C4, D4 = 2.08 m

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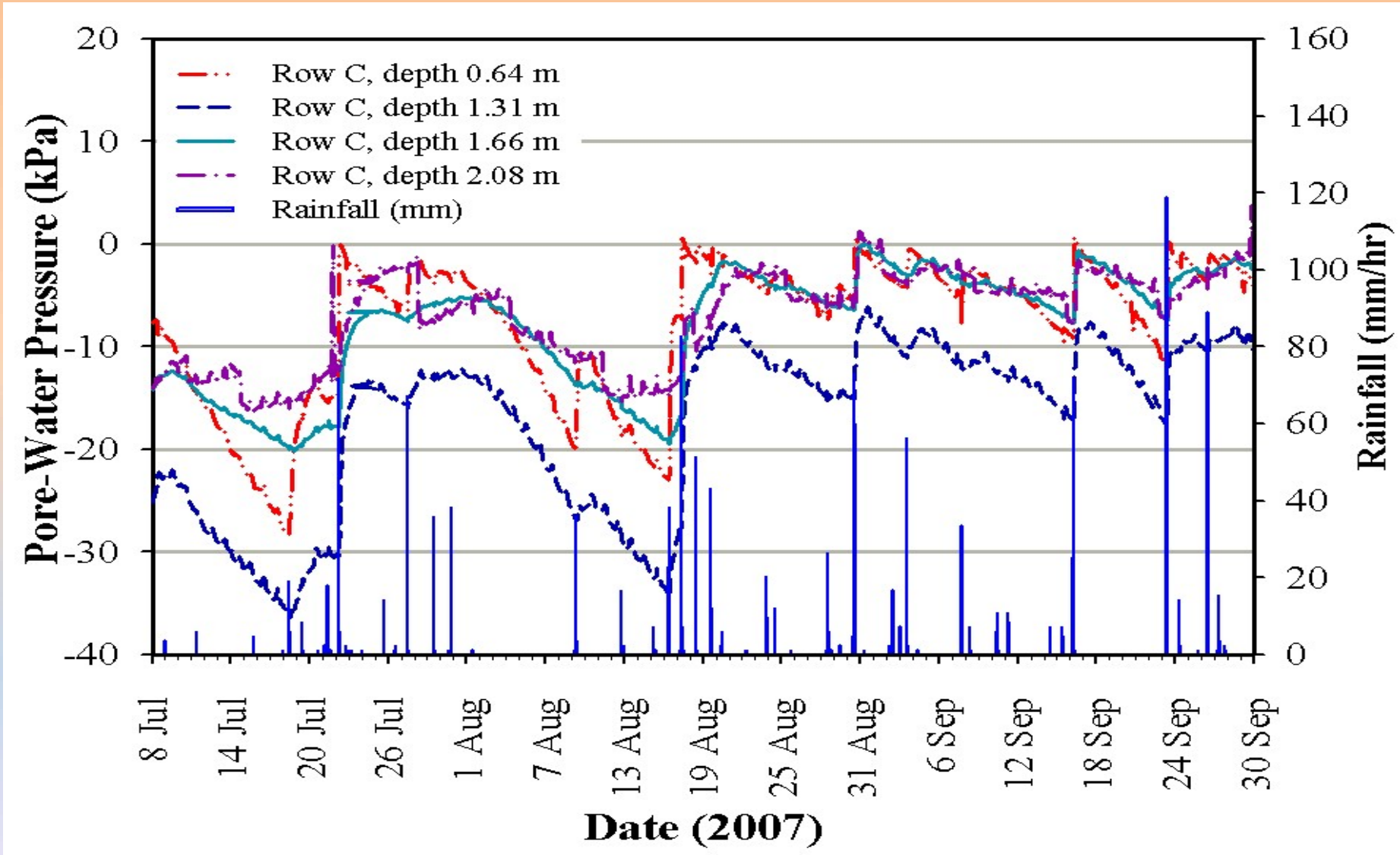
Results and Discussions
Bukit Timah Granite

- **Monitoring period: July to September 2007.**
- **Total amount of rainfall on 16 September 2007 was 345.6 mm.**
- **Maximum rainfall intensity = 72 mm/hr.**
- **Depths of groundwater table (from the ground surface) on 7 May 2008:**
  - **at the crest of slope: 16.2 m**
  - **at the mid slope: 10.7 m**
  - **at the toe of slope: 4.3 m.**

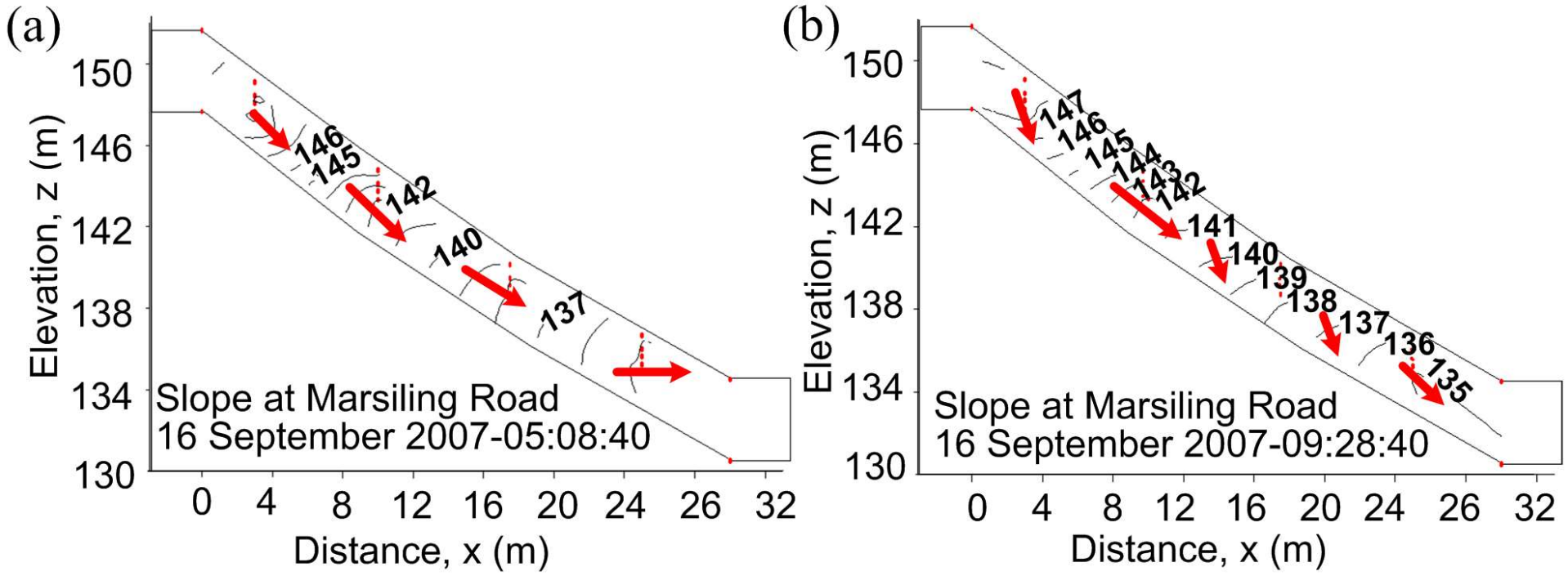
Pore-water pressure readings at various depths



Marsiling Road slope

(monitoring period: July–September 2007)

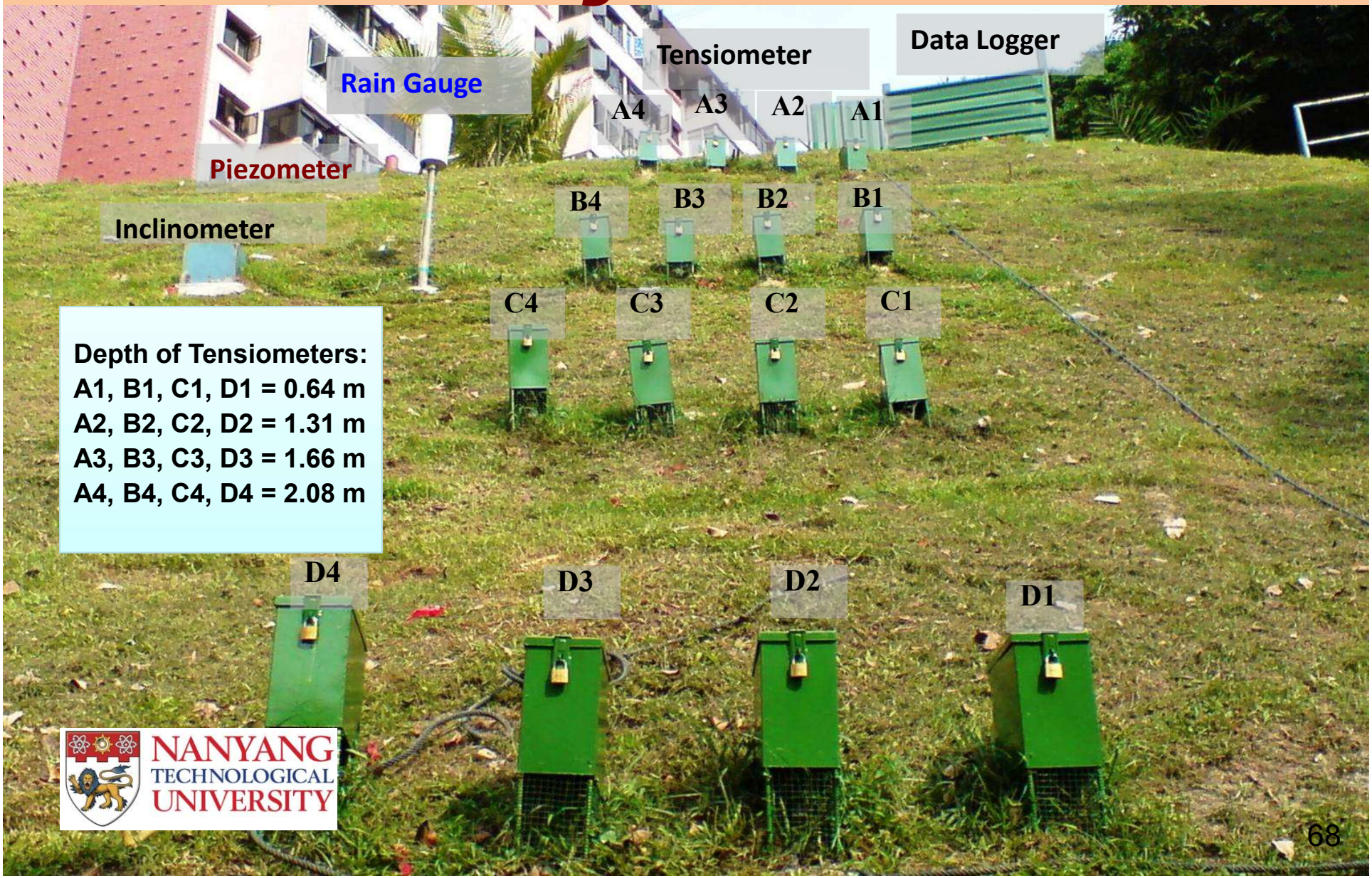
Total head contours of Marsiling Road site on 16 September 2007



(a) Before rainfall

(b) After rainfall

Locations of Instruments for On-line Monitoring in Jalan Kukoh



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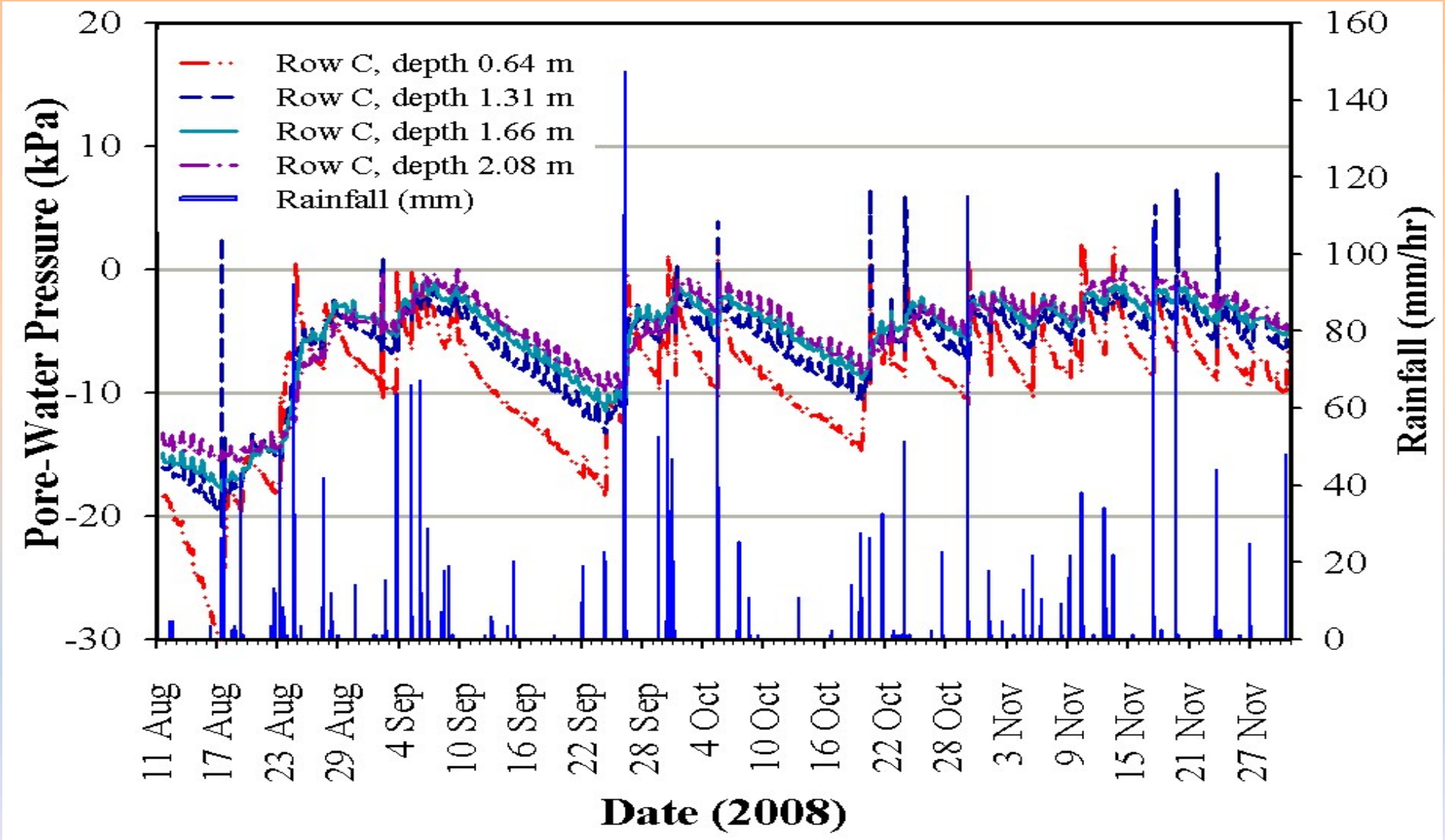
Results and Discussions
Sedimentary Jurong Formation

- **Monitoring period: August to November 2008.**
- **Total amount of rainfall on 23 August 2008 was 100.2 mm.**
- **Maximum rainfall intensity = 92.4 mm/hr.**
- **Depths of groundwater table (from the ground surface):**
  - **at the crest of slope: 10.50 m**
  - **at the mid slope: 9.9 m**
  - **at the toe of slope: 2.1 m**

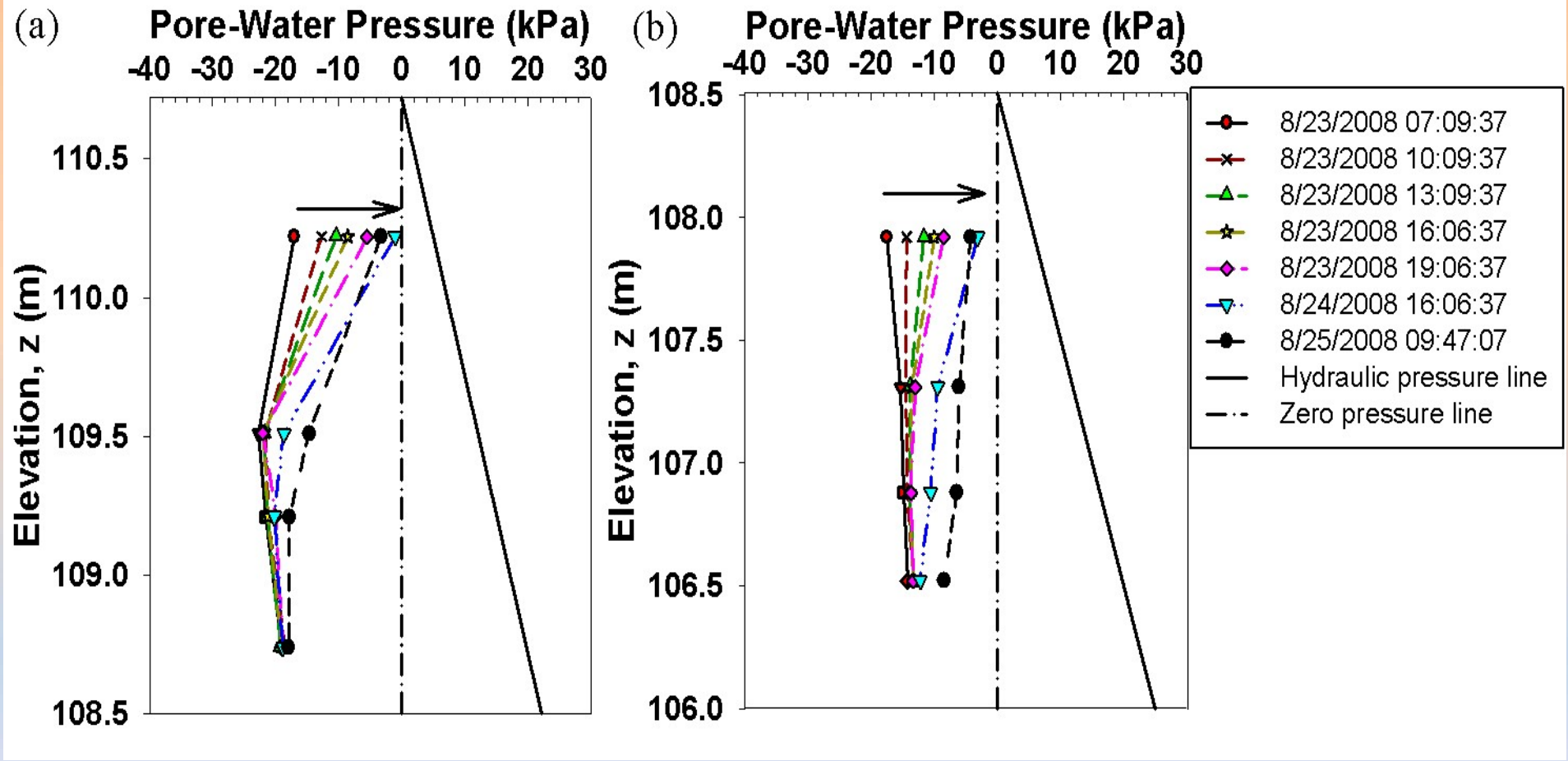
Pore-water pressure readings at various depths



Jalan Kukoh slope

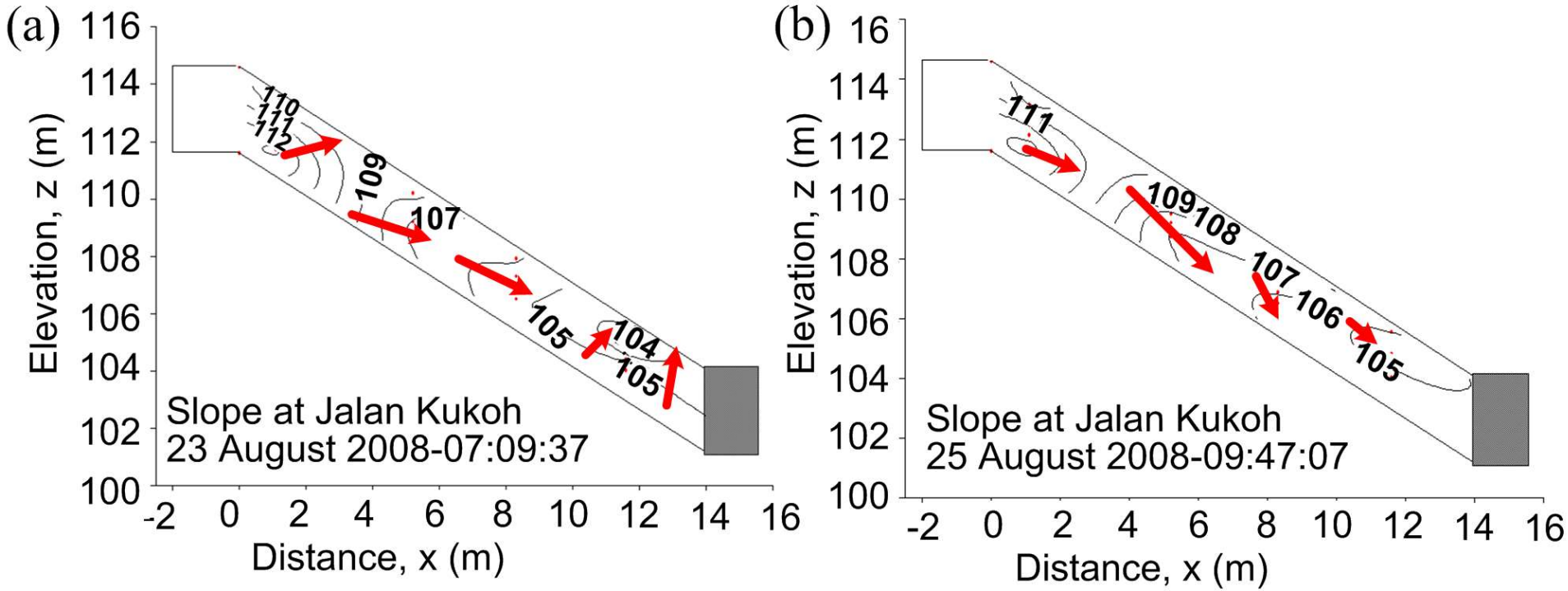
(monitoring period: August-November 2008)

Pore-water pressure profiles on 23 August 2008 during rainfall at Jalan Kukoh slope



(a) Row B **(b) Row C**

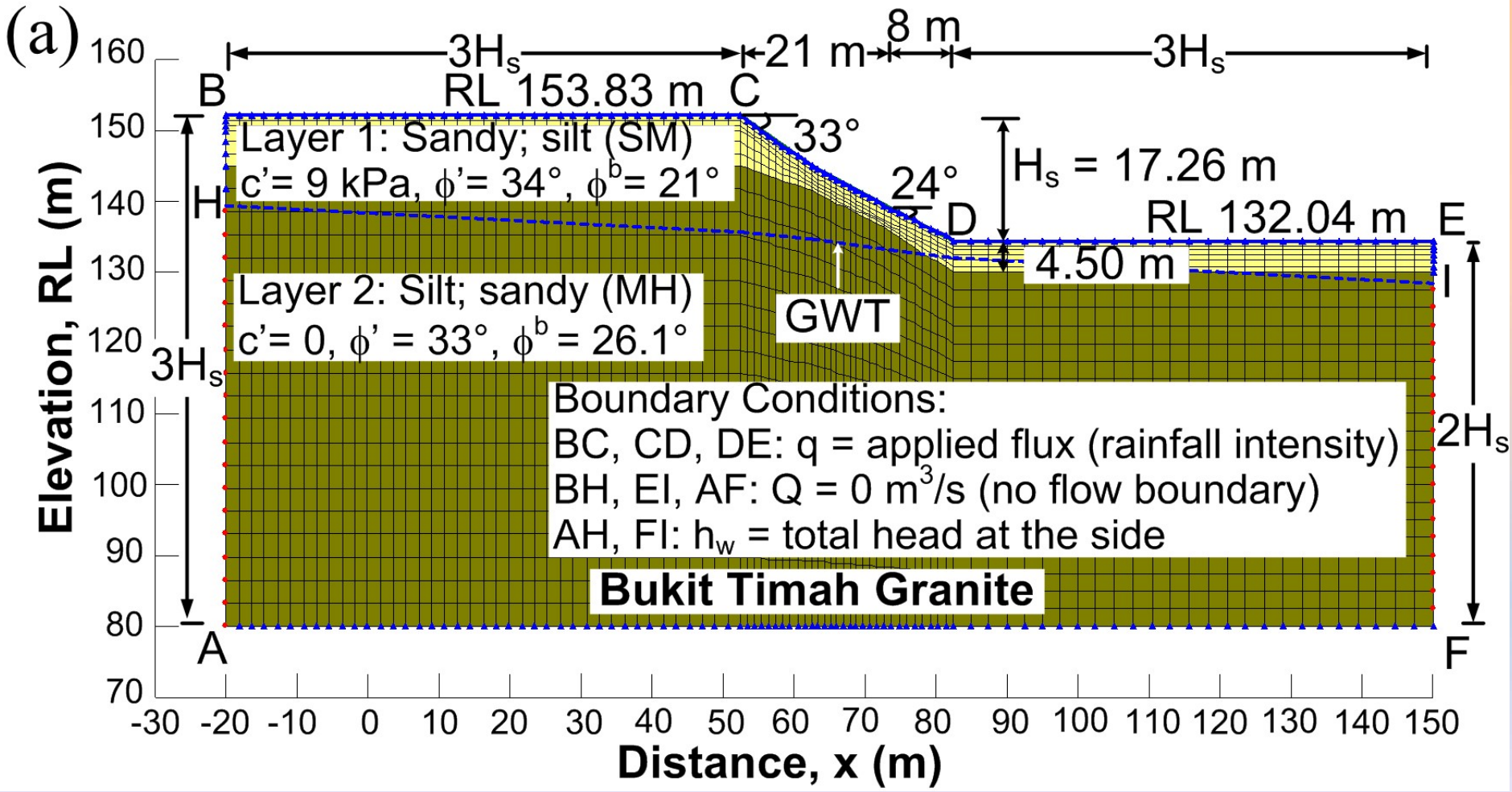
Total head contours of Jalan Kukoh site on 23 August 2008



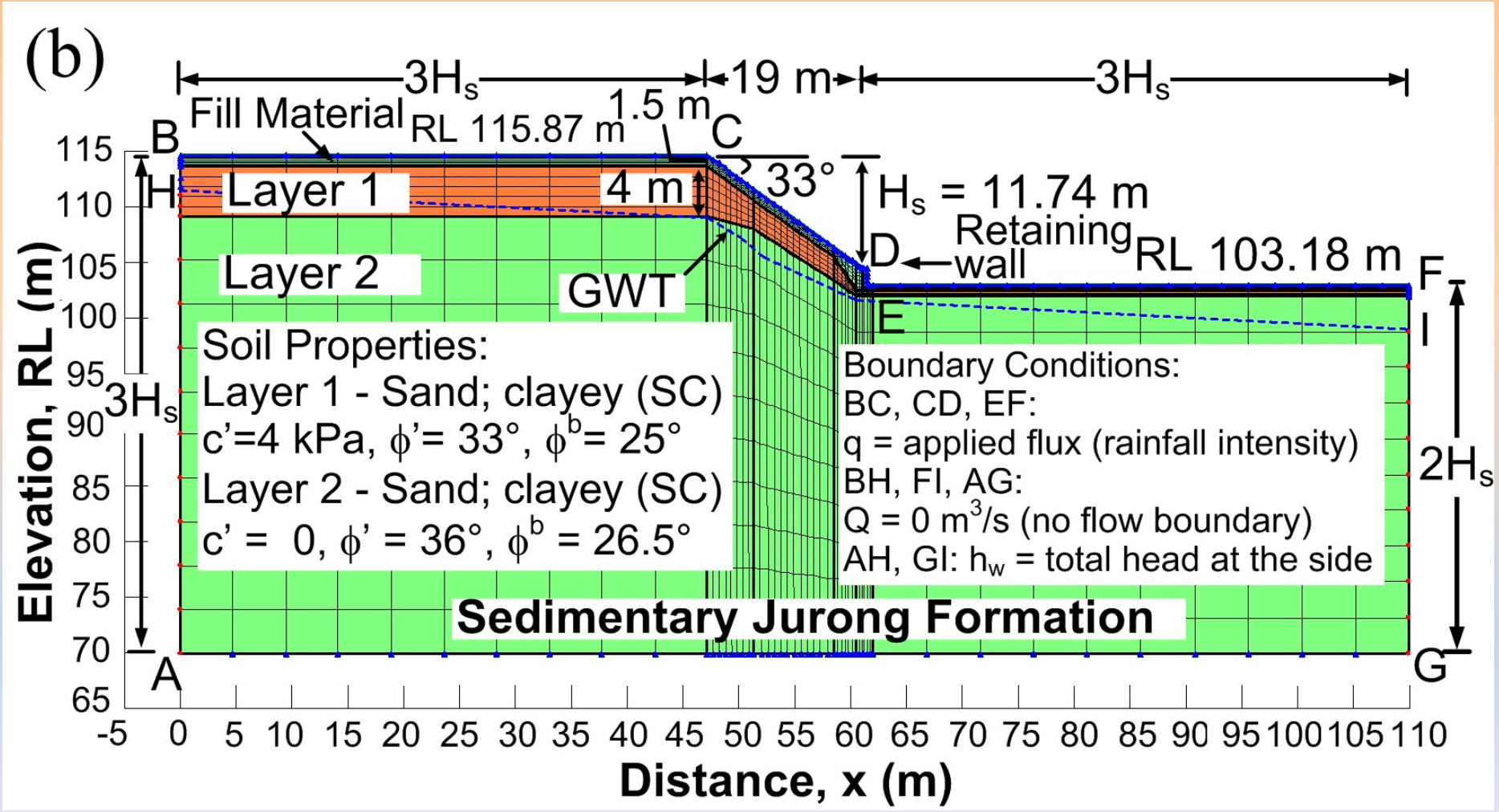
(a) Before rainfall

(b) After rainfall

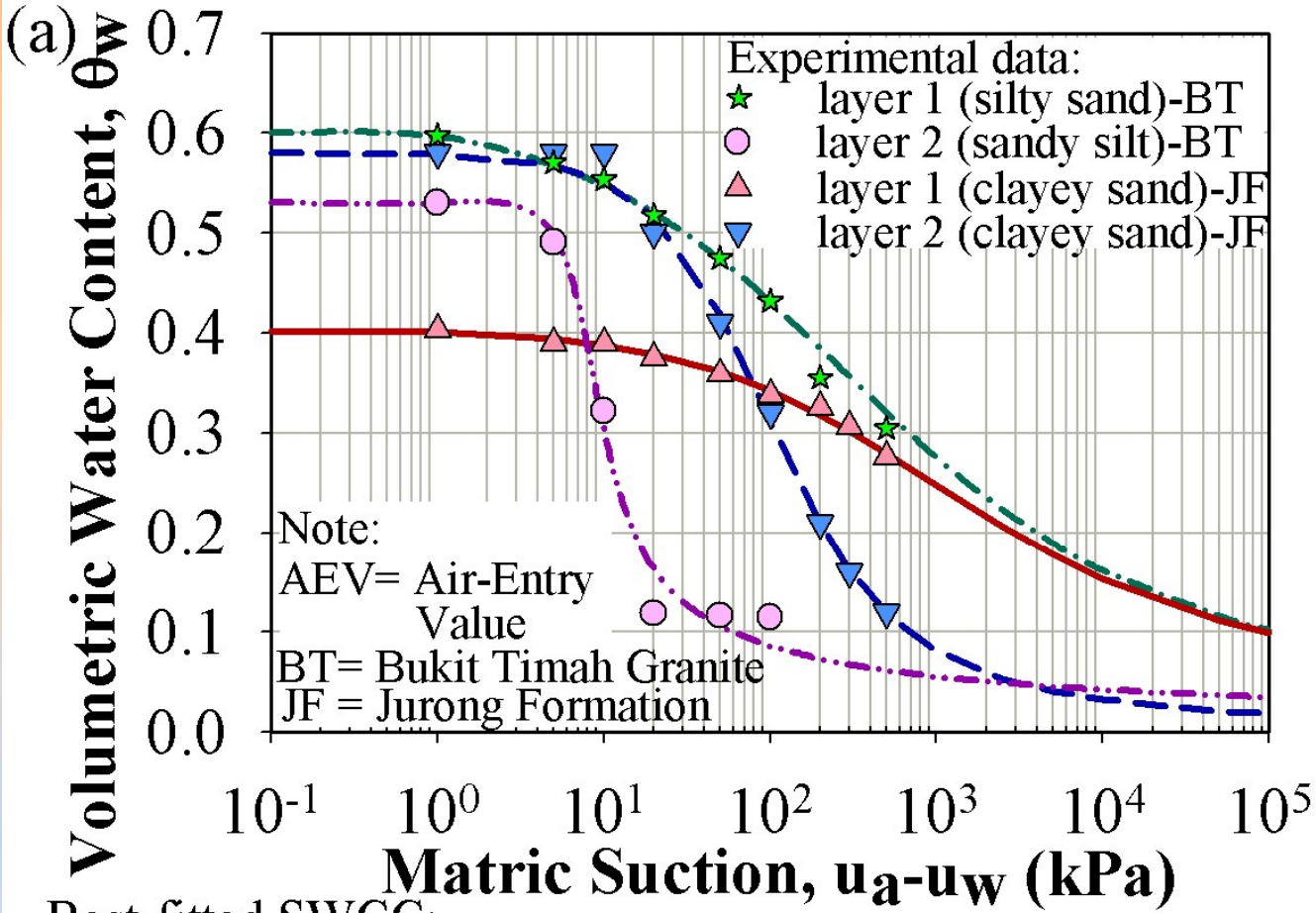
Finite element mesh and boundary conditions of Marsiling Road



Finite element mesh and boundary conditions of Jalan Kukoh slopes



Hydraulic properties

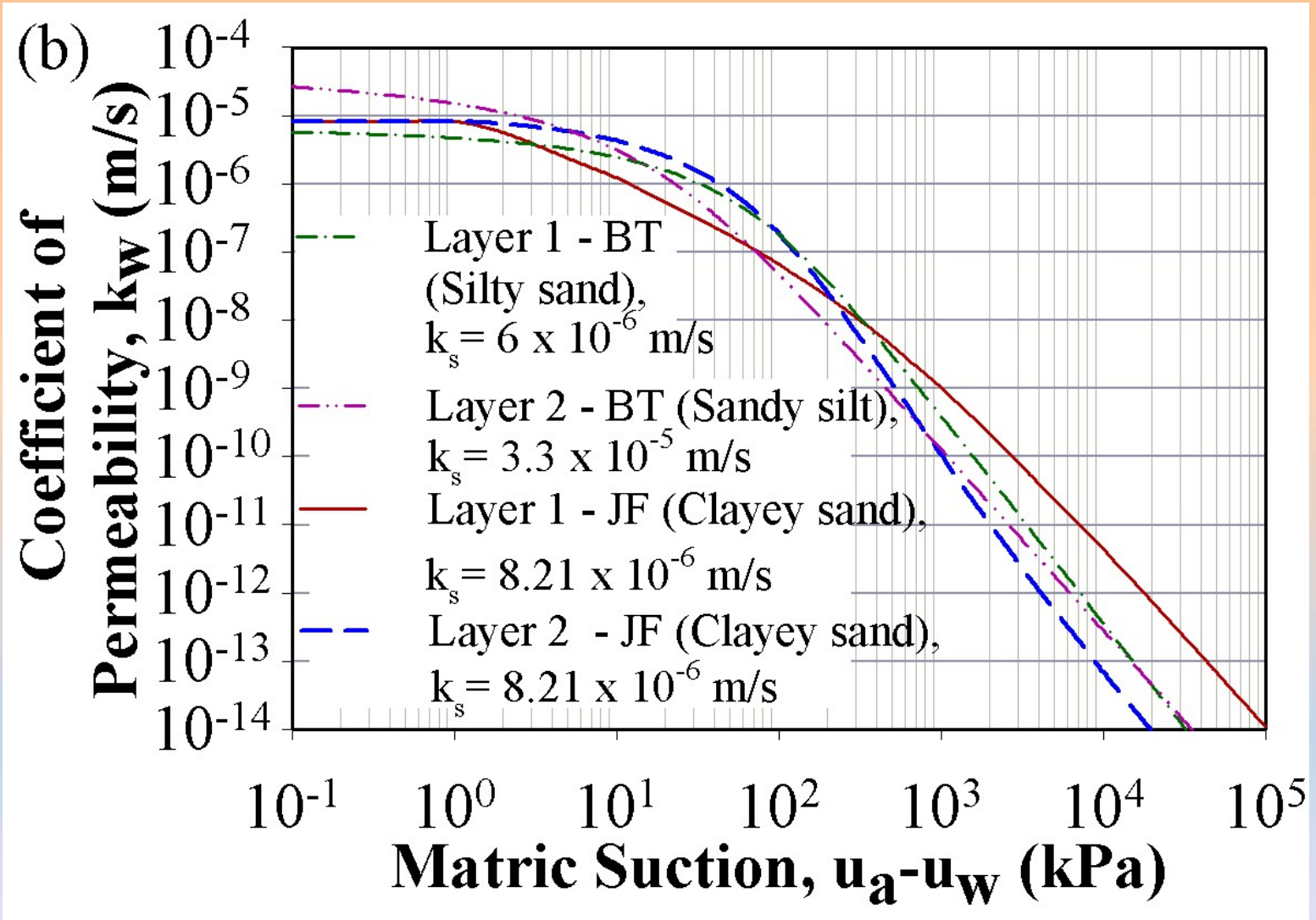


Best-fitted SWCC:

- layer 1 (clayey sand) - JF (a=298 kPa, n=0.62, m=1.08, AEV = 50 kPa)
- layer 2 (clayey sand) - JF (a=65 kPa, n=1.27, m=1.54, AEV = 20 kPa)
- layer 1 (silty sand) - BT (a=101 kPa, n=0.55, m=1.33, AEV = 15 kPa)
- layer 2 (sandy silt) - BT (a=7 kPa, n=5, m=0.7, AEV = 5 kPa)

Soil-water characteristic curves of residual soils from sedimentary Jurong Formation and Bukit Timah Granite

Hydraulic properties



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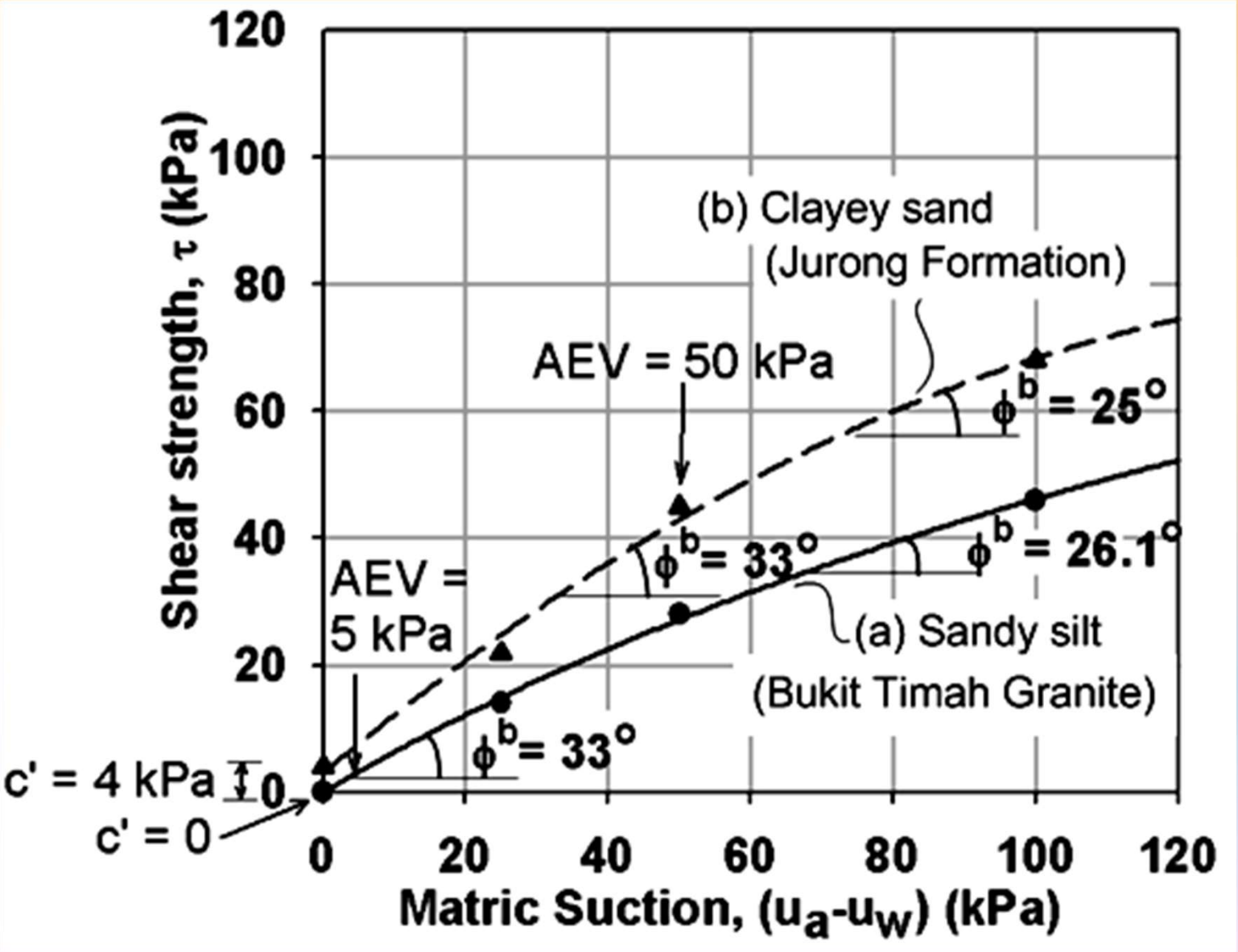
Permeability functions of residual soils from sedimentary Jurong Formation and Bukit Timah Granite

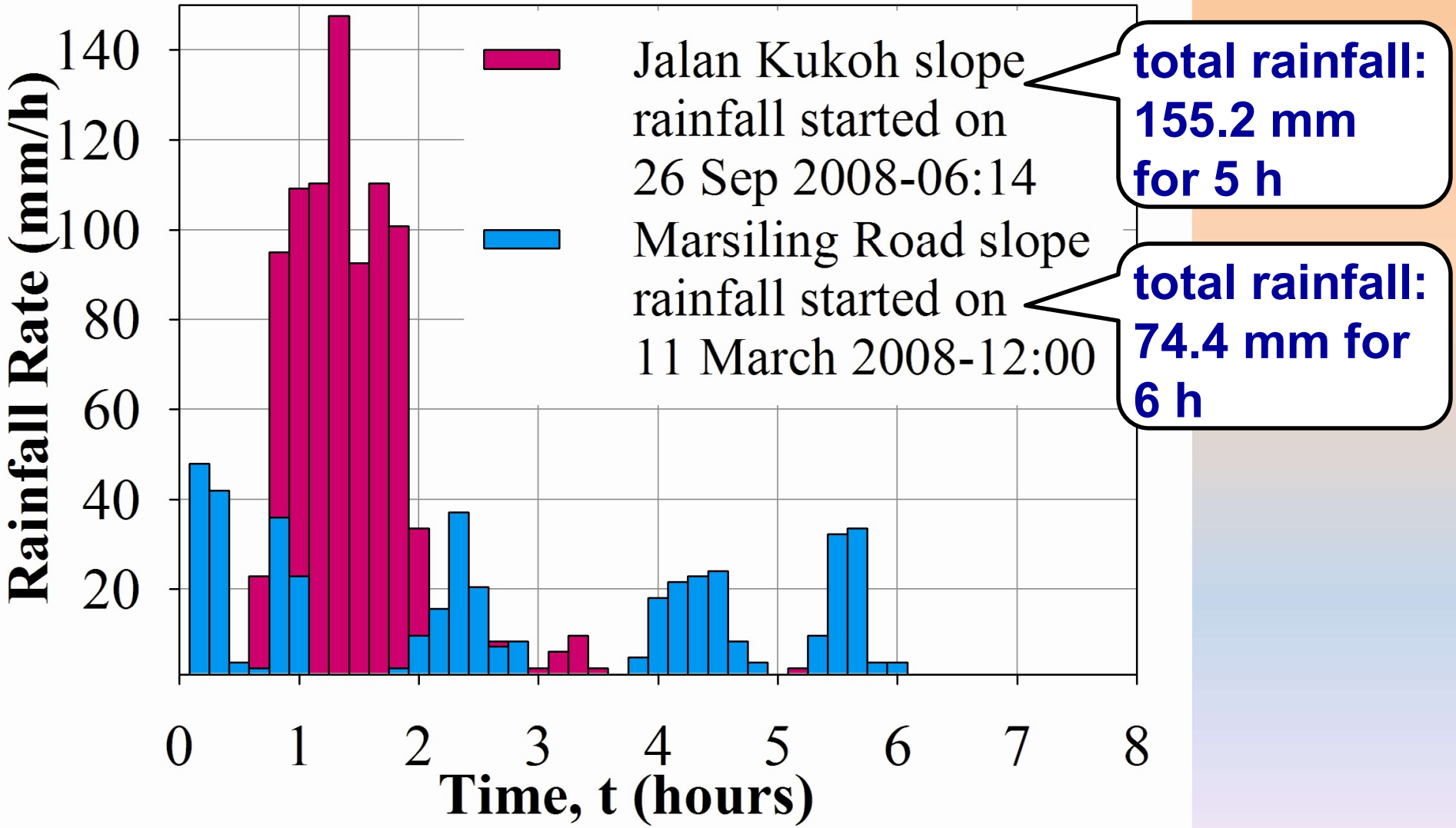
Table 1 Shear strength properties of soils

Parameters	Bukit Timah Granite		Sedimentary Jurong Formation	
	Silty sand	Sandy silt	Clayey sand I	Clayey sand II
Effective cohesion, c' (kPa)	9	0	4	0
Effective angle of friction, ϕ' (°)	34	33	33	36
ϕ^b angle (°)	21	26.1	25	26.5
Total density, ρ_t (Mg/m^3)	2.03	1.88	1.84	1.92

Shear strength versus matric suction



Rainfall rate used in the analyses of Marsiling Road and Jalan Kukoh slopes

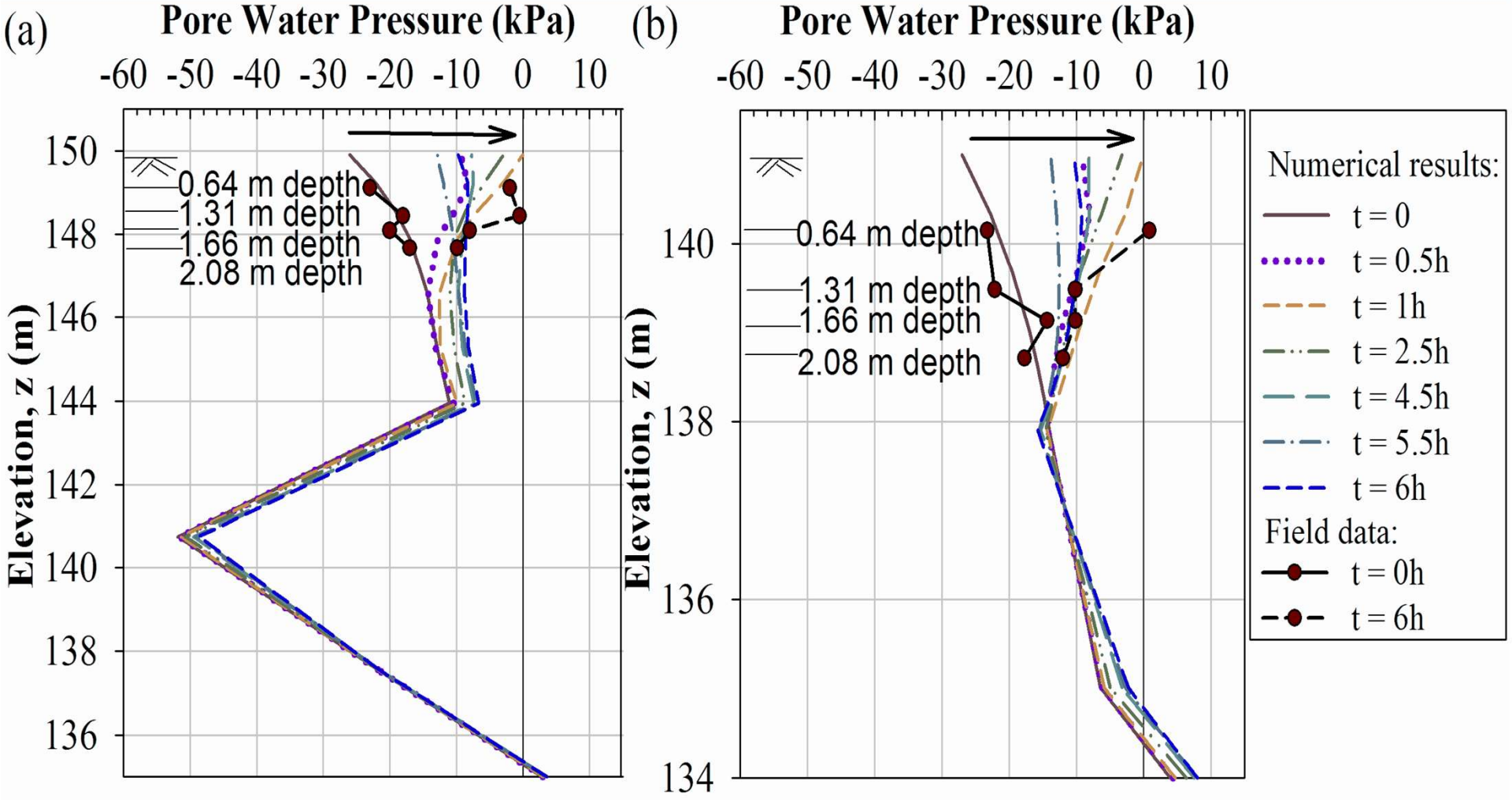


Seepage analysis

- No ponding condition was applied to the surface of slope model.
- Evaporation and evapotranspiration are not simulated in this study.
- Initial conditions for the slope models were limited to negative pore-water pressures of 75 kPa to avoid unrealistic pore-water pressures.
- The seepage analyses of rainwater infiltration into the slope can be performed using the following equation:

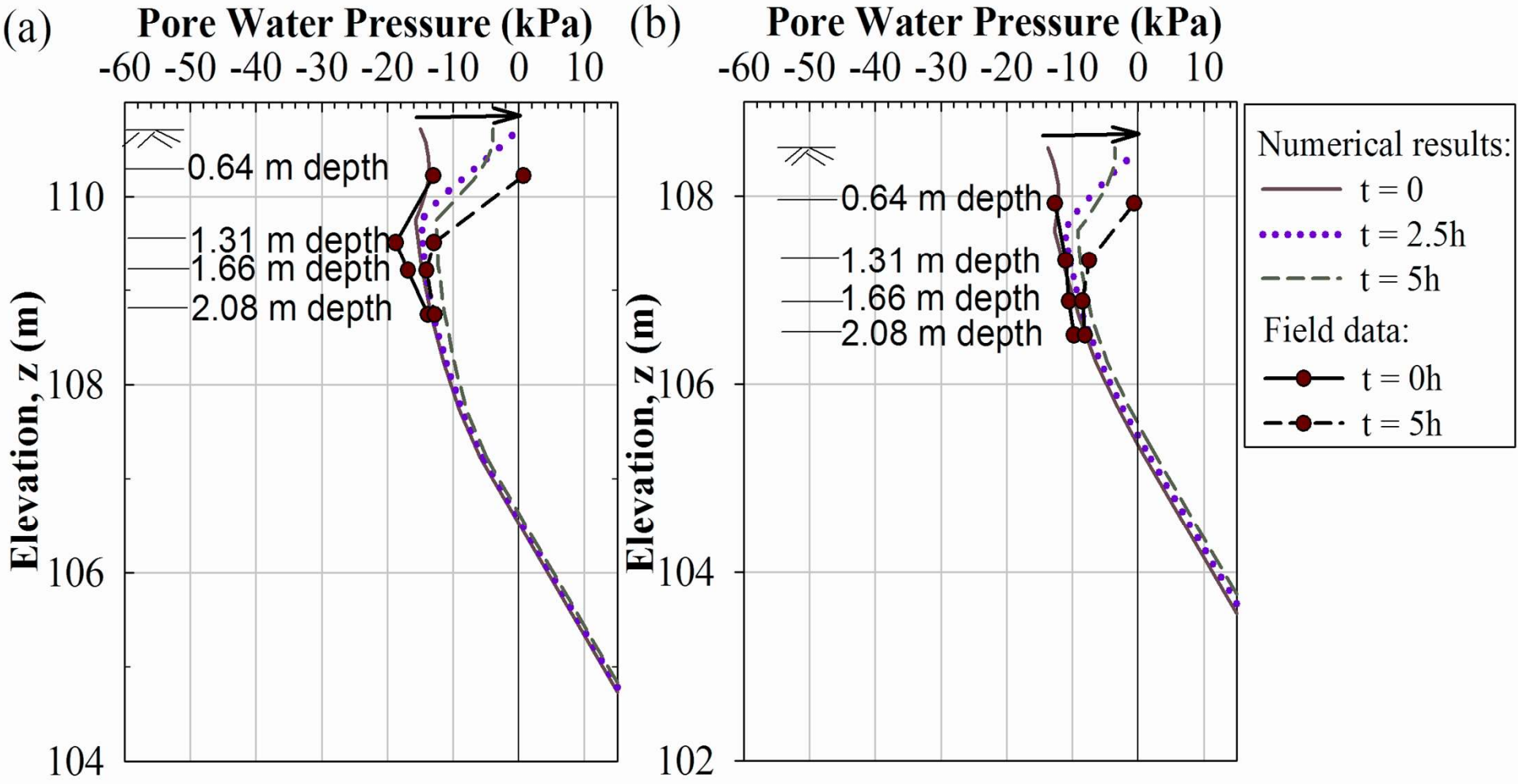
$$\frac{\partial}{\partial x}\left(k_w \frac{\partial h_w}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right)=m_2^w \rho_w g \frac{\partial h_w}{\partial t} \quad (8)$$

Pore-water pressure profiles



Pore-water pressure profiles obtained from numerical analyses versus field data: (a) crest and (b) near toe of Marsiling Road slope from the beginning of rainfall (t=0) until the end of rainfall (t=6 h)

Pore-water pressure profiles



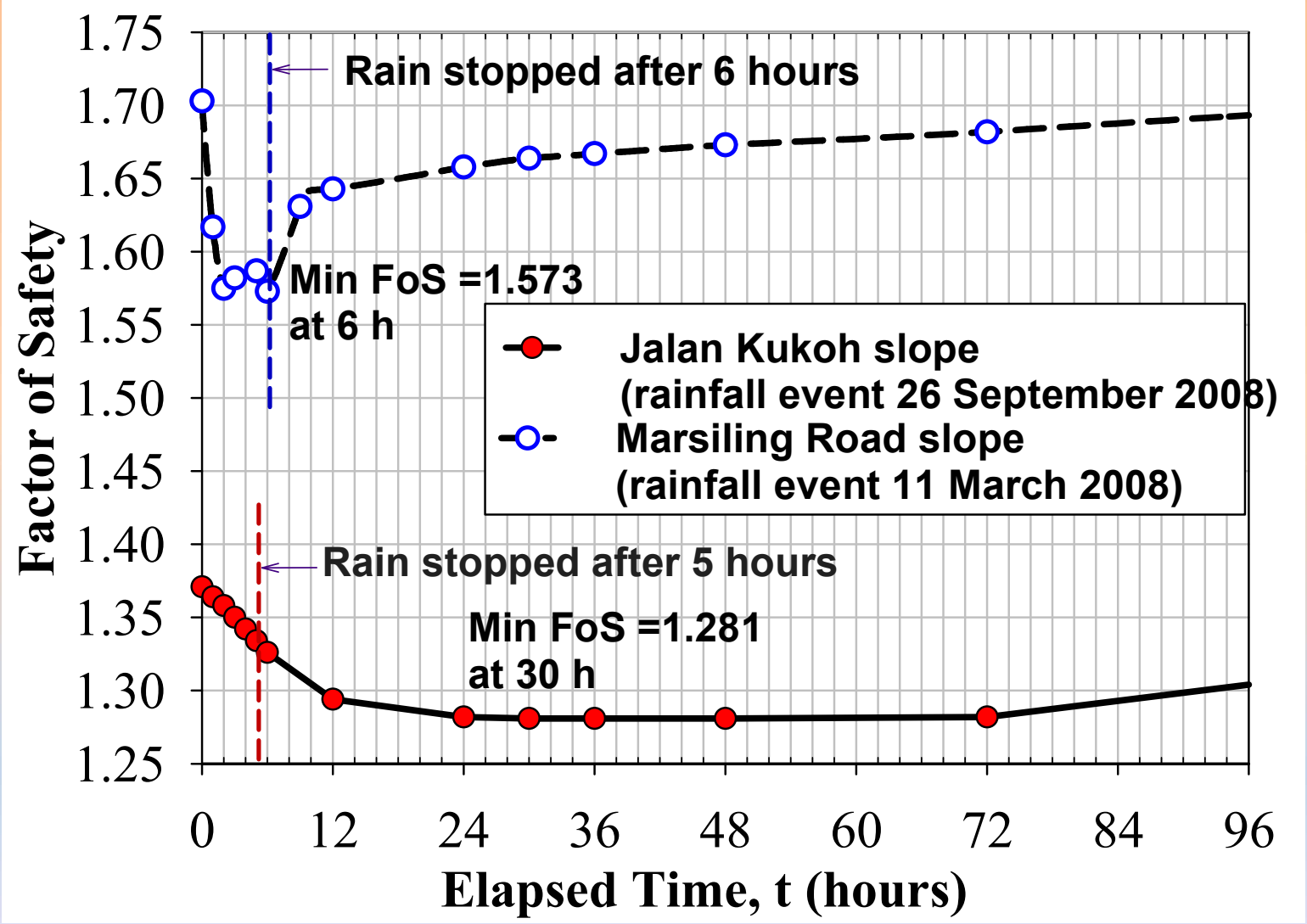
Pore-water pressure profiles obtained from numerical analyses versus field data: (a) near crest and (b) near toe of Jalan Kukoh slope from the beginning of rainfall (t=0) until the end of rainfall (t=5 h)

Slope stability analysis

- **The computed pore-water pressures from the transient seepage analyses using finite element can then be as input to slope stability analyses.**
- **The factor of safety, F_s, calculation is based on Bishop's simplified method as the following equation:**

$$F_s = \frac{\sum \left[c'\beta R + \left\{ N - u_w \beta \frac{\tan\phi^b}{\tan\phi'} - u_a \beta \left(1 - \frac{\tan\phi^b}{\tan\phi'} \right) \right\} R \tan\phi' \right]}{Aa + \sum Wx - \sum Nf} \quad (10)$$

Factor of safety variations



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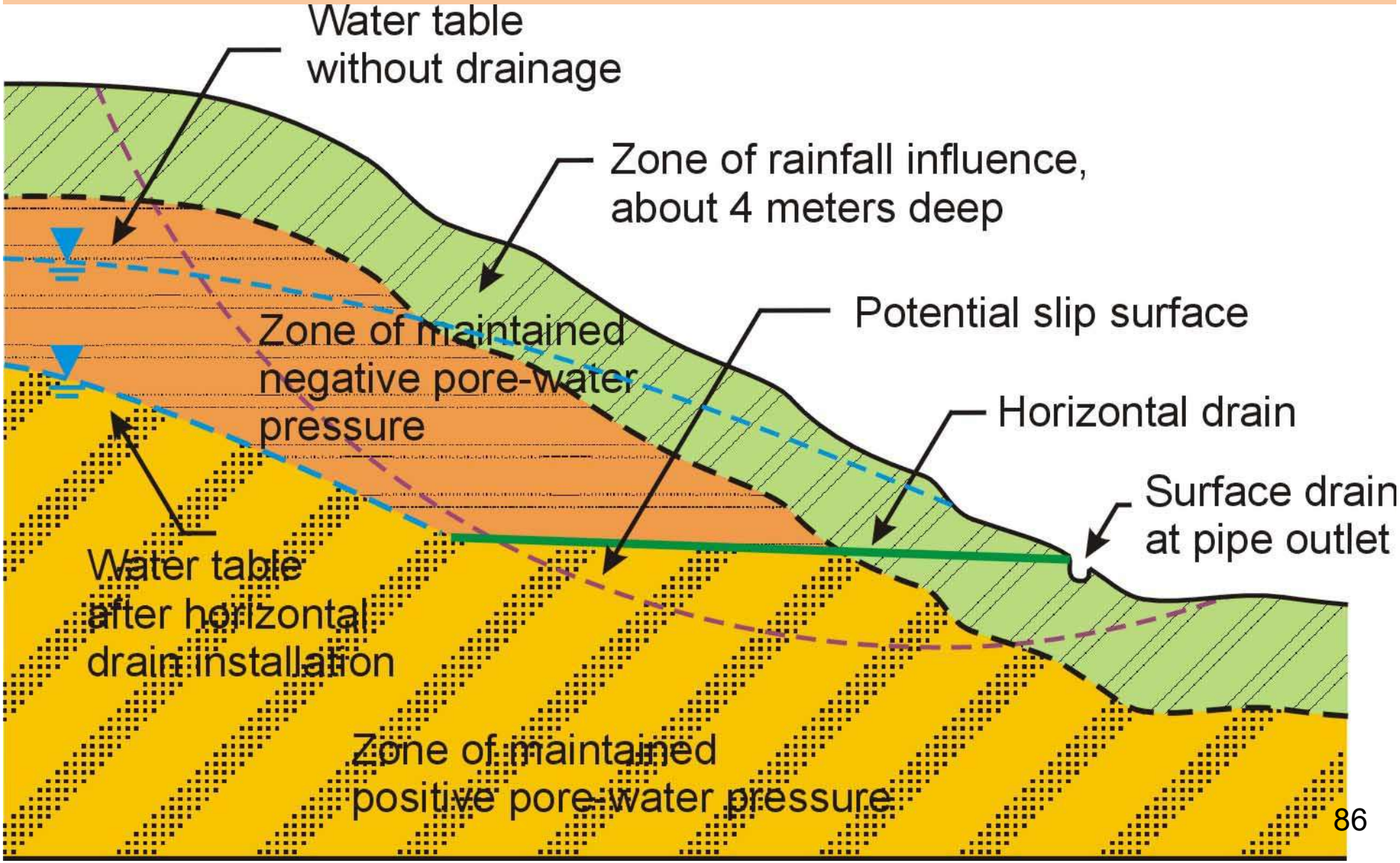
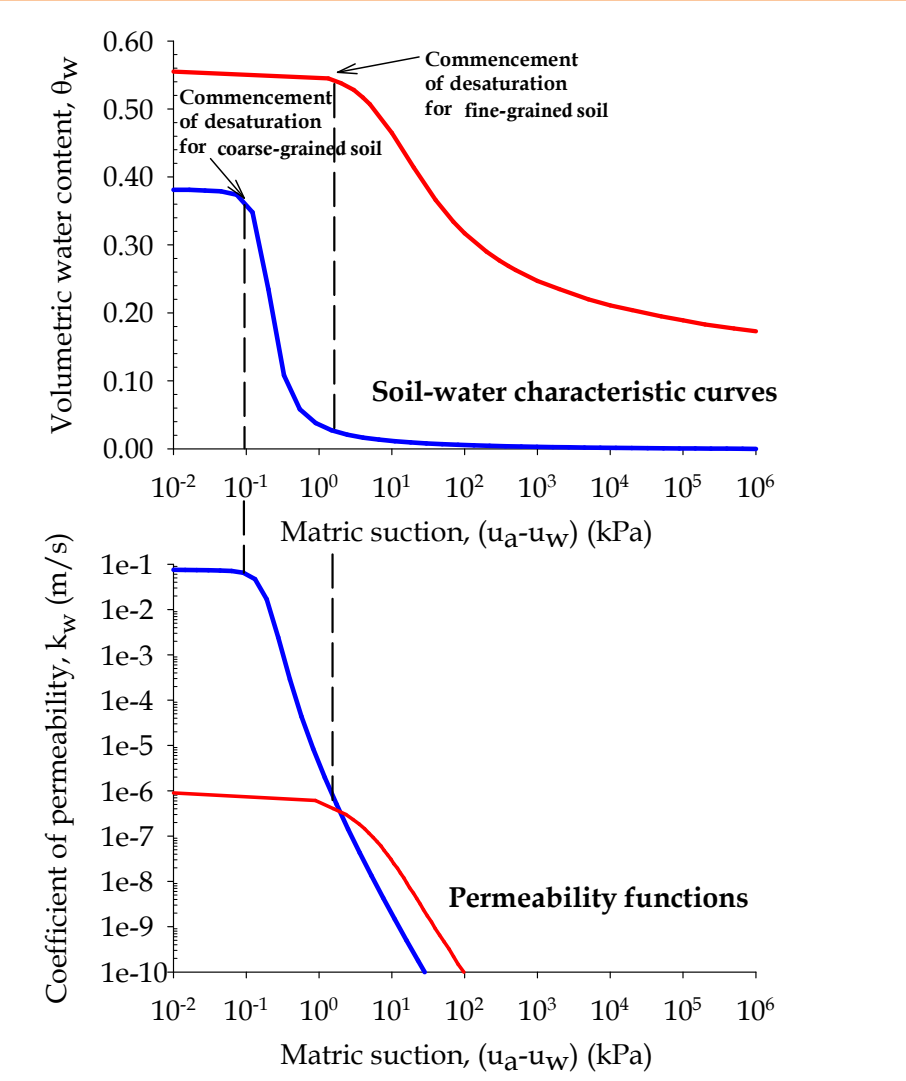
Factor of safety changes of Jalan Kukoh and Marsiling Road sites during infiltration and drying processes on 26 September and 11 March 2008, respectively

Preventive Measures for Rainfall-induced Slope Failures using the principles of Unsaturated Soil Mechanics

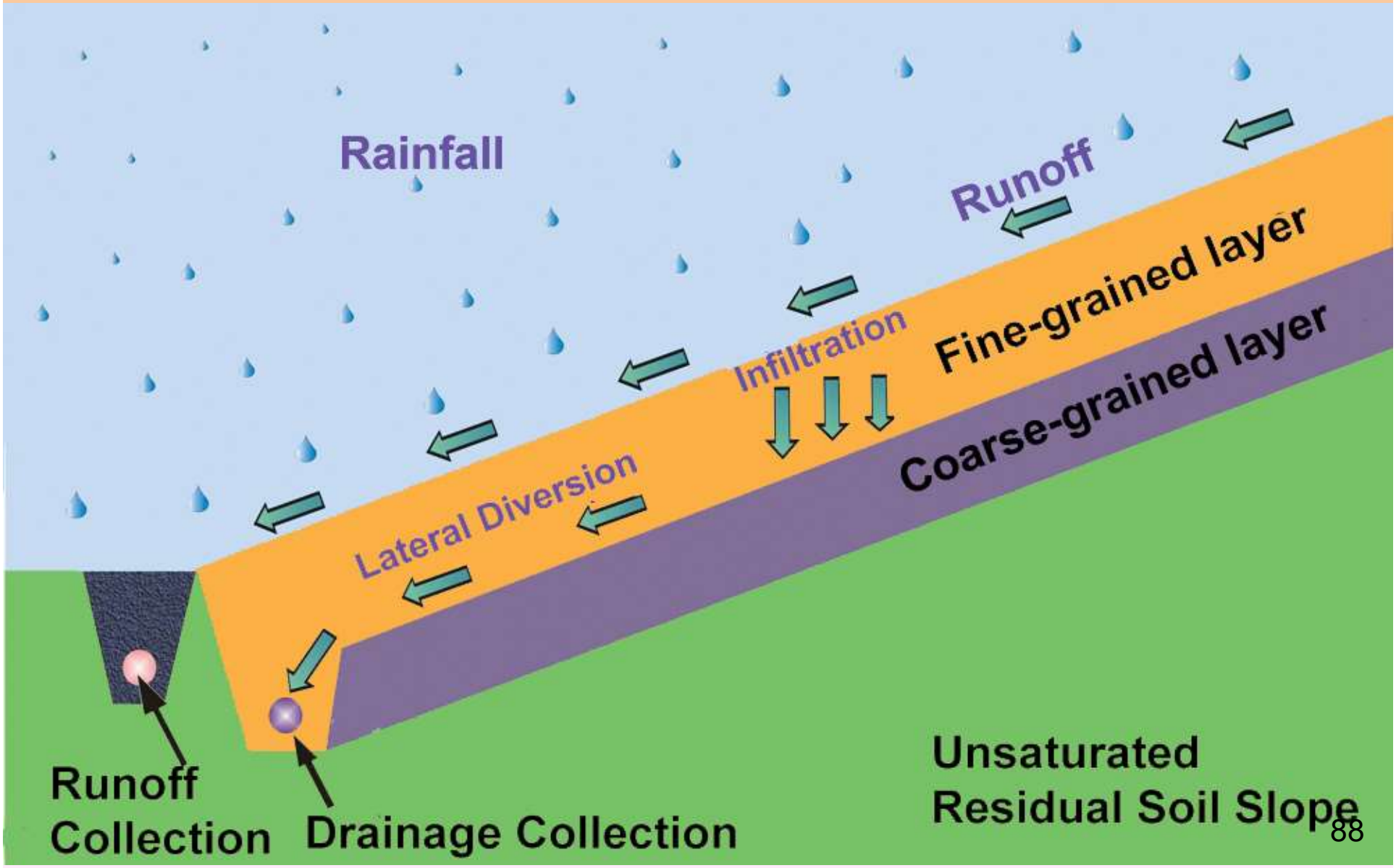
Horizontal Drain for Controlling of Groundwater Table



Relationship between SWCC and permeability functions



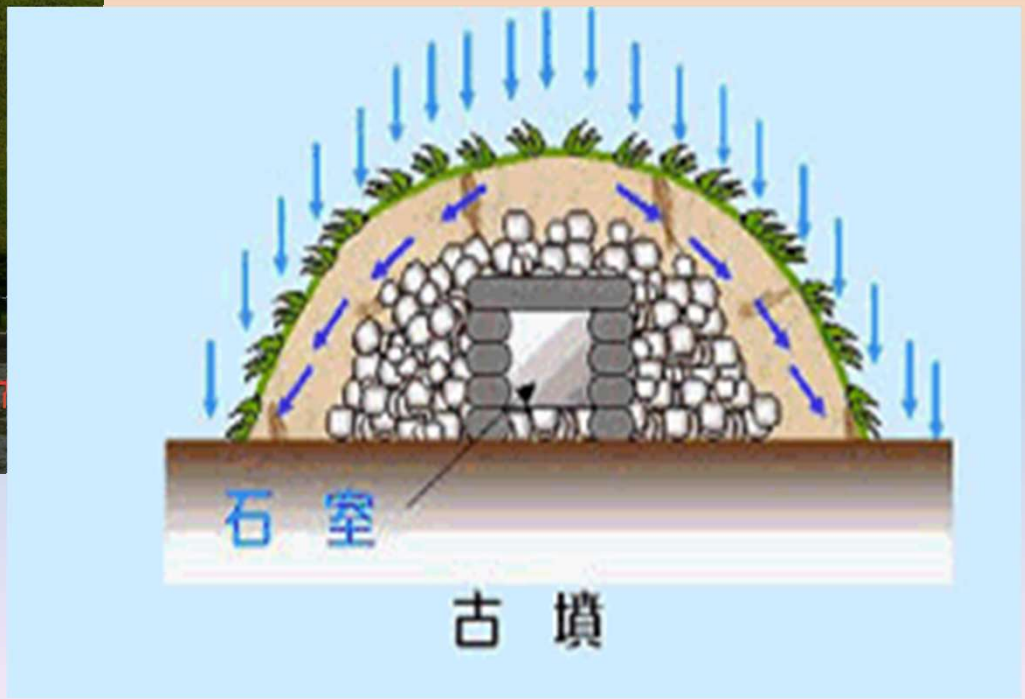
Capillary Barrier System for Minimizing Rainwater Infiltration



Preservation of Tumulus Mound using Capillary Barrier in Japan

Sawada, M., Mimura, M. and Yoshimura, M. (2017) "Infiltration Control using Capillary Barriers for Conservation of Historical Tumulus Mounds" Japanese Geotechnical Society Special Publication, 5(2):5-01

Capillary Barrier System for Minimizing Rain Infiltration in Royal Family Tombs in Korea



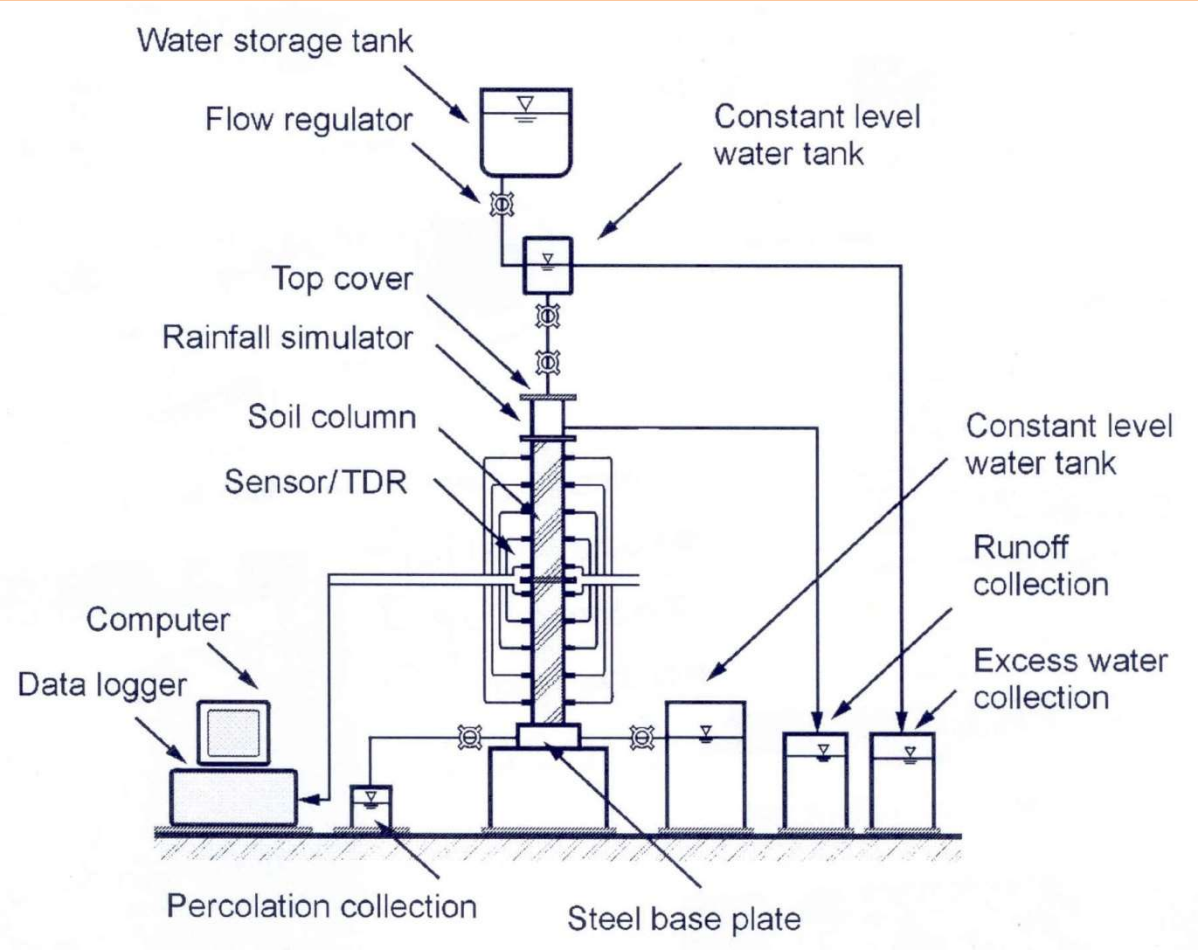
Obtained from http://www.n-kokudo.co.jp/tec_civil/capillary_02.html

Capillary Barrier System for Minimizing Rain Infiltration in Royal Family Tombs in Korea

Historical Development of Capillary Barrier System (CBS)

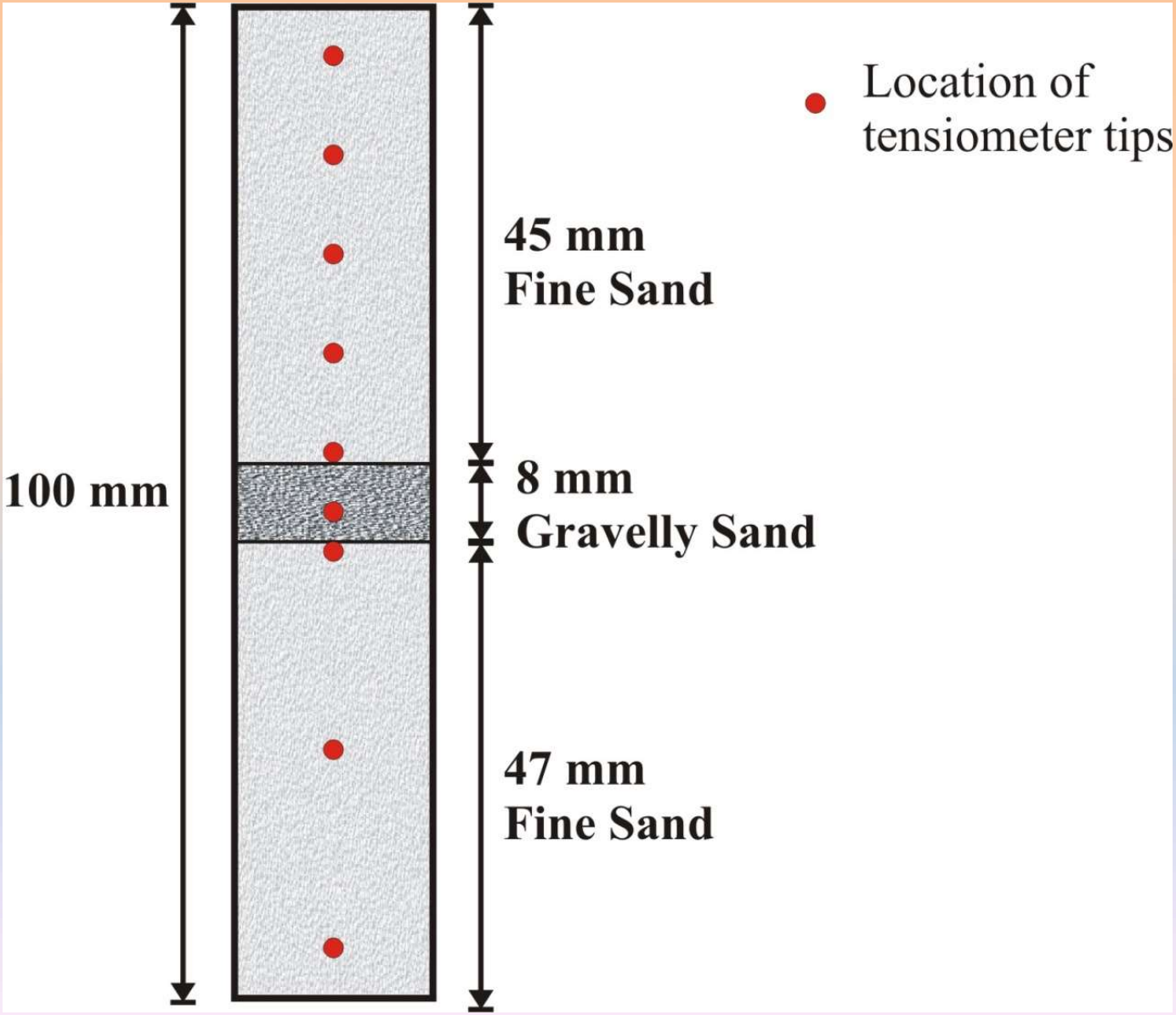
Year	Work	Reference
1998	1-D column to study the infiltration characteristics of CBS	Yang et al. (2004)
2000	Mechanism of sloping CBS under high rainfall conditions	Tami et al. (2004)
2003	Use of modified residual soil for fine-grained layer in CBS	Indrawan et al. (2006)
2004	Potential use of residual soil and geosynthetic material in CBS	Krisdani et al. (2006)
2006 - 2015	CBS for slope repair in Bedok (2006), Ang Mo Kio (2009), Tampines (2010), Matilda (2015)	Rahardjo et al. (2007), (2012), (2013)
2010	Development of dual capillary barrier (DCB) system using recycled materials	Harnas et al. (2014)
2012	Joint Patent for Modular Cover System (NTU-HDB)	
2013	DCB for landfill cover system	Rahardjo et al. (2013)
2015	Development of GeoBarrier system for slope protection and retaining structure	Rahardjo et al. (2015)
2015-2020	Use of GeoBarrier system as slope stabilization at Orchard Boulevard (2015), at NorthShore (2018), Bidadari (2020)	

Experimental Set-up of 1-D Capillary Barrier Model in Laboratory

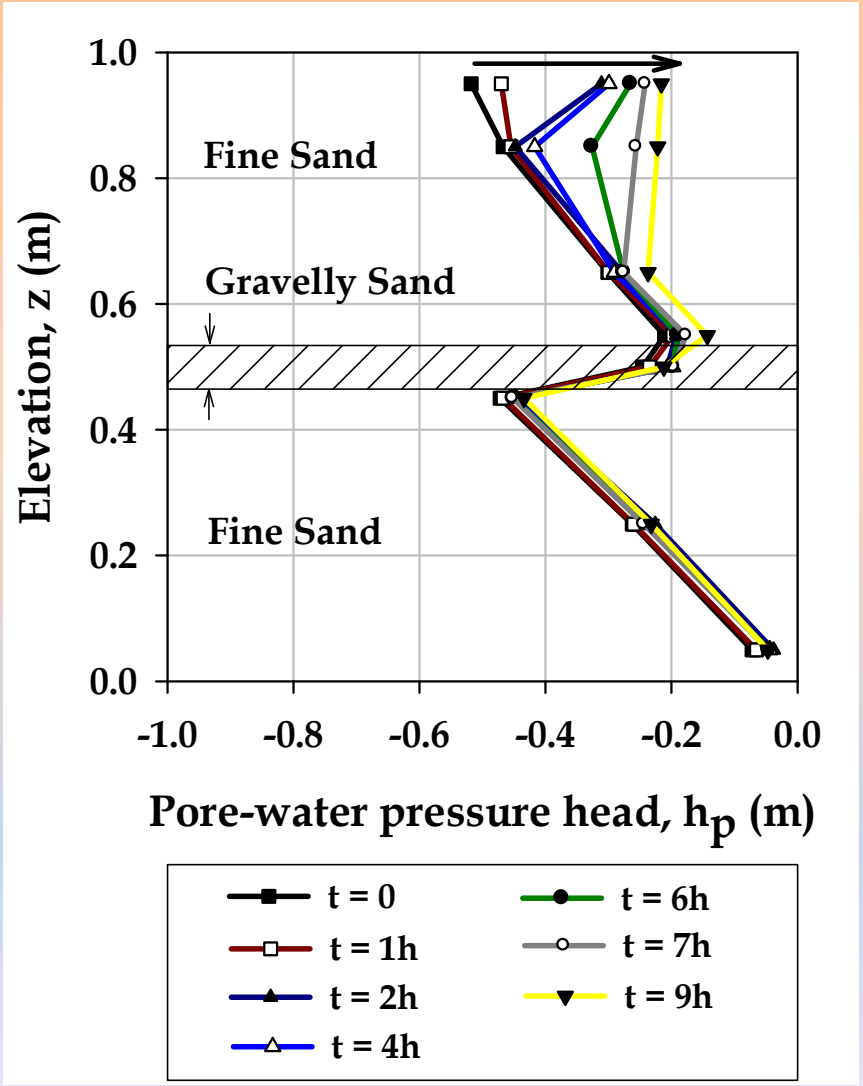


Schematic diagram of the infiltration column apparatus (Yang et al., 2004)

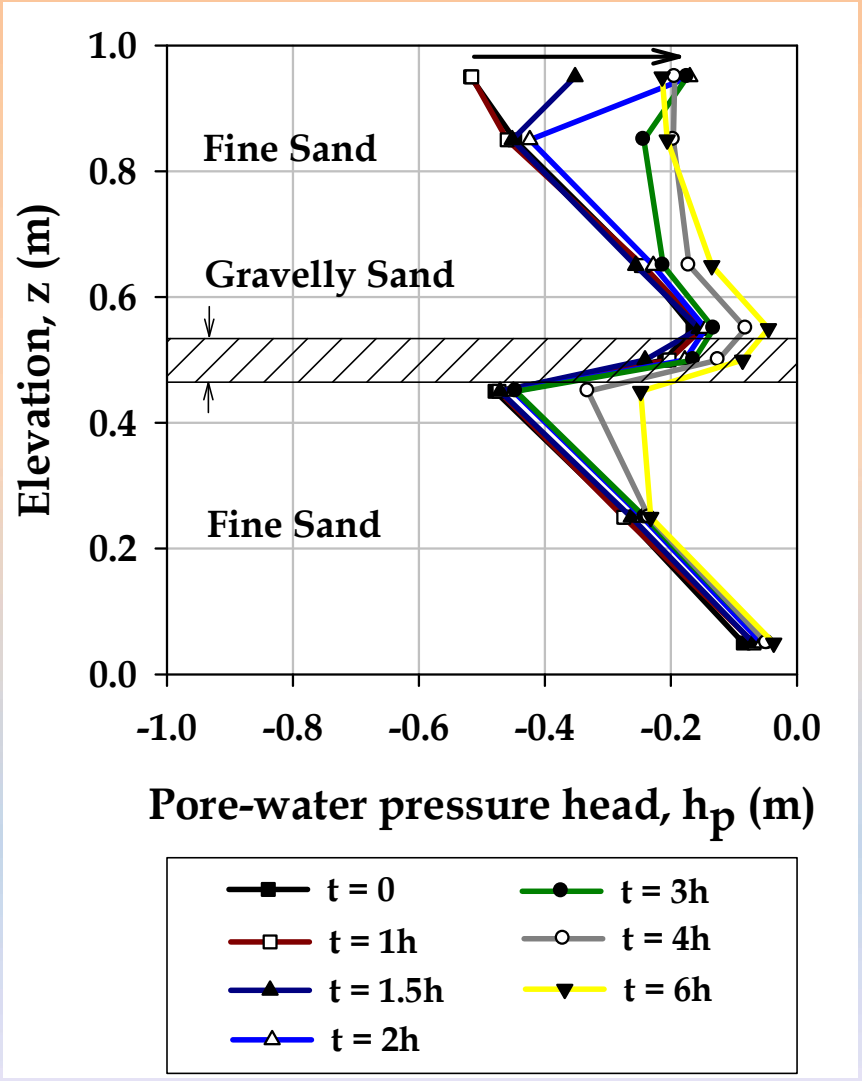
Schematic Diagram of The Capillary Barrier Column



Rainfall Tests on Capillary Barrier Column

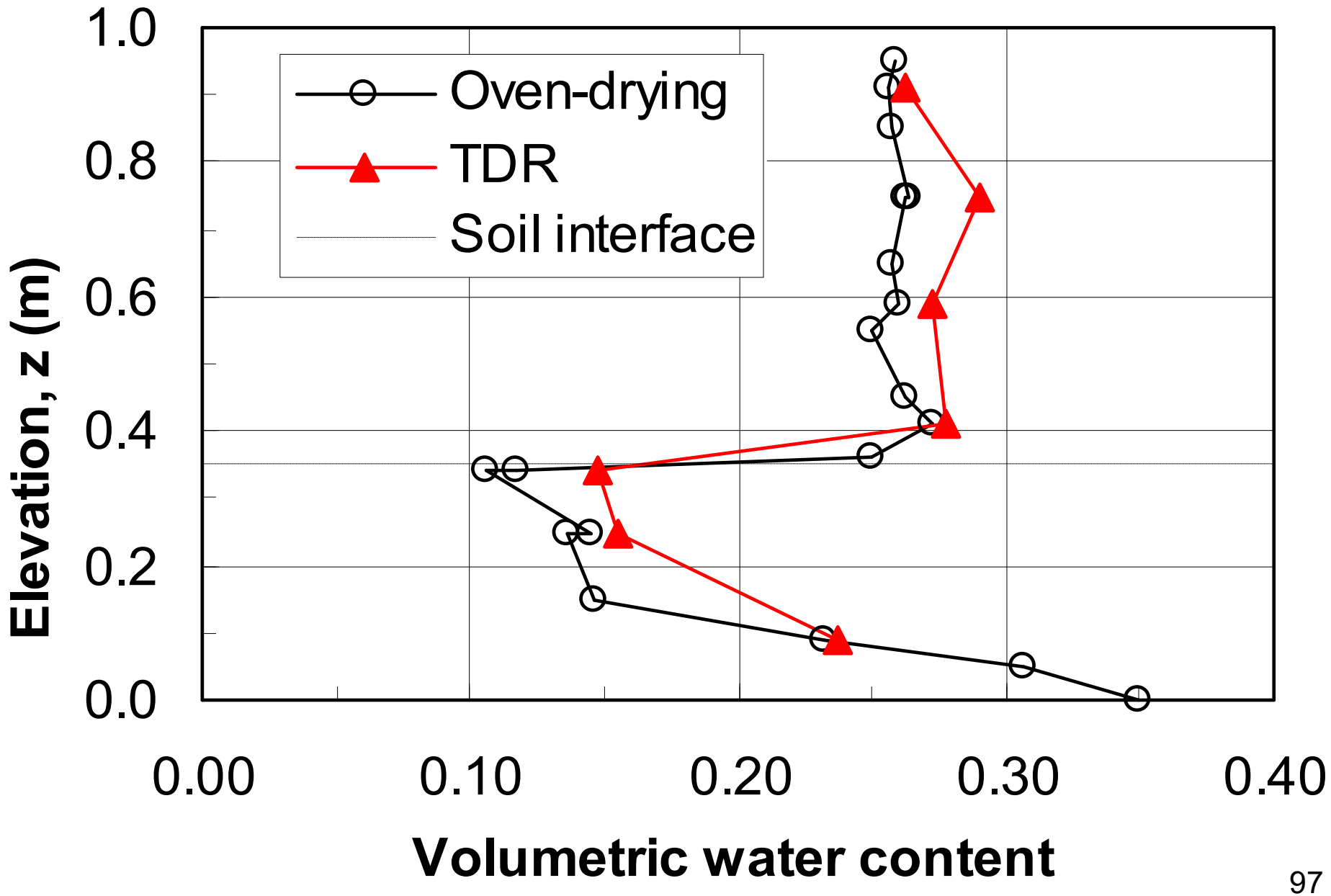


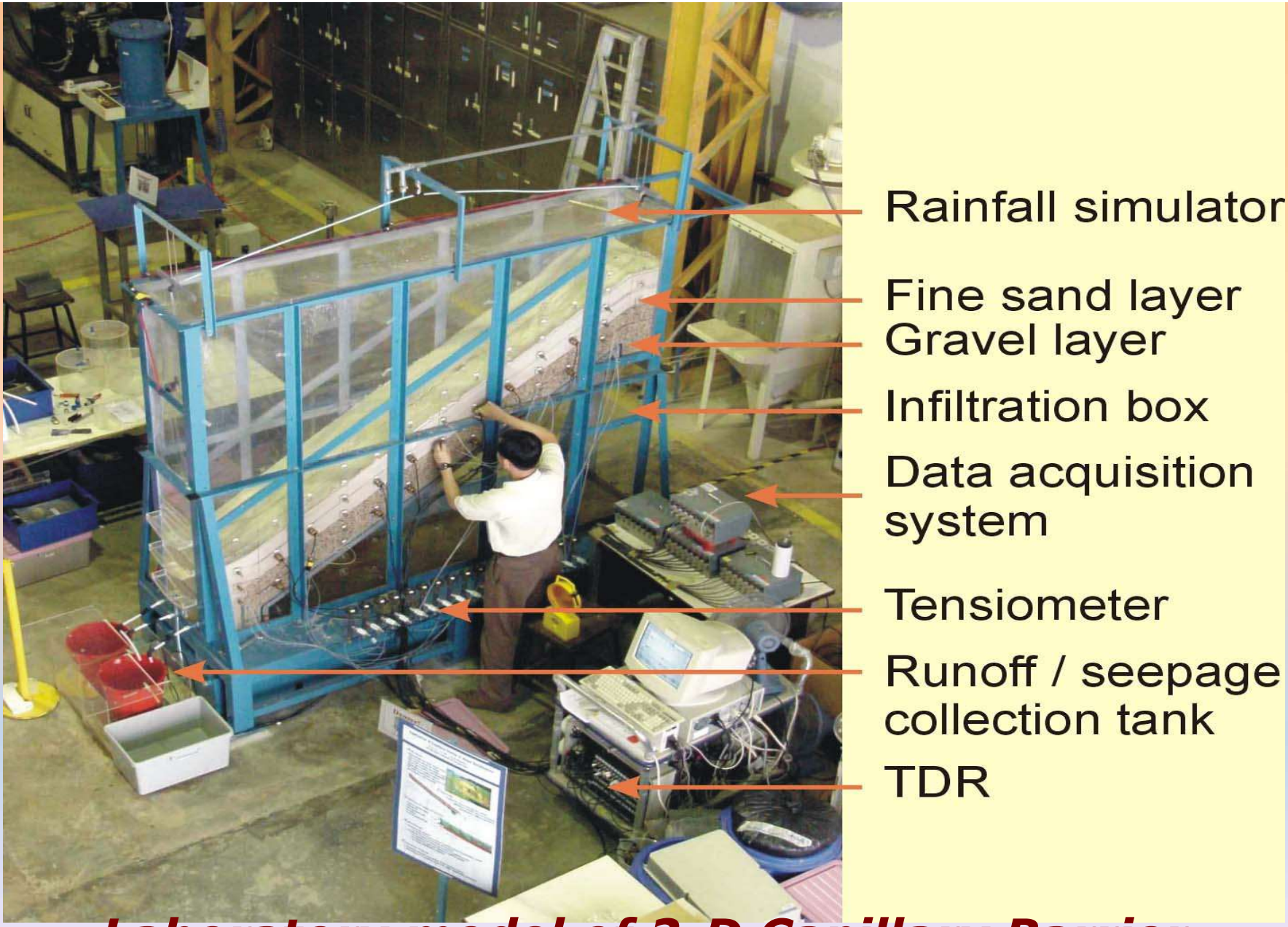
(a) Test RF1 (4.9 mm/hr for 9 hr)



(b) Test RF2 (5.8 mm/hr for 6 hr)

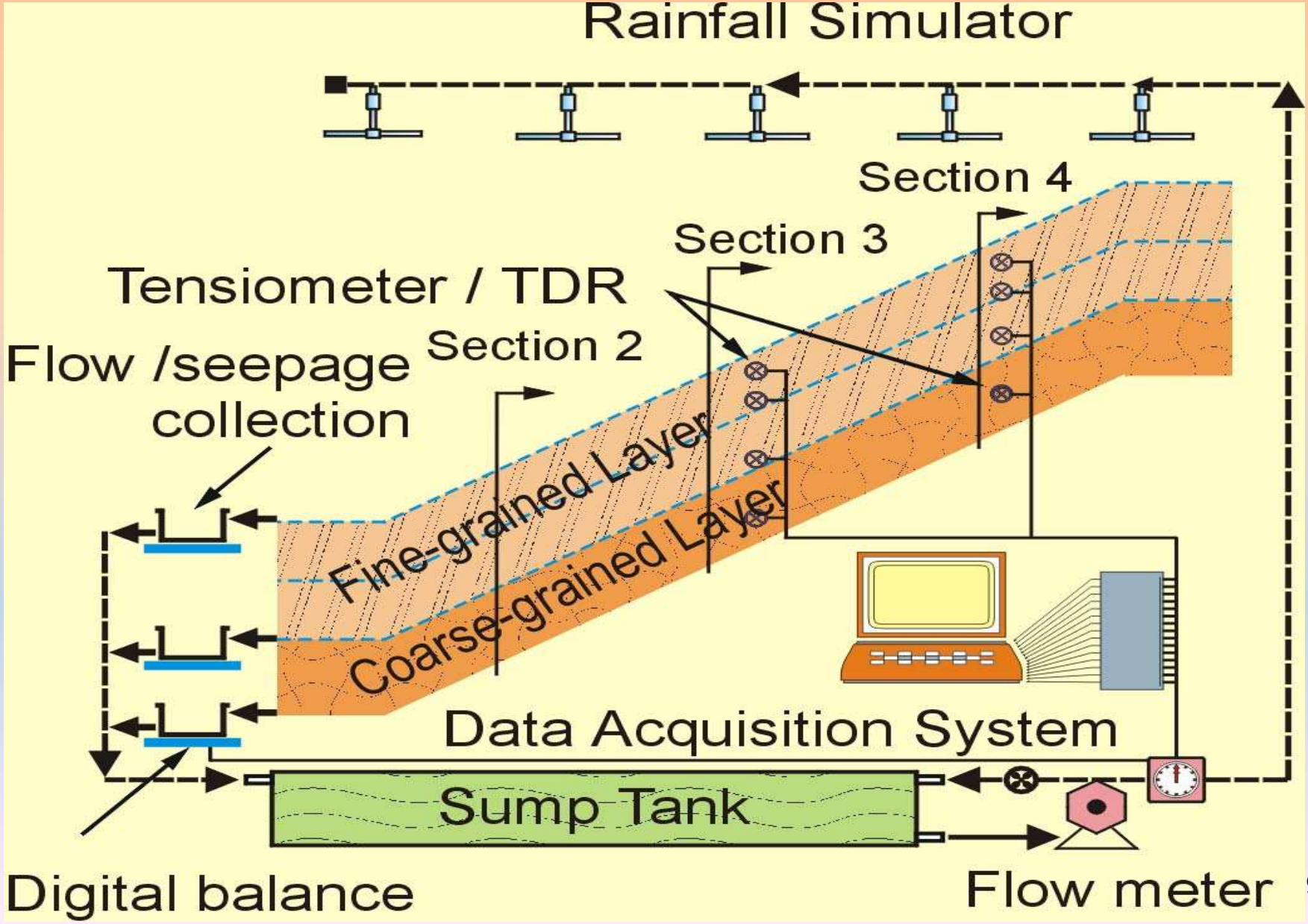
Installation of Time Domain Reflectometry and Tensiometer Tip

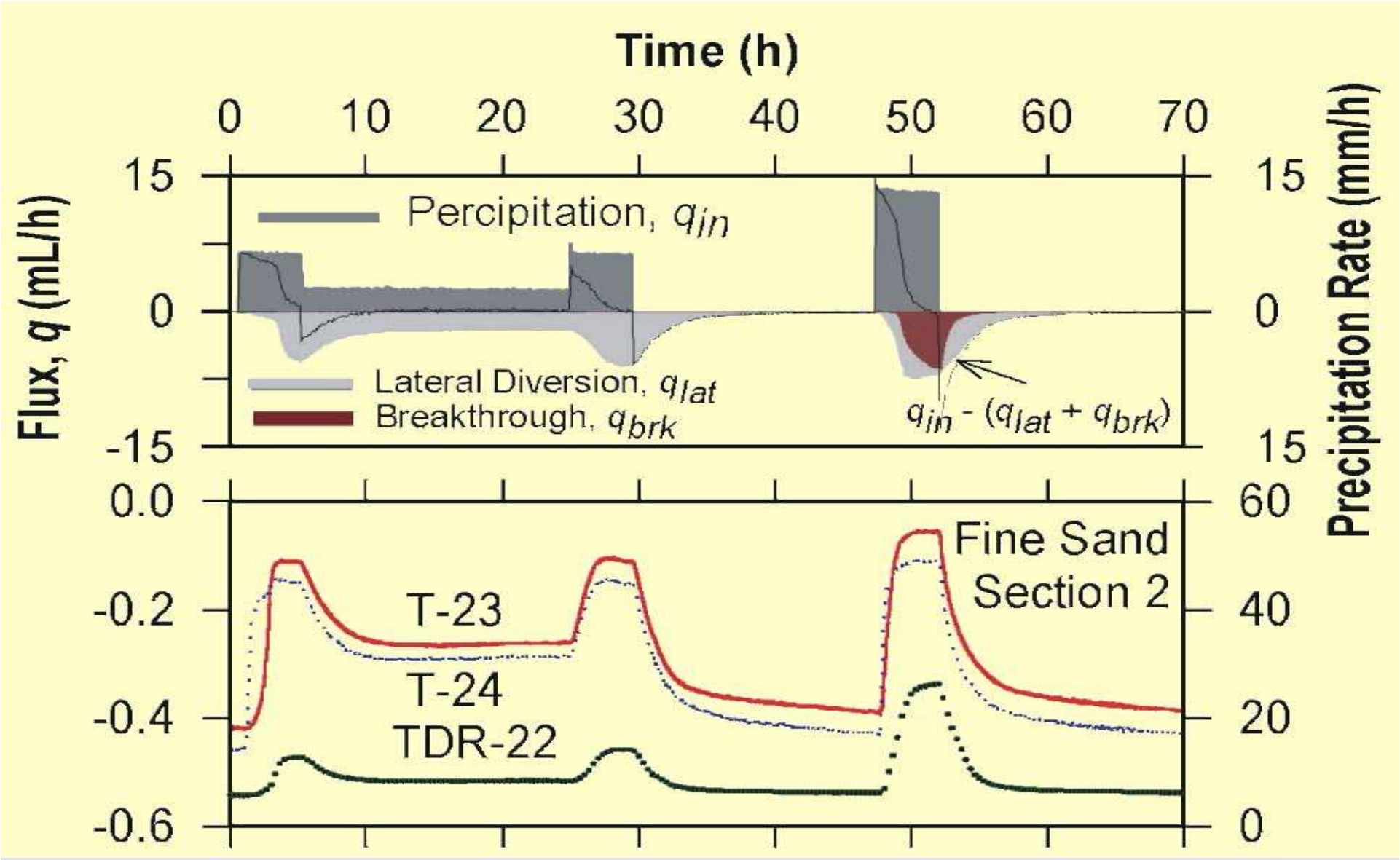

Oven-drying
TDR
Soil interface
Elevation, z (m)
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.10
0.20
0.30
0.40
Volumetric water content



Laboratory model of 2-D Capillary Barrier Model

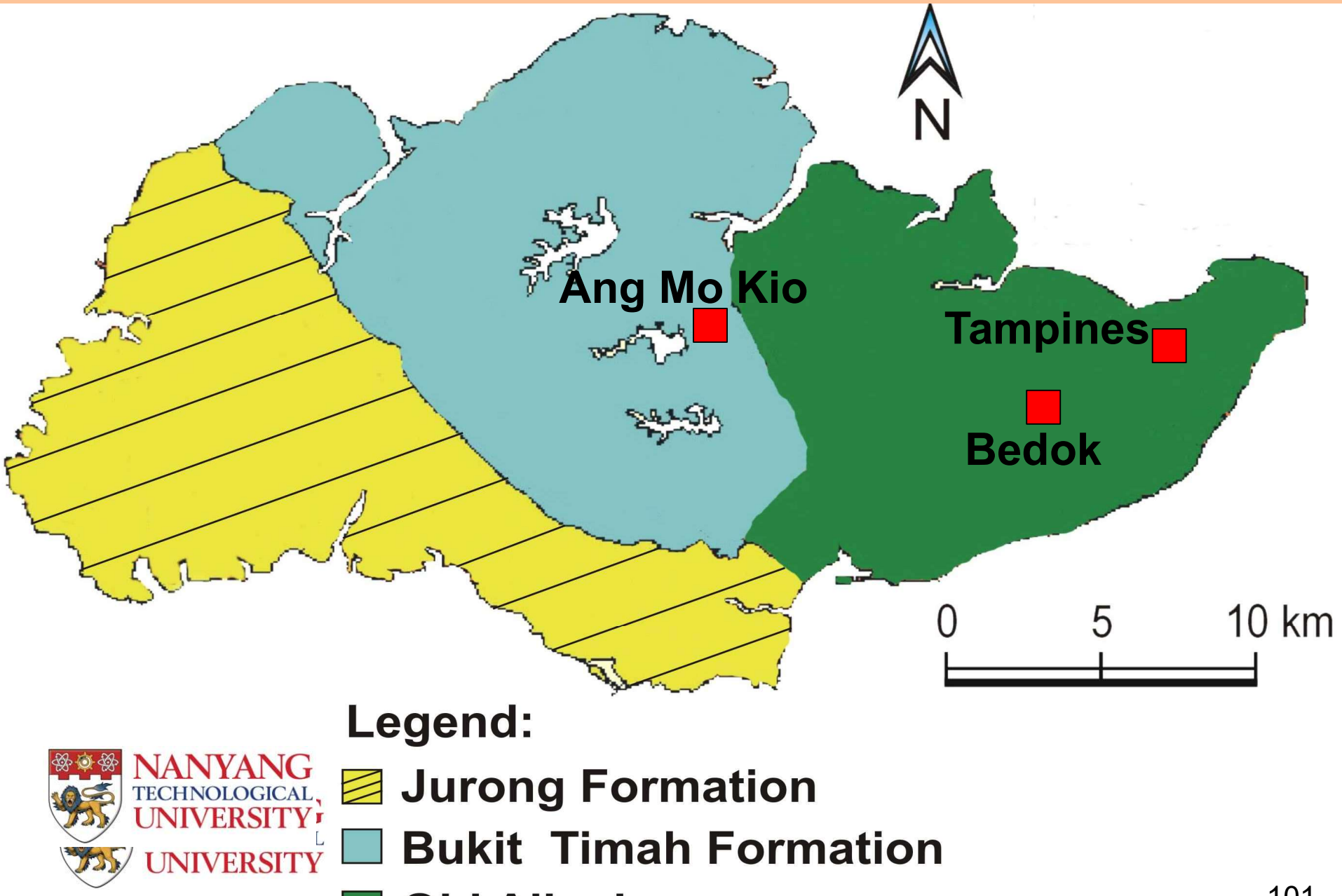
Schematic Diagram of 2-D Capillary Barrier Model in Laboratory (Tami et al., 2004)





Time histories of flux, pressure head and volumetric water content

Location of Slope with CBS in Singapore



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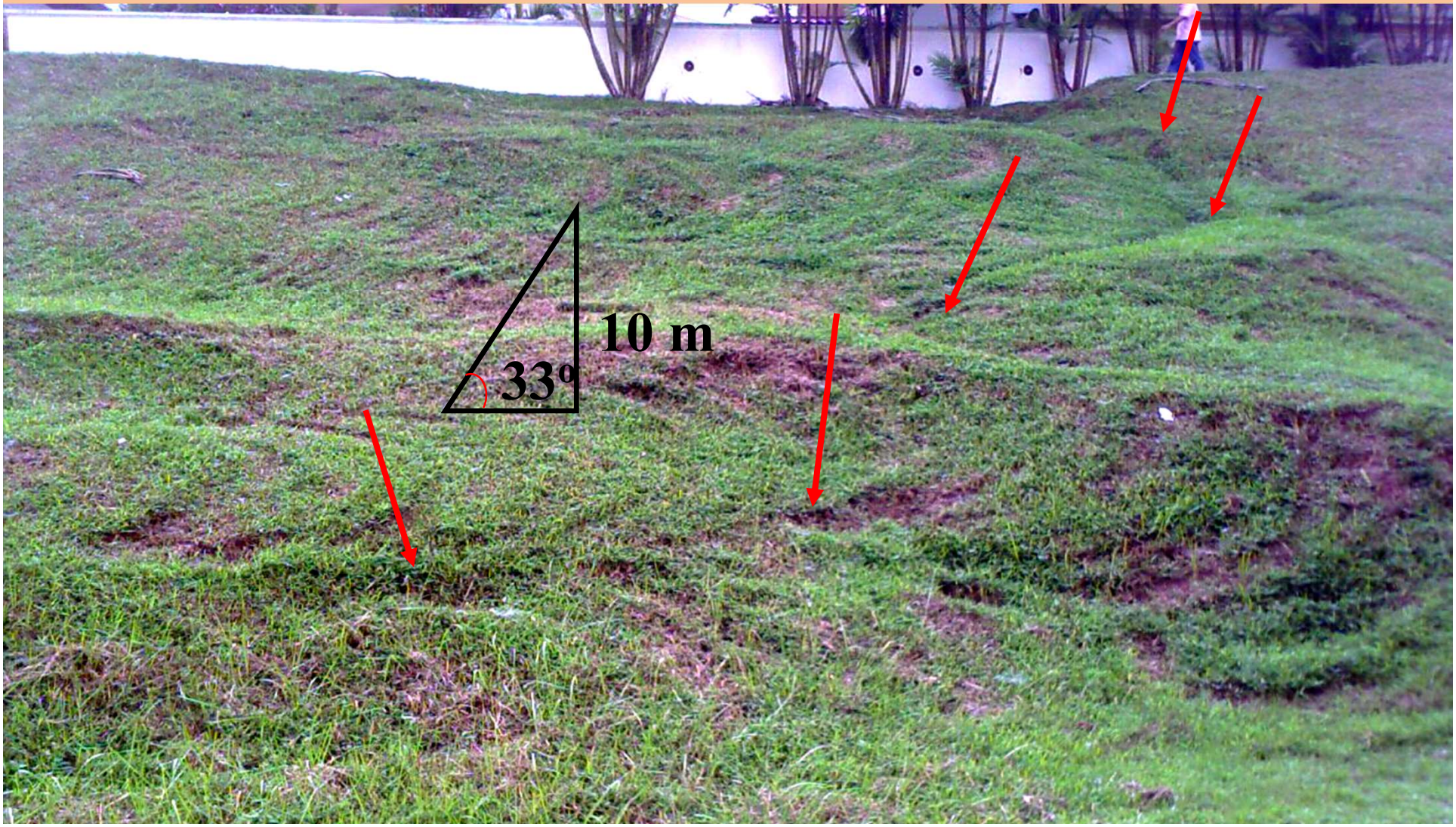
Construction of the capillary barrier system

Final condition

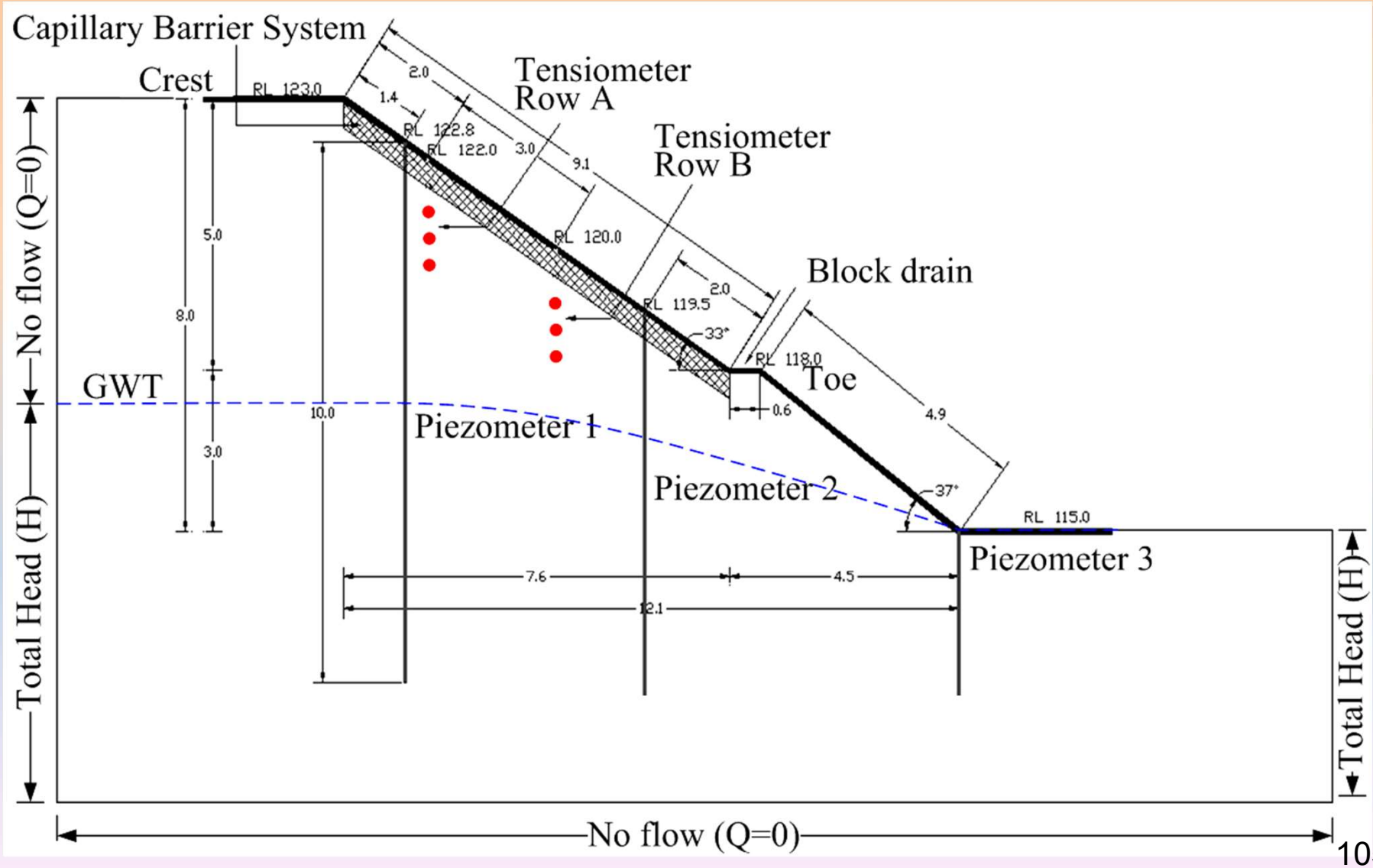
Site Overall View at Ang Mo Kio



Tension crack and shallow failure on 8 Jan 2006

The total area of the slope to be covered with a capillary barrier system ~ 140 m^2

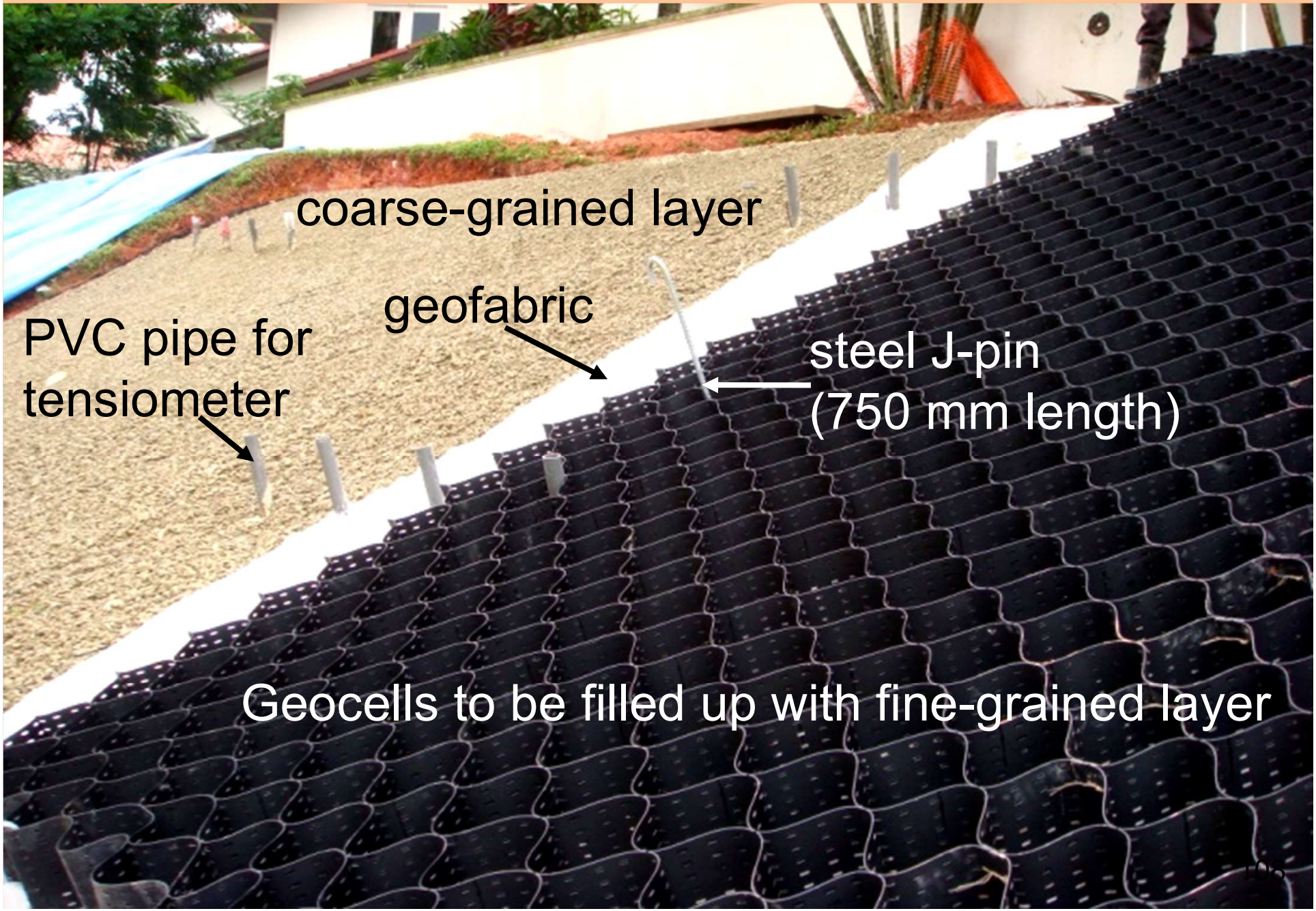
Schematic Diagram of Capillary Barrier System at Ang Mo Kio slope



Laying of Bottom Geocells

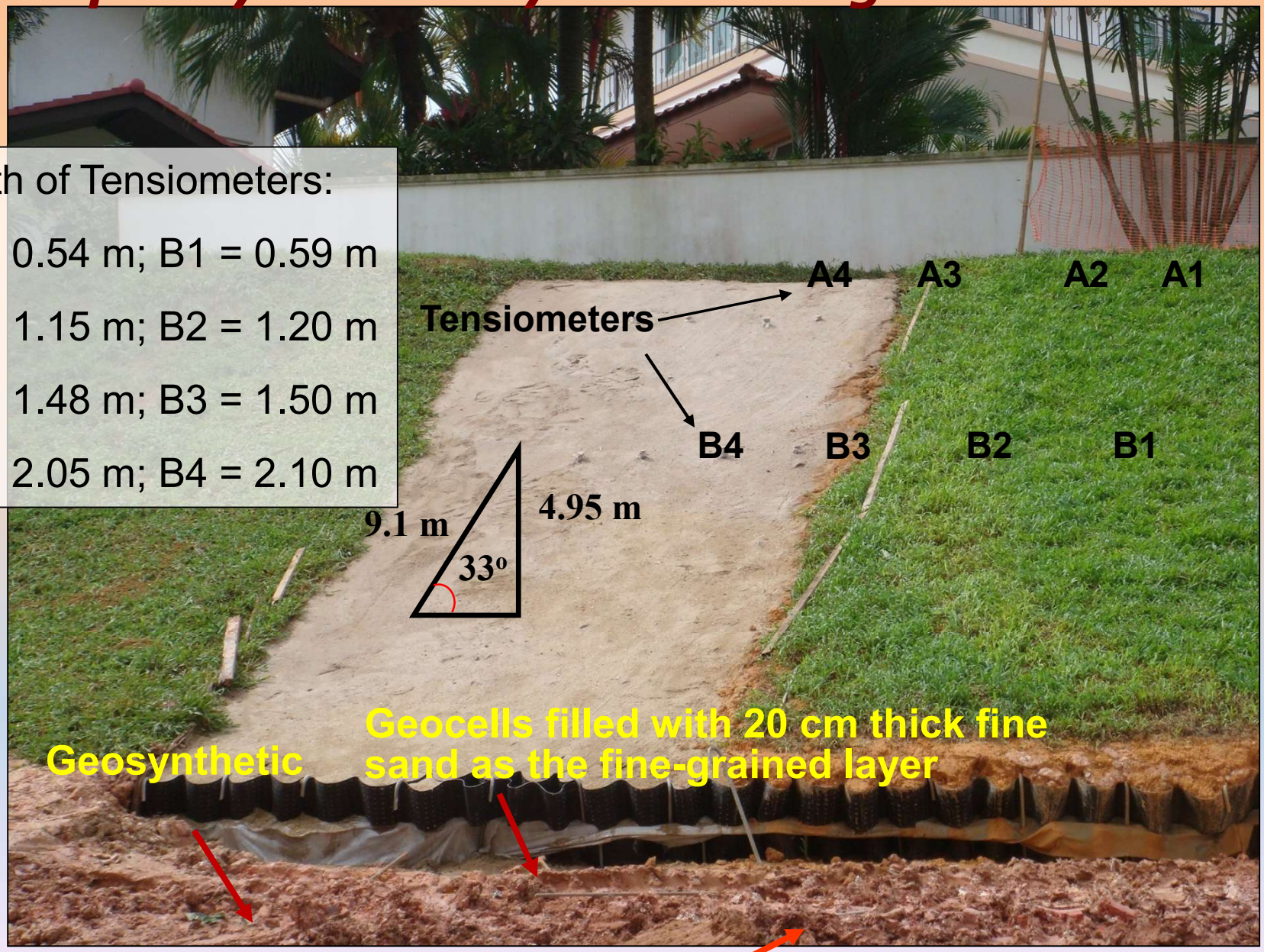
Laying of Coarse-grained Layer at Ang Mo Kio

Laying of Separator Layer and Top Geocells

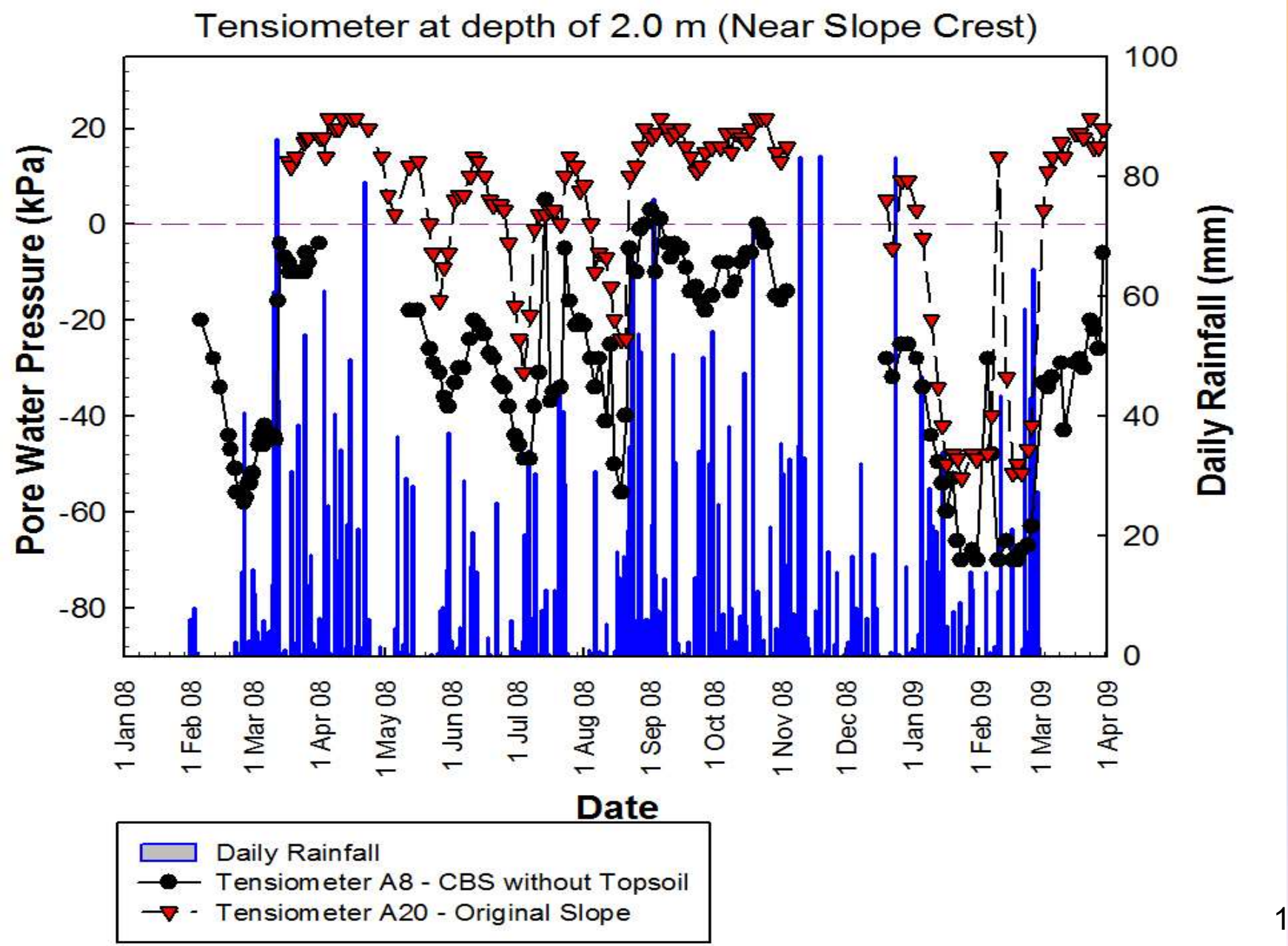


Laying of Fine-grained Layer at Ang Mo Kio

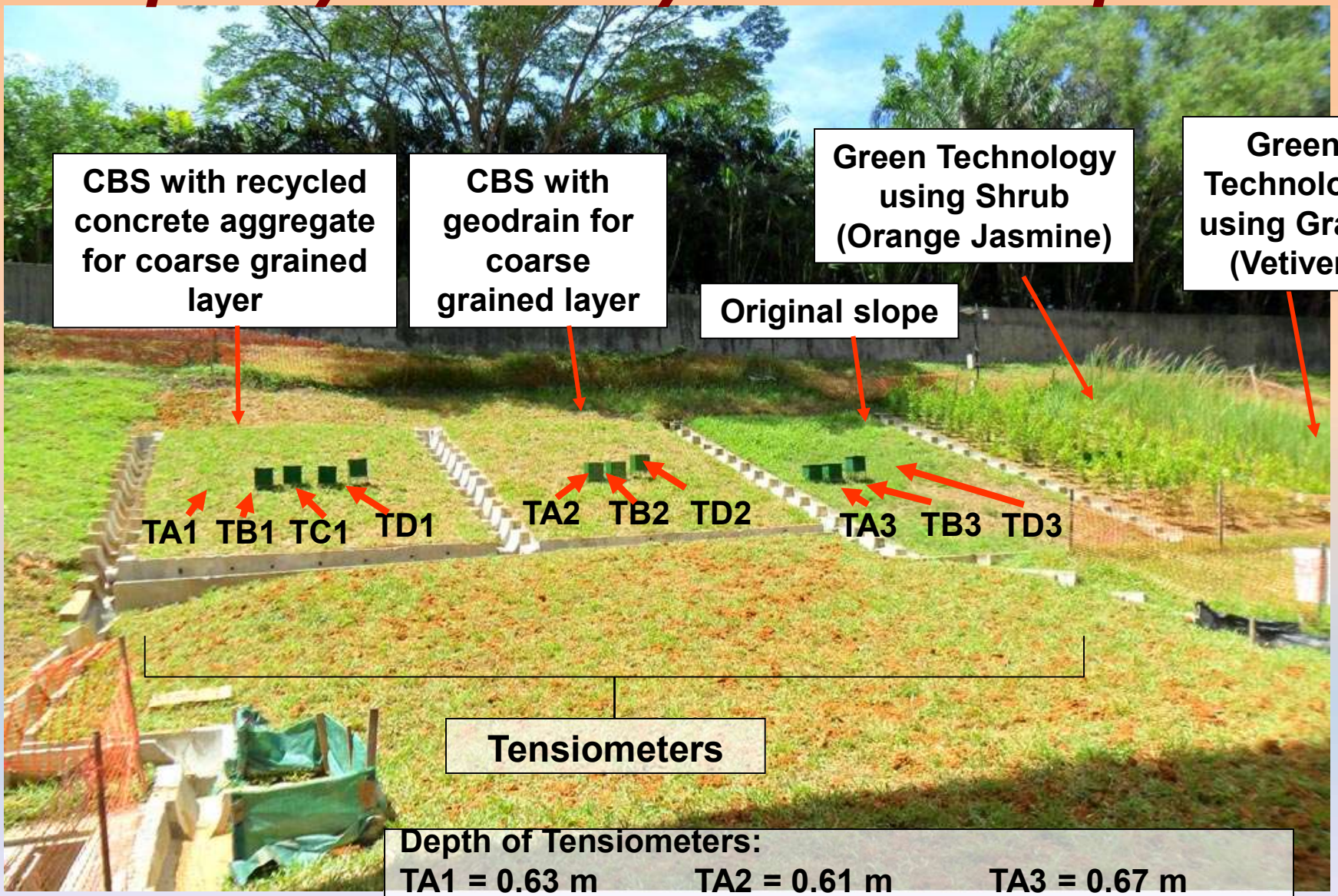
Capillary Barrier System at Ang Mo Kio St 21



Tensiometer at Depth of 2.0 m

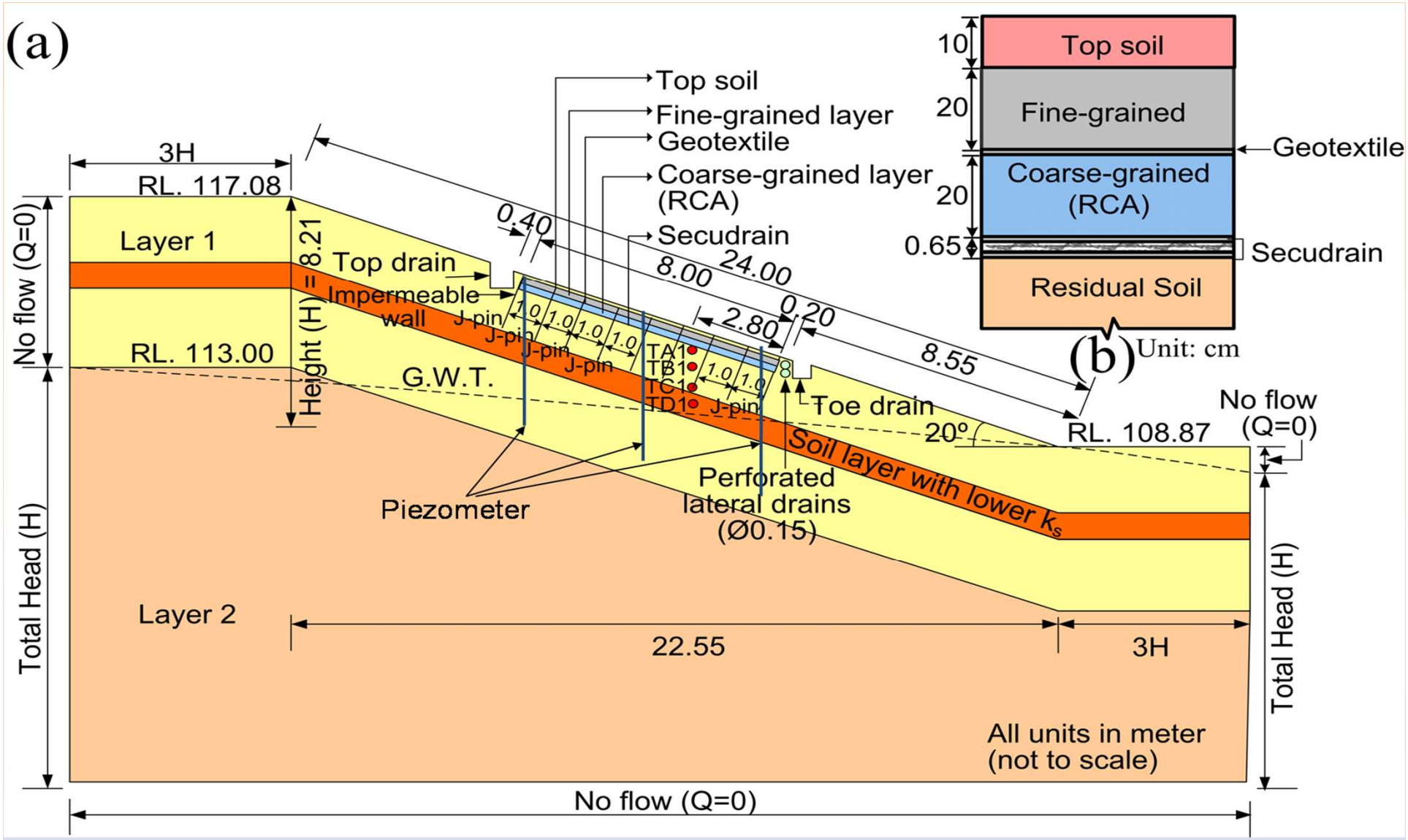


Capillary Barrier System at Tampines



Depth of Tensiometers:

TA1 = 0.63 m	TA2 = 0.61 m	TA3 = 0.67 m
TB1 = 1.18 m	TB2 = 1.23 m	TB3 = 1.29 m
TC1 = 1.48 m		
TD1 = 1.76 m	TD2 = 1.81 m	TD3 = 1.84 m



(a) Schematic diagram of CBS with RCA as the coarse-grained layer and (b) Cross-section of CBS with RCA as the coarse-grained layer,

J-pins installation for fine-grained layer

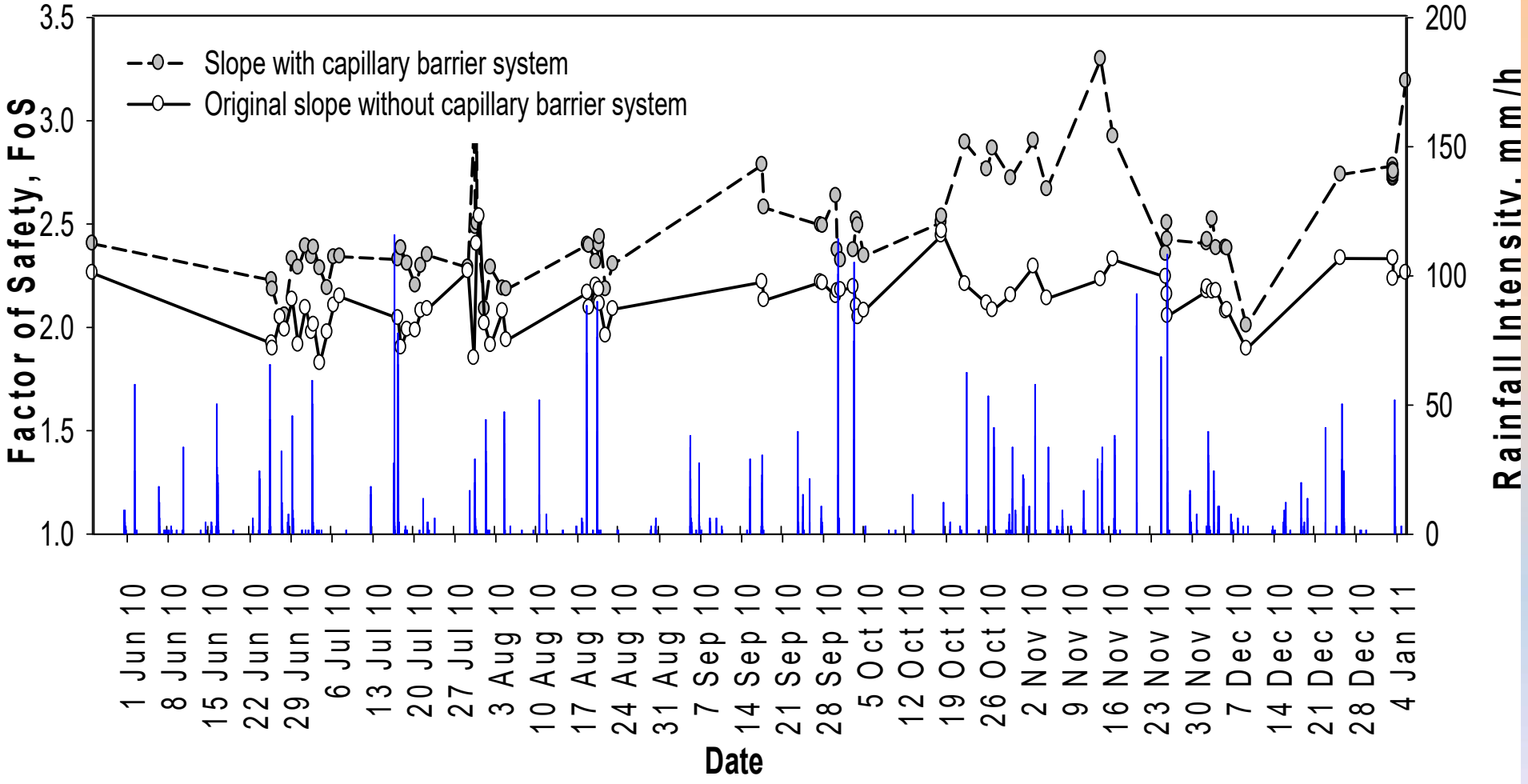
Shorter J-pins were pre-installed for coarse-grained layer of Capillary Barrier System

Longer J-pins were pre-installed for fine-grained layer of Capillary Barrier System

Recycled crushed concrete aggregate backfilling for coarse-grained layer

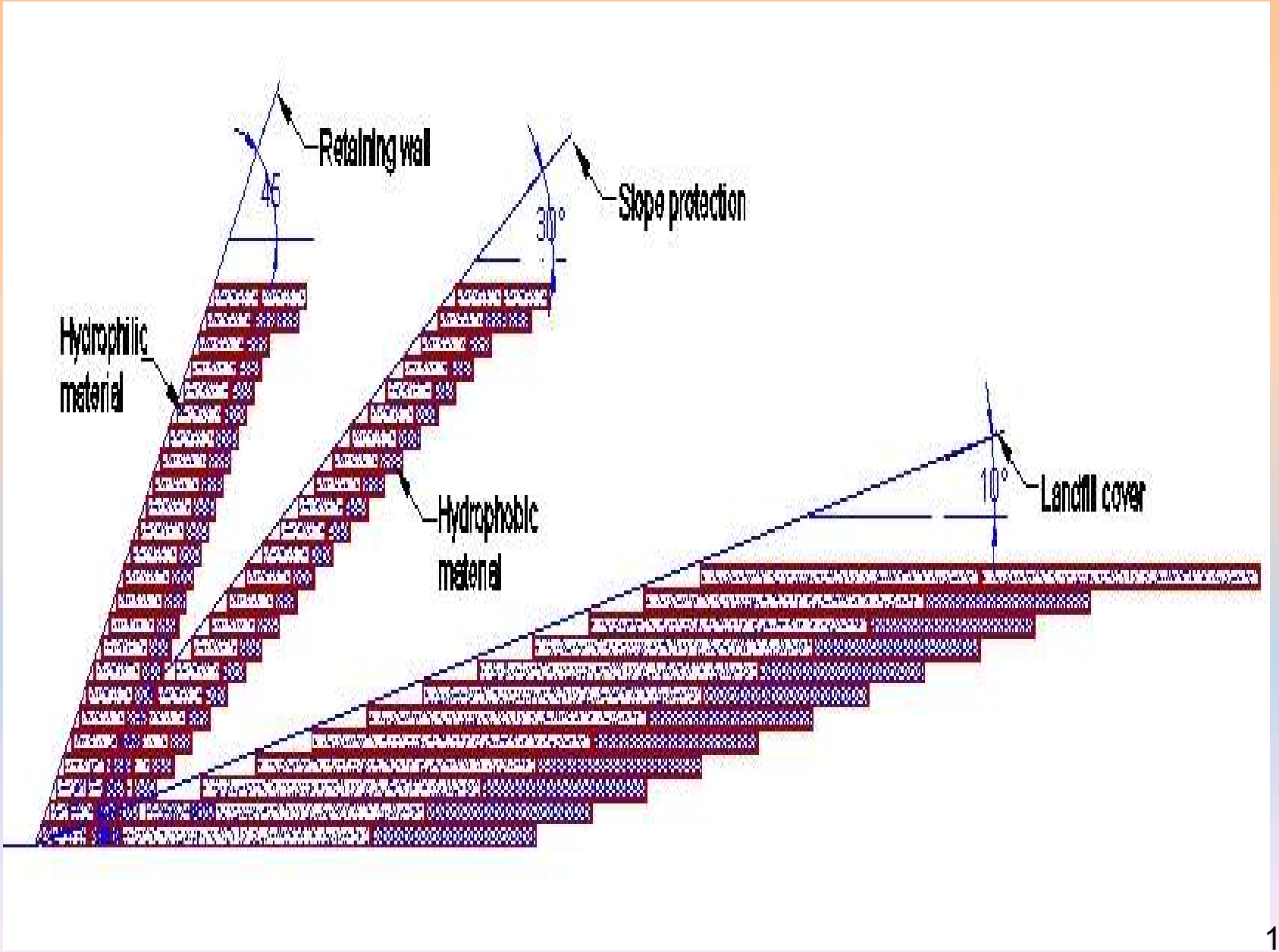

Laying Geocell for fine-grained layer of Capillary Barrier System
J-pin
PVC casings for tensiometer
Geocell
Fine sand backfilling for fine-grained layer

Factor of Safety Variations for Slope with and without Capillary Barrier System

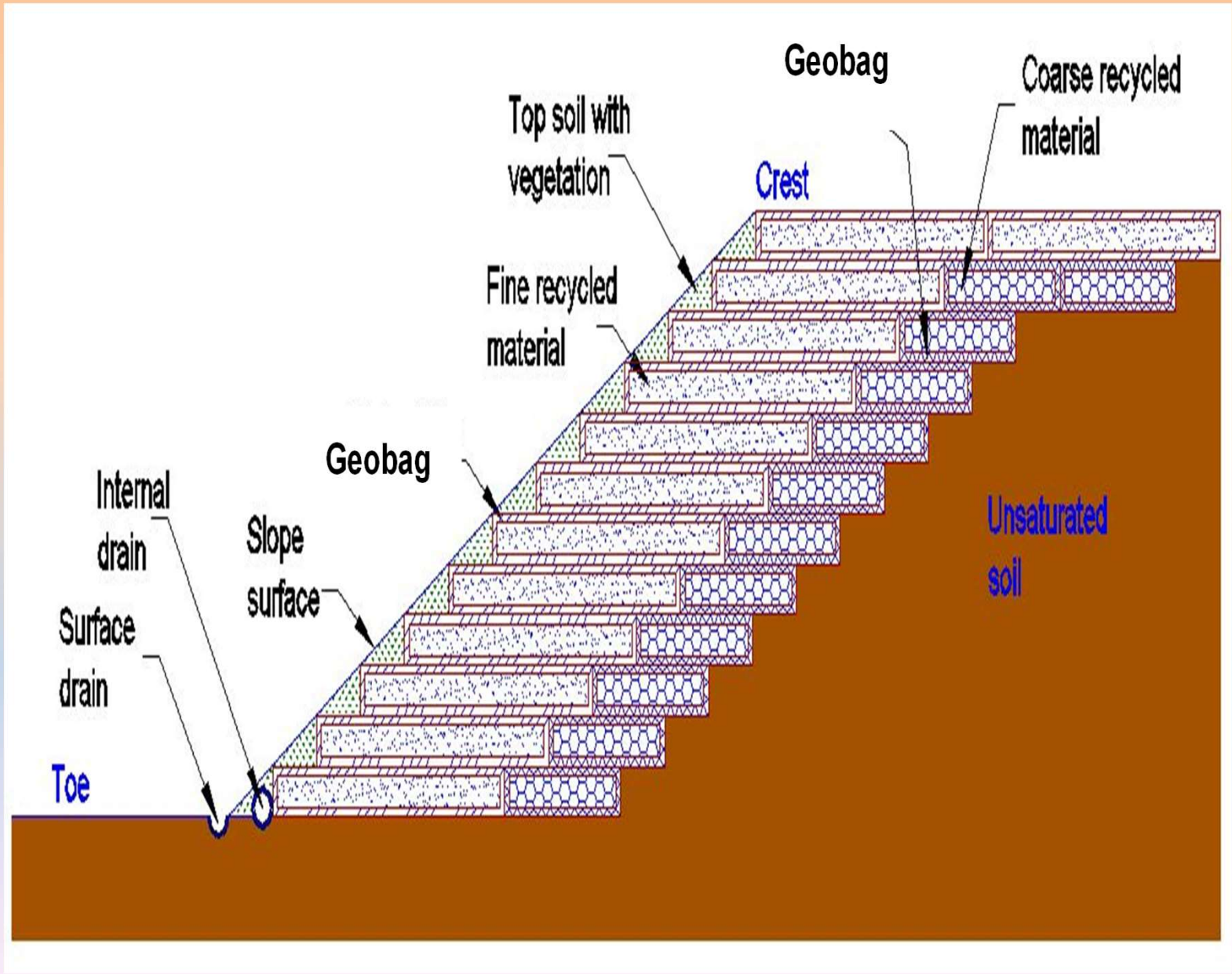


Another Application in a Housing Project

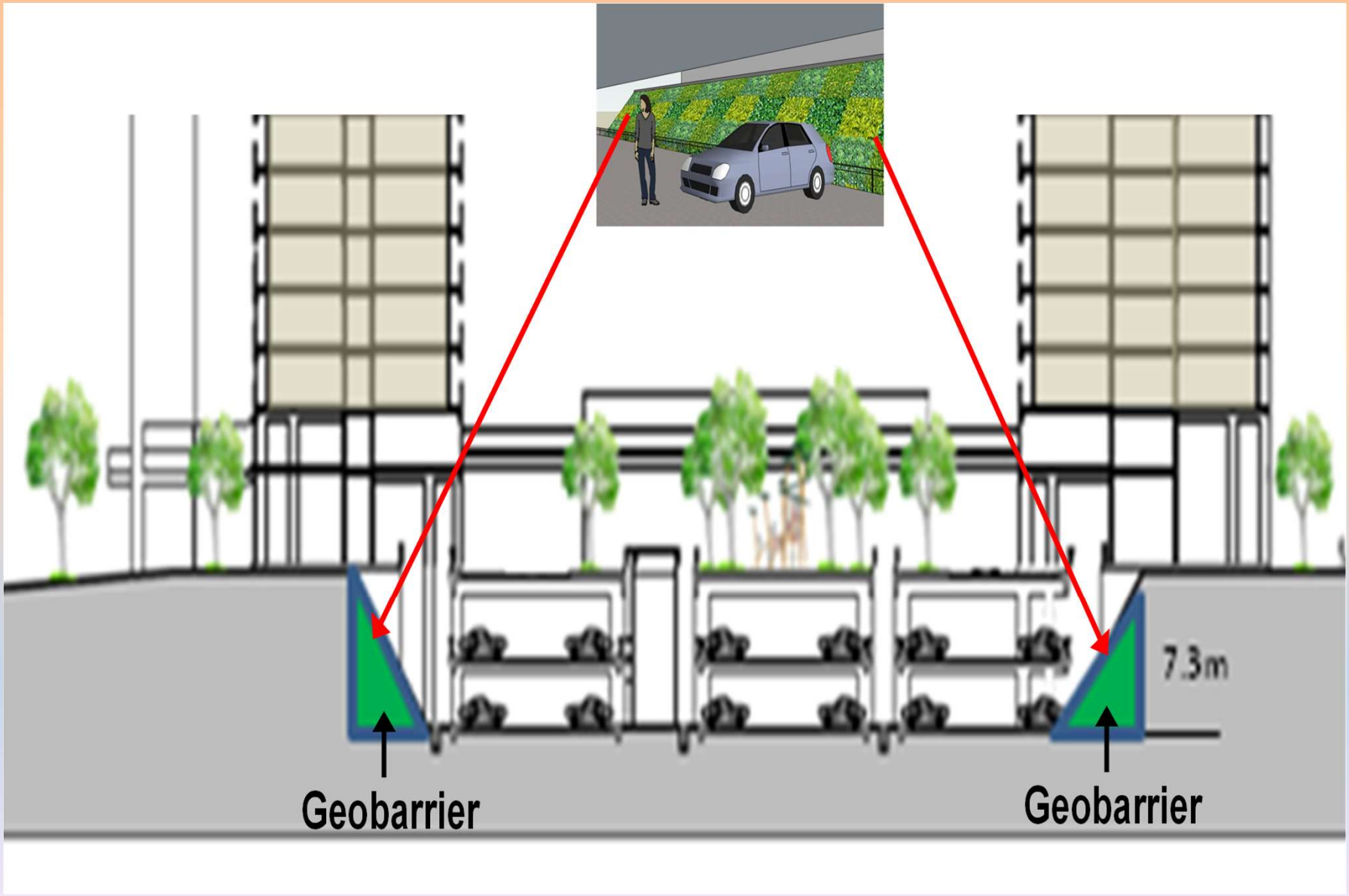
Geobarrier System for Use in Different Slope Angles



Schematic Diagram of Geobarrier System



Application of GeoBarrier System



Wall-free Multi-level Basement Carpark

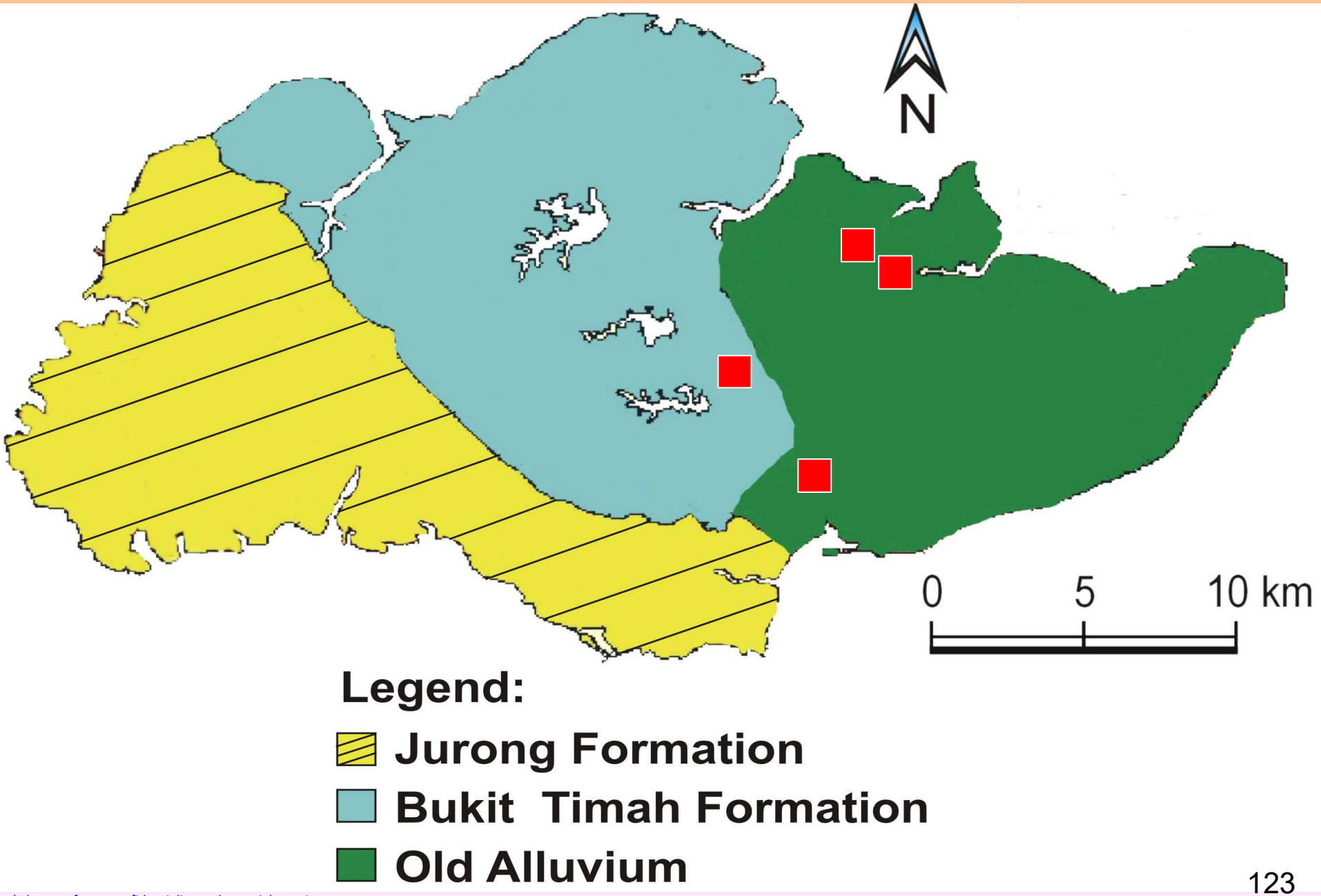
GeoBarrier System

- GeoBarrier sytem (GBS) is a retaining structure incorporating the capillary barrier system
- Non cohesive Fine and coarse recycled materials are used as fine- and coarse-grained layers within GBS
- The appearance of GBS is enhanced to incorporate suitable vegetation (deep rooted grass, shrubs) as added green cover.

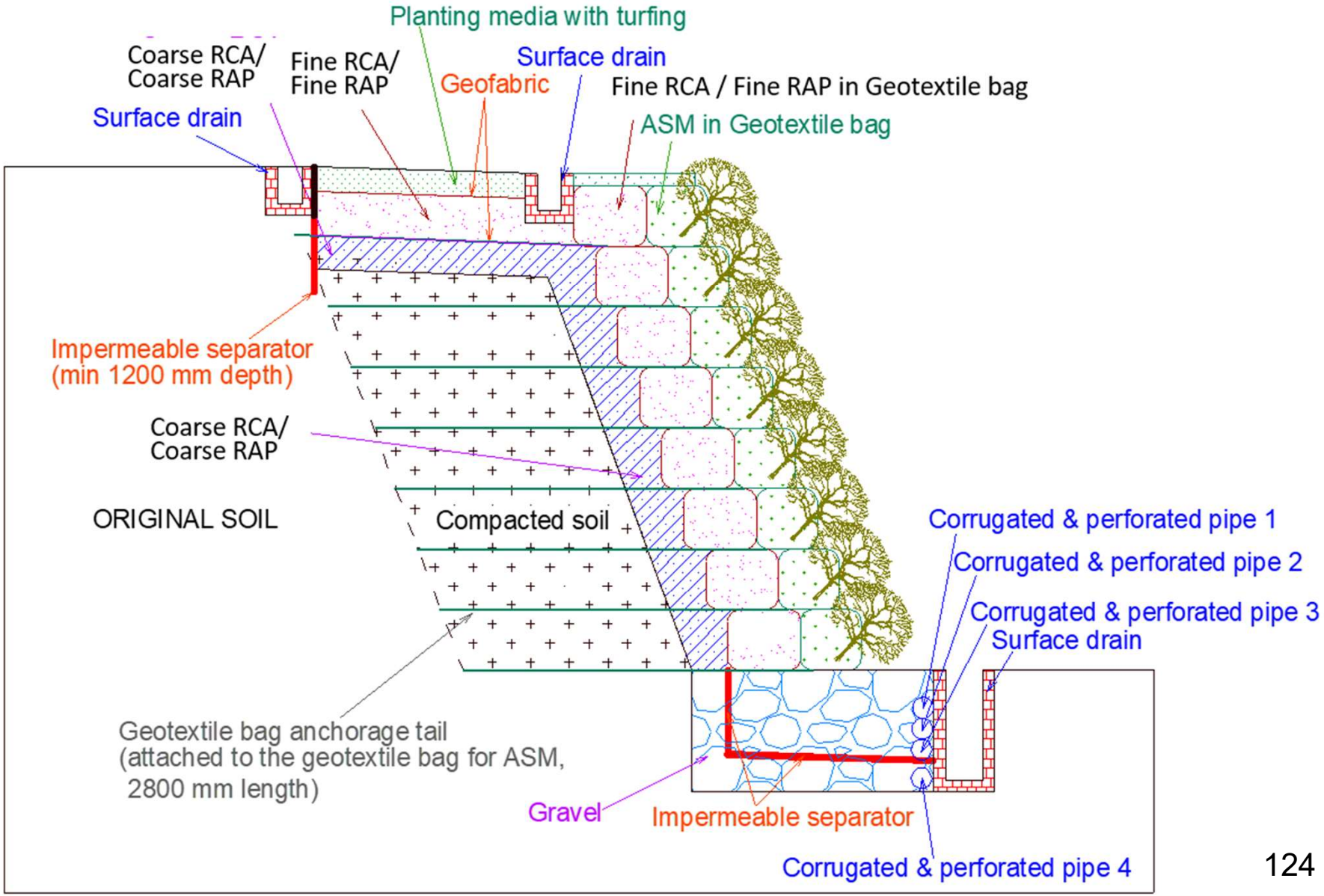
GeoBarrier System

- GBS reduces the coefficient runoff (avoiding flooding) and prevent erosion during rainfall since rainwater is directed properly into main drainage via drainage layer (fine-grained layer) of GBS.

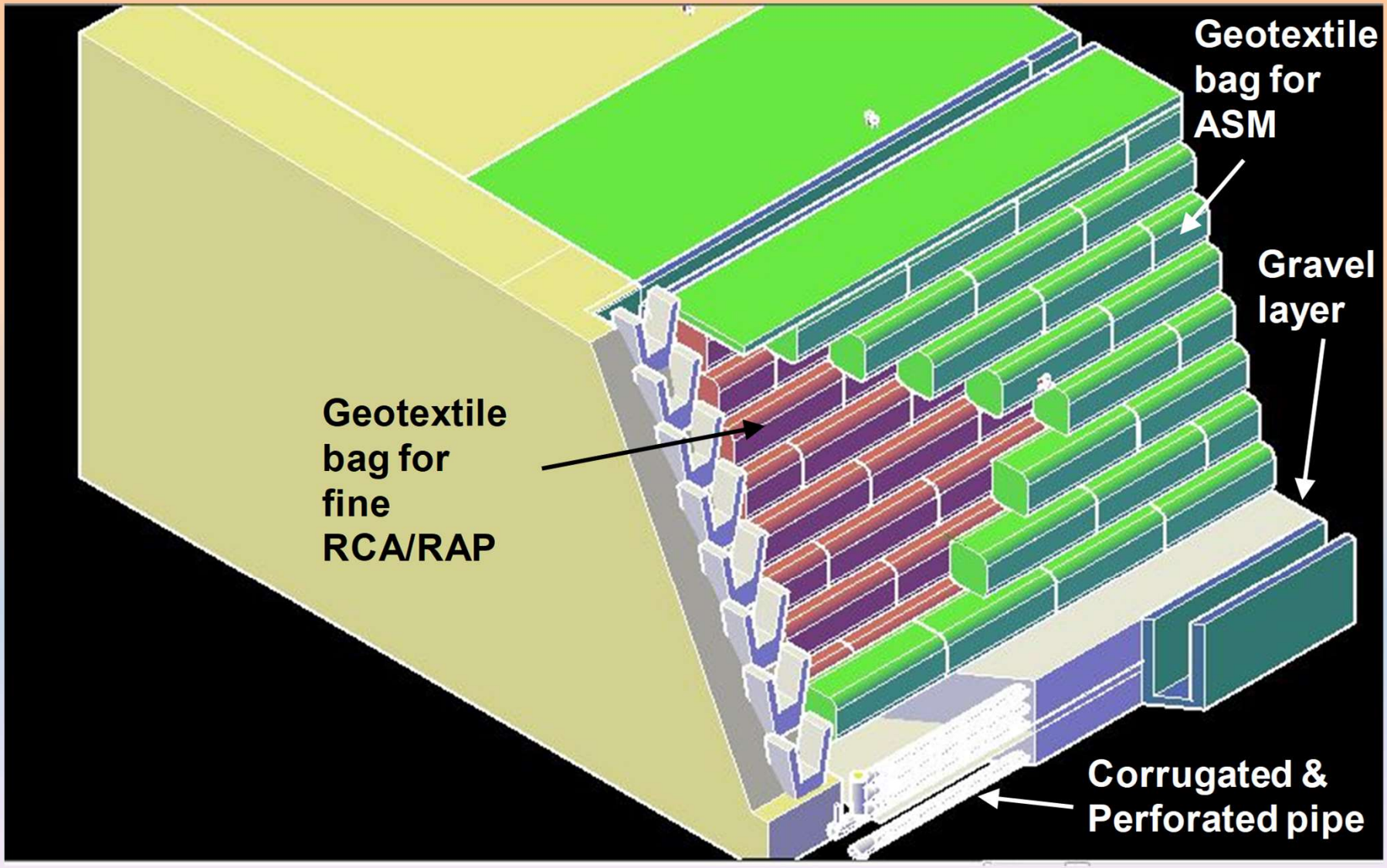
Locations of Slope with GBS in Singapore



Schematic Diagram of Geobarrier System Constructed at Orchard



GeoBarrier System (GBS)

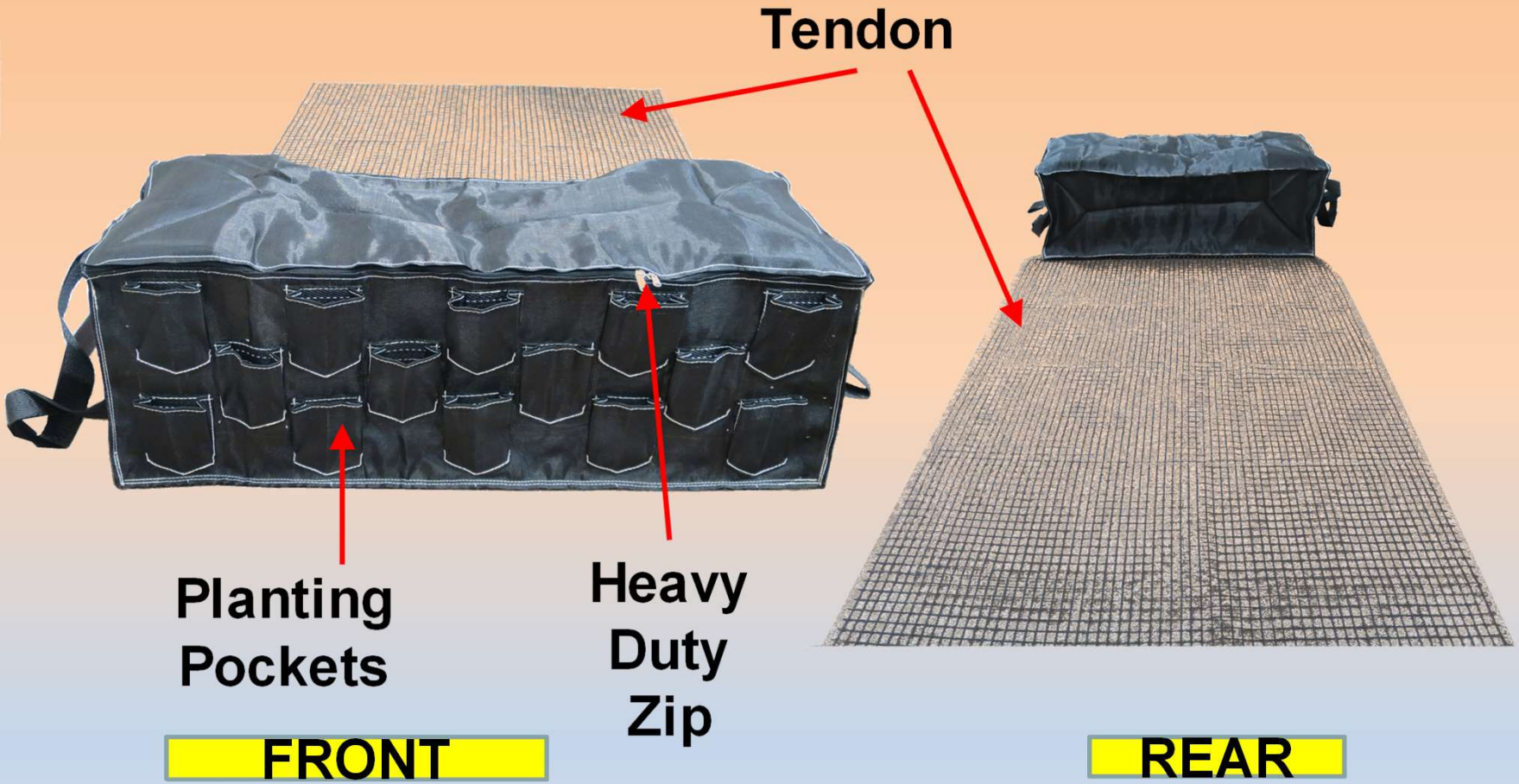


Detail of GeoBarrier System (GBS)

(a) Fine material bag

(b) ASM bag with geogrid tail

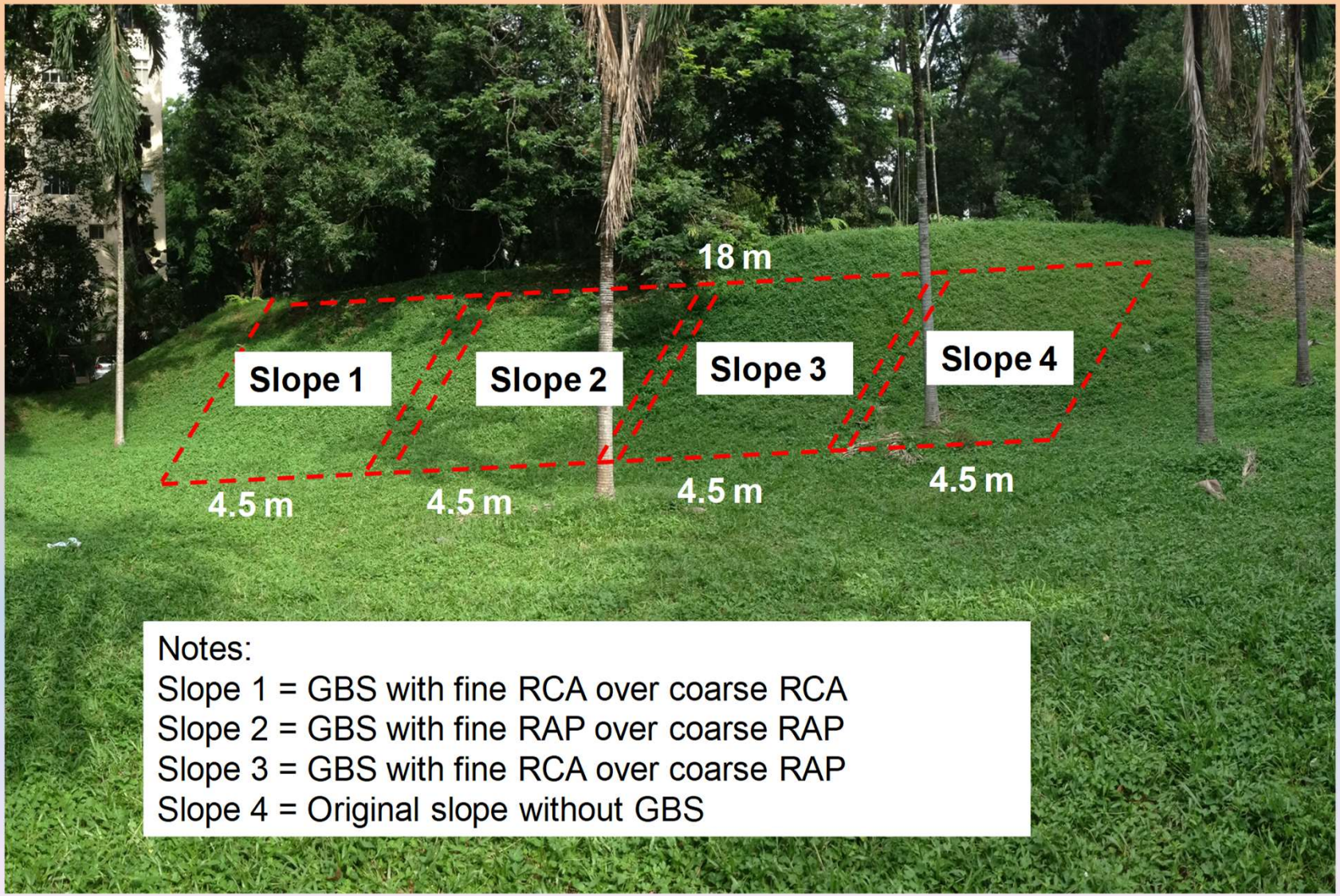
Geotextile Bag for Planting Vegetation



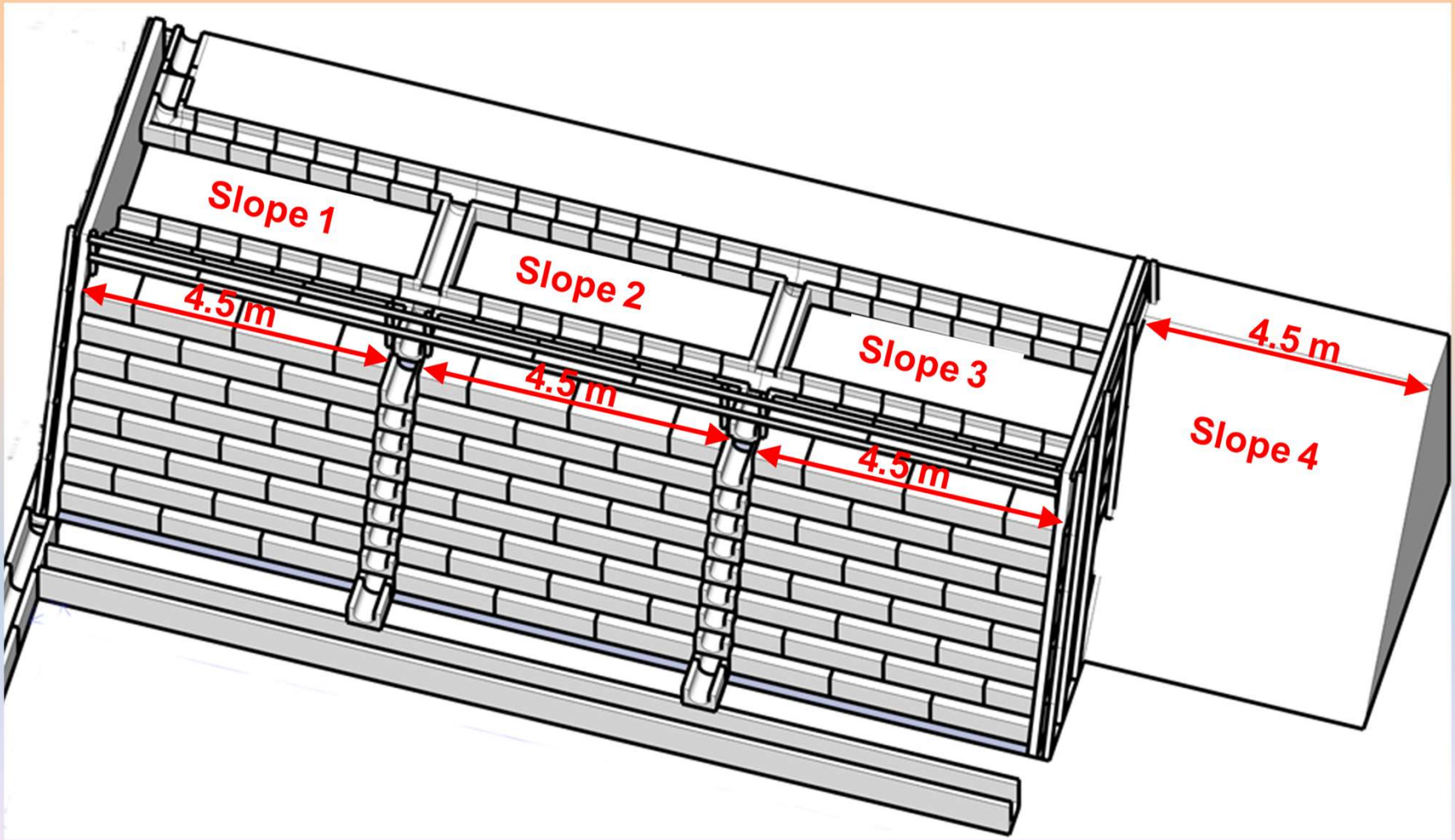
Patent filed:

Rahardjo, H., E.C. Leong, A. Satyanaga, Q. Zhai, L.H. Wong, H.S. Tan, C.L. Wang. "A Bag, System And Method For Using The Same", Application No. YF2016P00434, PCT/SG2016/050470, December, 2016, Singapore.

Original Site Condition before Construction of Geobarrier System



3-D View of Geobarrier System and Original Slopes at Orchard Boulevard



Recycled Concrete Aggregate (RCA) used as Geobarrier System Materials

Fine recycled concrete aggregate

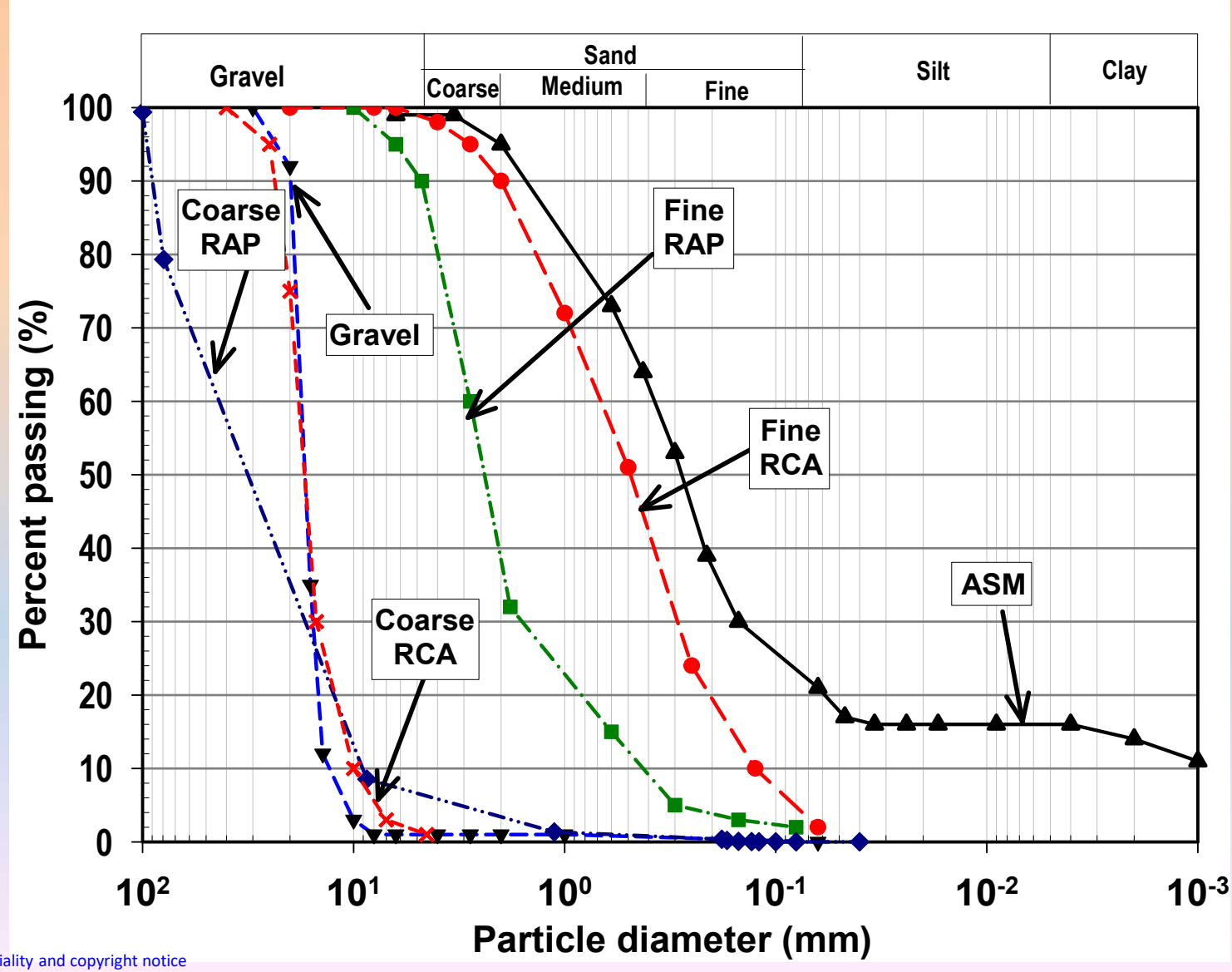
Coarse recycled concrete aggregate

Reclaimed Asphalt Pavement (RAP) used as Geobarrier System Materials

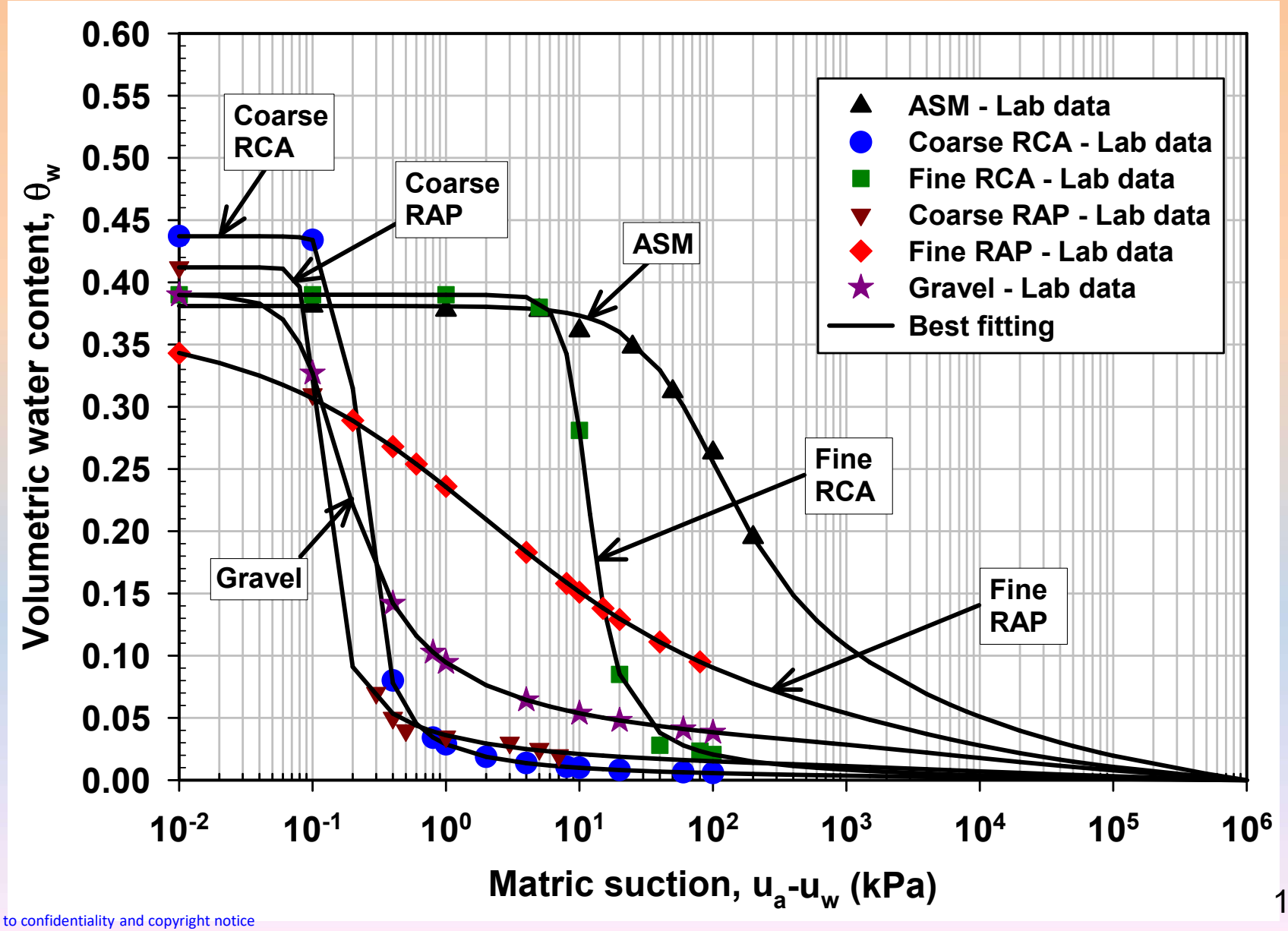
Fine reclaimed asphalt pavement

Coarse reclaimed asphalt pavement

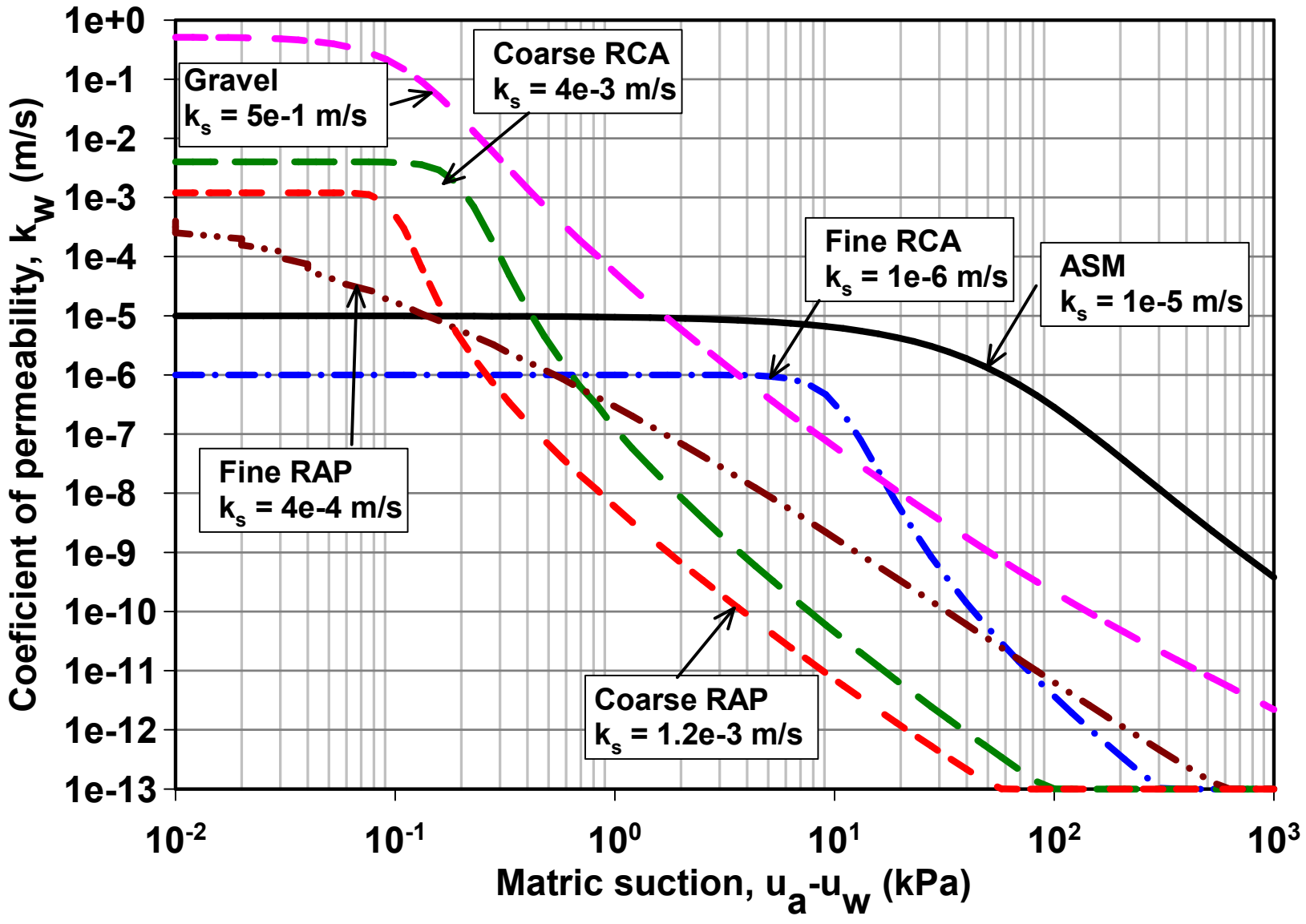
Grain-size Distribution of Materials used in Geobarrier System



Soil-water Characteristic Curve of Materials used in Geobarrier System



Permeability Function of Materials used in Geobarrier System



Construction of GeoBarrier System for Residual Soil Slope at Orchard Boulevard

Jan 2016: Site Mobilization

Feb 2016: Construction of GBS

Mar 2016: Installation of instrumentation

May 2016: Planting of vegetation

Construction of GeoBarrier System for Residual Soil Slope at Orchard Boulevard

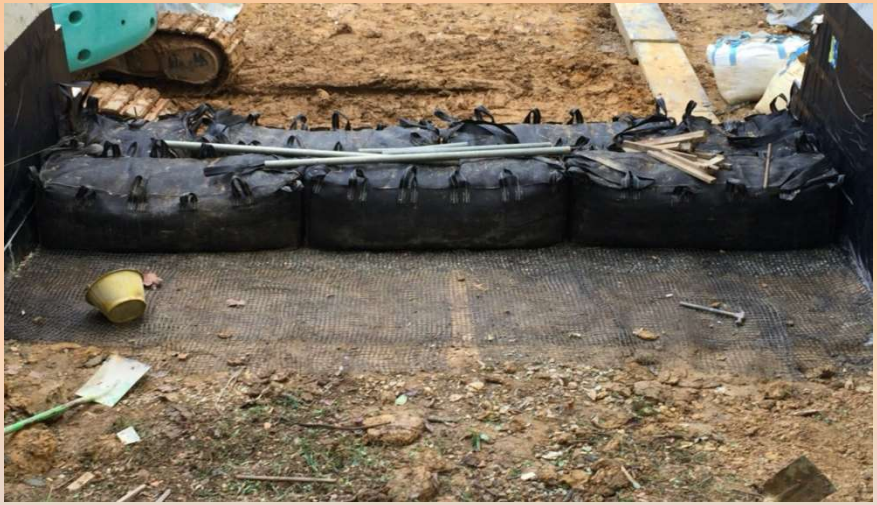
Delivery of materials to site

Filling of fine RCA into Geobags

Drain Installation

Laying of Gravels

Construction of GeoBarrier System for Residual Soil Slope at Orchard Boulevard



Placing of geobags (with tails)

Compaction of soil behind GBS

Provision of piping for installation of instrumentation

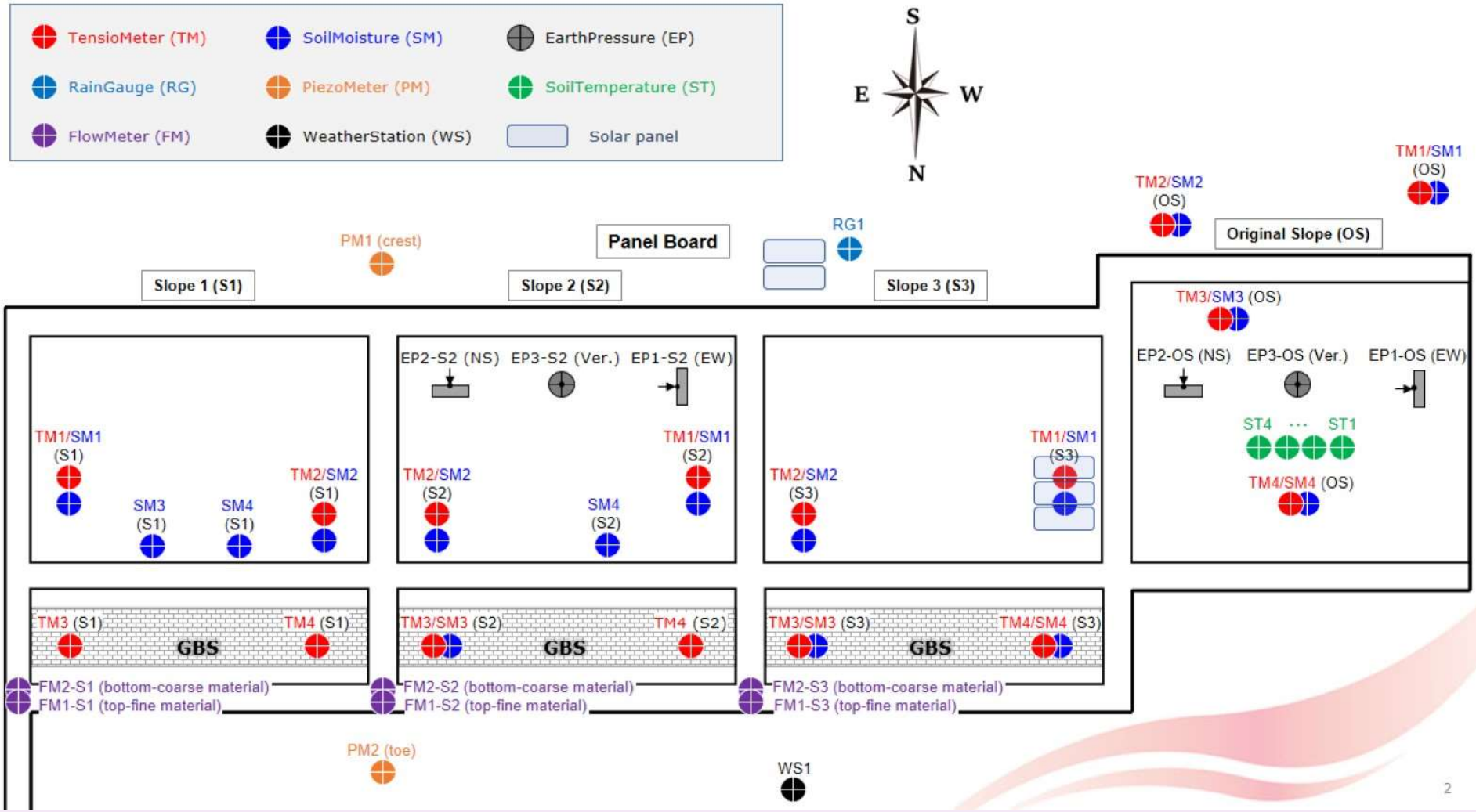
Preparation for drain at crest.

Overall View of GBS after Construction

Completion of Geobarrier System Construction

Notes:
Slope 1 = GBS with fine RCA over coarse RCA
Slope 2 = GBS with fine RAP over coarse RAP
Slope 3 = GBS with fine RCA over coarse RAP

Instrumentation Locations within Slopes with Geobarrier System and Original Slope at Orchard Boulevard



Instrumentation of GeoBarrier System for Residual Soil Slope at Orchard Boulevard

Jet-fill tensiometer manufactured by Soilmoisture (Model 2725)

ICT tensiometer transducer (Model GT3-30)

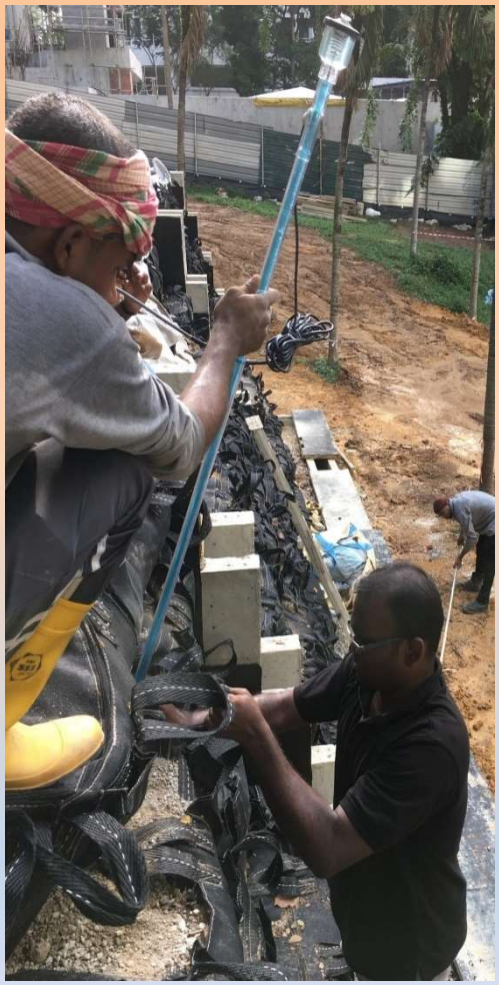
Water content reflectometer (Model CS616) and data logger manufactured by Campbell Scientific

Earth Pressure Cell

Tipping bucket rain-gauge

Weather Station

Installation of Tensiometers



During installation at Slope

After installation at Slope

During installation at Crest

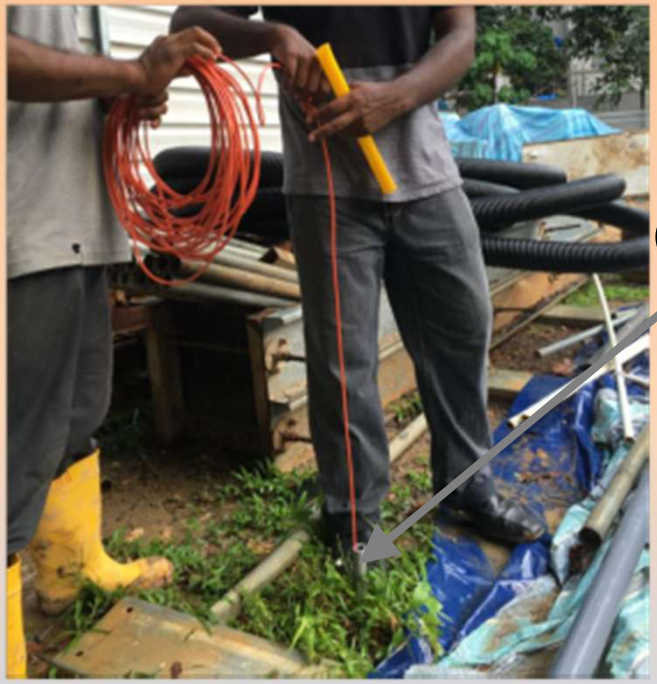
After installation at Crest

Installation of Soil Moisture Sensors

Installation of soil moisture sensors with PVC tube

Installation of soil moisture sensors without PVC tube

Installation of Piezometer Transducer



Cassagrande piezometer

Piezometer transducer

Cassagrande piezometer

Installation of Earth Pressure Cell within GBS Slope

Vertical direction

North-South direction

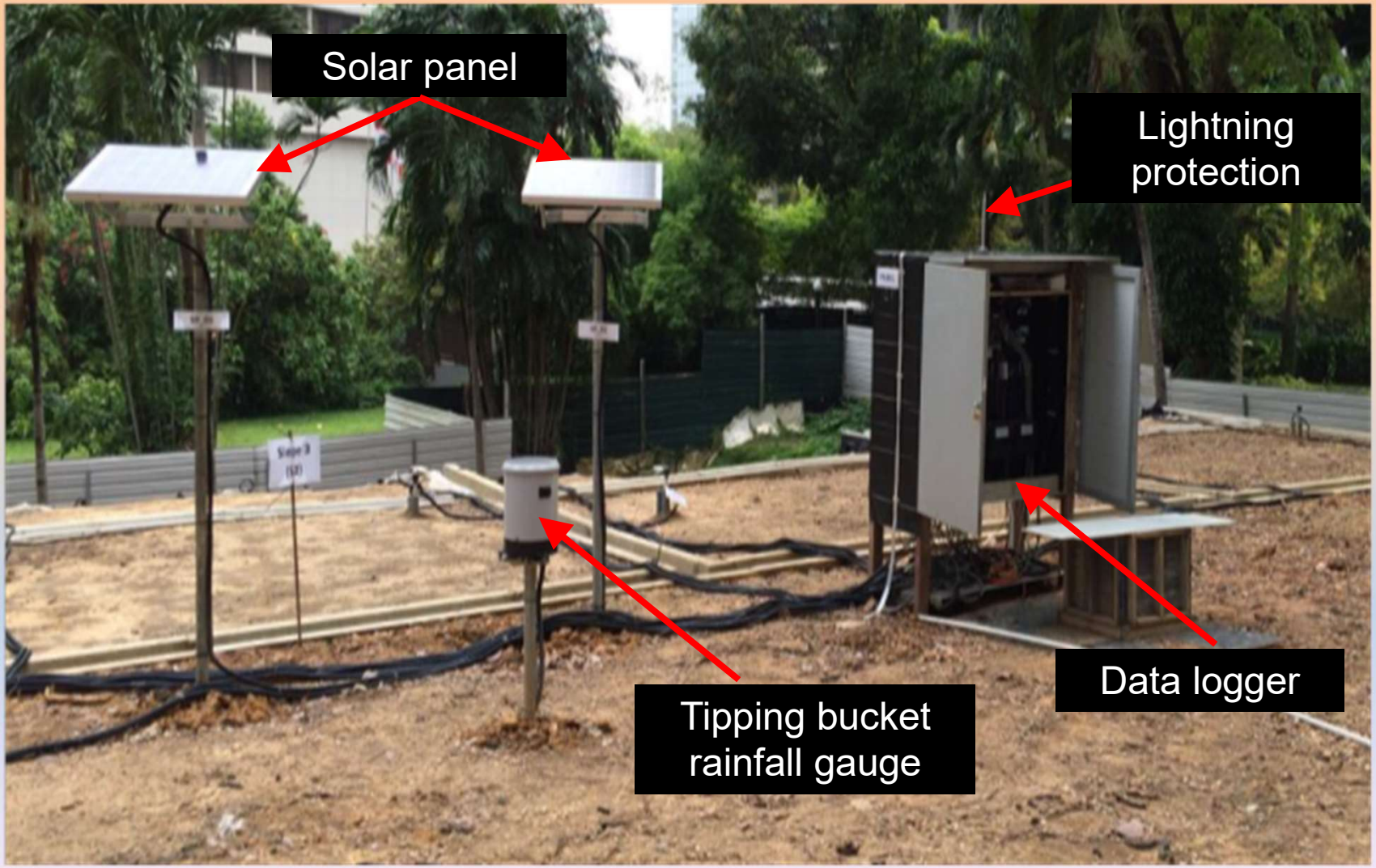
Installation of Weather Station

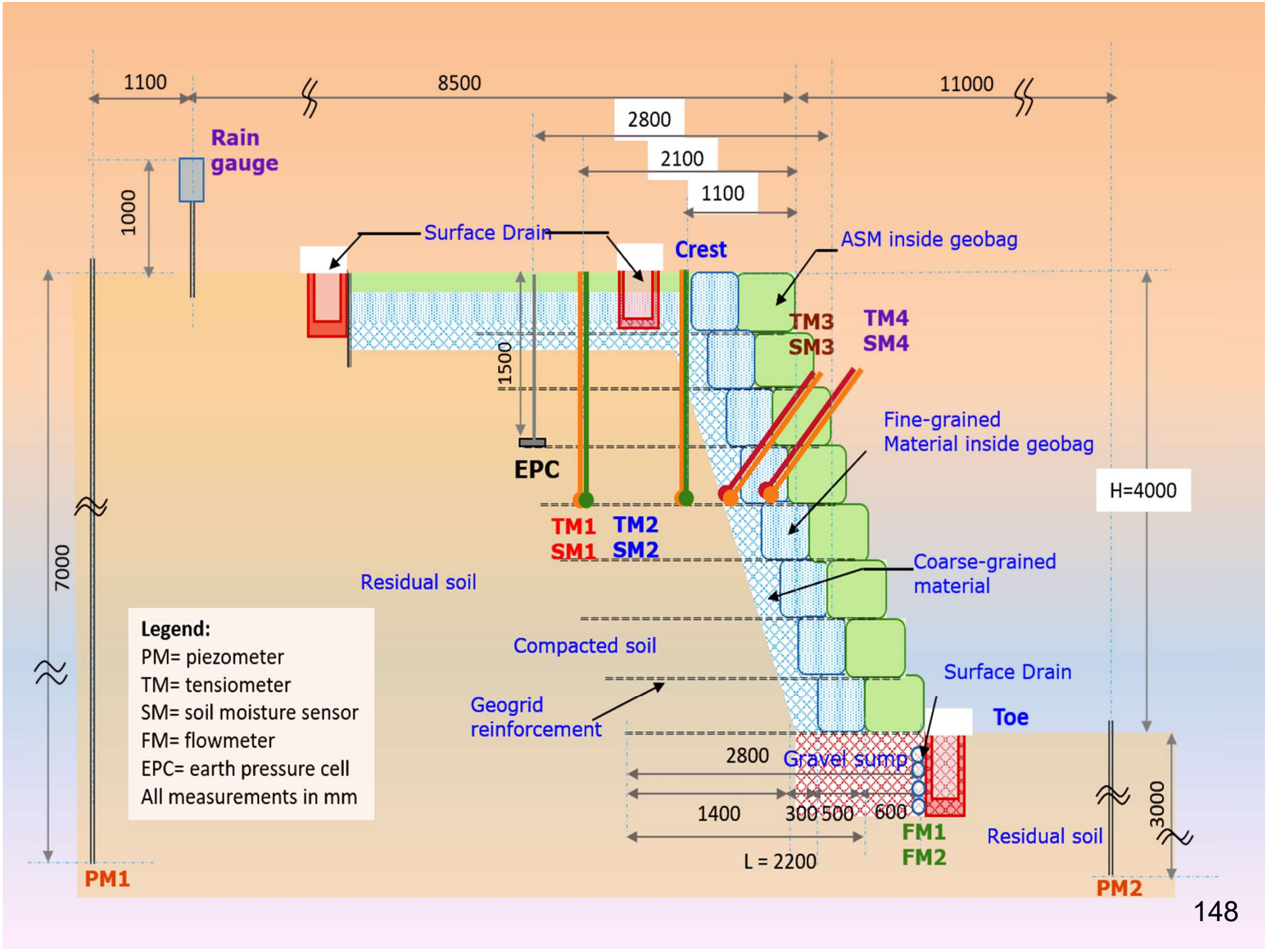
Wind speed sensor

Air temperature & relative humidity

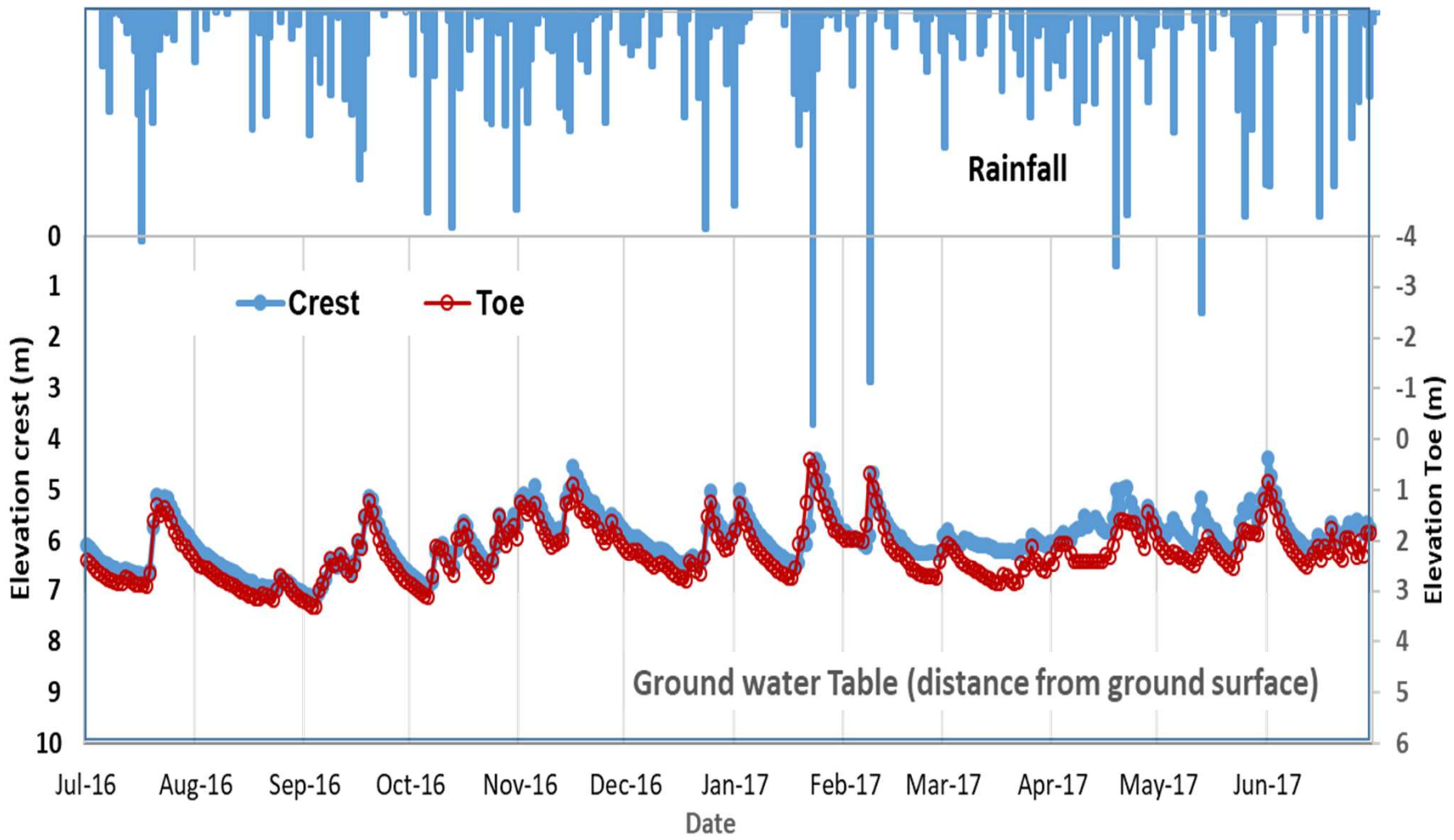
Weather Station

Data Acquisition System

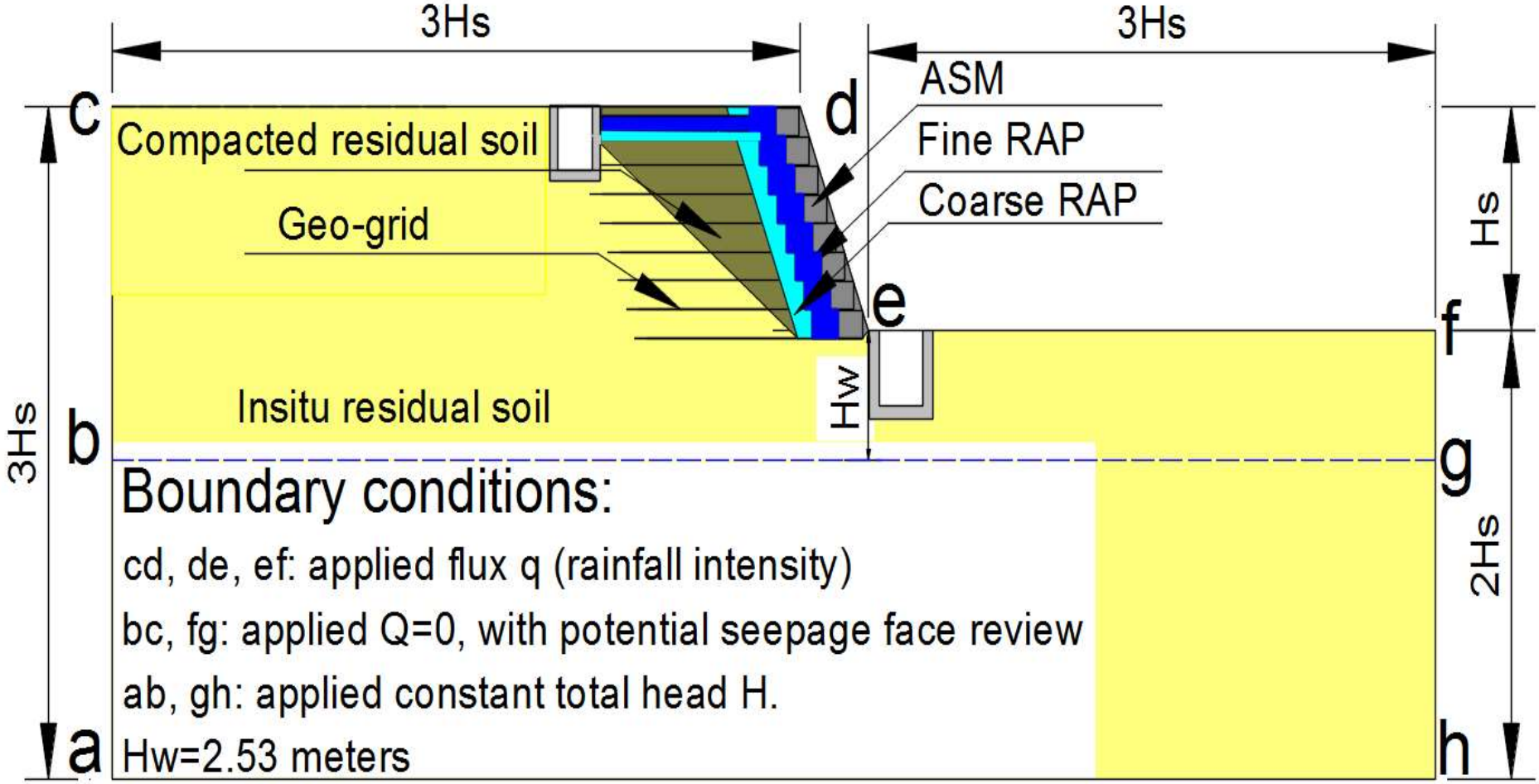



1100
8500
11000
2800
2100
1100
Rain gauge
1000
Surface Drain
Crest
ASM inside geobag
TM3
SM3
TM4
SM4
1500
EPC
Fine-grained
Material inside geobag
H=4000
TM1
SM1
TM2
SM2
Residual soil
Coarse-grained
material
7000
Compacted soil
Surface Drain
Geogrid
reinforcement
Toe
2800
Gravel sump
1400
300
500
600
FM1
FM2
L = 2200
Residual soil
3000
PM1
PM2
Legend:
PM= piezometer
TM= tensiometer
SM= soil moisture sensor
FM= flowmeter
EPC= earth pressure cell
All measurements in mm

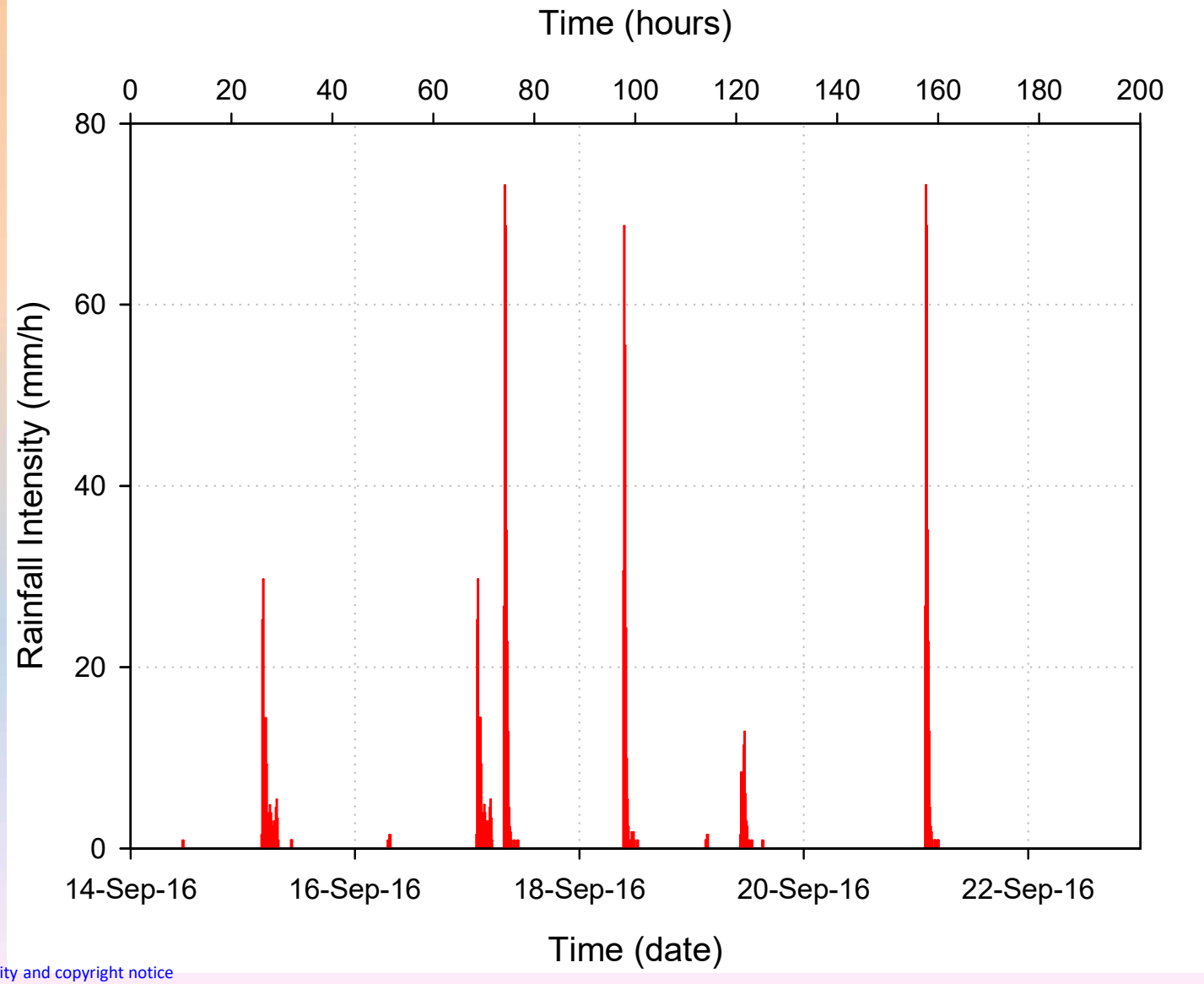
Groundwater Table Variations



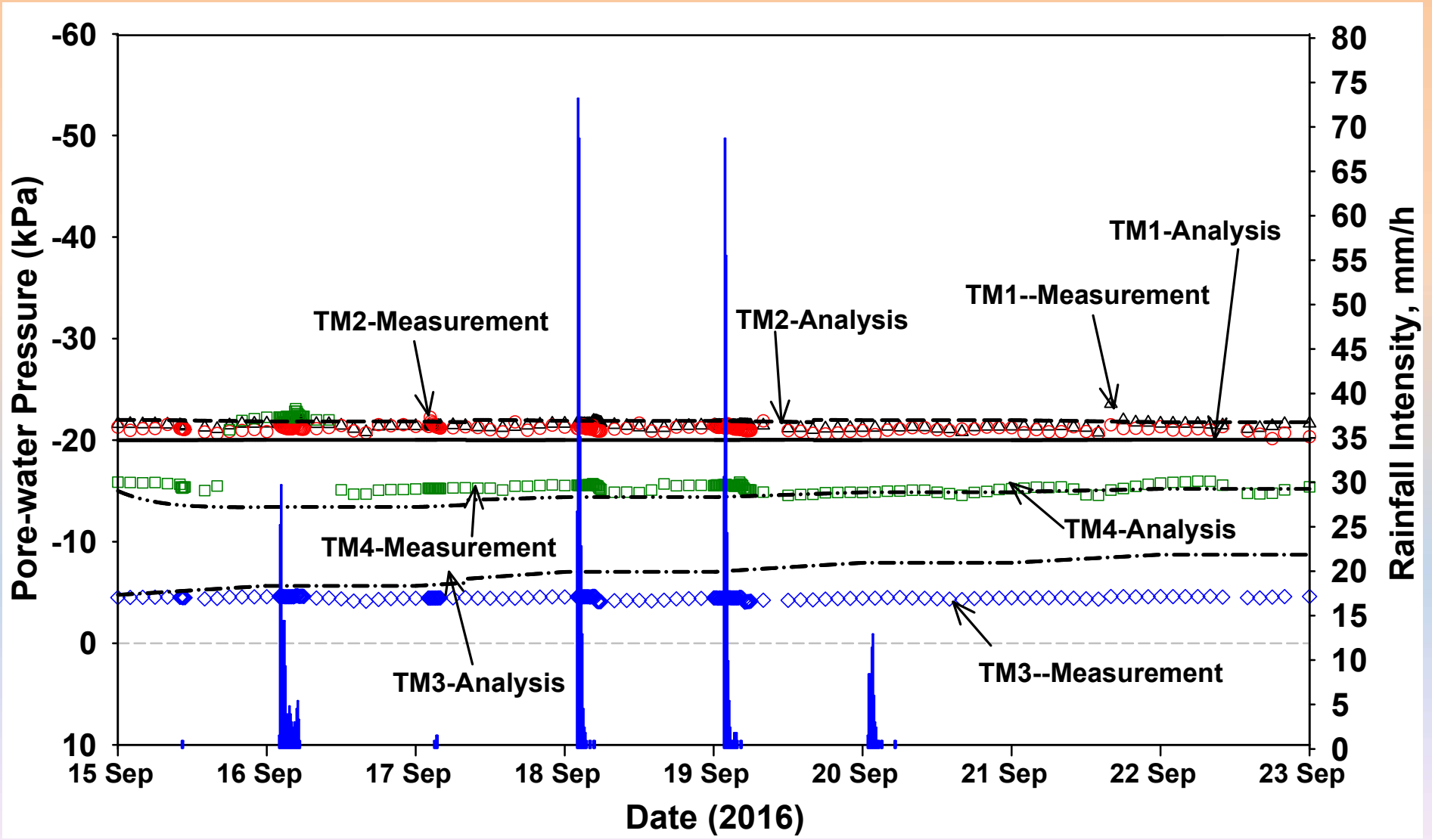
Numerical Model for Finite Element Seepage Analyses



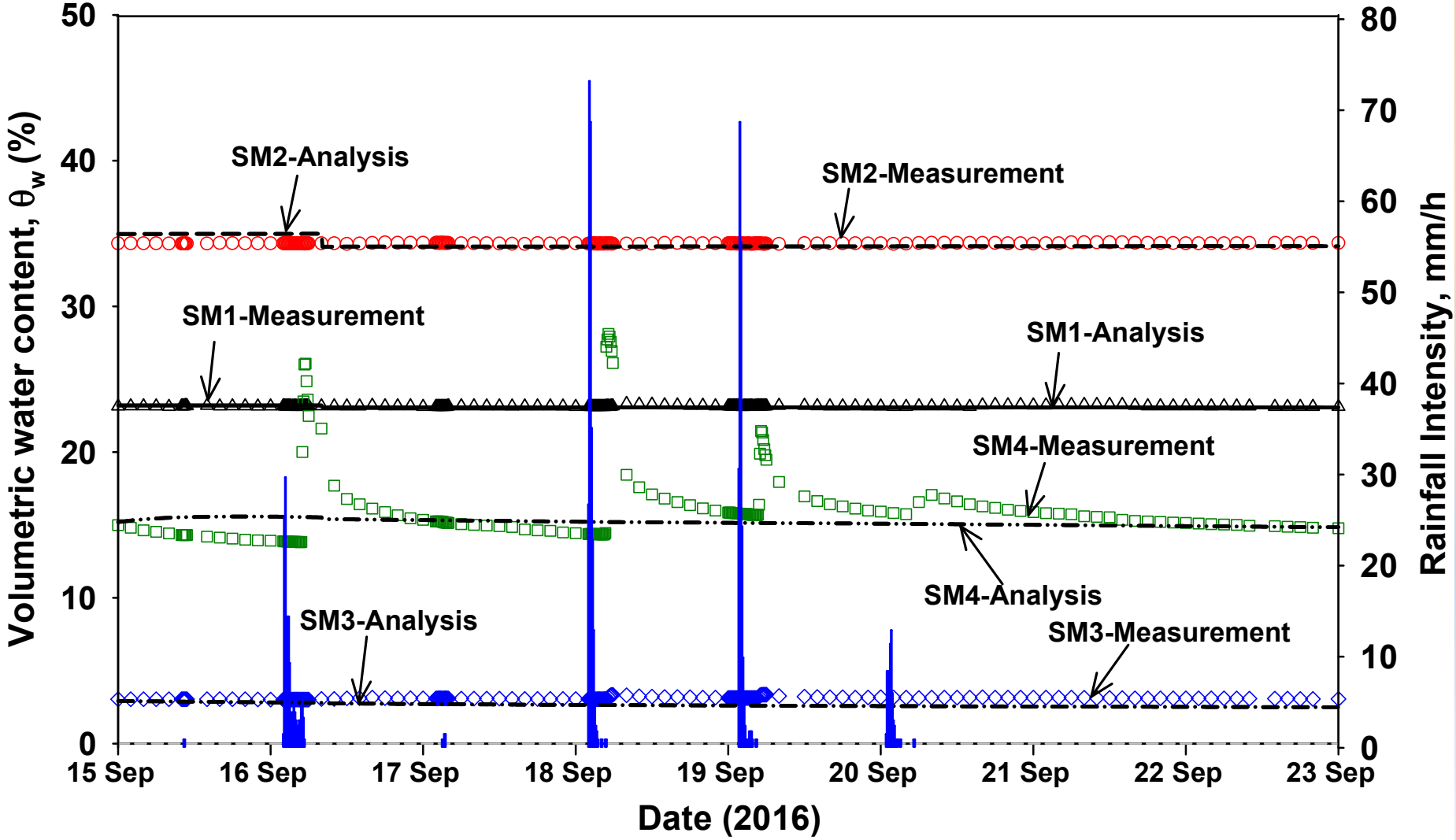
Rainfall Variations from 15-Sep 2016 0:00 am to 22-Sep 2016 23:50 pm



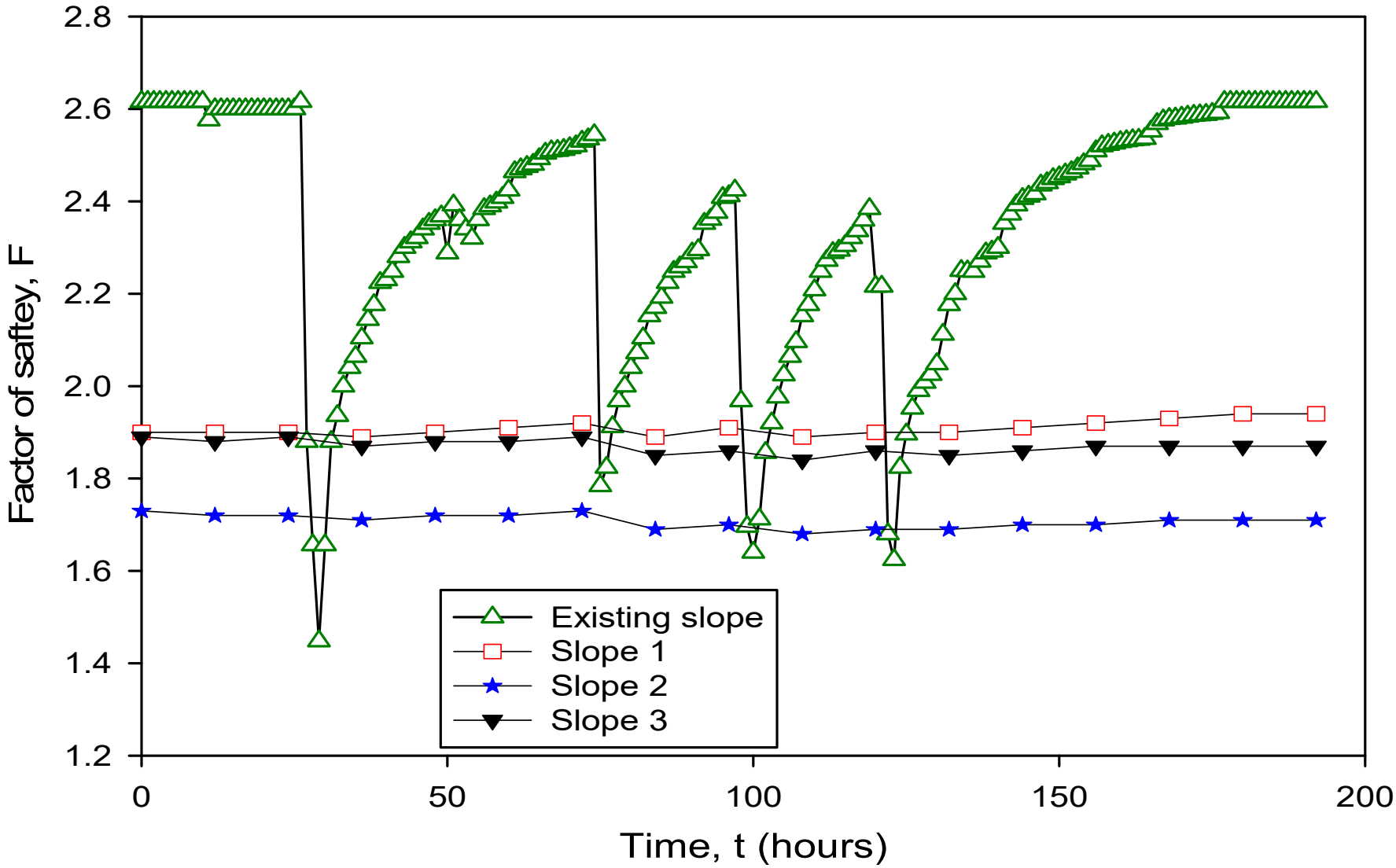
Pore-water Pressure Variations during and after Rainfall for Geobarrier System Slope 2



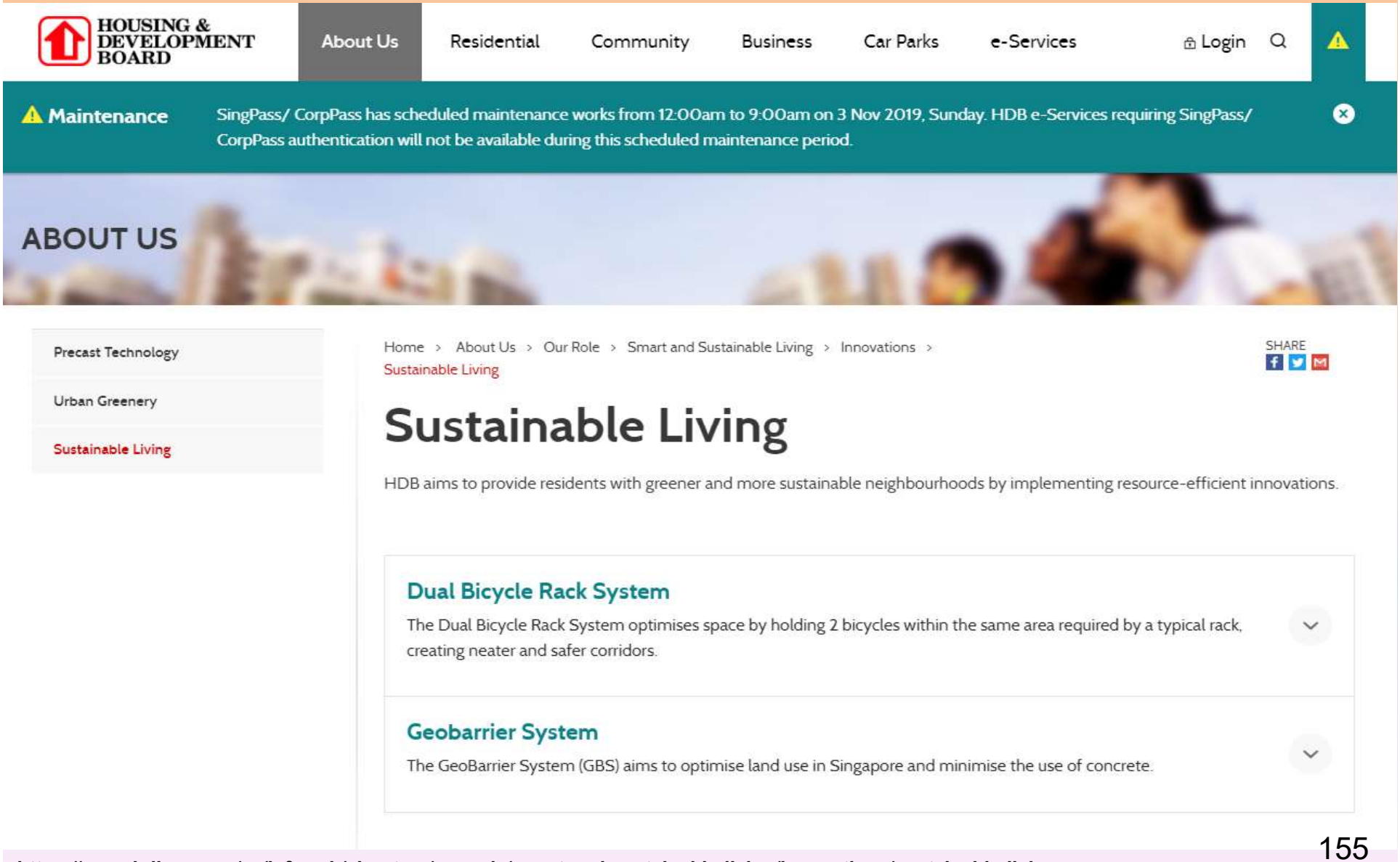
Volumetric Water Content Variations during and after Rainfall for Geobarrier System Slope 2



Comparison of FOS for GBS slope and Original Slope during Rainfall Period



GeoBarrier System as part of Sustainable Living (from HDB Singapore)



https://www.hdb.gov.sg/cs/infoweb/about-us/our-role/smart-and-sustainable-living/innovations/sustainable-living-page

Geobarrier System as part of Sustainable Living (from HDB Singapore)

Geobarrier System

The GeoBarrier System (GBS) aims to optimise land use in Singapore and minimise the use of concrete.

With continuous urbanisation and development, Singapore faces increasing land constraints and a growing reliance on the use of concrete. Concrete has a large carbon footprint, and contributes up to 5% of annual global CO_2 production.

The GeoBarrier System (GBS) aims to optimise land use in Singapore and minimise the use of concrete through its 2 main functions: Earth Retention and Slope Stabilisation.

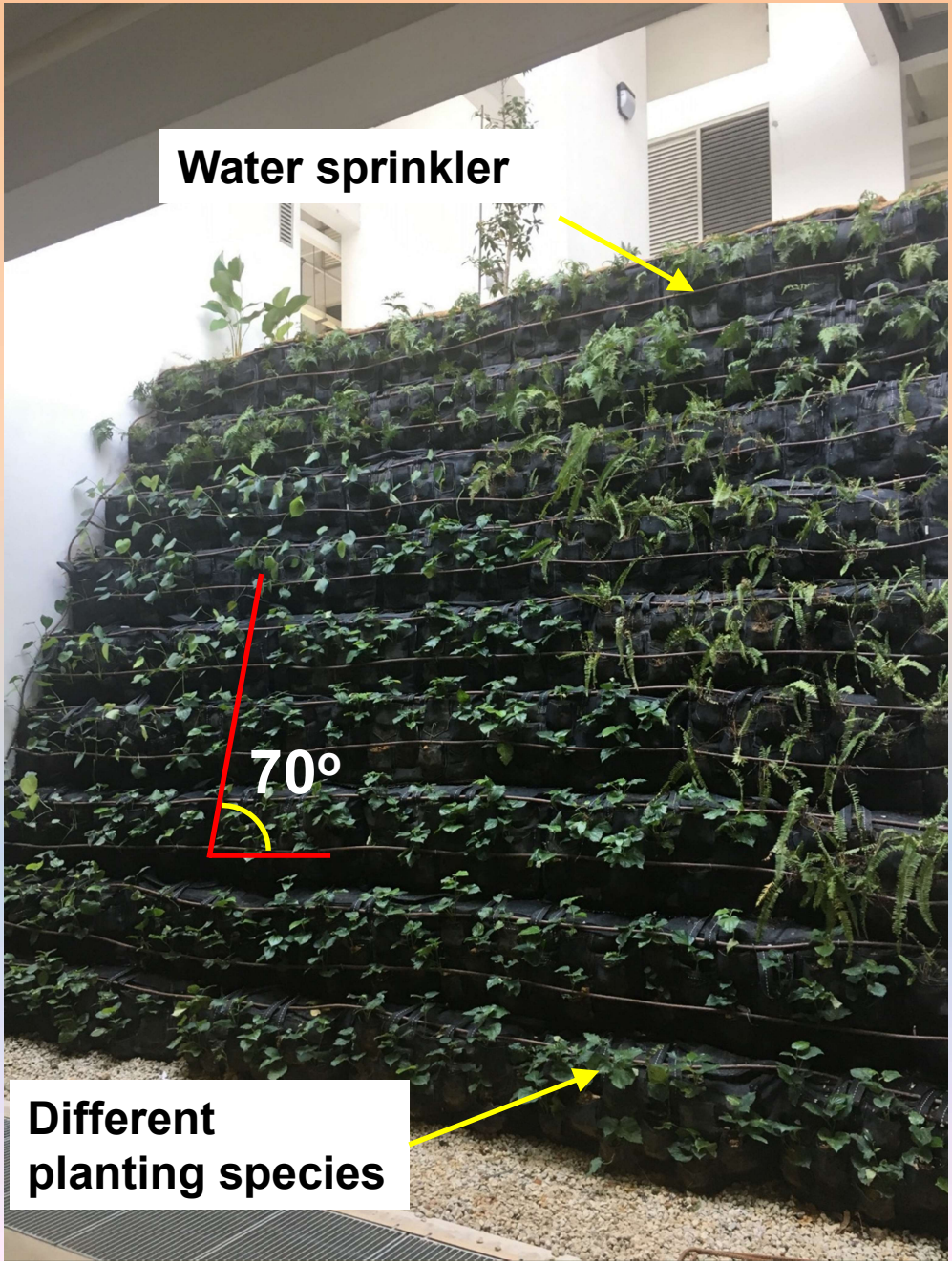
The GBS' earth retaining capability allows it to stabilise steep slopes and free up additional land by:

- Optimising designs of underground structures for multi-level basement car parks and within undulating terrains
- Minimising rainwater infiltration to maintain slope stability

Construction of GBS in a Housing Project

Planting of different species of vegetation

Construction of GBS in a Housing Project

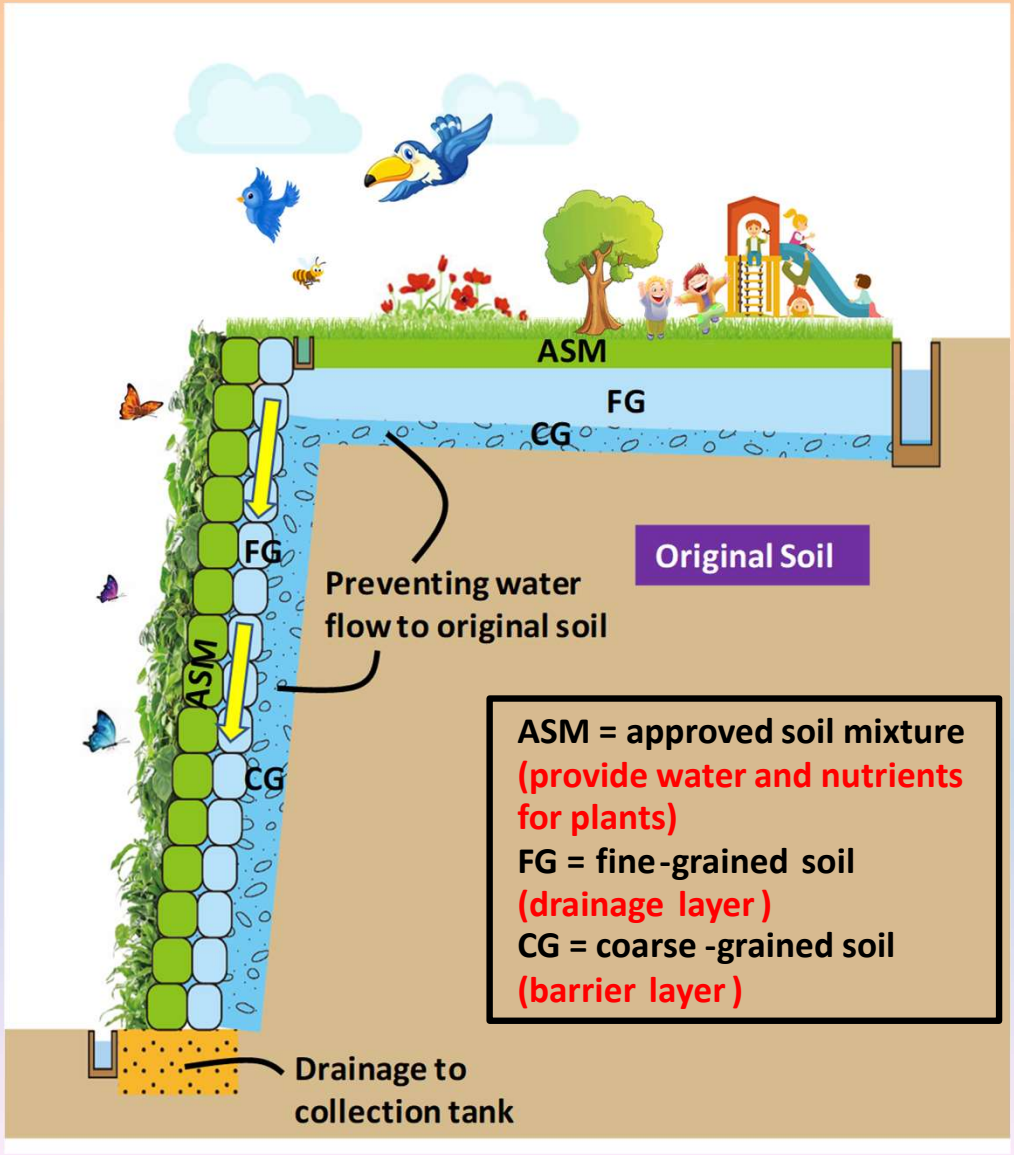


Completion of planting of different species of vegetation

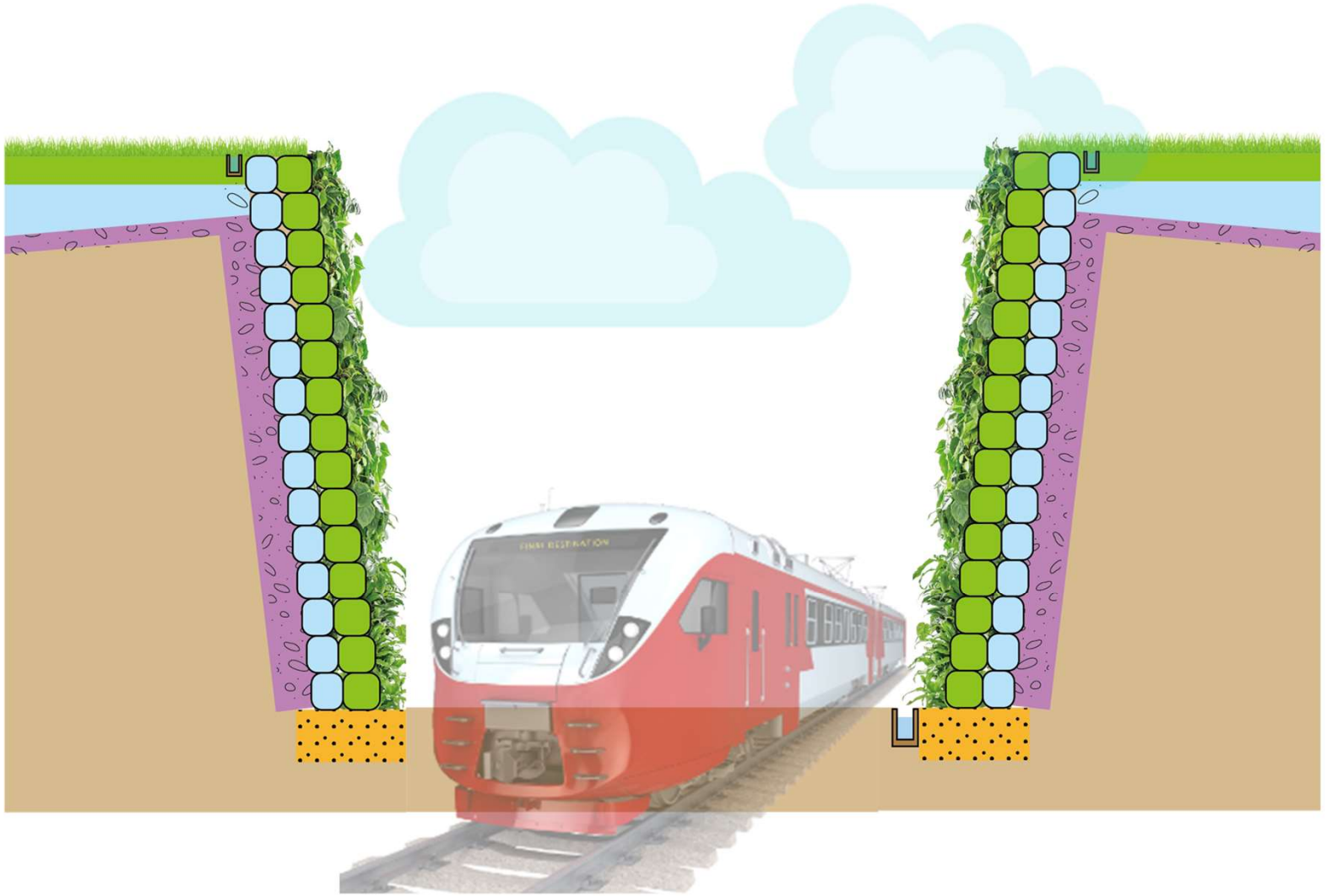
Construction of GBS in a Housing Project

Completion of GBS

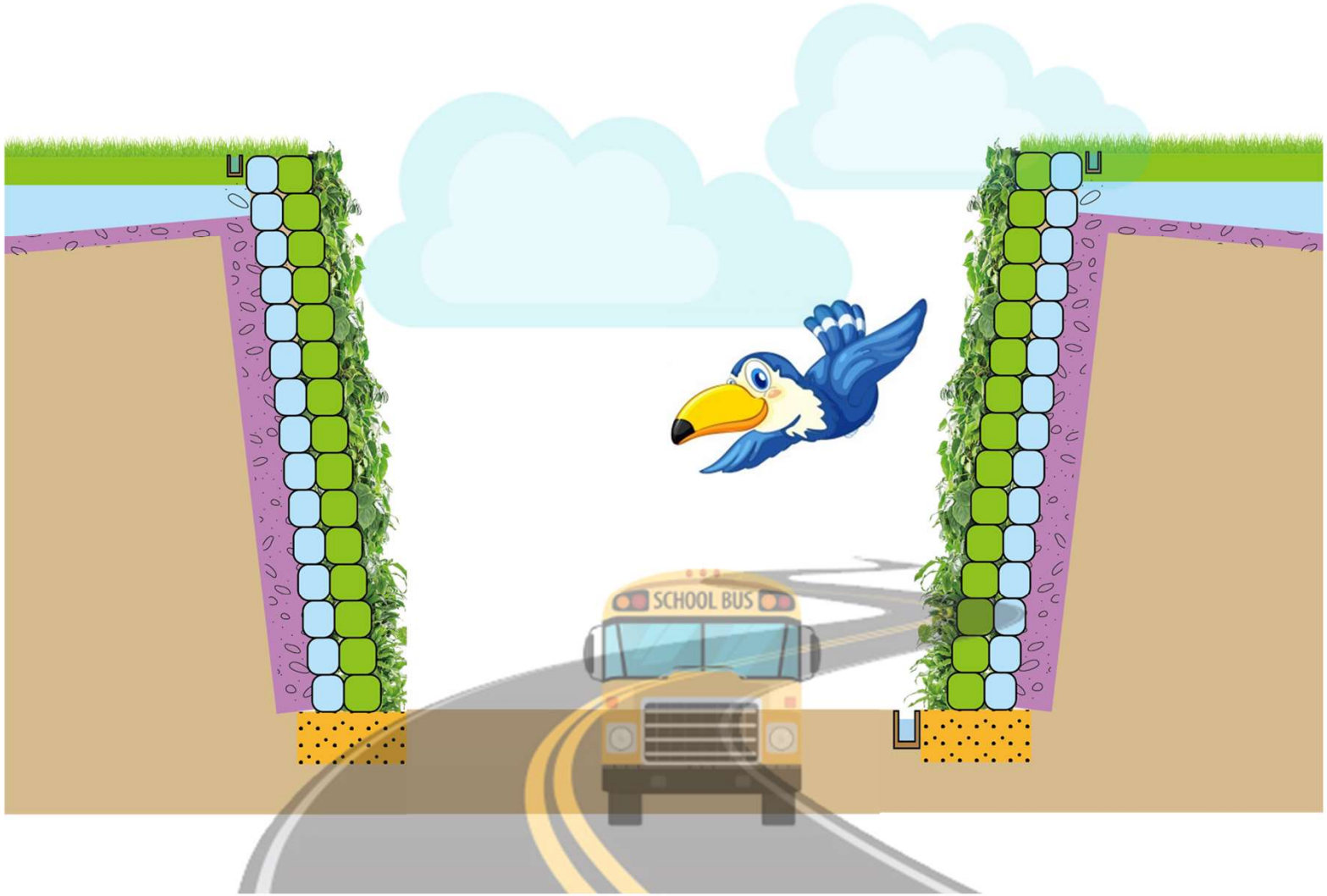
GeoBarrier System for Community Activities, Flora and Fauna



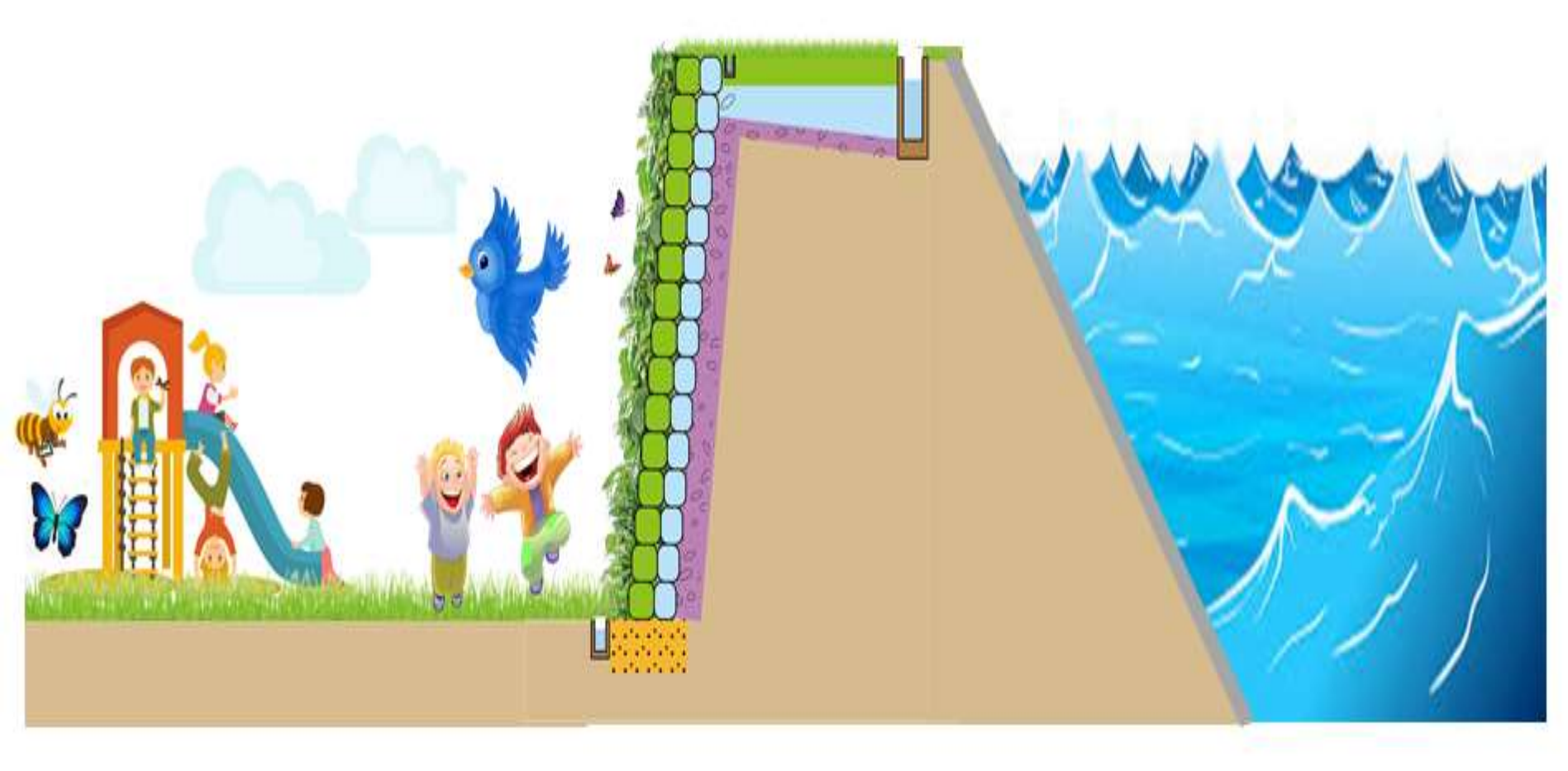
GeoBarrier System for Green Corridor



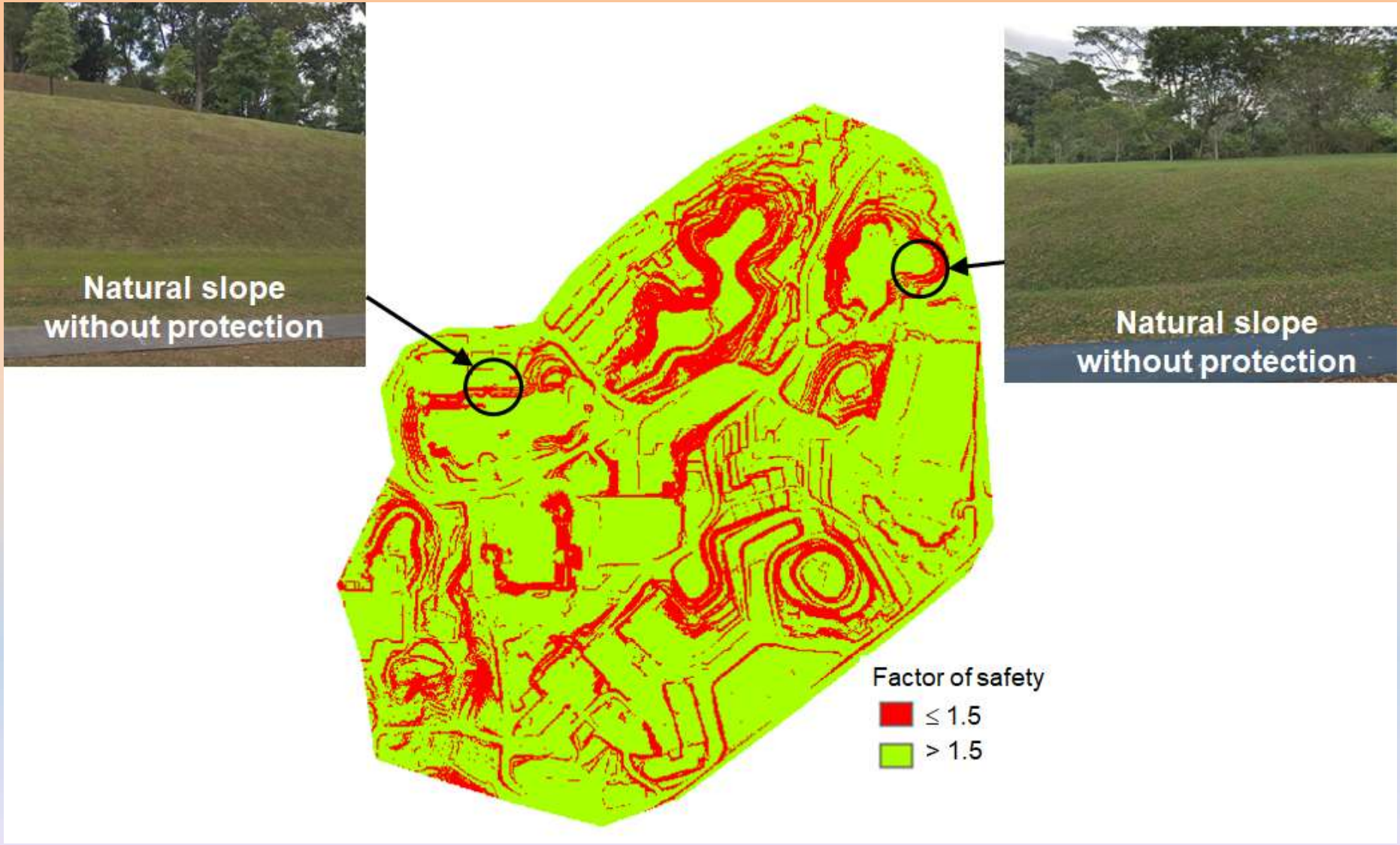
GeoBarrier System for Slopes along Highway



GeoBarrier System for Polder / Embankment



Slope Susceptibility Map of NTU Zone

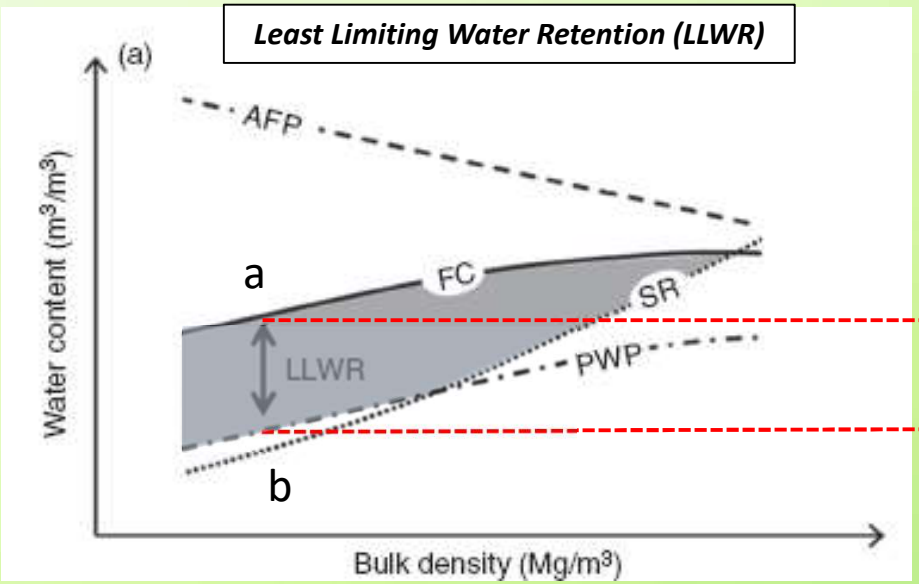


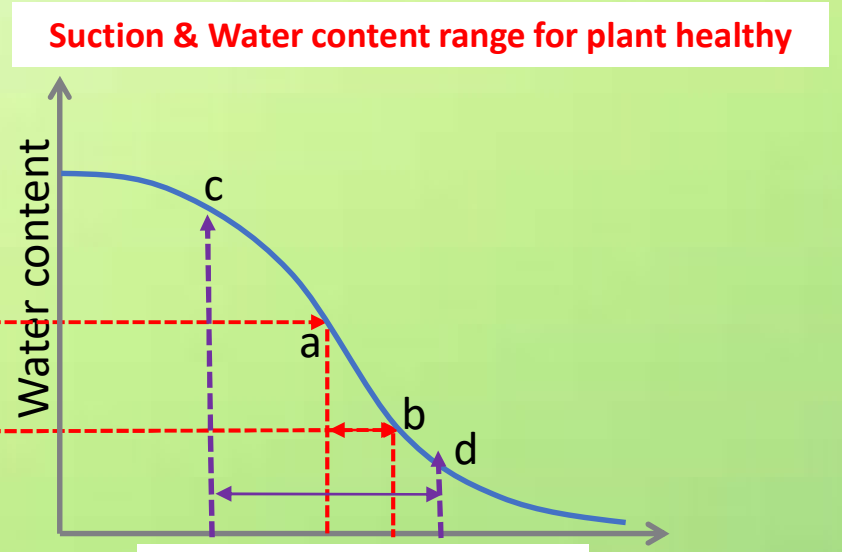
Distributions of Factor of Safety within NTU zone with the assumption of fully saturated slope

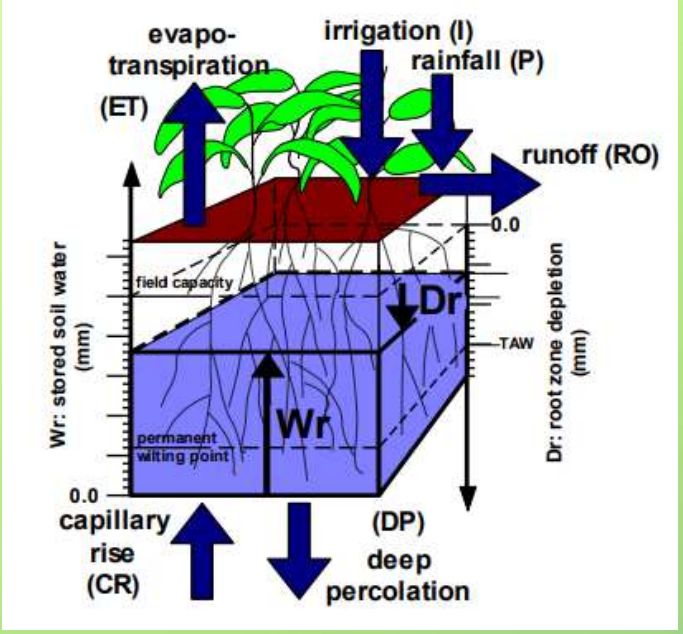
Slope Susceptibility Map of NTU Zone

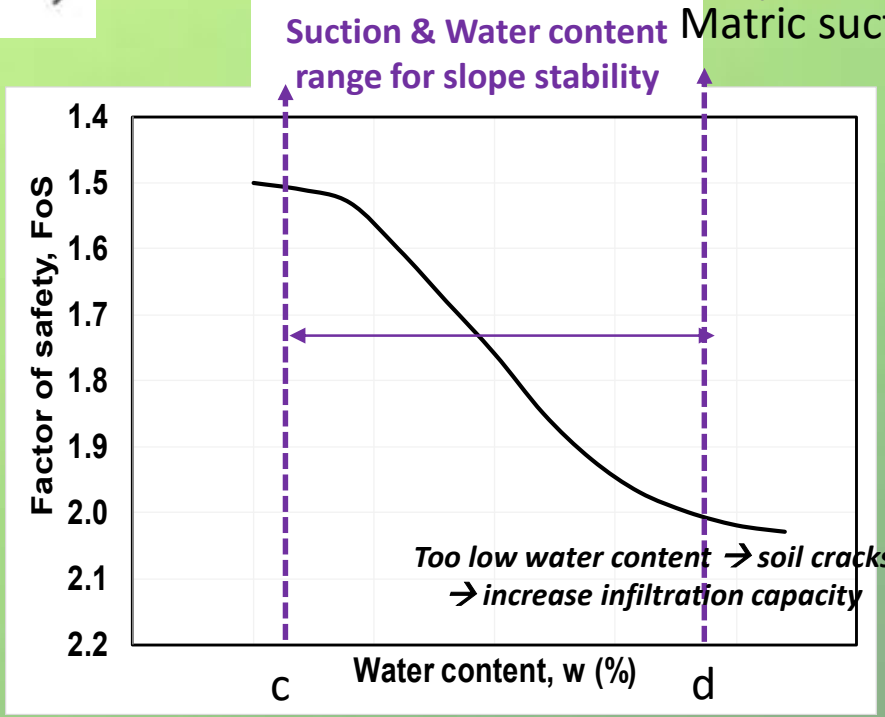
Distributions of Factor of Safety within NTU zone with the incorporation of unsaturated soil properties

Unsaturated Soil for Plant Health and Slope Stability







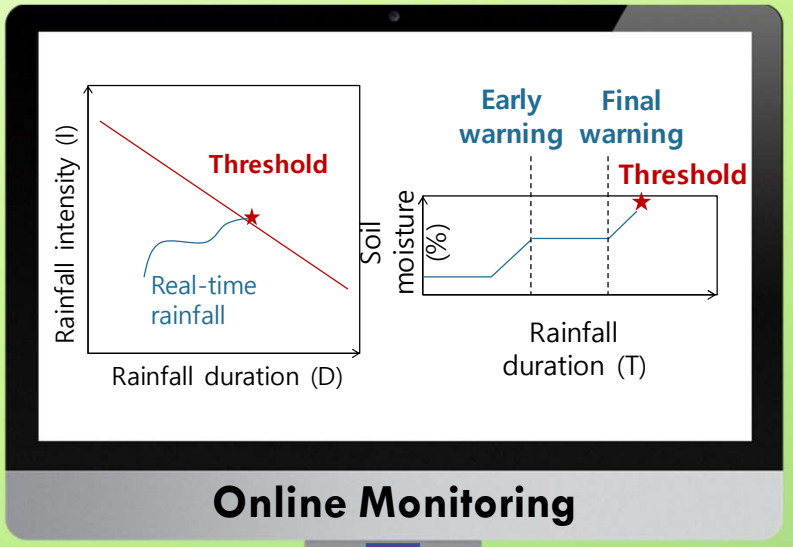


Proposed Sensing Technology in this Study

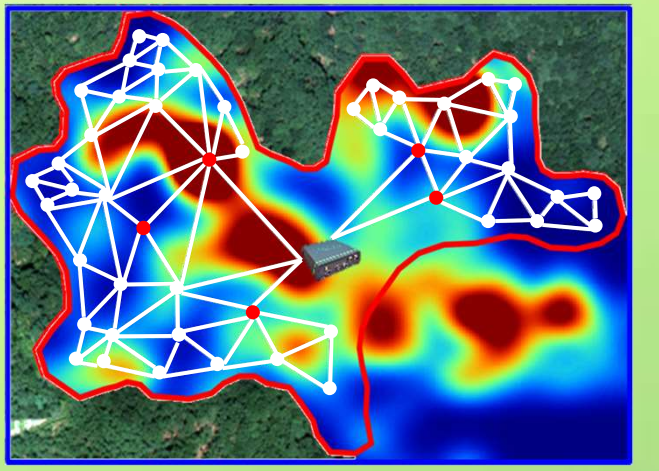
Plant health and stability monitoring

If rain
10 min loop

4G connection



Big data transmission



Spatial interpolation of soil moisture

Potential Intellectual Property 2

Apps

Internet of Things (IoT)

Application of Unsaturated Soil Mechanics to Tree Stability

Effect of Rainfall on Tree Stability

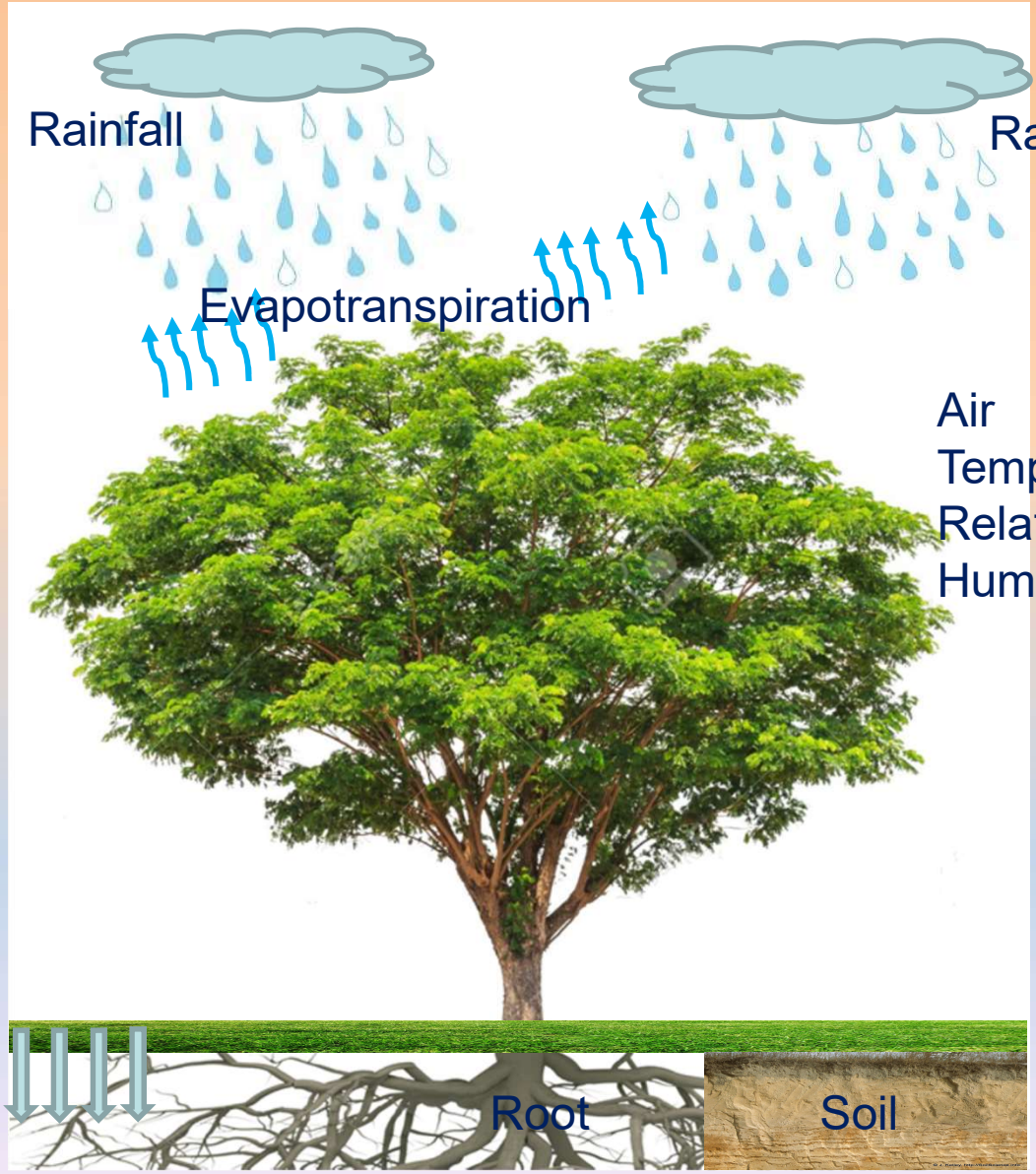
Uprooted Trees in Singapore in June 2010 (Heavy Rainfall)

Samanea Saman **(Raintree)**

Tree and Environment Relationship

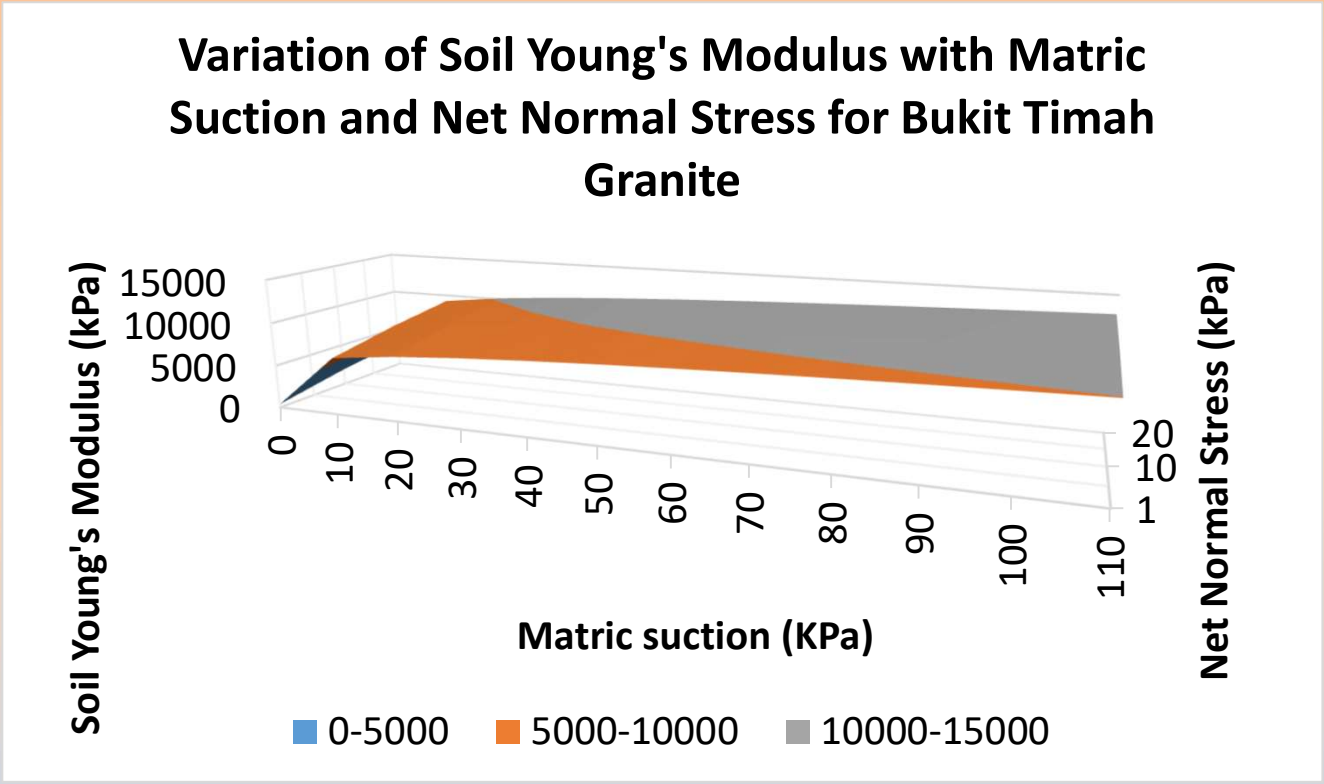
Solar Radiation

Wind



Root plate of the air spaded *Syzygium grande.*

Root plate of *Khaya senegalensis*

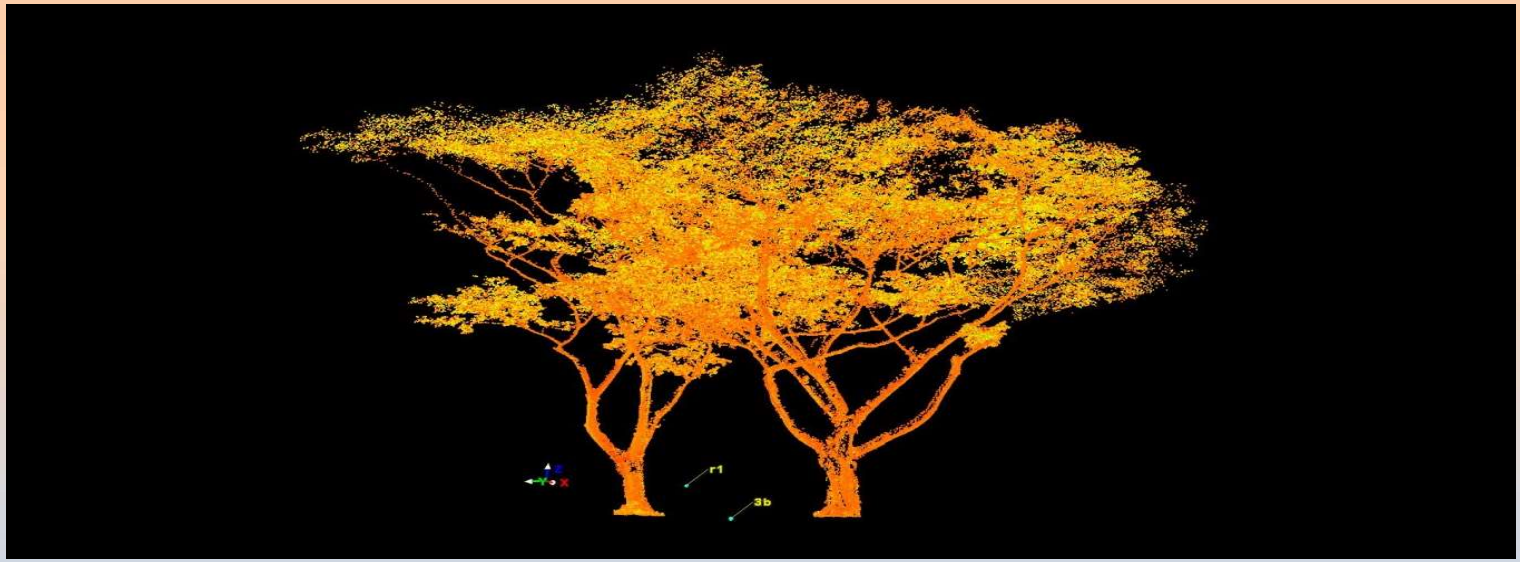


$$E = 90.5P_a\left(\frac{\sigma_n - u_a}{P_a}\right)^{0.69} + 92.8P_a\left(\frac{u_a - u_w}{P_a}\right)^{0.18} + 18.9P_a\left(\frac{(\sigma_n - u_a)(u_a - u_w)}{P_a^2}\right)^{0.99}$$

(Rahardjo, et al. 2011)

Reference: ***Rahardjo, H., F. Melinda, E.C. Leong and R.B. Rezaur (2011). "Stiffness of a Compacted Residual Soil". Journal of Engineering Geology, June, Vol. 120, pp. 60–67.***

Laser Scanning for Tree



2 x Samanea Saman (Raintree)

Processed point cloud of the two trees at Telok Blangah rise without background clutter

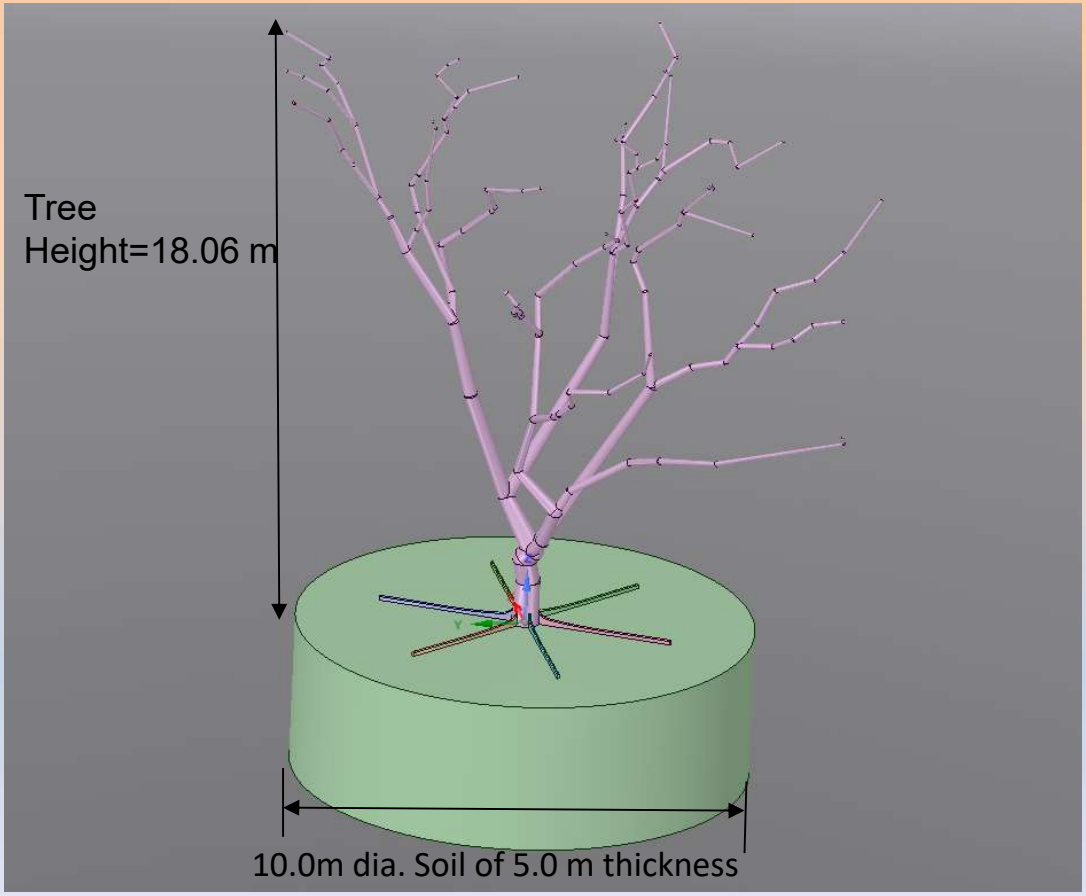
Laser Scanning for Tree

2 x Samanea Saman (Raintree)

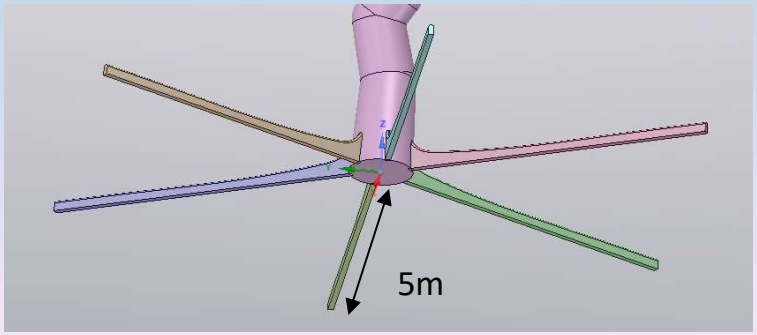
The same two trees but with the majority of the leaves removed and thus highlighting the branch detail

Effect of Soil Softening due to Rainfall on Tree Stability

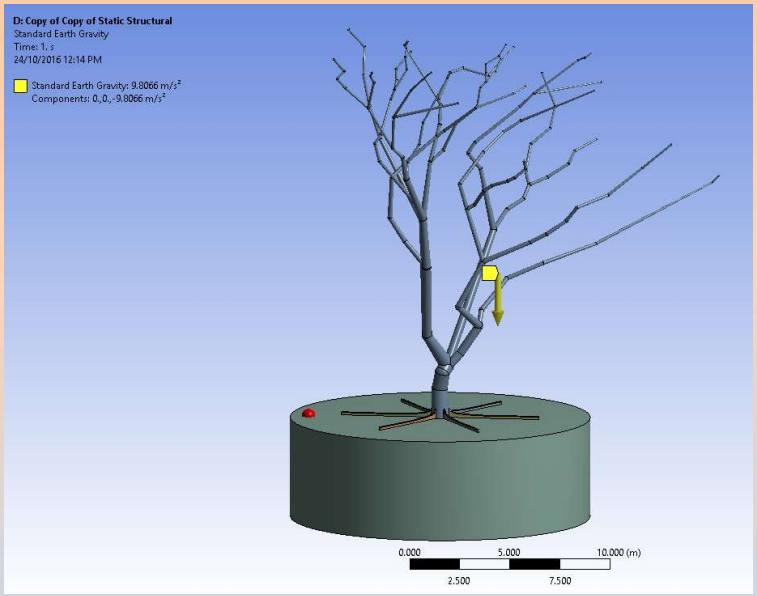
ANSYS modelling of raintree

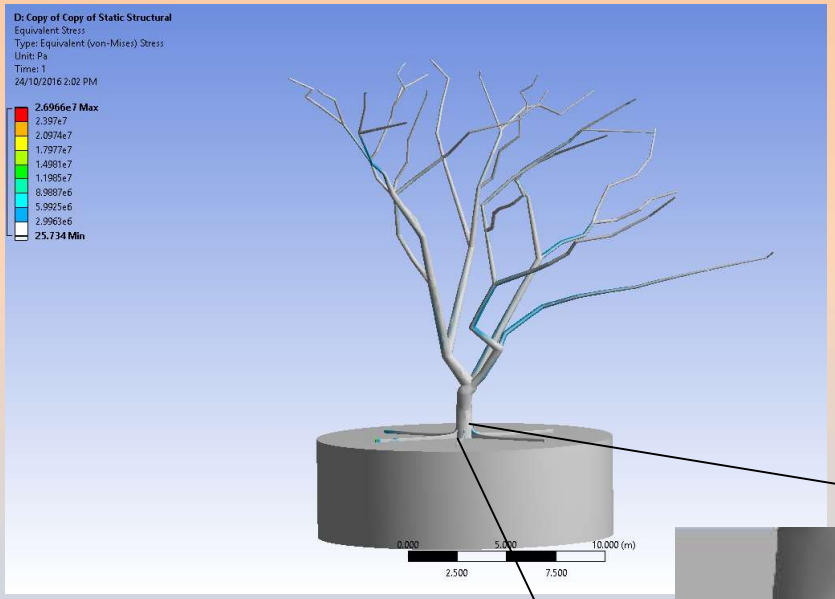


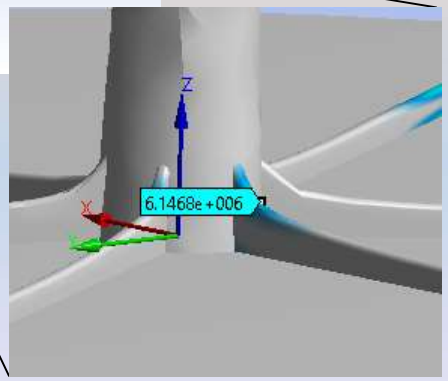
- **Fixed support at base of soil cylinder**
- **Maximum stresses is at the branches (shown in figure)**
- **6 Lateral roots**
- **Wood flexural strength 40MPa**
- **Wood density 800kg/m3**
- **Wood Elastic modulus 3GPa**
- **Soil Elastic modulus 0.5 to 10MPa**



Load case 1.1 : Self-weight only

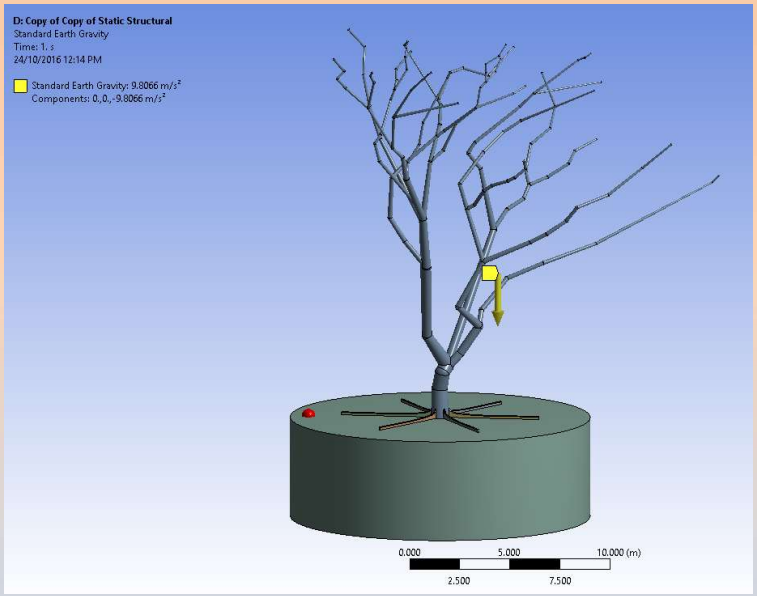


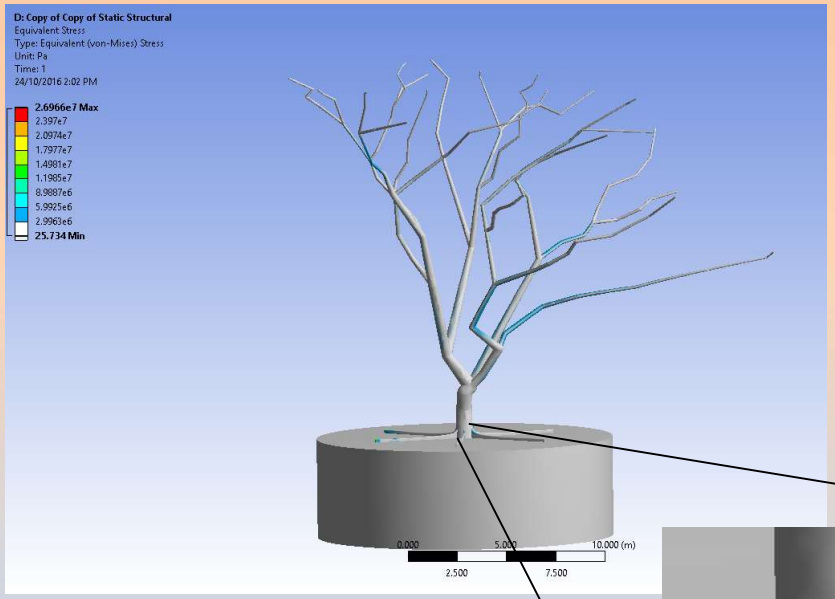


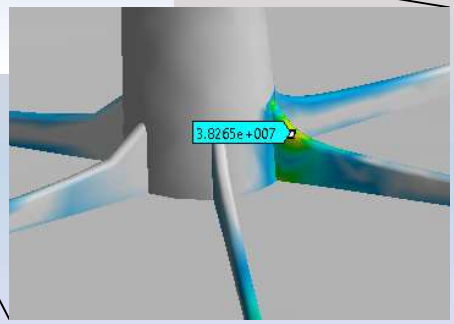


- Yellow arrow denotes the direction of the earth's gravity
- The sides and bottom of the soil cylinder are fixed
- **Soil E modulus 10 MPa**
- Buttress shows stress of about **6.2 MPa (Compression)**

Load case 1.5 : Self-weight only

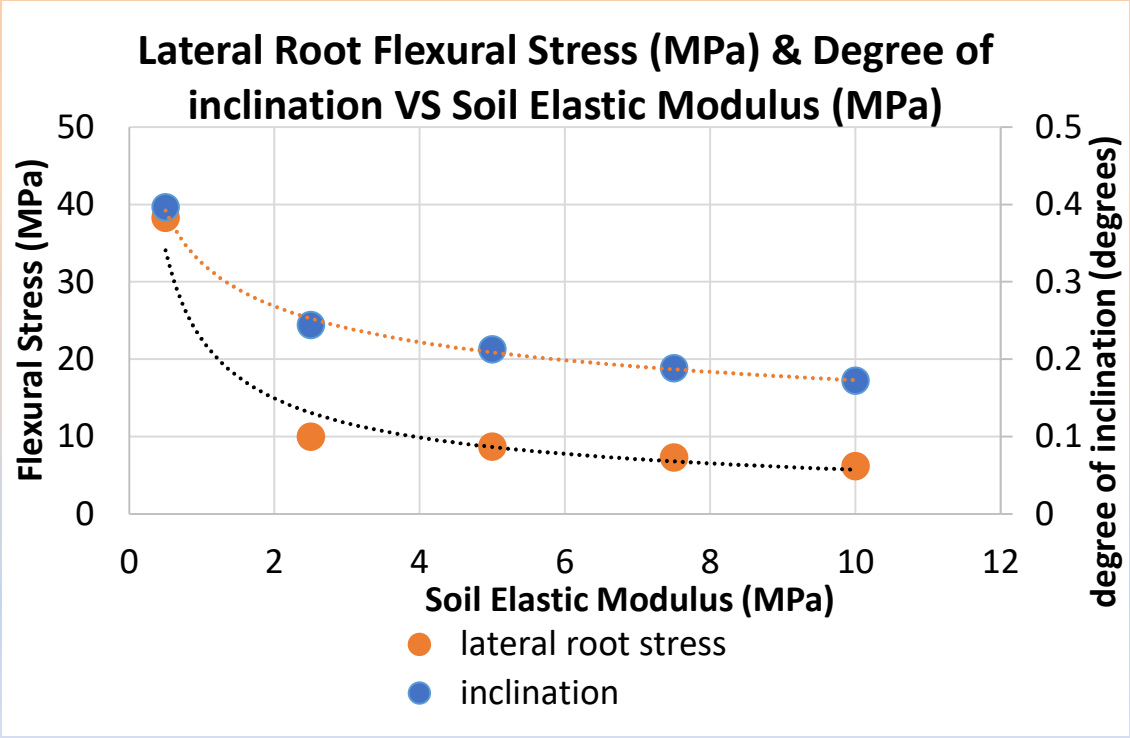






- Yellow arrow denotes the direction of the earth's gravity
- The sides and bottom of the soil cylinder are fixed
- **Soil E modulus 0.5 MPa**
- Buttress shows stress of about **38.3 MPa (Compression)**

Tree inclination due to reduction in soil elastic modulus.



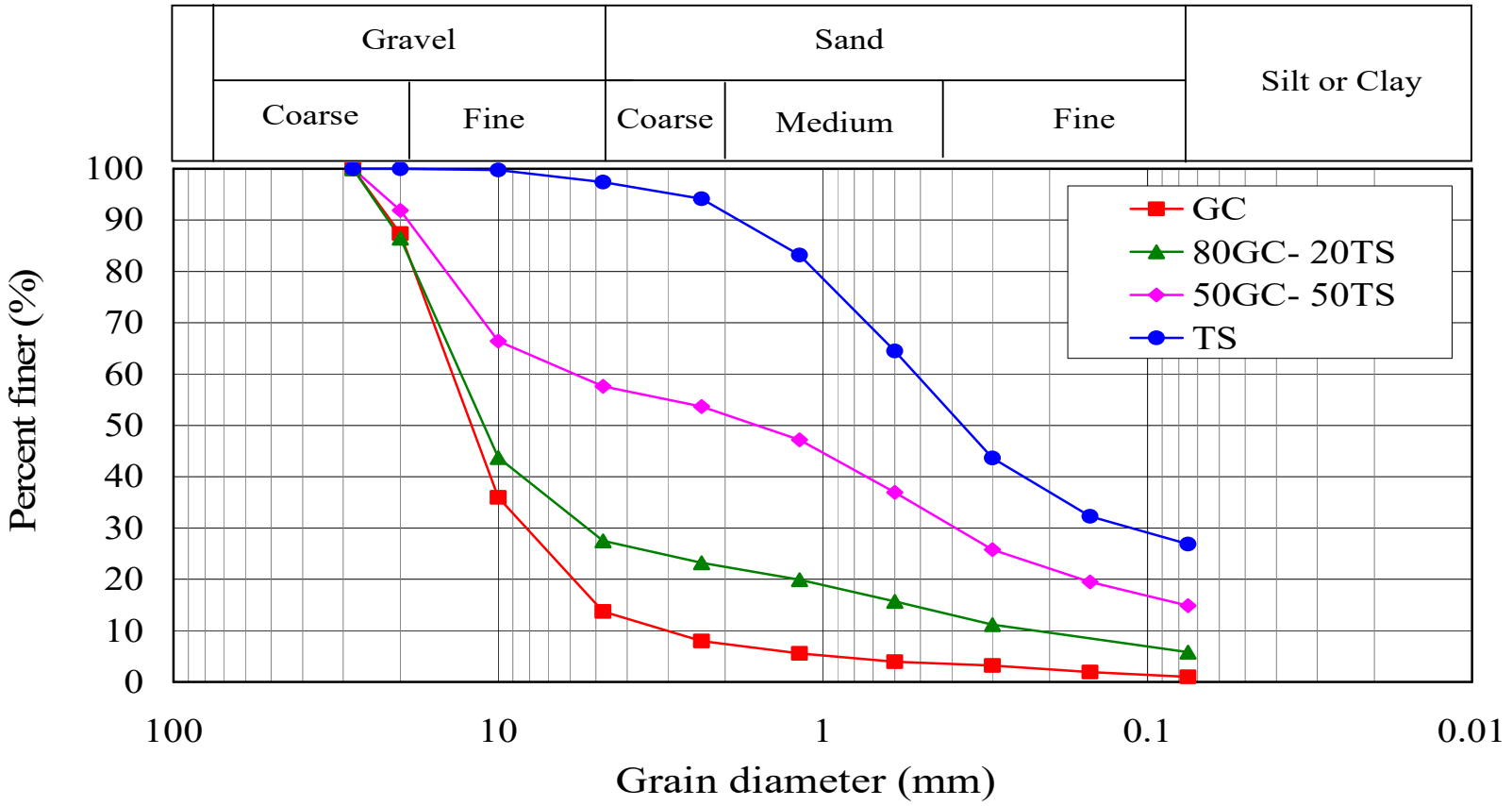
- For this geometry of tree, changes in the soil elastic modulus accounts for less than a degree of inclination
- Other factors can also cause higher magnitude non growth based tree inclination (e.g. decay induced reduction of support.)

Soil Mixtures for Improving Tree Stability

Granite chip

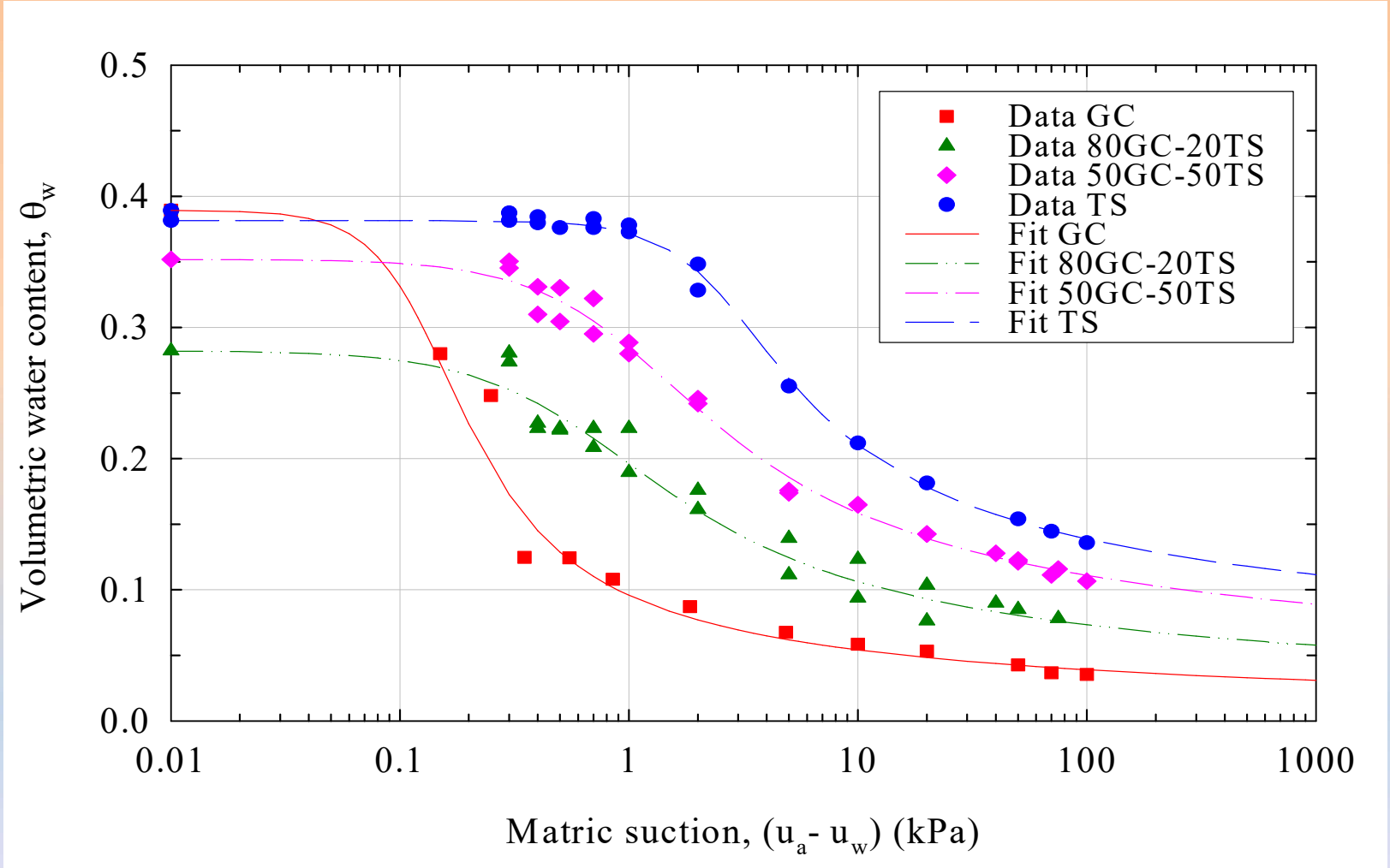
Top soil

Soil Mixtures for Improving Tree Stability



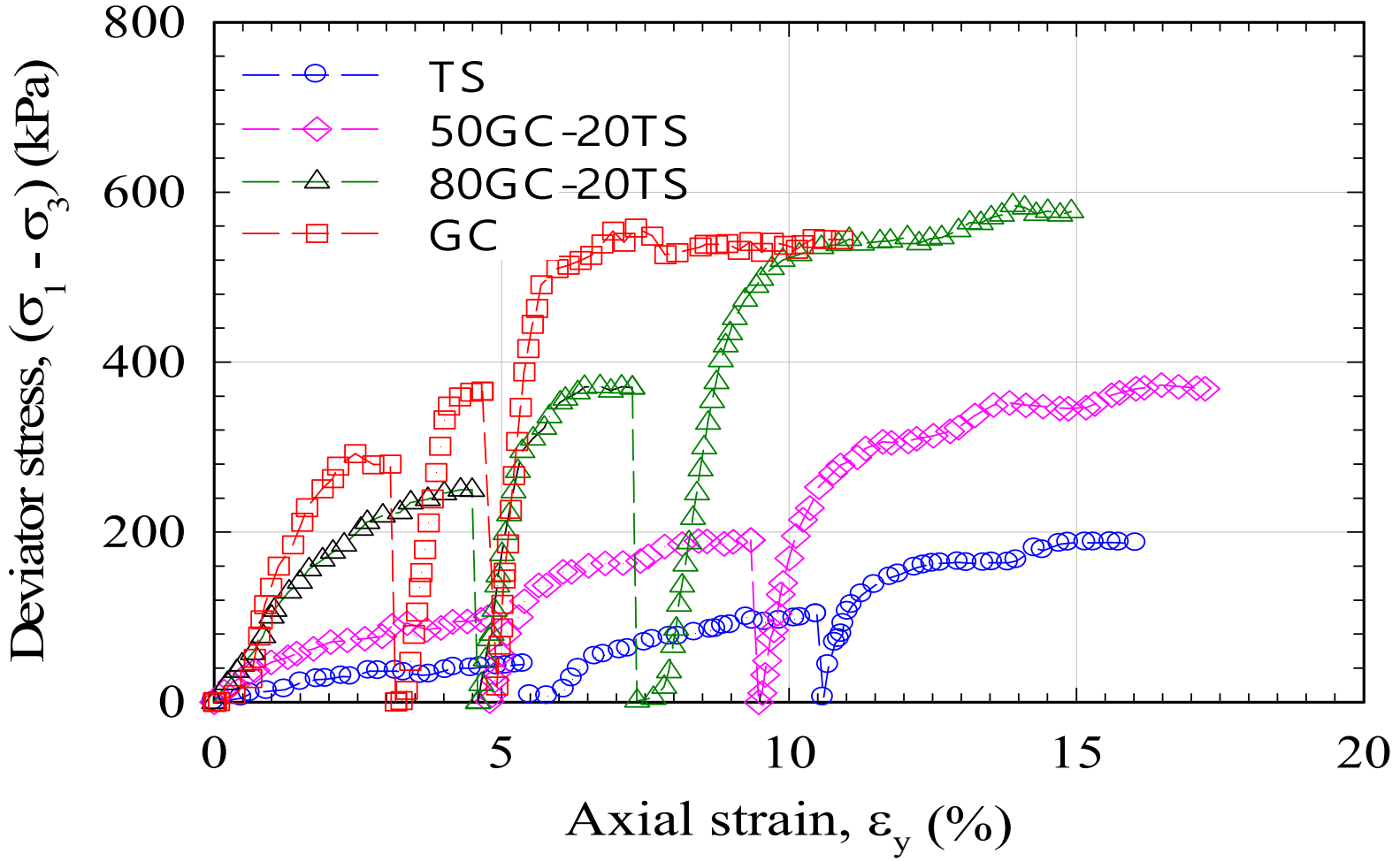
Grain-size distributions of the granite chip (GC), top soil (TS), and soil mixtures of 80% granite chip-20% top soil (80GC-20TS) & 50% granite chip-50% top soil (50GC-50TS) based on dry mass

Soil Mixtures for Improving Tree Stability



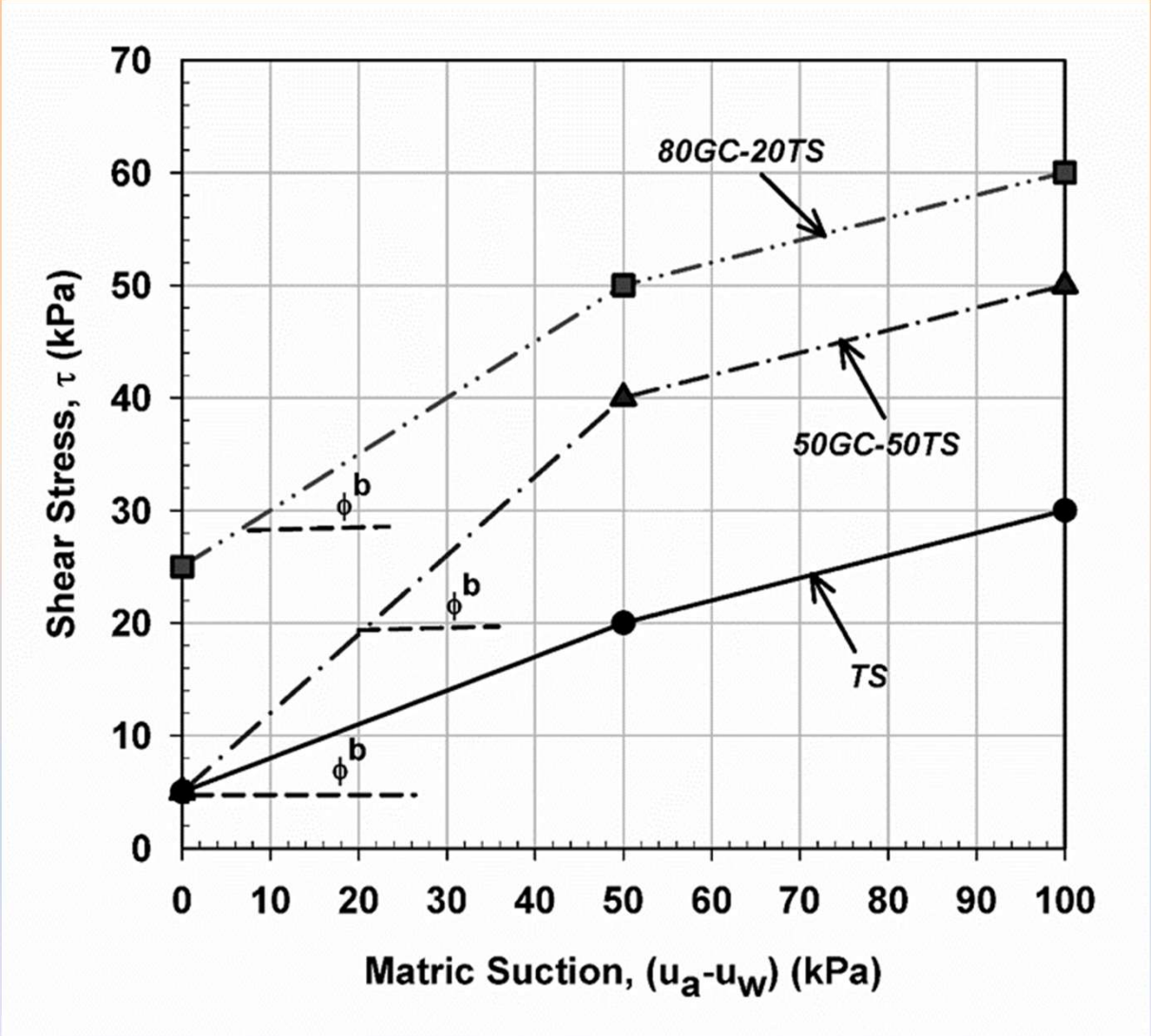
SWCCs of the granite chip (GC), top soil (TS), and soil mixtures of 80% granite chip-20% top soil (80GC-20TS) & 50% granite chip-50% top soil (50GC-50TS)

Soil Mixtures for Improving Tree Stability



Shear strengths of top soils and soil mixtures

Soil Mixtures for Improving Tree Stability



Unsaturated shear strengths of top soil (TS), soil mixtures of 80% granite chip-20% top soil (80GC-20TS) and 50% granite chip-50% top soil (50GC-50TS)

Preparation of field plots at IMM site

Planting holes

Preparation of field plots at IMM site

Planting *Samanea Saman*
(Raintree)

Tree Pulling Exercise conducted by NParks and NTU in front of IMM

Pull-out test

Samanea Saman (Raintree)

Dissemination of Results

1st Asian Conference on Unsaturated Soil in Singapore (18-19 May 2000)

Seminars on Unsaturated Soil in Singapore

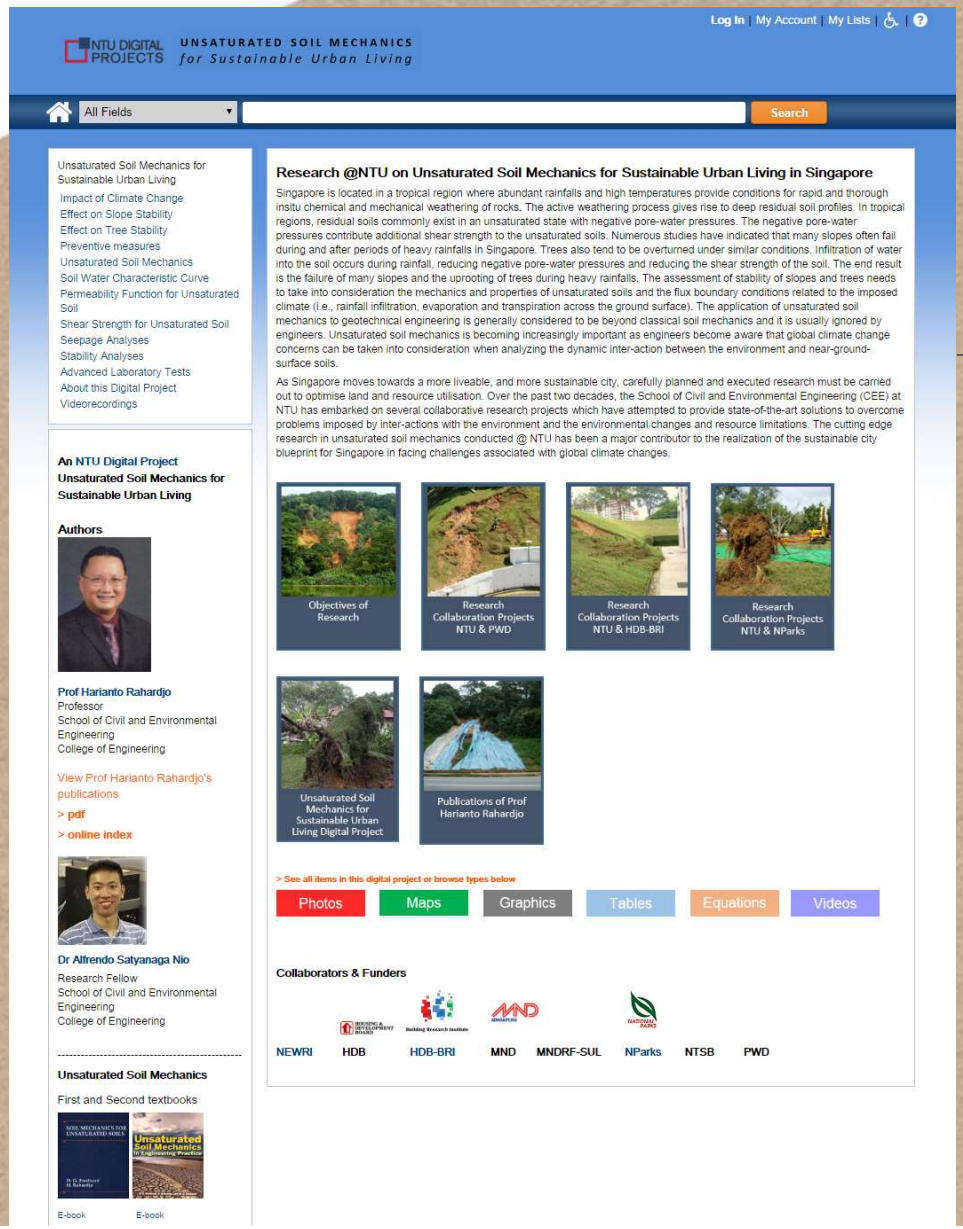
HDB-NTU Seminar on Unsaturated Soil Mechanics in Nov 2008 - Keynote Paper on *Unsaturated Soil Mechanics in Engineering Practice* (41st Terzaghi Lecture)

MND-HDB-NTU Seminar on Unsaturated Soil Mechanics for Sustainable Urban Living in Feb 2016

Tan Swan Beng (TSB) Public Lecture Series on "Application of Unsaturated Soil Mechanics for Environmental Protection and Sustainability " in March 2014 in NTU, Singapore

NANYANG TECHNOLOGICAL UNIVERSITY

www.ntu.edu.sg/library/unsaturatedsoil



UNSATURATED SOIL MECHANICS

for Sustainable Urban Living

A Digital Project, Unsaturated Soil Mechanics for Sustainable Urban Living in Singapore, is now Live!

NTU DIGITAL PROJECTS

Thank you