A One Week Online Faculty Development Programme (3rd – 7th June, 2024) on

Recent Advances and Research Scope in Geotechnical Engineering

Department of Civil Engineering, Jorhat Engineering College, Assam, India

The Arena of Landslides and Slope Instabilities
An Overview of Landslide Analyses Approaches

Arindam Dey

Department of Civil Engineering

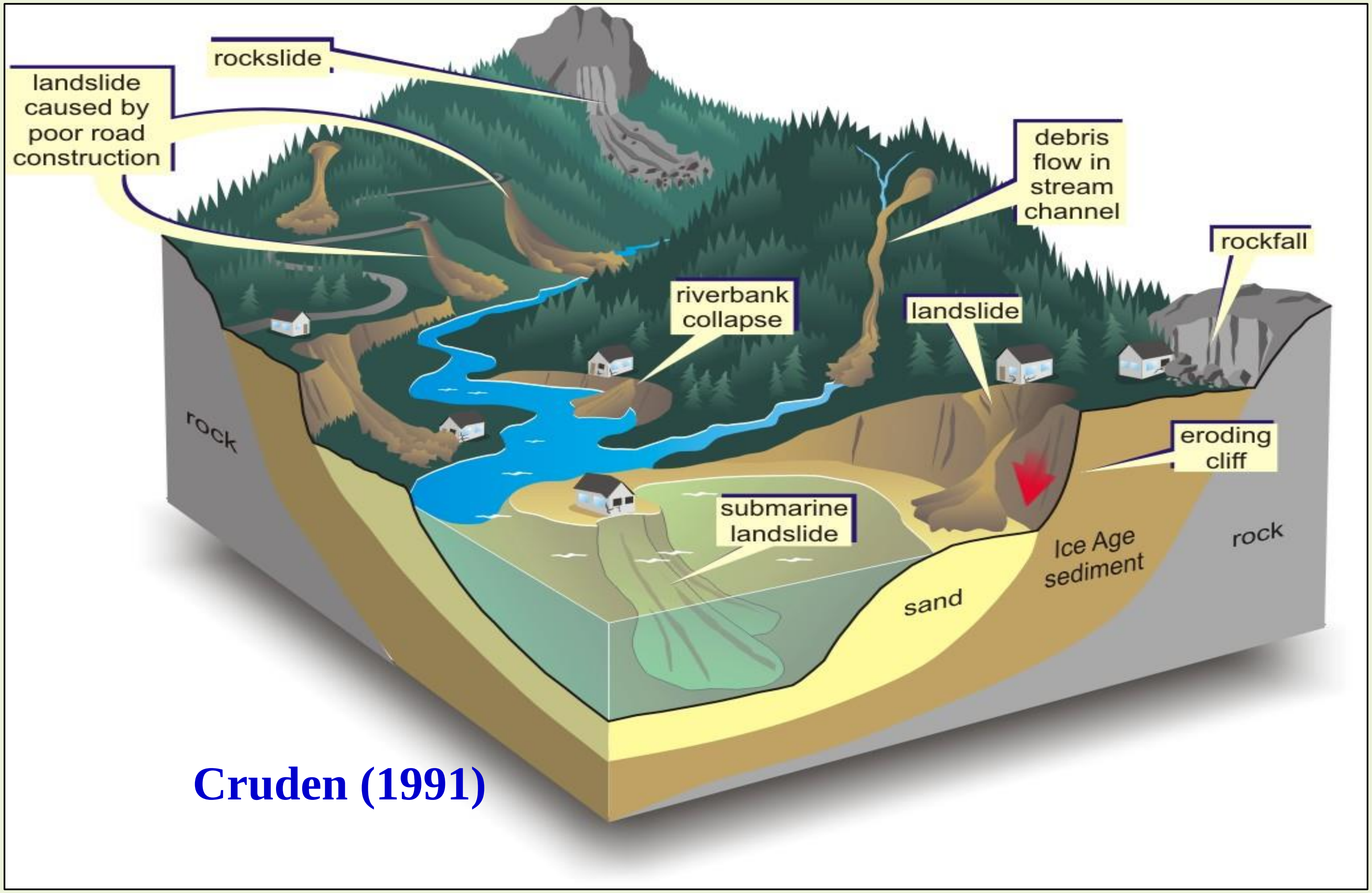
& Center for Disaster Management and Research

IIT Guwahati

Introductory Remarks and Recap

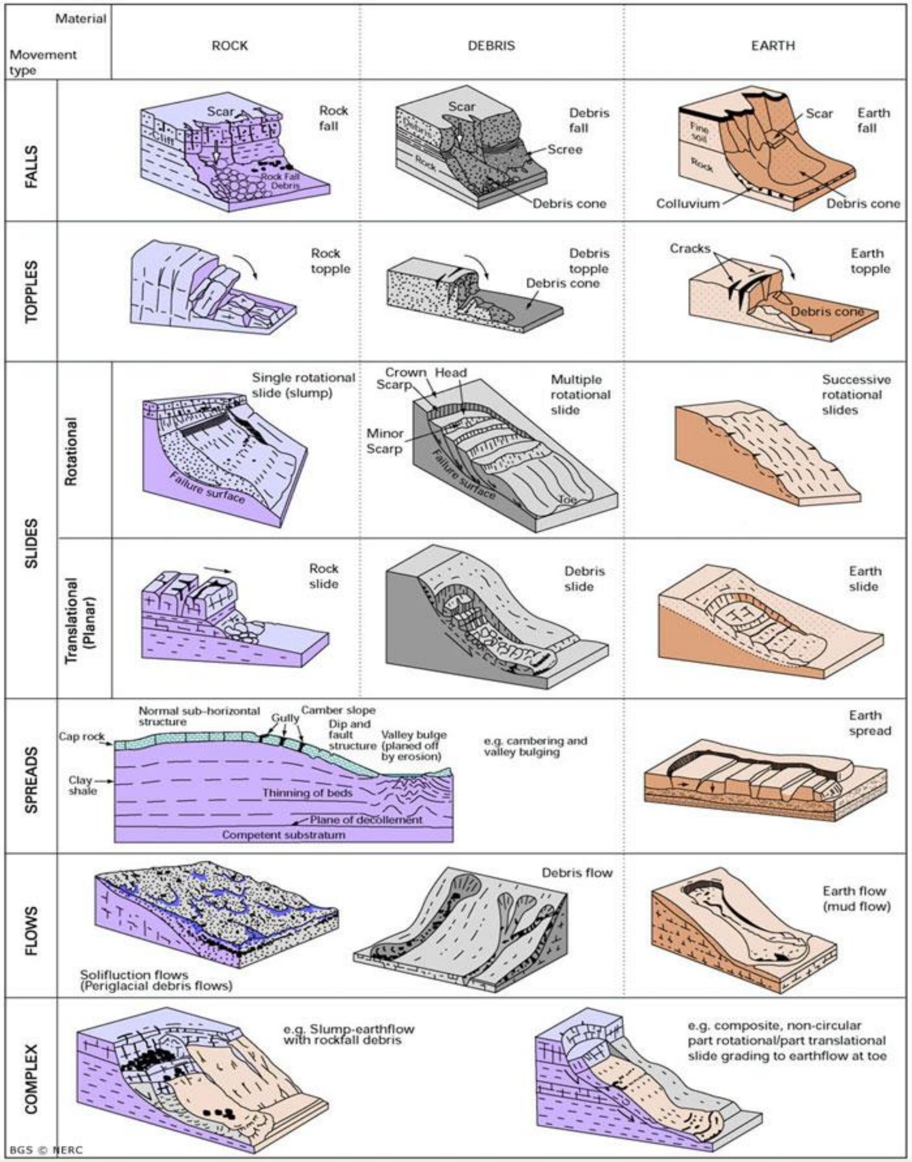
Slope Instabilities and Landslides

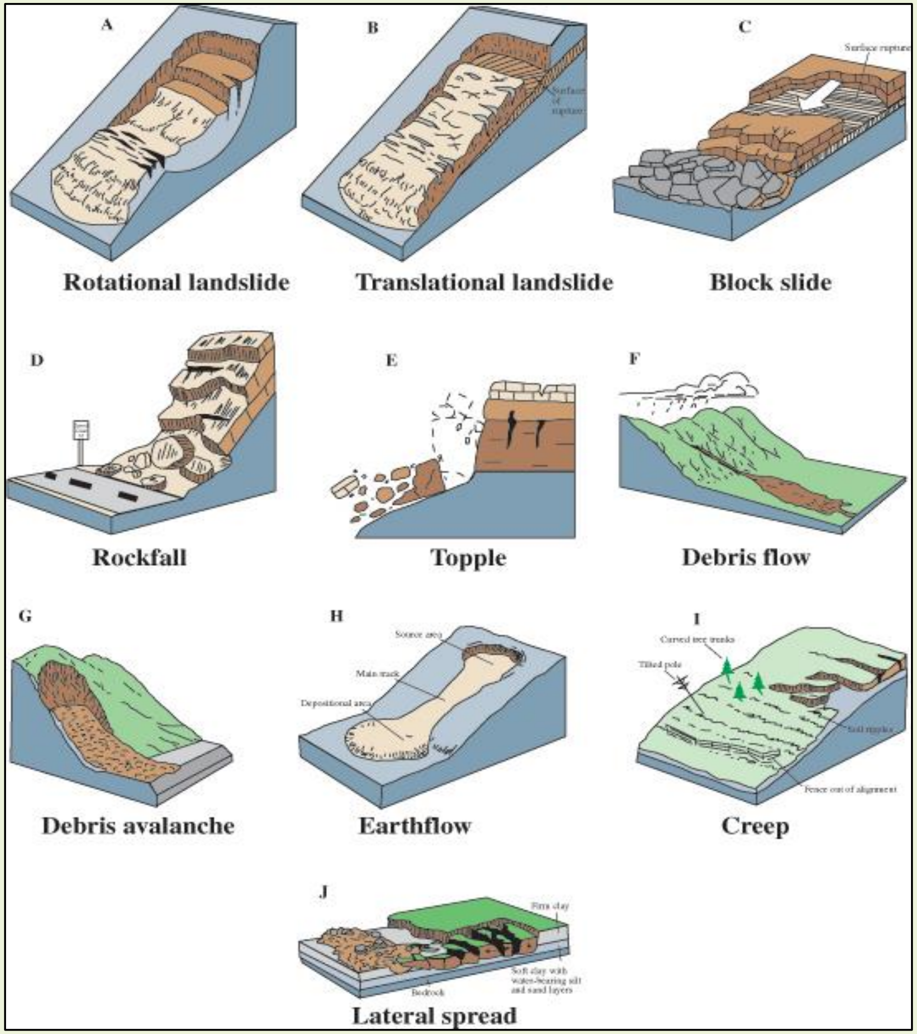
Movement of mass of rock, debris or earth down a slope



Cruden (1991)

Classification of Landslides: Types of Failure





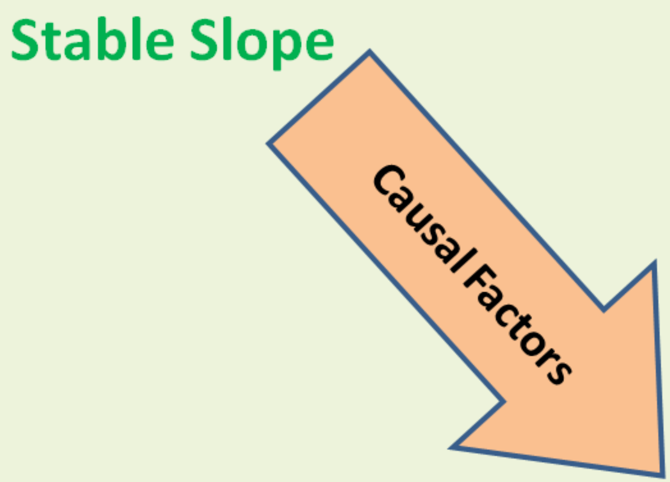
Varnes, 1978; Cruden and Varnes, 1996

Classification of Landslides: Velocity of Failure

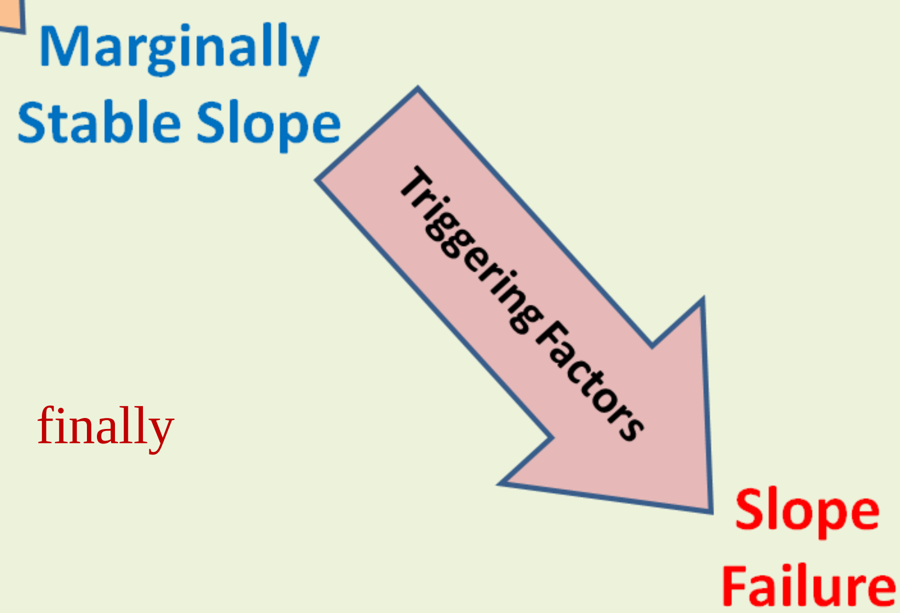
Velocity Class	Description	Velocity (mm/sec)	Typical Velocity	Probable Destructive Significance
7	Extremely Rapid			Catastrophe of major violence; buildings destroyed by impact of displaced material; many deaths; escape unlikely
		5×10^3	5 m/sec	
6	Very Rapid			Some lives lost; velocity too great to permit all persons to escape
		5×10^1	3 m/min	
5	Rapid			Escape evacuation possible; structures; possessions, and equipment destroyed
		5×10^{-1}	1.8 m/hr	
4	Moderate			Some temporary and insensitive structures can be temporarily maintained
		5×10^{-3}	13 m/month	
3	Slow			Remedial construction can be undertaken during movement; insensitive structures can be maintained with frequent maintenance work if total movement is not large during a particular acceleration phase
		5×10^{-5}	1.6 m/year	
2	Very Slow			Some permanent structures undamaged by movement
		5×10^{-7}	15 mm/year	
1	Extremely SLOW			Imperceptible without instruments; construction POSSIBLE WITH PRECAUTIONS

Cruden and Varnes, 1996

Landslides: CAUSE and TRIGGER



- Causes of landslide
  - ❖ *Factors that make the slope vulnerable to failure*
  - ❖ *Factors that predisposes the slope to become unstable*



- Landslide trigger
  - ❖ The single event that finally initiates the landslide.

Causes of Landslide

Natural Causes

Geological Causes

- Weathering
  - Chemical
  - Physical
  - Biological
- Structure
  - Stratification
  - Orientation

Morphological Causes

- Topography
- Surface Cover
- Slope inclination
- Erosion
  - Toe erosion
  - Gully erosion
- Subterranean
  - Solution
  - Piping
- Deposition
  - On slope face
  - On crest
- Tectonic activities
  - Uplift

Hydrological Causes

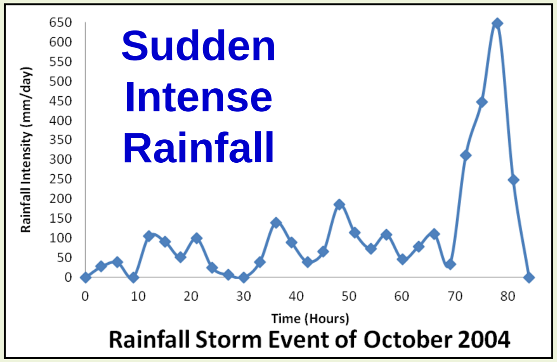
- Rainfall
- Runoff
- Infiltration
- Percolation
- Seepage

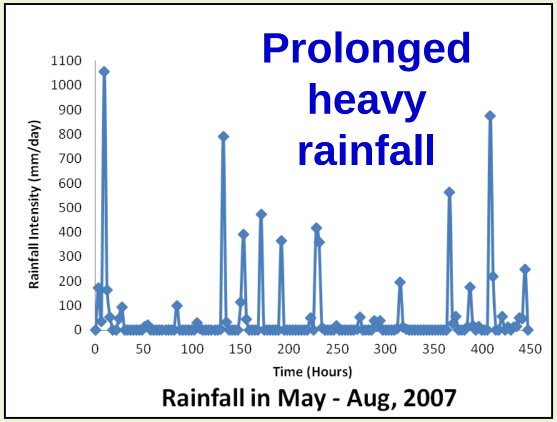
Anthropogenic Causes

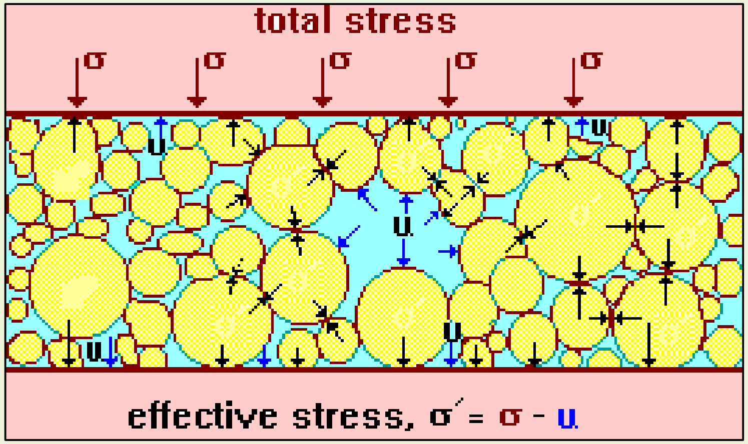
- Encroachment
- Unscientific cutting of hill slopes
- Deforestation
- Unplanned drainage and Sewerage system
- Unplanned construction of roads

Landslide Triggers

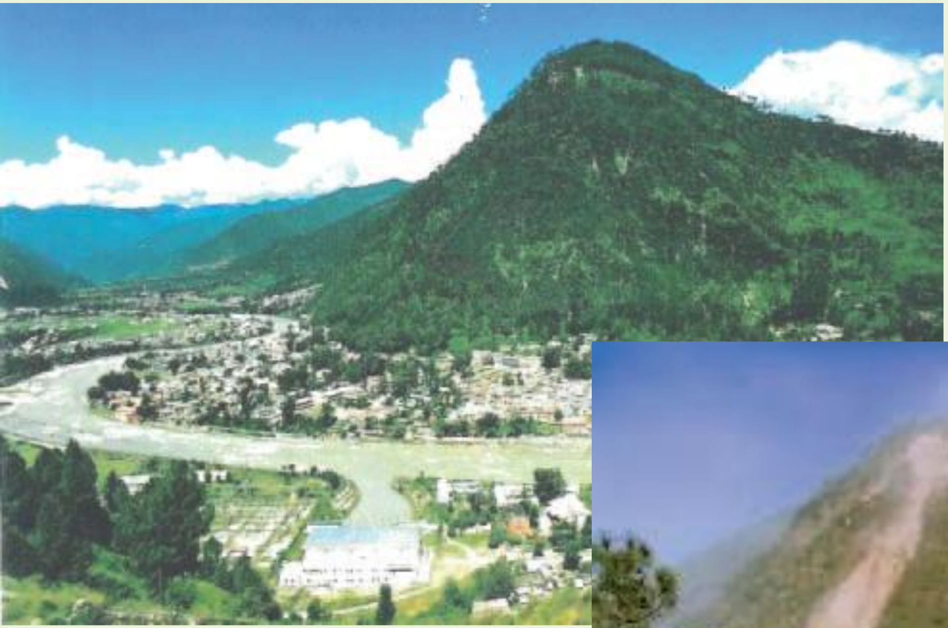
- Rainfall
  - ❖ Sudden intense rainfall
    - ▪ Mostly lead to erosion induced shallow landslides
      - • Predominantly renders surface runoff than percolation
  - ❖ Prolonged heavy rainfall
    - ▪ Mostly lead to deep-seated landslides
      - • Allow deeper percolation of water within the slope
- Seismicity
  - ❖ Stress induced due to seismic shaking
  - ❖ Generation of pore water pressure
- Toe-excavation (in many instances)
  - ❖ Inhabitation
  - ❖ Transport route development

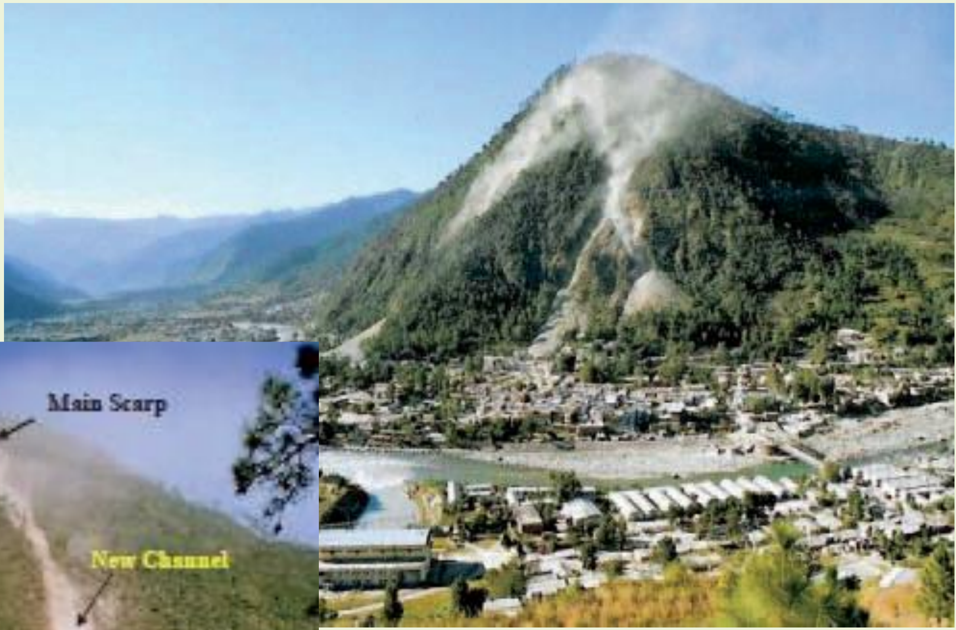


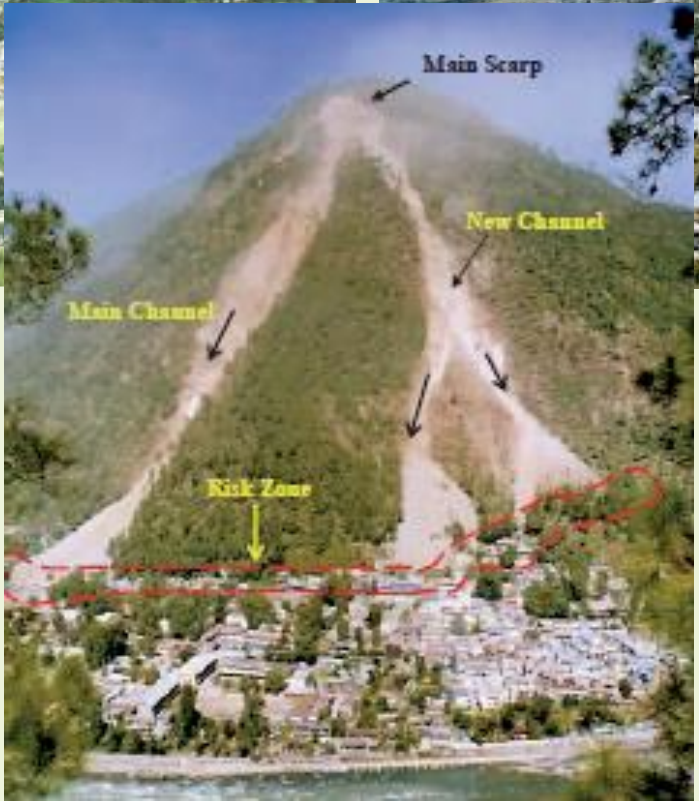




Typical Examples of Slope Instability







Varunavat Parvat Landslide

Uttarkashi, Uttarakhand

24 September 2003

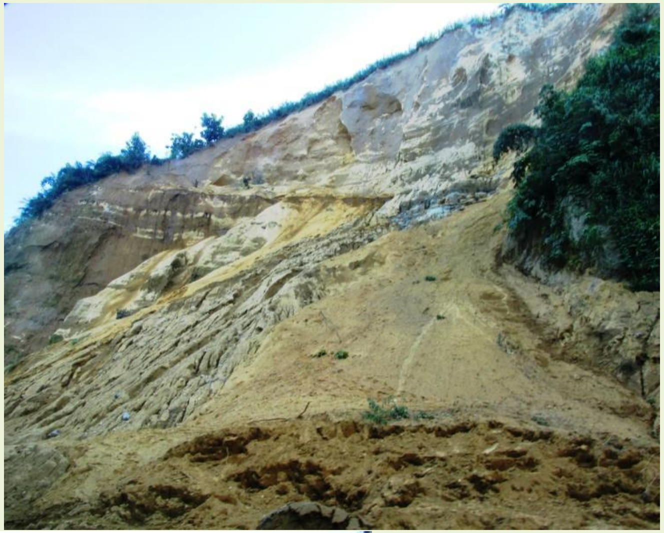
Typical Examples of Slope Instability

Malegaon Mudslide

Malegaon, Pune, Maharashtra

30 July 2014

Typical Examples of Slope Instability



Banderdewa Mudslide

Arunachal Pradesh

2013

Typical Examples of Slope Instability

Some Landslides in Assam

2013

Typical Examples of Slope Instability

Some Landslides in Guwahati

2012

Typical Examples of Slope Instability

Landslide near Narayana Hospital, 2020

Gauripur Landslide, Opposite to IIT Guwahati

2020

Typical Examples of Slope Instability

Landslide beneath Raj Bhawan Guwahati

2020

Debris Flows, Nepal, 2021

Assam Flood and New Haflong Debris Flows 2022

Chamoli Glacier Outburst, Chamoli, 2021

Typical Examples of Slope Instability

Rockfall at Guwahati-Shillong Road

Rockfall at Sangla Valley, Himachal Pradesh, 2021

Cliff Topple, Brazil, 2021

Typical Examples of Slope Instability

Landslide in Sonapur

2011

Earthquake Induced Landslide

- Palu, Indonesia, 2018
  - Sulawesi earthquake
    - M7.5

Earthquake Induced Landslide

- Palu, Indonesia, 2018

Typical Examples of Slope Instability

Seismic Slope instability in Saiphum, Mizoram

2013

Typical Examples of Slope Instability

Slope instability due to faulty excavation technique in North Guwahati due to Steep Excavation

2015

Sirmaur Valley Landslide, Himachal Pradesh, 2021

Glacier Wall Breakoff, Kinnaur, HP, 2021

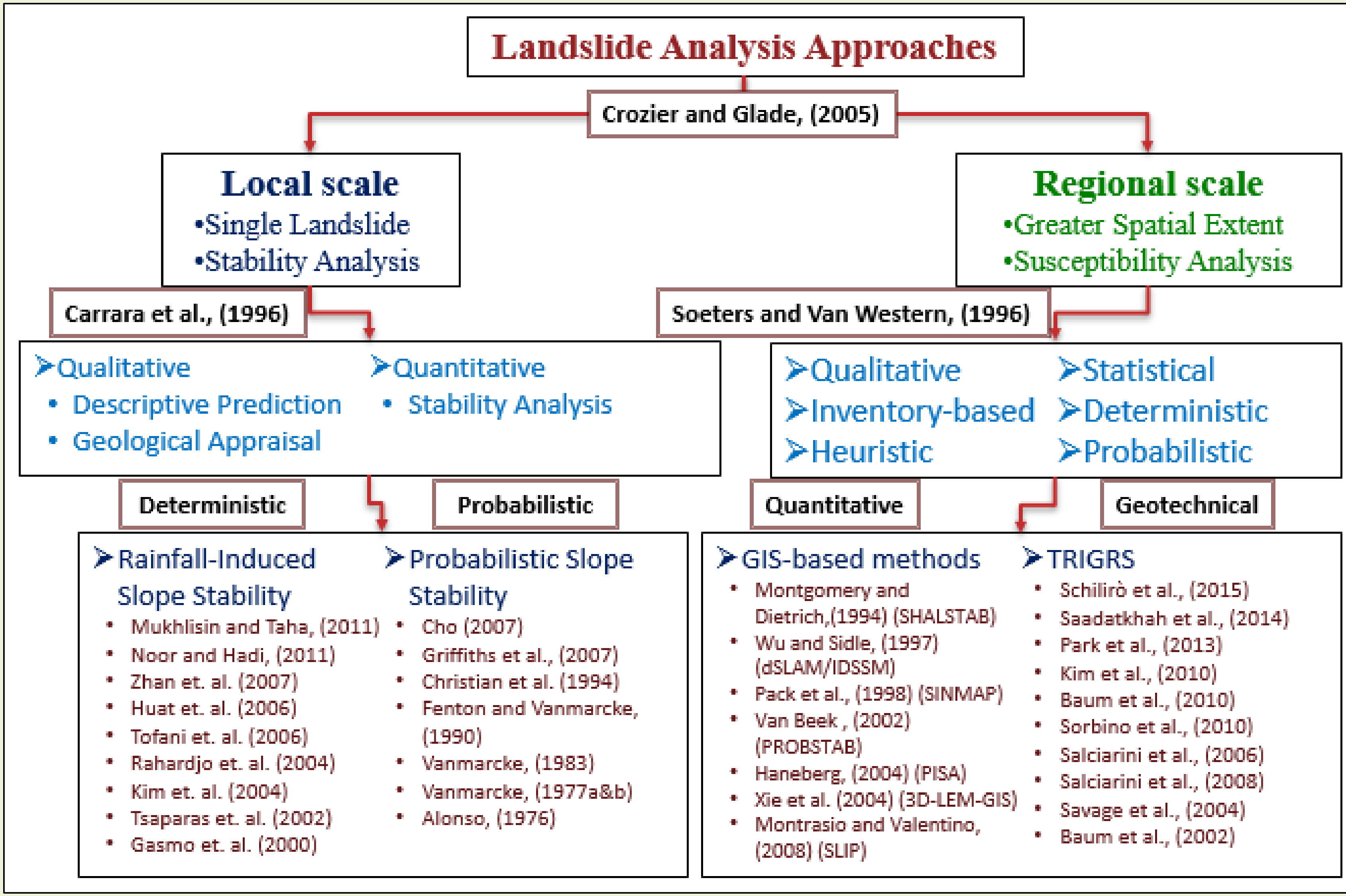
Avalanche at Kedarnath, 2021

Landslide Analysis Approaches

Aims of Slope Stability/Landslide Analysis

- Target objectives of slope stability analysis
  - Understand the development and formation of natural slopes and the processes responsible for different natural features
  - Assessment of the possibility of landslides involving natural and existing engineered slopes
  - Assessment of the stability of slopes under both short-term and long-term scenarios subjected to various causal factors
  - Analyze the landslides and understand their failure mechanisms subjected to triggering factors (precipitation, seismicity and toe cutting)
  - Enable the redesign of failed slopes and planning and design of preventive and remedial measures wherever necessary

Landslide Analysis Approaches



Landslide Analysis Approaches

Local Scale Analyses

Methods of Local-Scale Slope Stability Analyses

Methods for Slope Stability Analysis

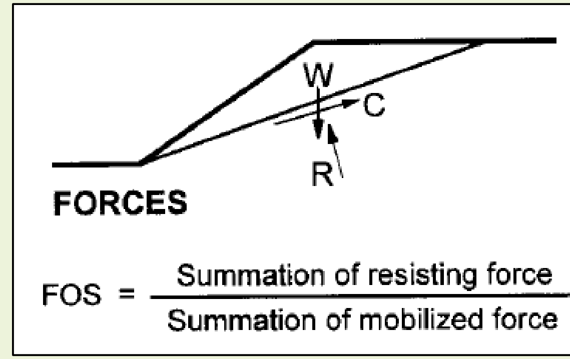
- Limit Equilibrium Methods
- Stress – Deformation Analysis
  - Continuum Modelling
    - Finite Element Method
    - Finite Difference Method
- Method of Wedges
- Discontinuum Methods
  - Discrete Element Method

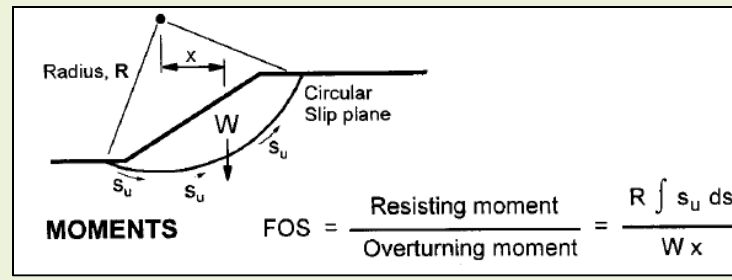
Mostly applied to Rock Slope Stability (Method of Wedges; Discontinuum Methods)

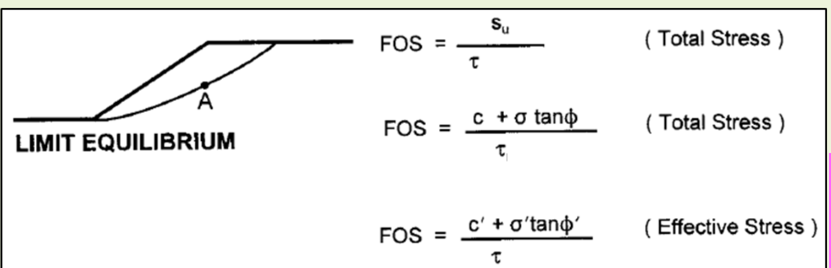
PLAXIS
GeoStudio
FLAC
GTS Midas
Talren
Geo5
Rocscience
Oasys

Factor of Safety / Factor of Uncertainty

- Based on the concept of static equilibrium
  - ❖ Define the 'Factor of Safety' of a slope
    - ▪ FoS = Strength / Stress developed
      - State of stability
        - ➢ FoS > 1 → Stable
        - ➢ FoS < 1 → Failed
        - ➢ FoS ≈ 1 → Incipient failure
      - Higher FoS covers for the higher uncertainty in the strength parameters considered



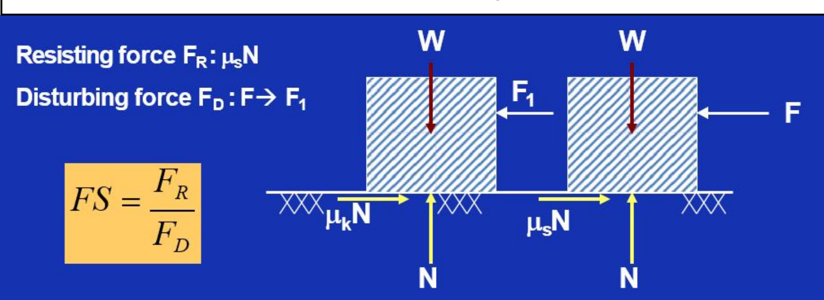


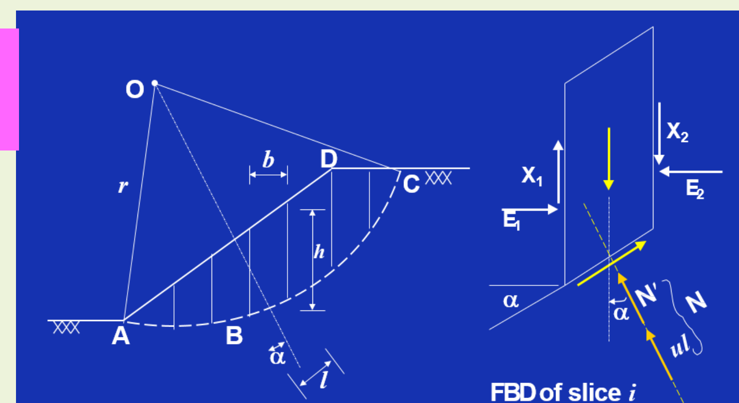


$$c_m = \frac{c}{F_C}$$

$$\tan\varphi_m = \frac{\tan\varphi}{F_\varphi}$$

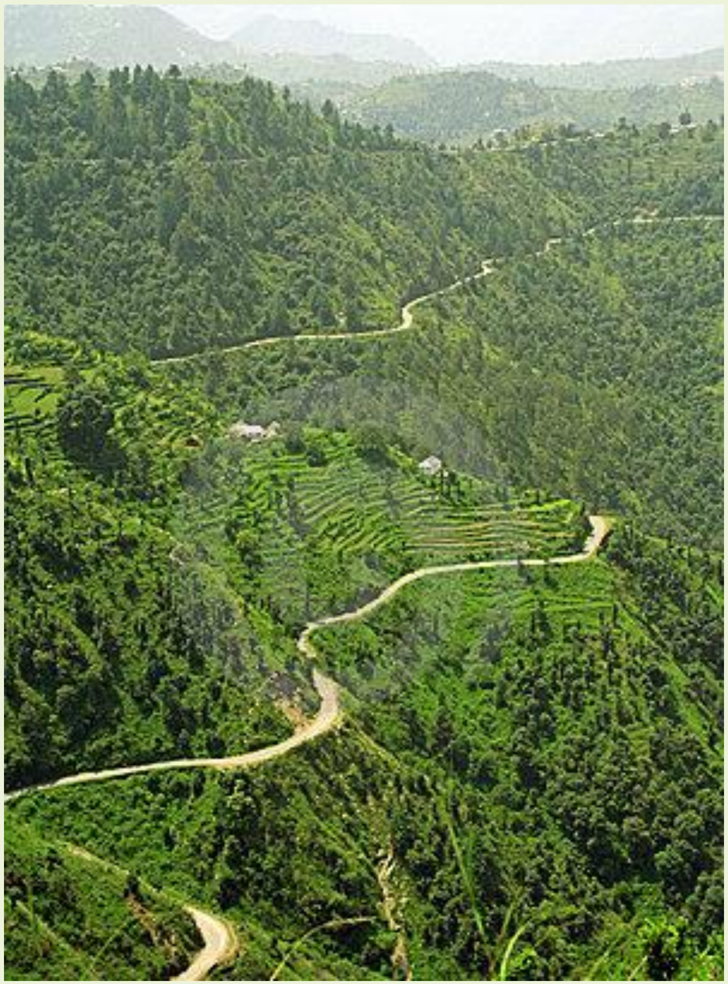
Strength Reduction Factor





Infinite Slopes

- Infinite Slope - Extend over long distances and great heights

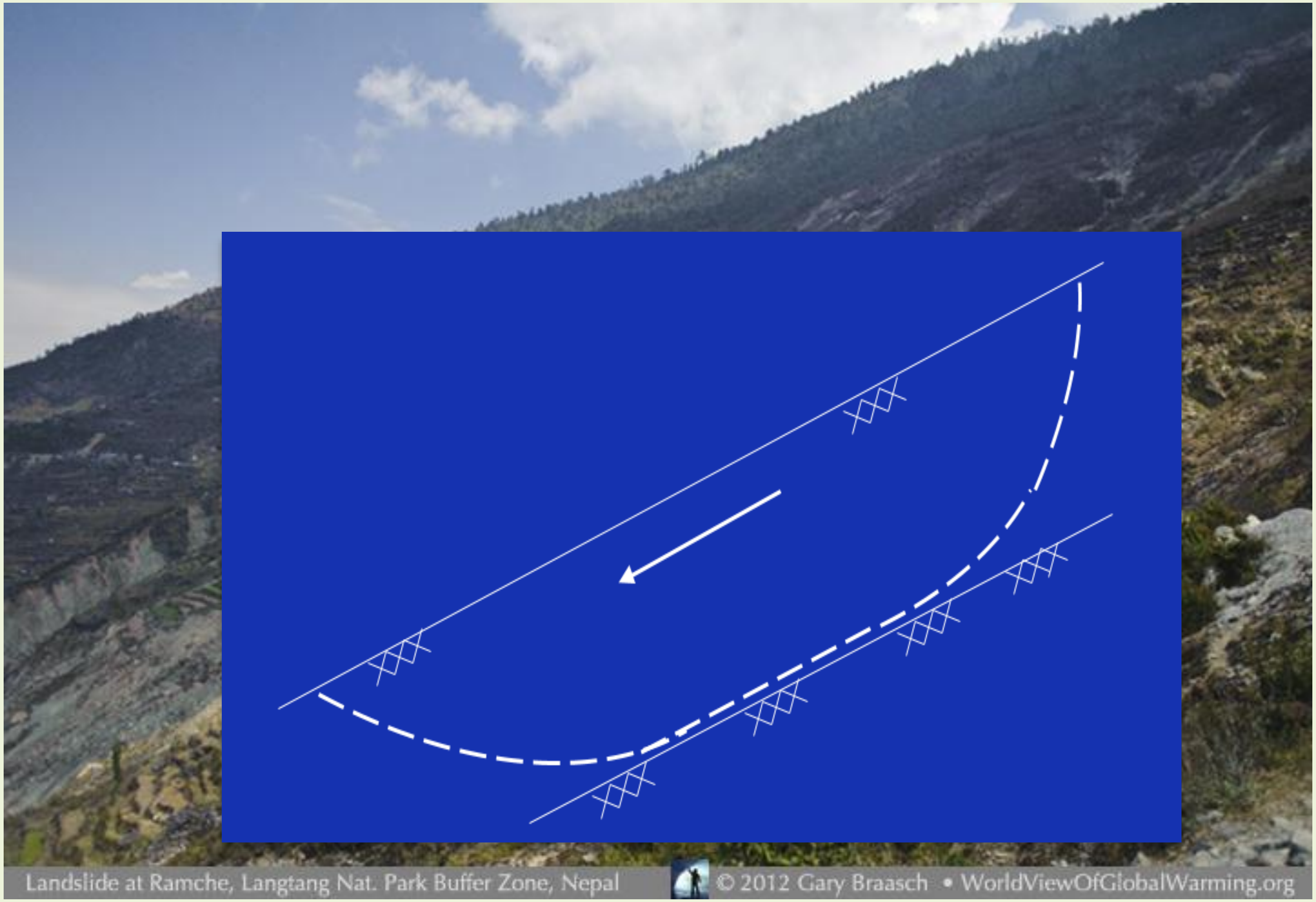


Ramche Landslide, Nepal, 2012

An example of progressive failure of slope

Infinite Slope and Analysis

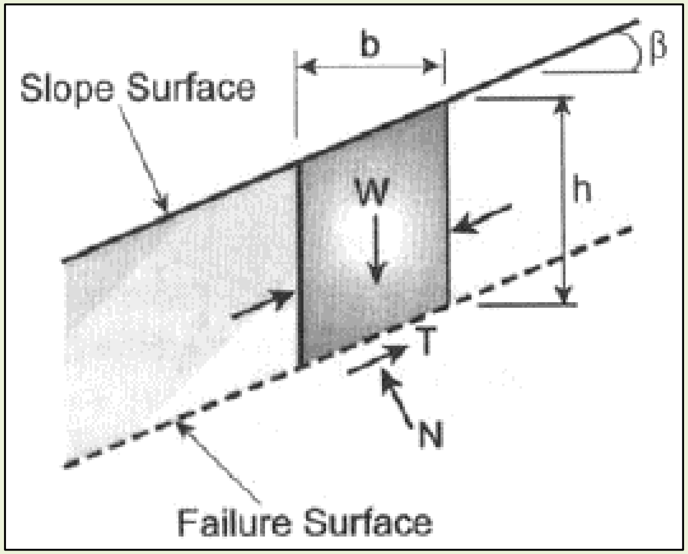
- Infinite Slopes - Extend over long distances and great heights
  - ❖ Translational Shallow Slip Analysis for Infinite slopes

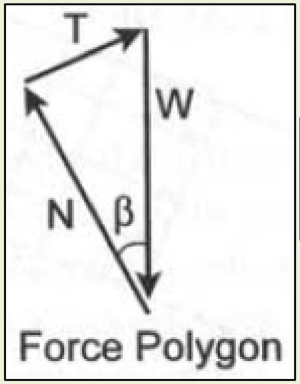


Infinite Slope and Analysis

- Infinite Slopes - Extend over long distances and great heights
  - ❖ Translational Shallow Slip Analysis for Infinite slopes

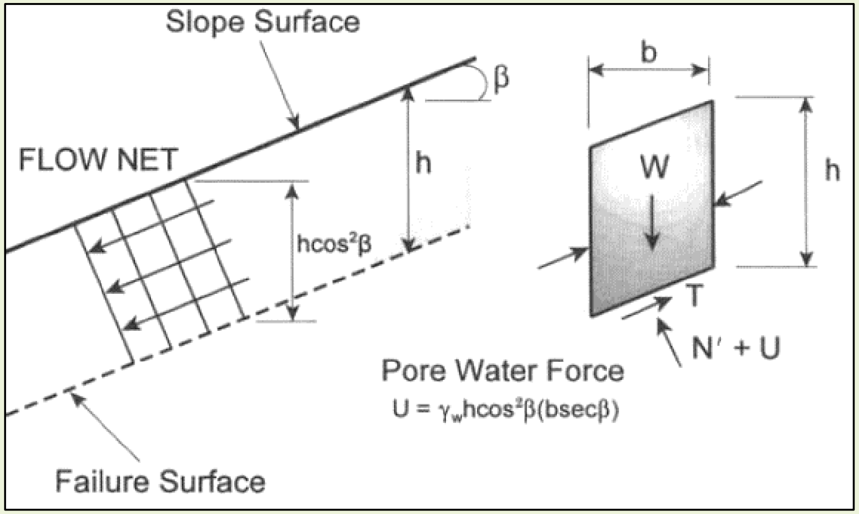
Dry Cohesionless Slopes





$$F = \frac{N \tan\phi}{W \sin\beta} = \frac{\tan\phi}{\tan\beta}$$

Homogeneous Saturated c-φ Slopes with Phreatic Surface at Slope Face



$$F = \frac{c' + h(\gamma_{sat} - \gamma_w)\cos^2(\beta)\tan\phi'}{\gamma_{sat}\, h \sin\beta \cos\beta}$$

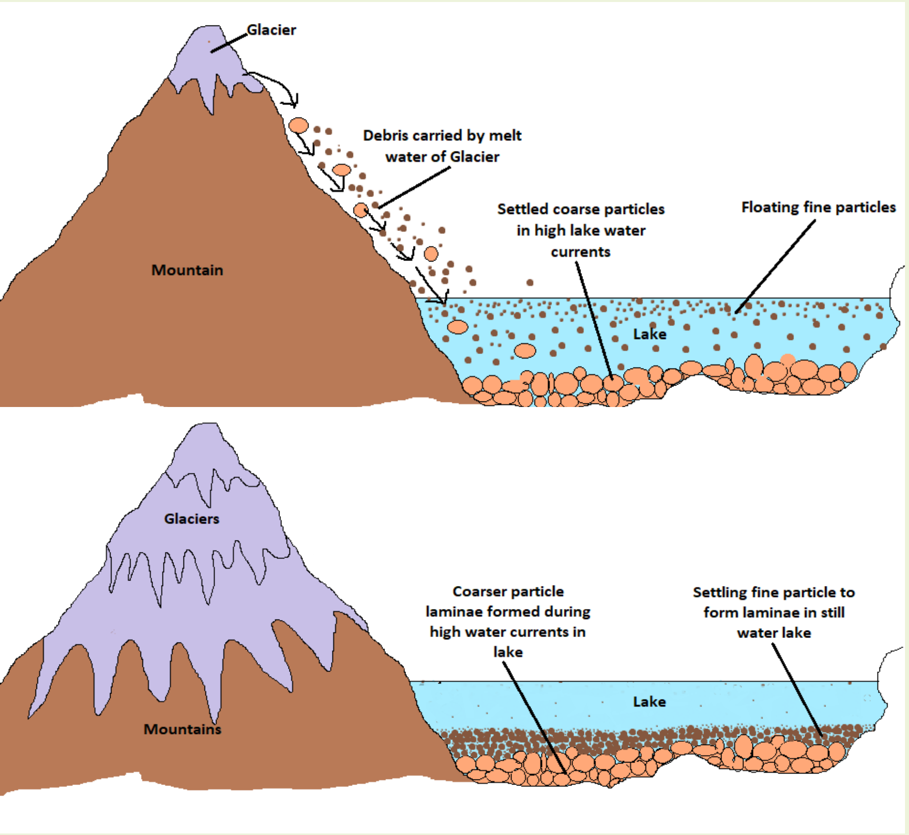
Homogeneous Saturated Sandy Slopes

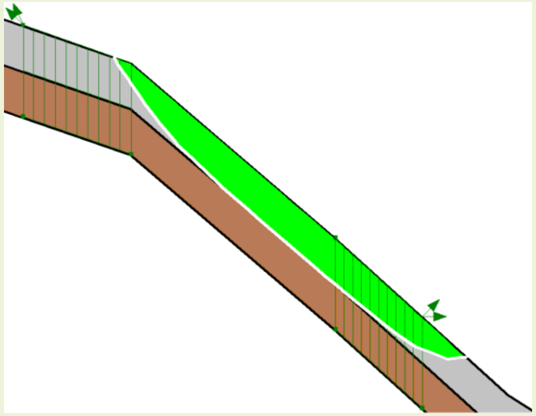
$$F = \frac{\gamma'}{\gamma_{sat}} \times \frac{\tan\phi'}{\tan\beta}$$

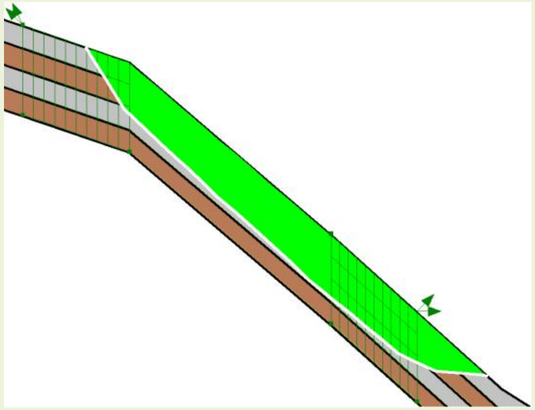
$$\gamma' = (\gamma_{sat} - \gamma_w)$$

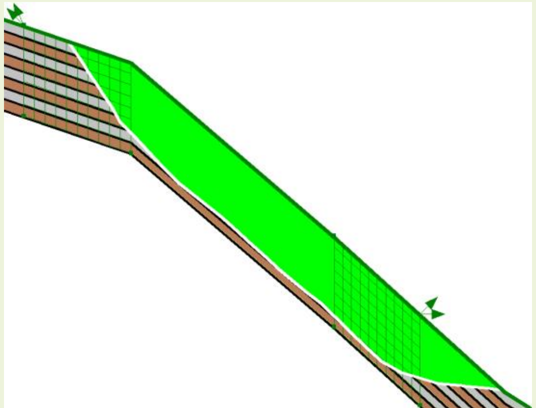
Glacio-Lacustrine Deposits

- Varved clays in glaciatic environment
  - ❖ Deposition of alternating layers of silt and clay due to annual glaciatic movement in the snow-clad mountains



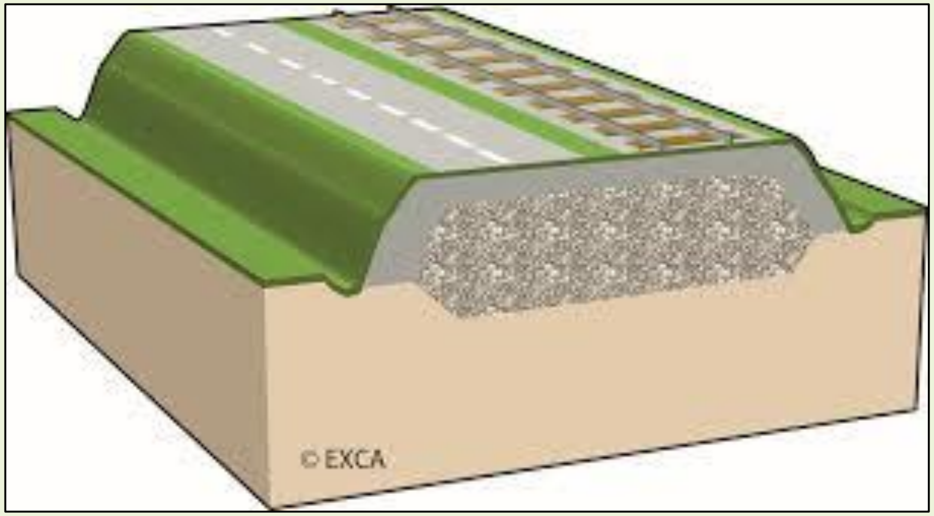


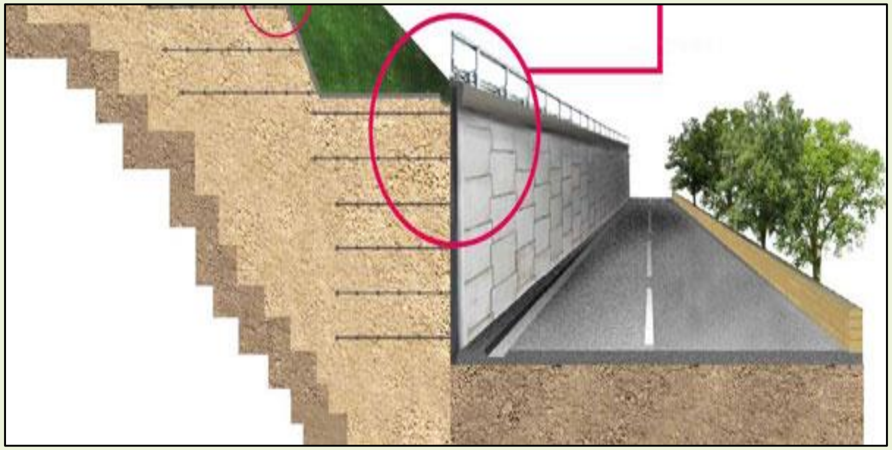


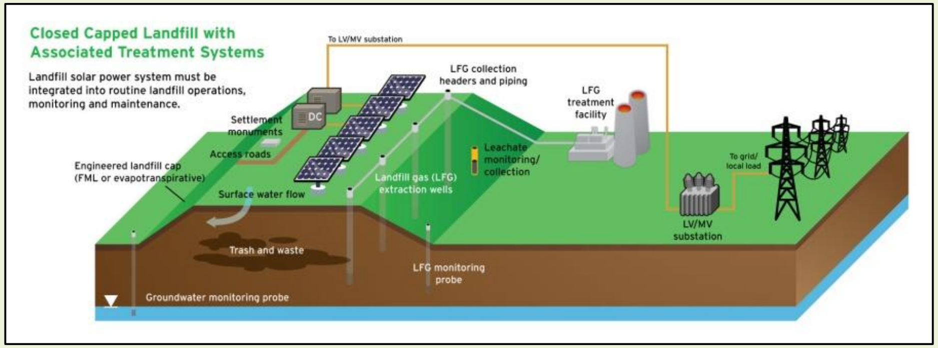


Finite Slopes and Analyses

- Finite slope – Local scale slopes bounded by surfaces in finite measurable dimensions

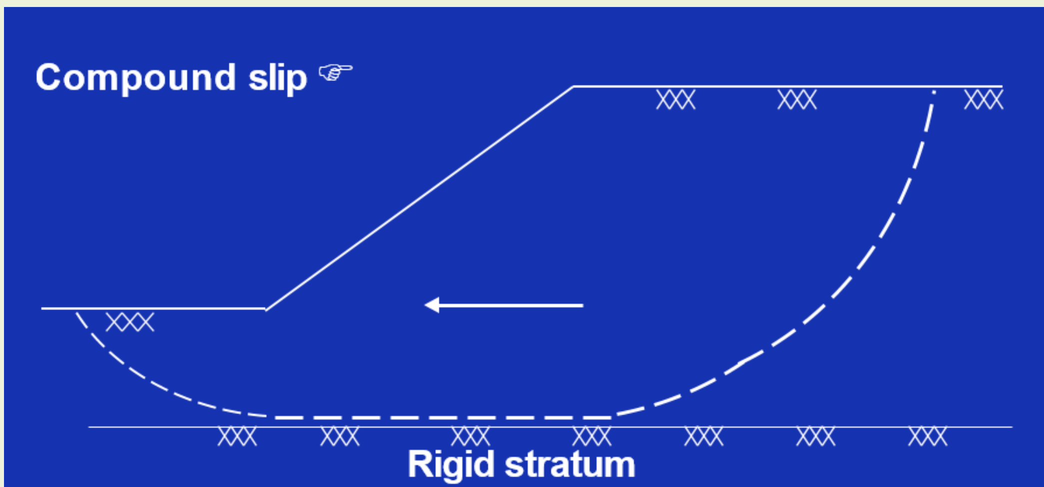


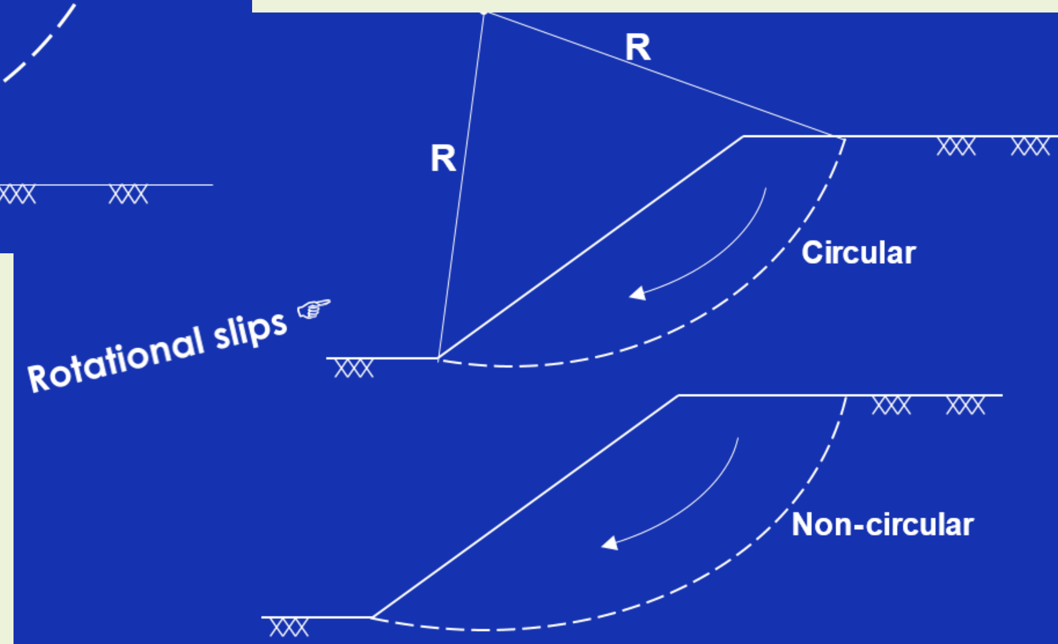




Finite Slope and Analyses

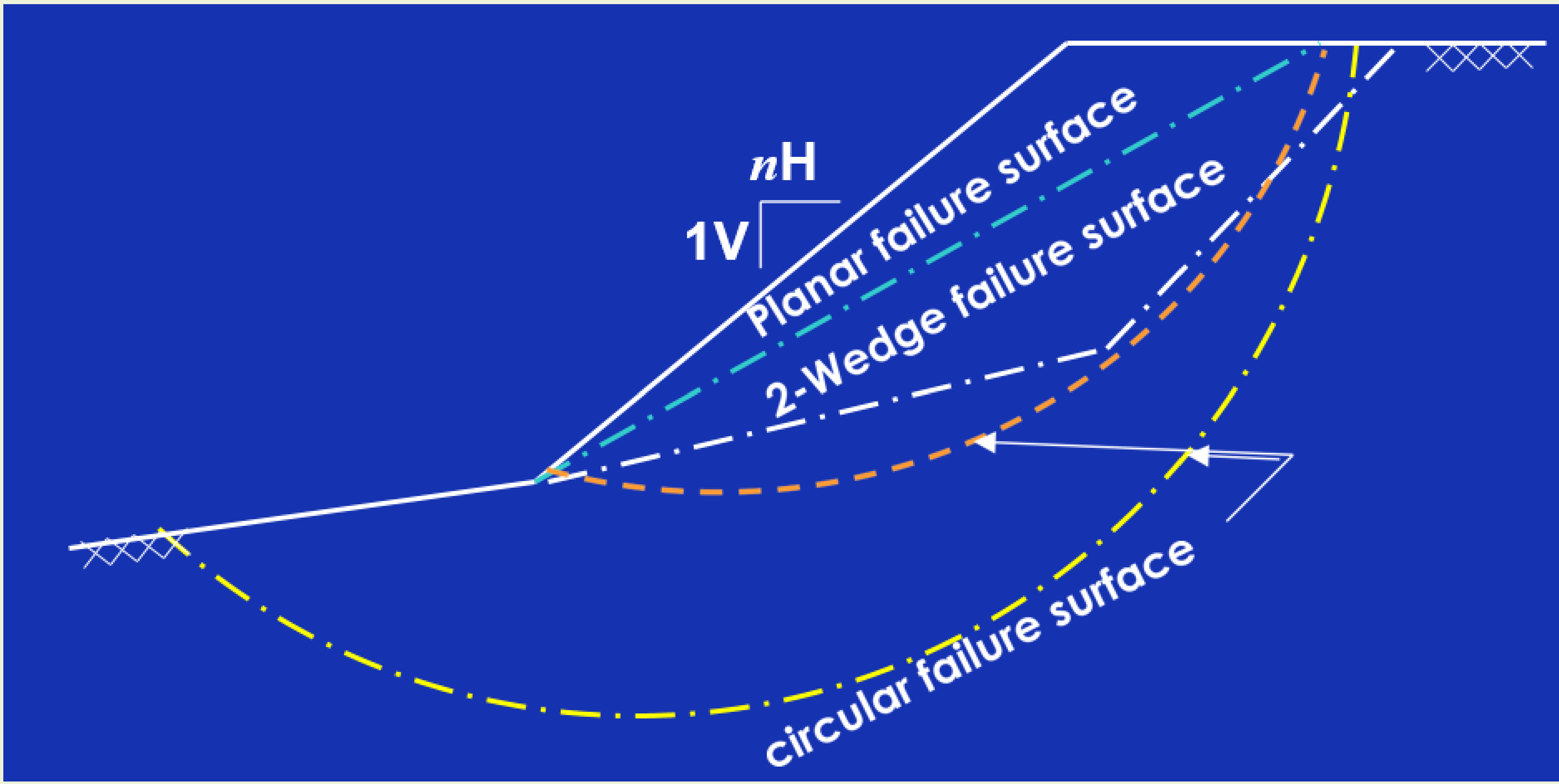
- Slope Stability Analysis
  - ❖ Rotational slips – No rigid base stratum
  - ❖ Compound slips – Presence of rigid base stratum





Finite Slope and Analyses

- Slope Stability Analysis
  - ❖ Various types of failure surfaces

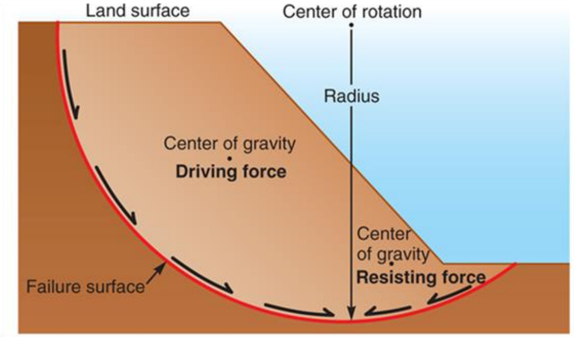


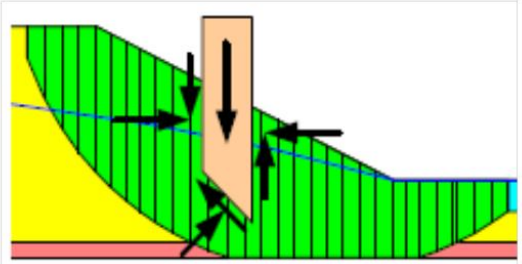
Finite Slope Stability Analyses

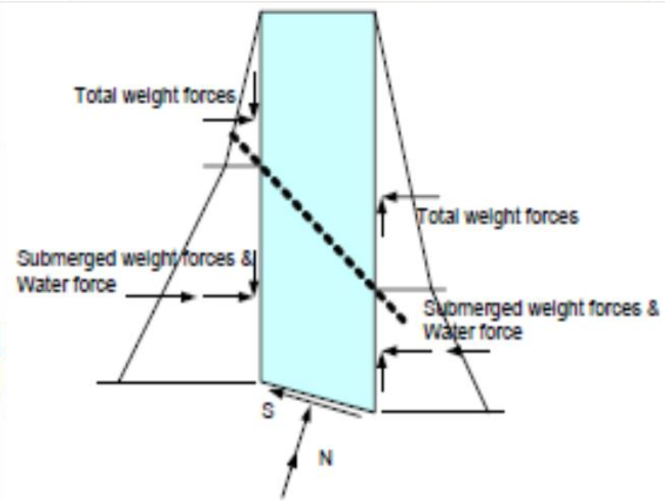
- Conventional Finite Slope Stability Analysis

Limit Equilibrium Methods:

- Friction Circle Method
- Method of Slices
  - Fellenius (1936)
  - Bishop (1955)
  - Morgenstern and Price (1965)
  - Spencer (1967)



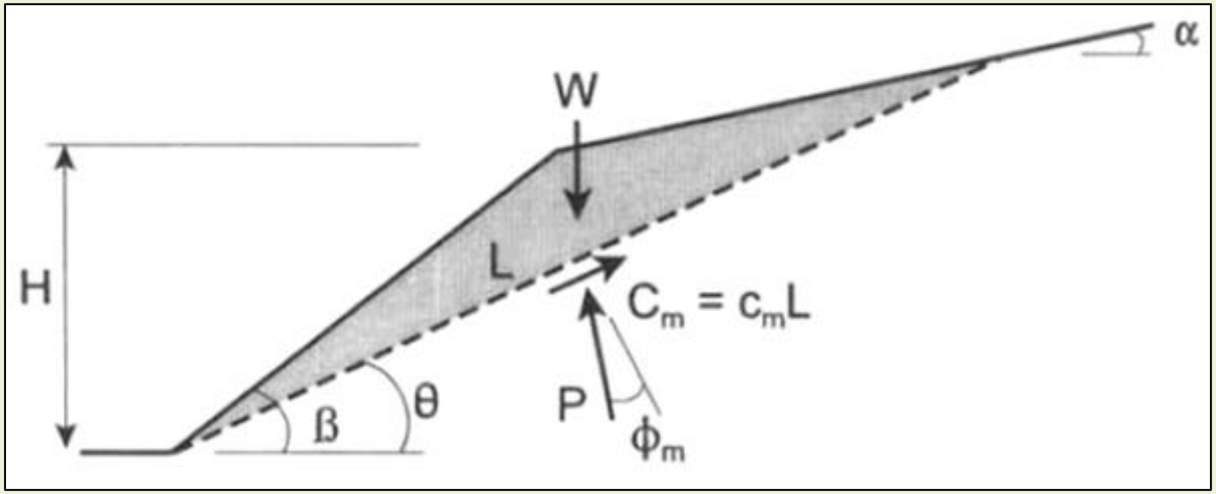


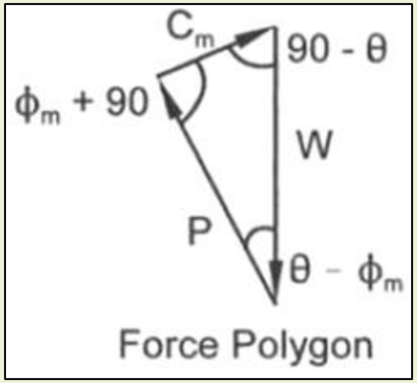


Method of slices for slope stability analysis showing assumed slip surface and interslice forces (GeoSlope International, 2007)

Finite Slope Stability Analyses

- Culmann's Method with Planar Failure Surface (c-φ soils)





$$c_m = \frac{1}{4}\gamma H \left[\frac{1-\cos(\beta-\phi_m)}{\sin\beta\cos\phi_m}\right]$$

$$c_m = \frac{c}{F_C}$$

$$\tan\varphi_m = \frac{\tan\varphi}{F_\varphi}$$

F_φ	φ_m	c_m	F_C

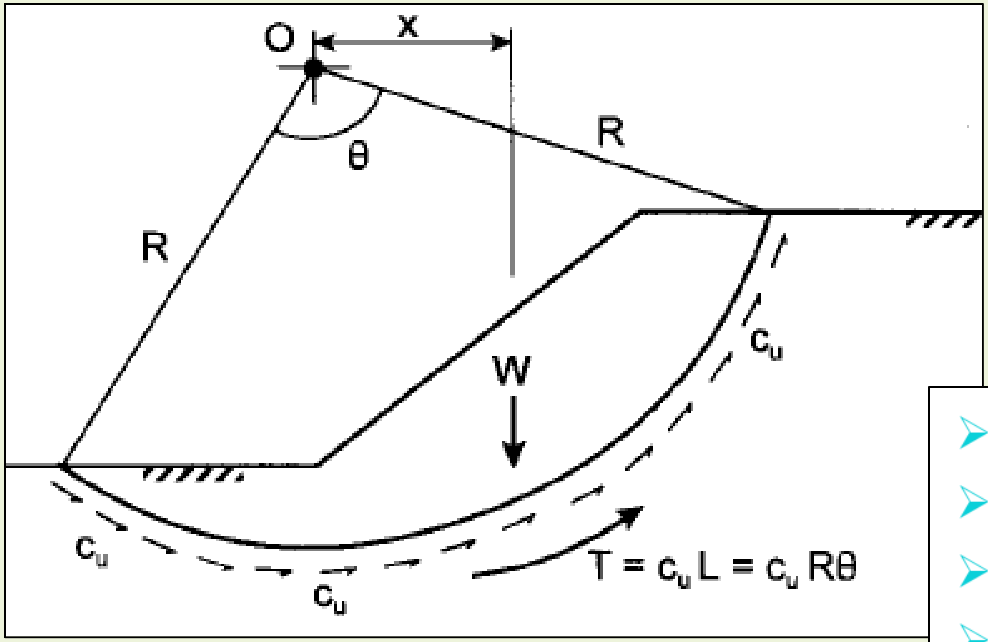
$F_C = F_\varphi = F$

For $F_C = F_\varphi = F = 1$

$$H_{crit} = \frac{4c}{\gamma}\left[\frac{\sin\beta\cos\phi}{1-\cos(\beta-\phi)}\right]$$

Finite Slope Stability Analyses

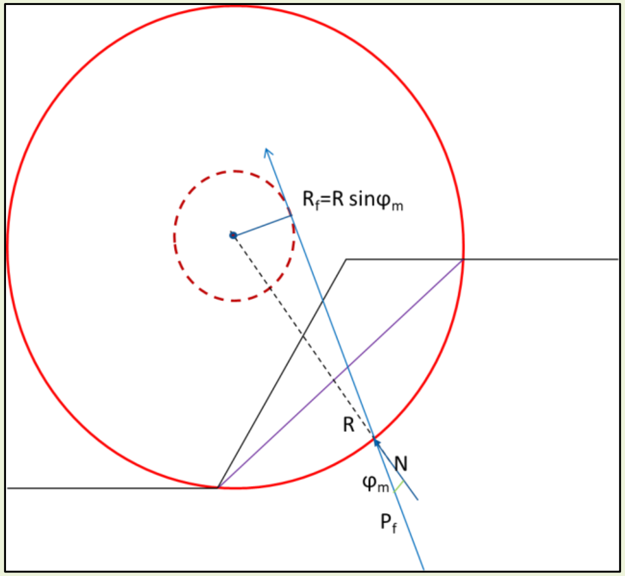
- Swedish Circle Method (*c* soils)

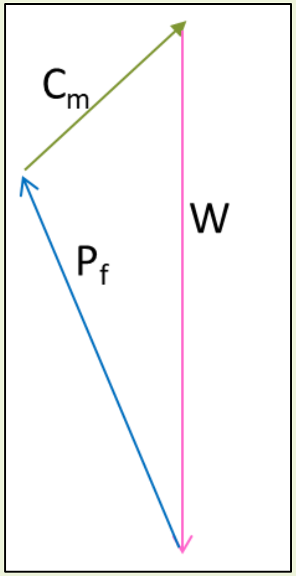


- Length of arc = $R.\theta$
- Maximum resistance = $c_u.R.\theta$
- Resistive moment = $c_u.R^2.\theta$
- Driving moment = $W.x$
- FOS = $\frac{c_u.R^2.\theta}{W.x}$

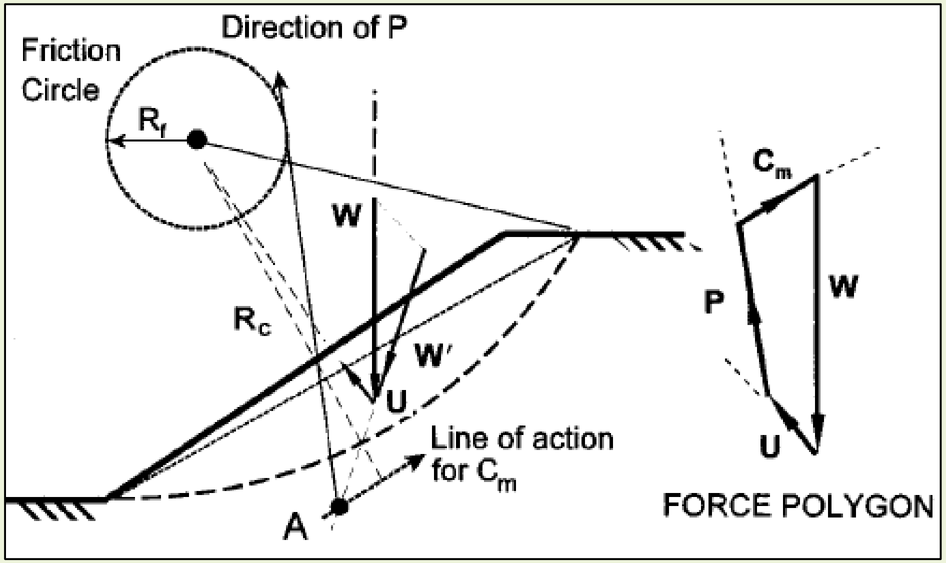
Finite Slope Stability Analyses

- Friction Circle Method (Graphical approach: $c - \varphi$ soils)





Homogeneous Saturated c-φ Slopes with Phreatic Surface at Slope Face



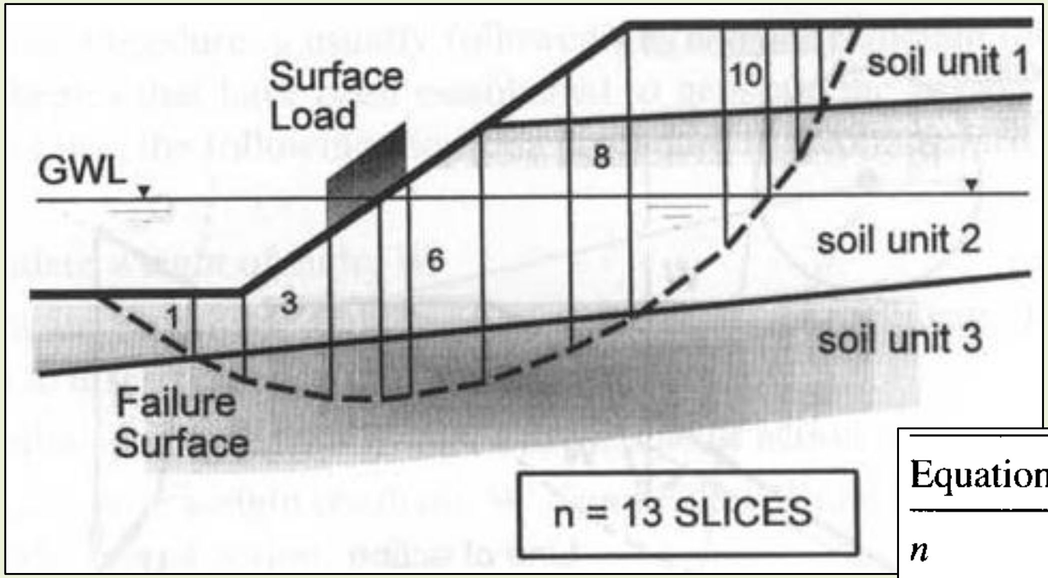
$$c_m = \frac{c}{F_C}$$

$$\tan\varphi_m = \frac{\tan\varphi}{F_\varphi}$$

$$F_C = F_\varphi = F$$

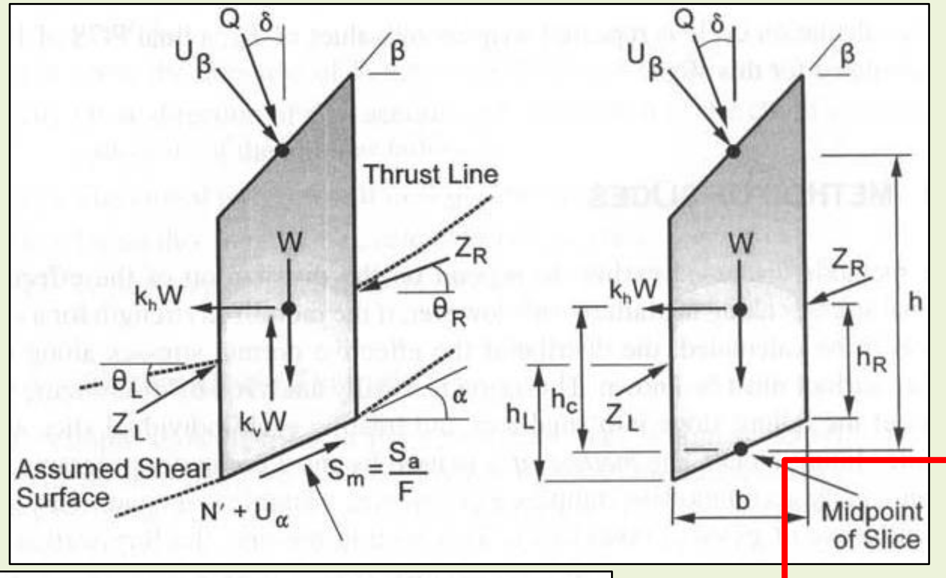
Finite Slope Stability Analyses

- Method of Slices ($c - \varphi$ soils)
  - ❖ Discretize the active/moving soil mass into many vertical slices
    - ▪ Treat individual slice as failing unit which has interaction with adjacent slide



Equations	Condition
n	Moment equilibrium for each slice
$2n$	Force equilibrium in two directions (for each slice)
n	Mohr–Coulomb relationship between shear strength and normal effective stress
$4n$	**Total number of equations**

Finite Slope Stability Analyses



Indeterminate: (2n-2)-n = n-2

- F = factor of safety
- S_a = available strength = $C + N' \tan\phi$
- S_m = mobilized strength
- U_α = pore water force
- U_β = surface water force
- W = weight of slice
- N' = effective normal force
- Q = external surcharge
- k_v = vertical seismic coefficient
- k_h = horiz. seismic coefficient
- Z_L = left interslice force
- Z_R = right interslice force
- θ_L = left interslice force angle
- θ_R = right interslice force angle
- h_L = height to force Z_L
- h_R = height to force Z_R
- α = inclination of slice base
- β = inclination of slice top
- δ = inclination of surcharge
- b = width of slice
- h = average height of slice
- h_c = height to centroid of slice

Unknowns	Variable
1	Factor of safety
n	Normal force at base of each slice, N'
n	Location of normal force, N'
n	Shear force at base of each slice, S_m
$n-1$	Interslice force, Z
$n-1$	Inclination of interslice force, θ
$n-1$	Location of interslice force (line of thrust)
$6n-2$	**Total number of unknowns**

Indeterminate: (6n-2)-4n = 2n-2

Finite Slope Stability Analyses

- Various types of 'Methods of Slices' developed over time
- A Group of Limit Equilibrium Approaches
  - ❖ Mainly differs on the variation of assumptions related to interslice forces
  - ❖ Differs on the basis of satisfying varying equilibrium conditions

Method	Force Equilibrium vertical	Force Equilibrium horizontal	Moment Equilibrium
Ordinary method of slices (OMS)	No	No	Yes
Bishop's simplified	Yes	No	Yes
Janbu's simplified	Yes	Yes	No
Lowe and Karafiath's	Yes	Yes	No
Corps of Engineers	Yes	Yes	No
Spencer's	Yes	Yes	Yes
Bishop's rigorous	Yes	Yes	Yes
Janbu's generalized	Yes	Yes	No
Sarma's	Yes	Yes	Yes
Morgenstern–Price	Yes	Yes	Yes

Finite Slope Stability Analyses

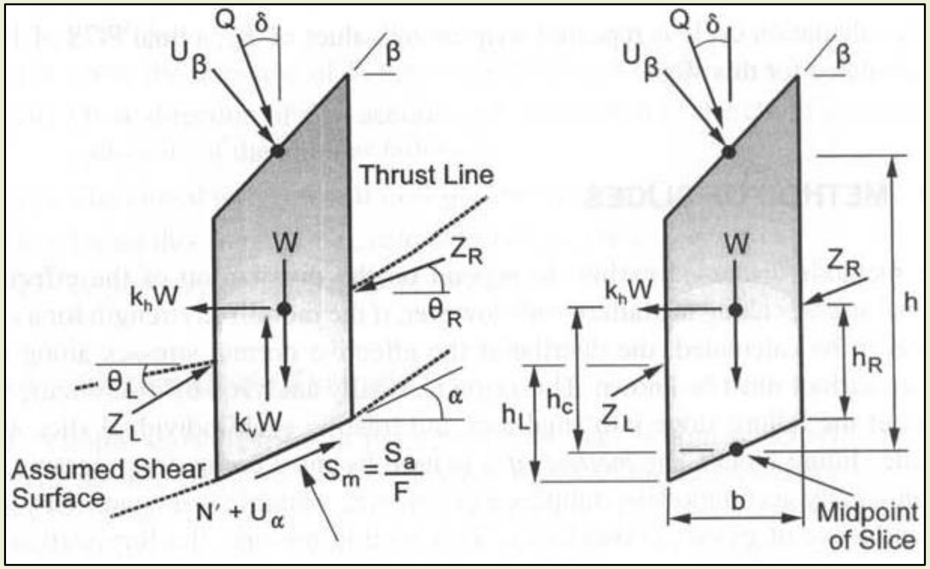
- Ordinary Method of Slices
  - ❖ Circular slip surface
  - ❖ Neglects all interslice forces [3(*n*-1) number unknowns neglected]
  - ❖ Over-determined [*n*-2-3(*n*-1) = -(2*n*-1)]
  - ❖ Only moment equilibrium is satisfied

$$F = \frac{\sum_{i=1}^{n} (C + N' \tan\phi)}{\sum_{i=1}^{n} A_1 - \sum_{i=1}^{n} A_2 + \sum_{i=1}^{n} A_3}$$

$$A_1 = (W(1-k_v) + U_\beta \cos\beta + Q\cos\delta)\sin\alpha$$

$$A_2 = (U_\beta \sin\beta + Q\sin\delta)\left(\cos\alpha - \frac{h}{R}\right)$$

$$A_3 = k_h W\left(\cos\alpha - \frac{h_c}{R}\right)$$



Finite Slope Stability Analyses

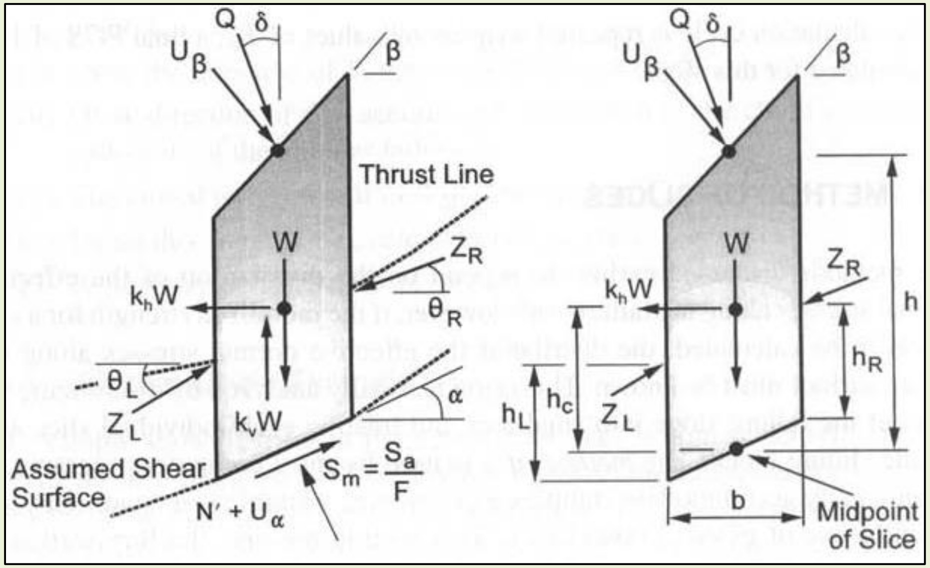
- Bishop's Simplified Approach
  - ❖ Circular slip surface
  - ❖ All interslice shear forces are zero → only normal interslice forces are considered
  - ❖ Over-determined [*n*-2-(*n*-1) = -1]
  - ❖ Horizontal force equilibrium is NOT satisfied
  - ❖ Overall moment equilibrium is satisfied

$$F = \frac{\sum_{i=1}^{n}(C + N'\tan\phi)}{\sum_{i=1}^{n} A_5 - \sum_{i=1}^{n} A_6 + \sum_{i=1}^{n} A_7}$$

$$A_5 = (W(1-k_v) + U_\beta \cos\beta + Q\cos\delta)\sin\alpha$$

$$A_6 = (U_\beta \sin\beta + Q\sin\delta)\left(\cos\alpha - \frac{h}{R}\right)$$

$$A_7 = k_h W\left(\cos\alpha - \frac{h_c}{R}\right)$$

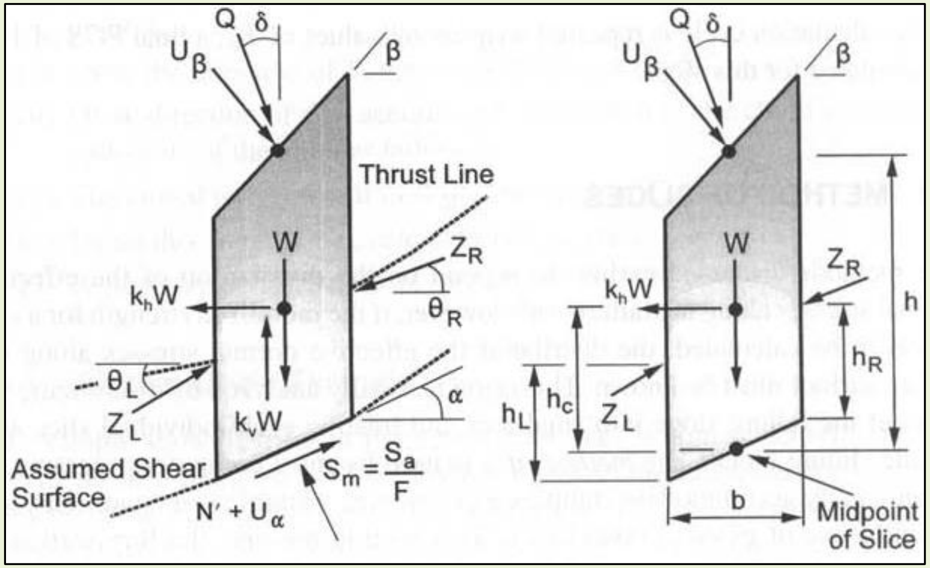


Finite Slope Stability Analyses

- Janbu's Simplified Approach
  - ❖ Slip surface need NOT be circular
  - ❖ All interslice shear forces are zero → only normal interslice forces are considered
  - ❖ Over-determined [*n*-2-(*n*-1) = -1]
  - ❖ Horizontal force equilibrium is not satisfied
  - ❖ Moment equilibrium is NOT satisfied

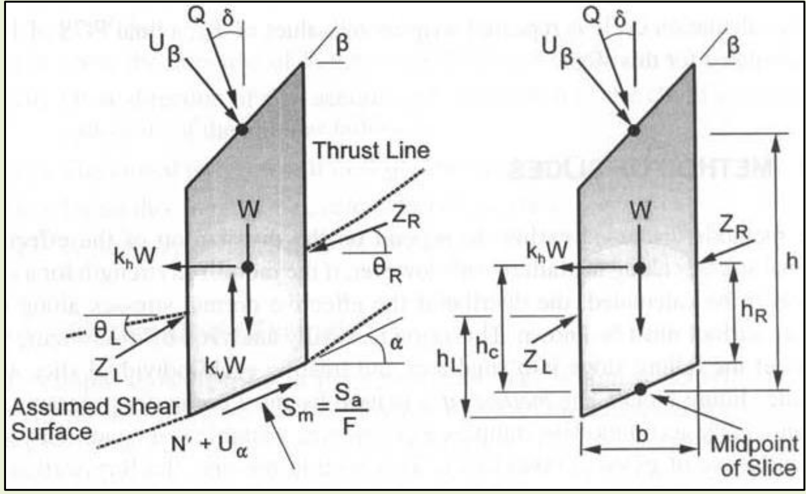
$$F = \frac{\sum_{i=1}^{n}[C + N' \tan\phi]\cos\alpha}{\sum_{i=1}^{n} A_4 + \sum_{i=1}^{n} N' \sin\alpha}$$

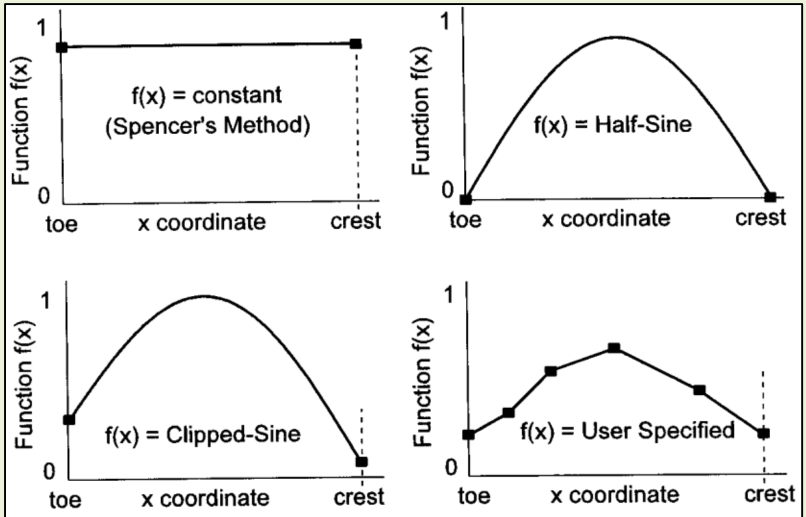
$$A_4 = U_\alpha \sin\alpha + W k_h - U_\beta \sin\beta - Q \sin\delta$$



Finite Slope Stability Analyses

- Generalized Limit Equilibrium (GLE) Approach
  - ❖ For individual slices
    - Satisfies Force Equilibrium
    - Satisfies Moment Equilibrium
  - ❖ For global system
    - May or May NOT satisfy both force and moment equilibrium simultaneously
  - ❖ It is a congregation of iterative analysis
    - Janbu's generalized approach
    - Spencer's method
    - Morgenstern-Price method
    - etc…

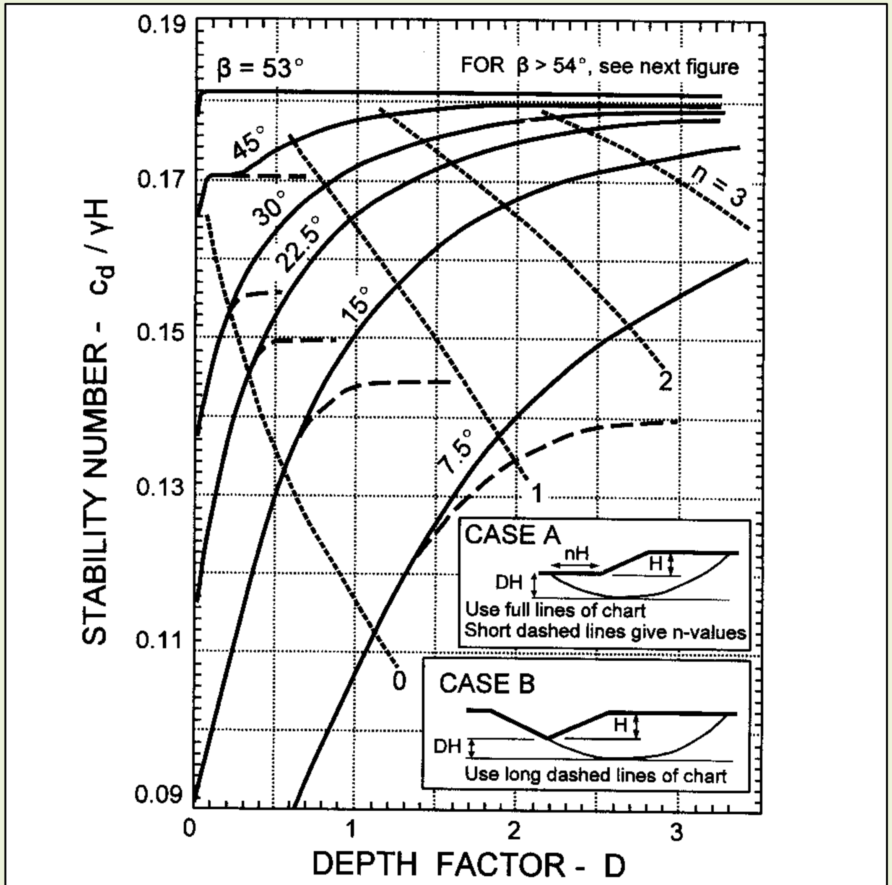




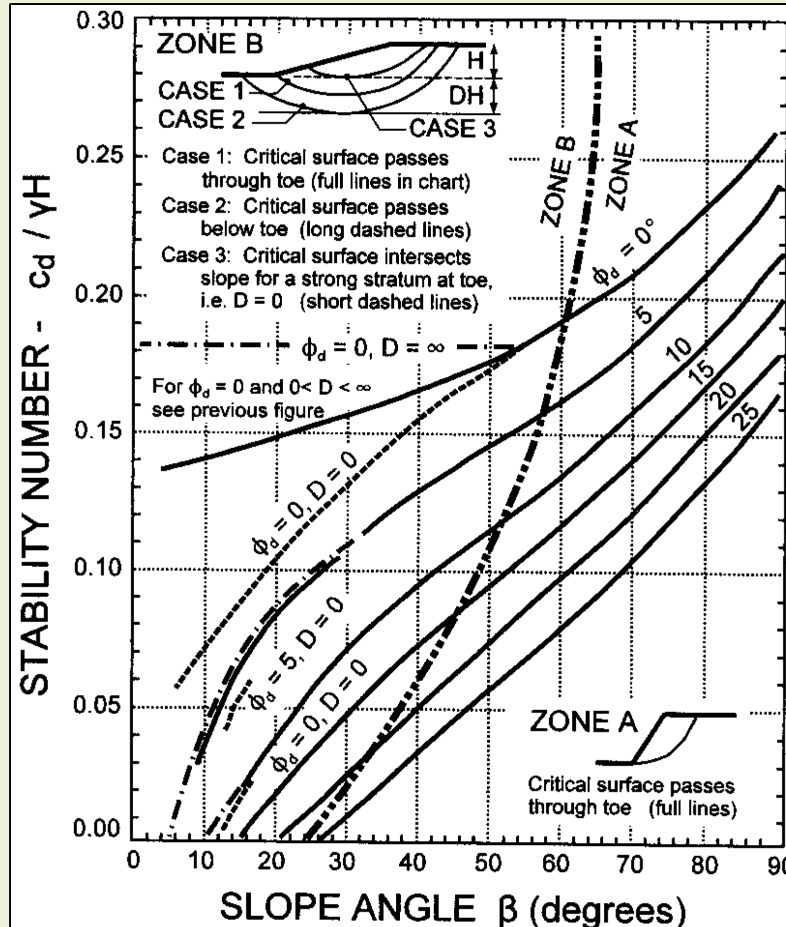
Examples of functions used to describe the variation of interslice force angles

Finite Slope Stability Analyses

- Stability Charts by various researchers
  - ❖ To make our life little bit simpler



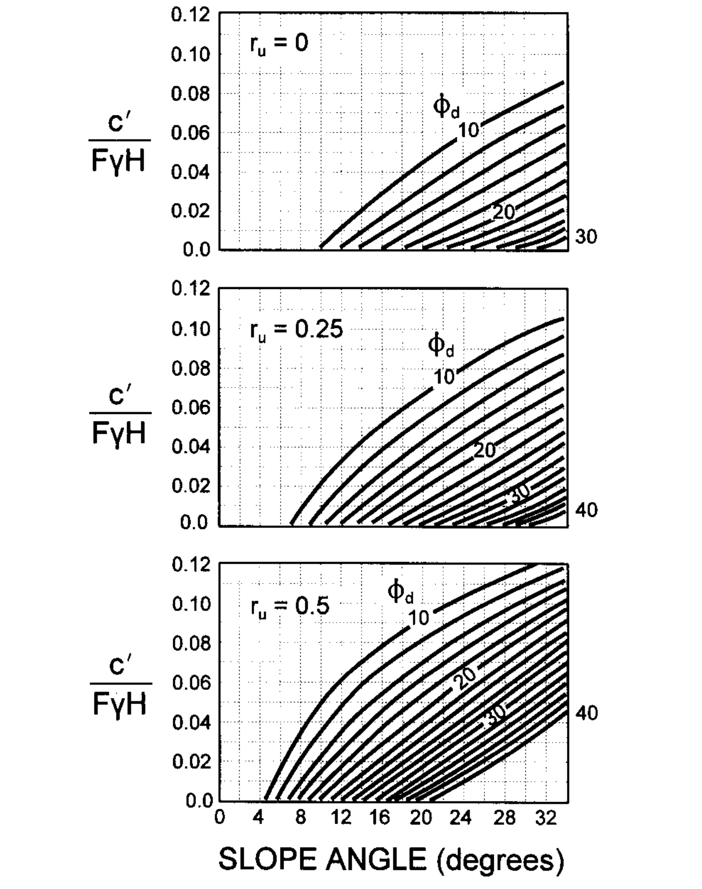
Taylor's chart for $\phi = 0$ conditions and for slope angles less than 54°.



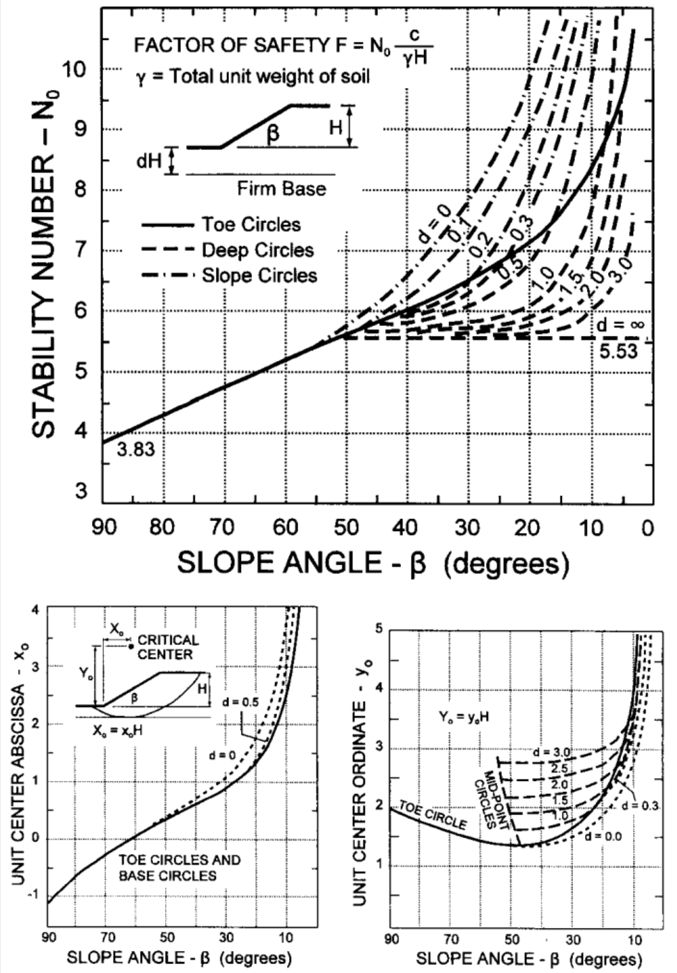
Taylor's chart for soils with friction angle

Finite Slope Stability Analyses

- Stability Charts by various researchers
  - ❖ To make our life little bit simpler



Stability chart for different pore pressure ratios. (Spencer, 1967)

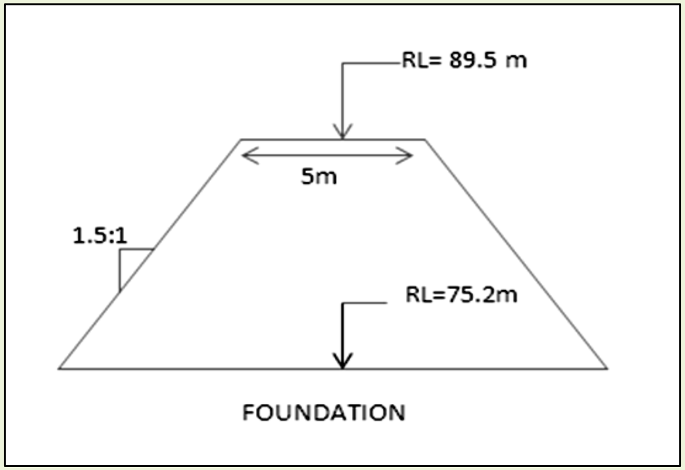


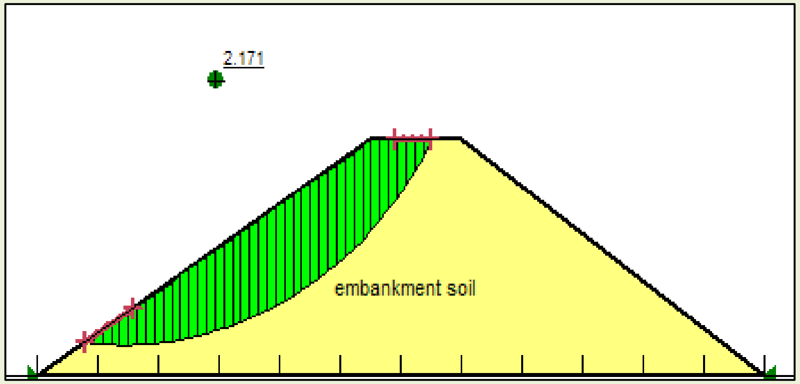
Stability charts for $\phi = 0$ soils. (Janbu, 1954)

Interpretations from a Finite Slope Stability Analysis

- Slope stability by various available limit equilibrium methods

Methods	Factor of safety
Culman's method of plane surface failure	6.4
Failure under undrained conditions	0.65
Friction circle method	2.846
Method of Taylor's stability no	2.268
Ordinary method of slices	2.014
Bishop's simplified method of slices	1.43
Bishop and Morgenstern method	1.025
Morgenstern method for rapid drawdown	….
Spencer's method	0.57





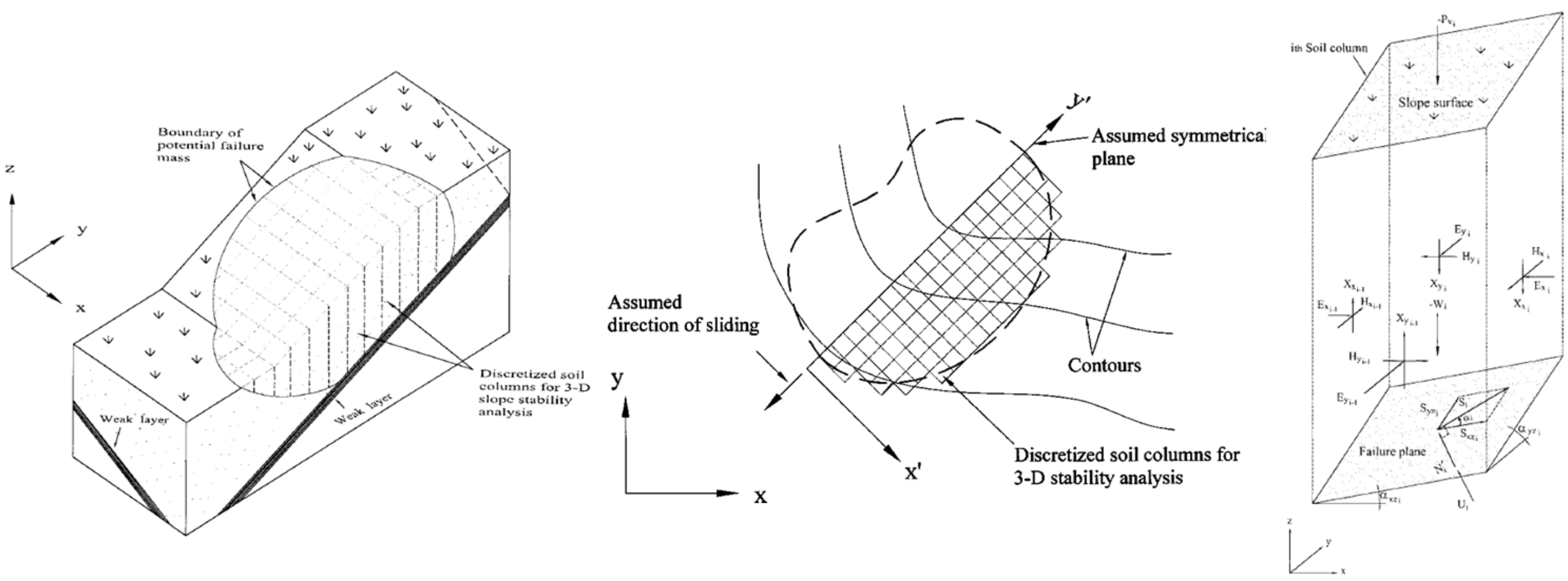
Methods	Factor of safety
Morgenstern and price	2.721
Ordinary method of slices	2.612
Bishop's simplified method	2.726
Janbu's simplified method	2.559
Spencer's method	2.723

Landslide Analysis on a Local Scale

- Slope Stability Limit Equilibrium Analysis

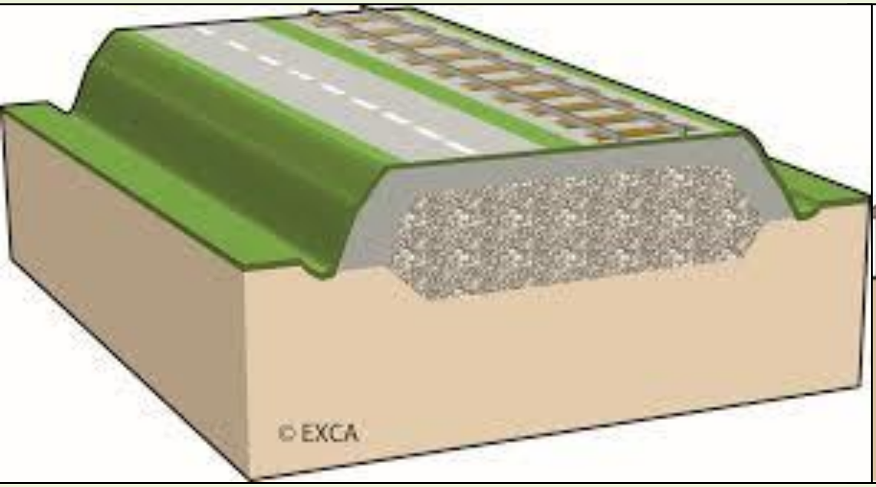
3D Limit Equilibrium Analysis

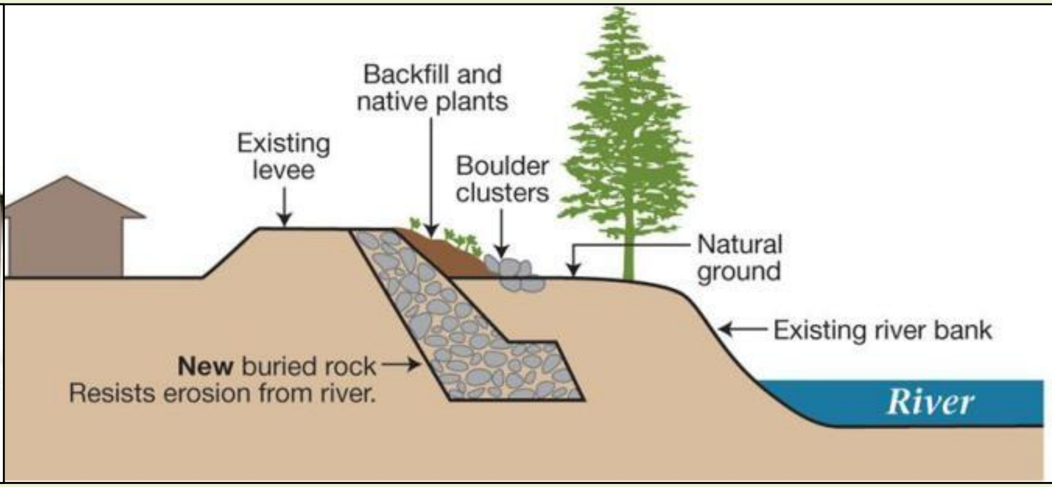
Huang and Tsai (2000), extends Bishop's simplified procedure, all inter-column forces are ignored, Moment equilibrium is considered about two mutually perpendicular horizontal axes and the Factor of Safety minimized considering sliding direction.



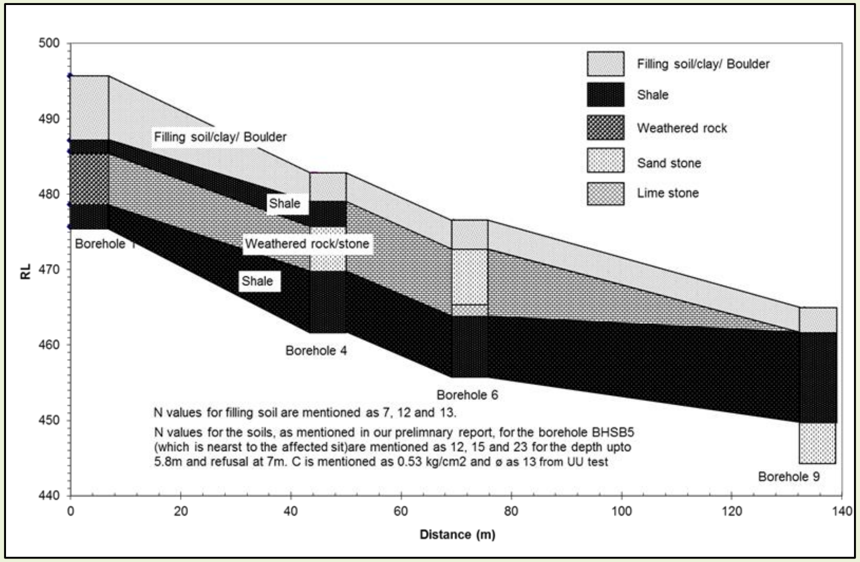
Infinite / Finite Slopes

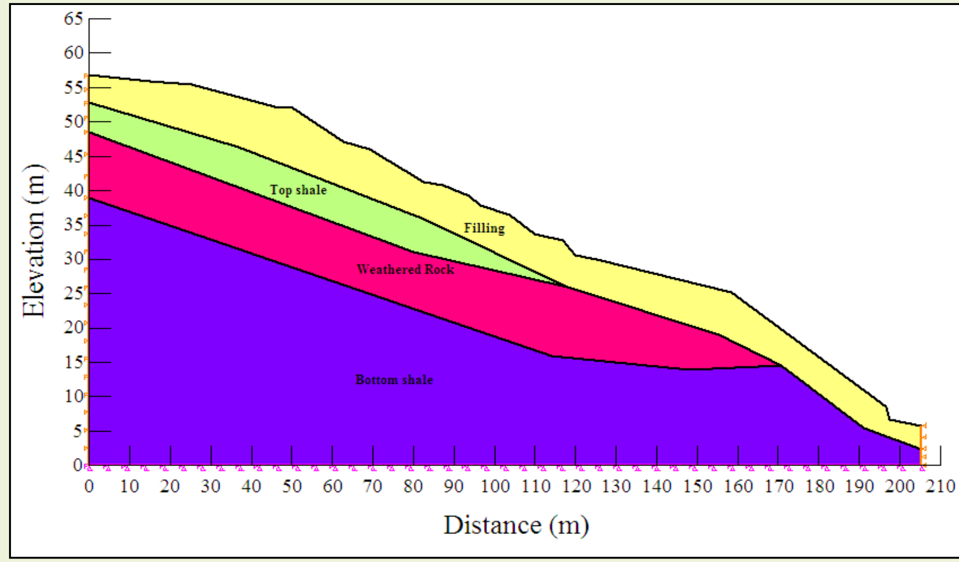
Geometry or Mechanism???

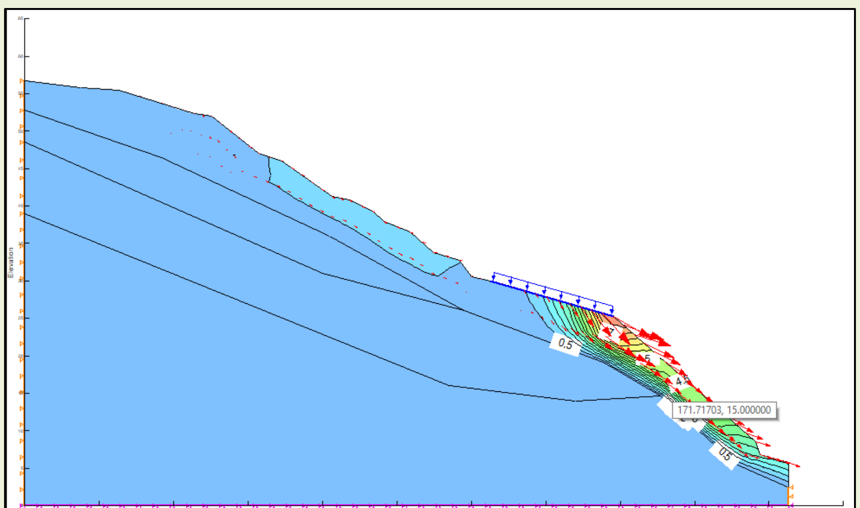


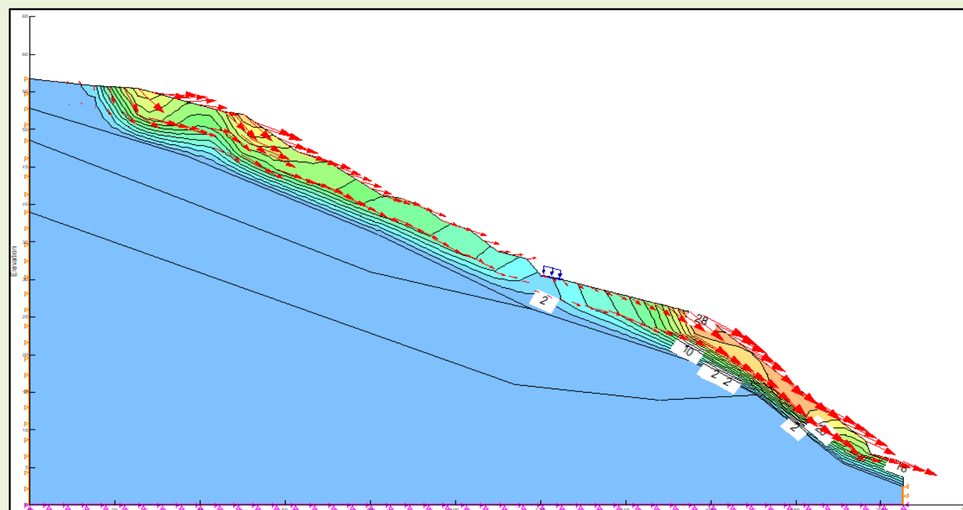


Infinite Slope Geometry with Infinite Failure Mechanism

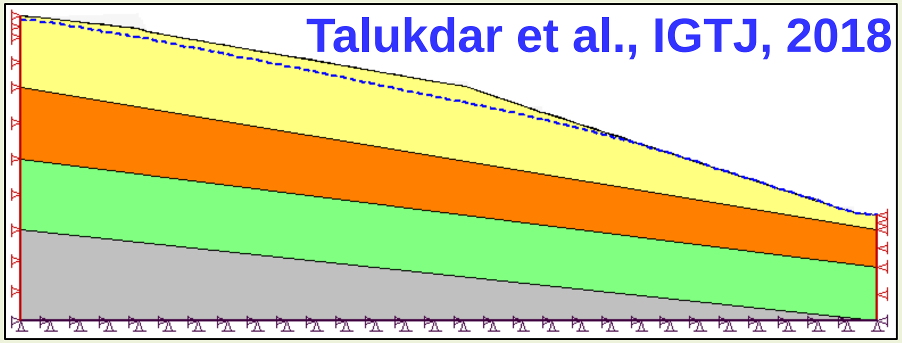


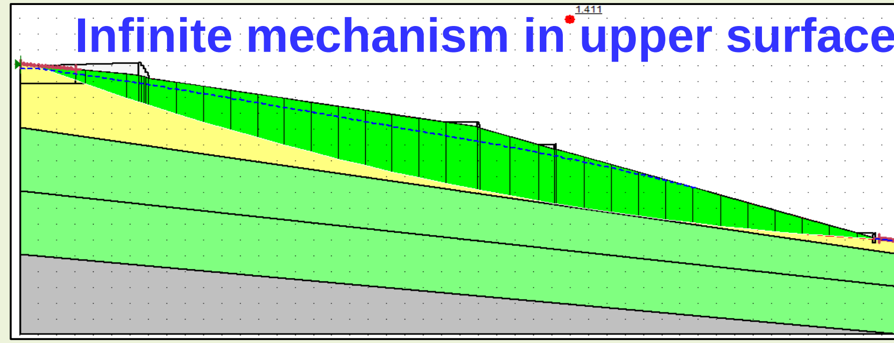


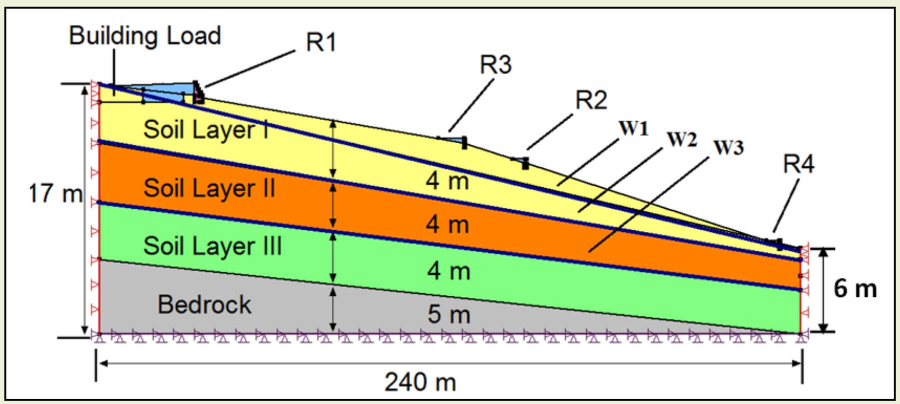


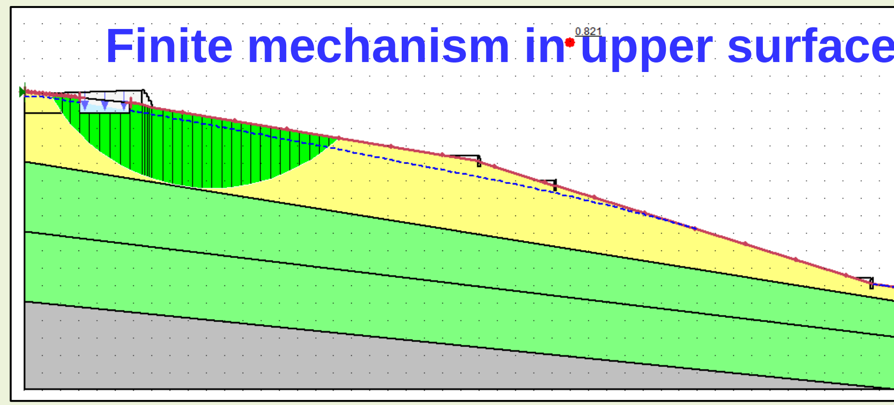


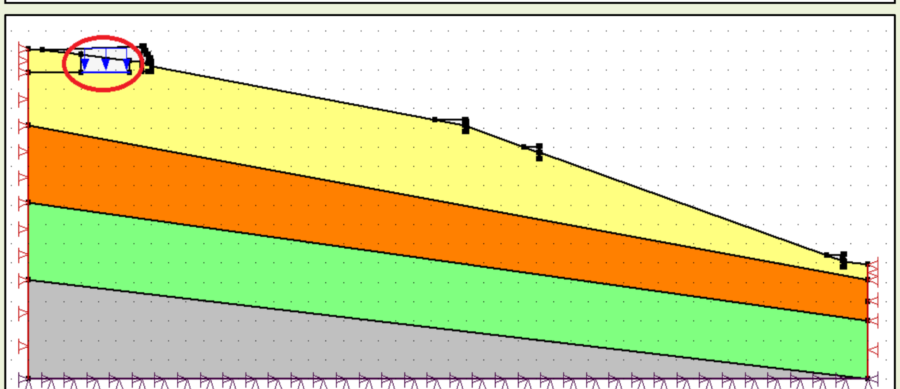
Infinite Slope Geometry with Finite Failure Mechanism

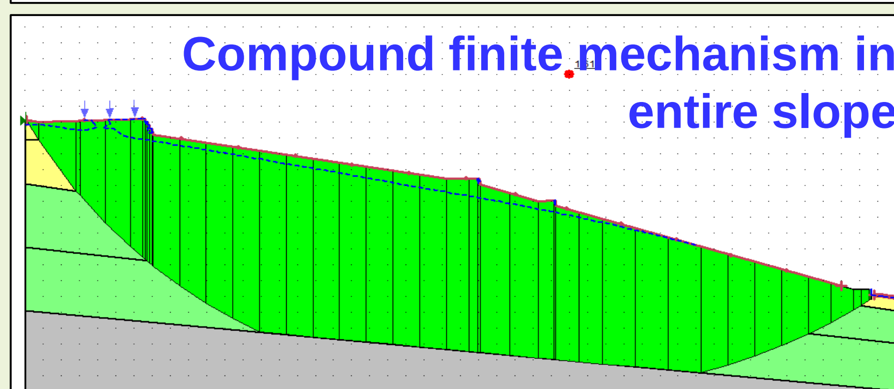




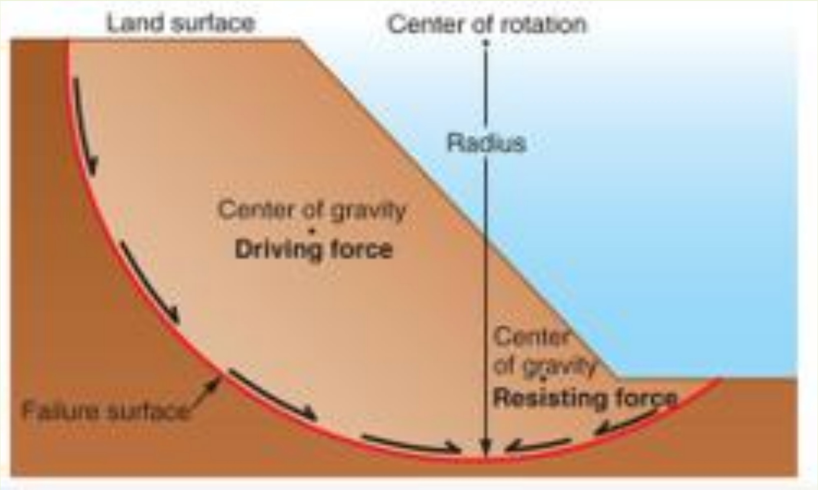


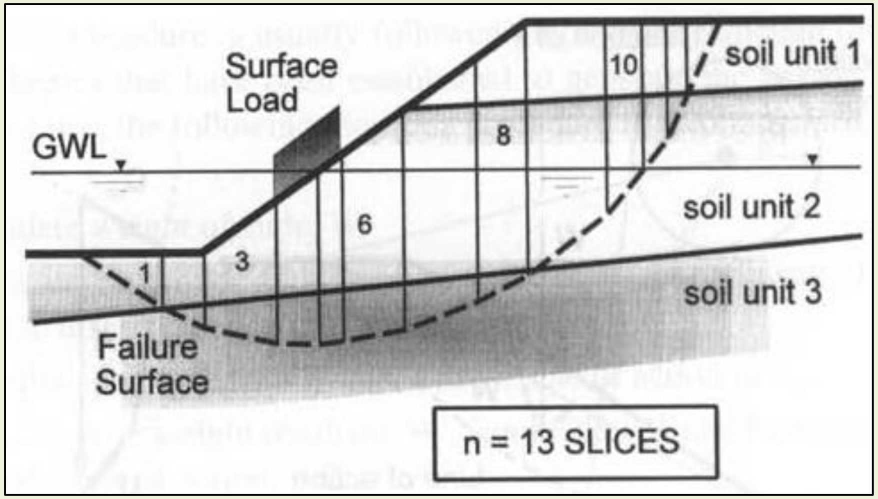


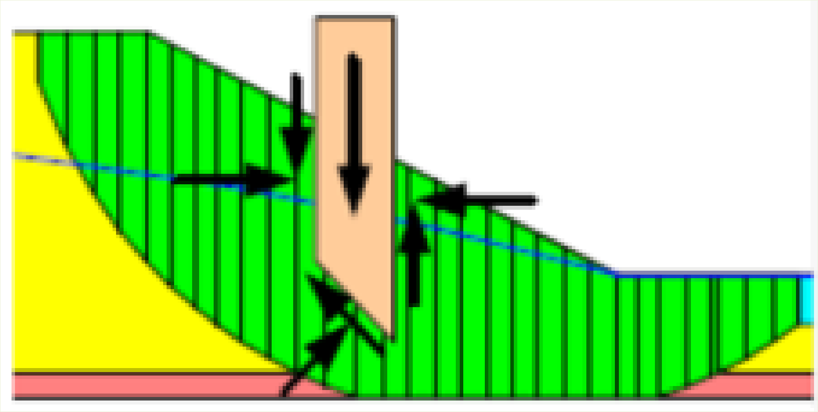


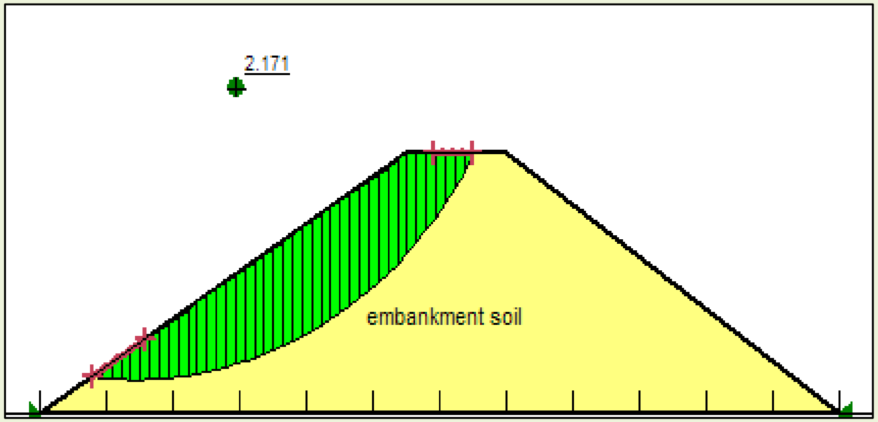


Finite Slope Geometry with Finite Failure Mechanism

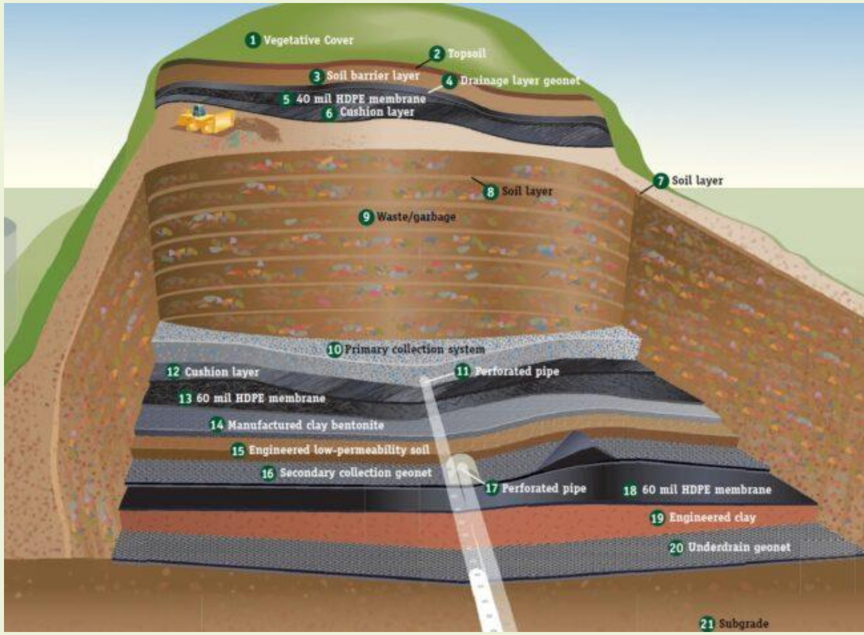


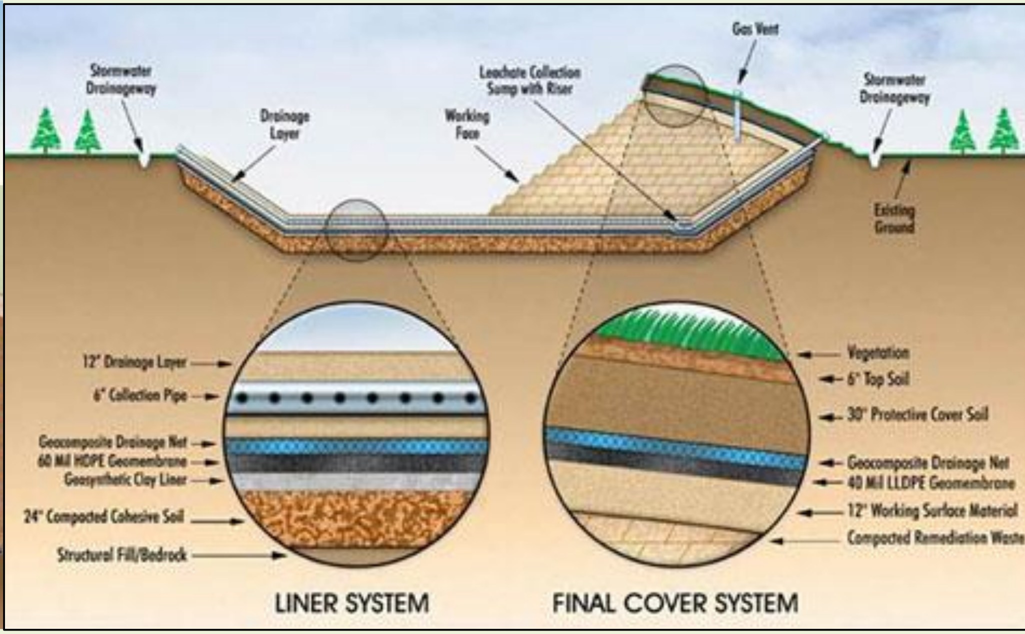


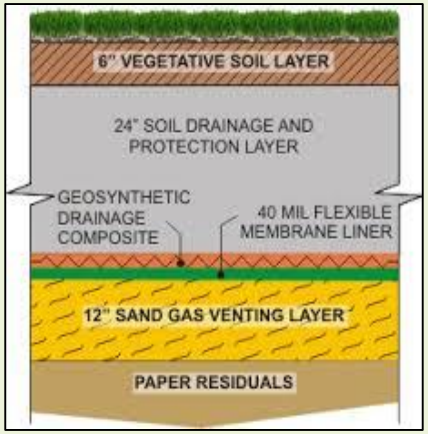


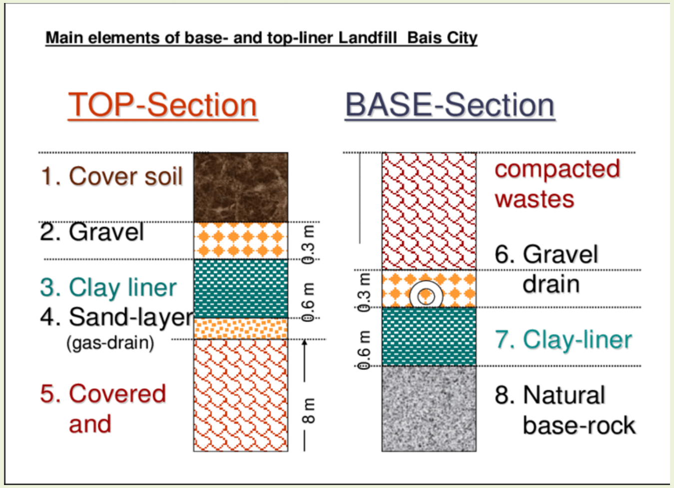


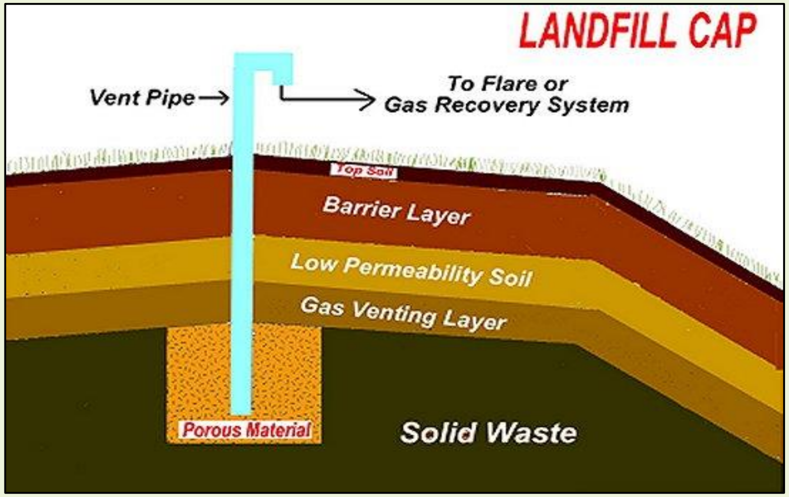
Finite Slope Geometry with Infinite Failure Mechanism



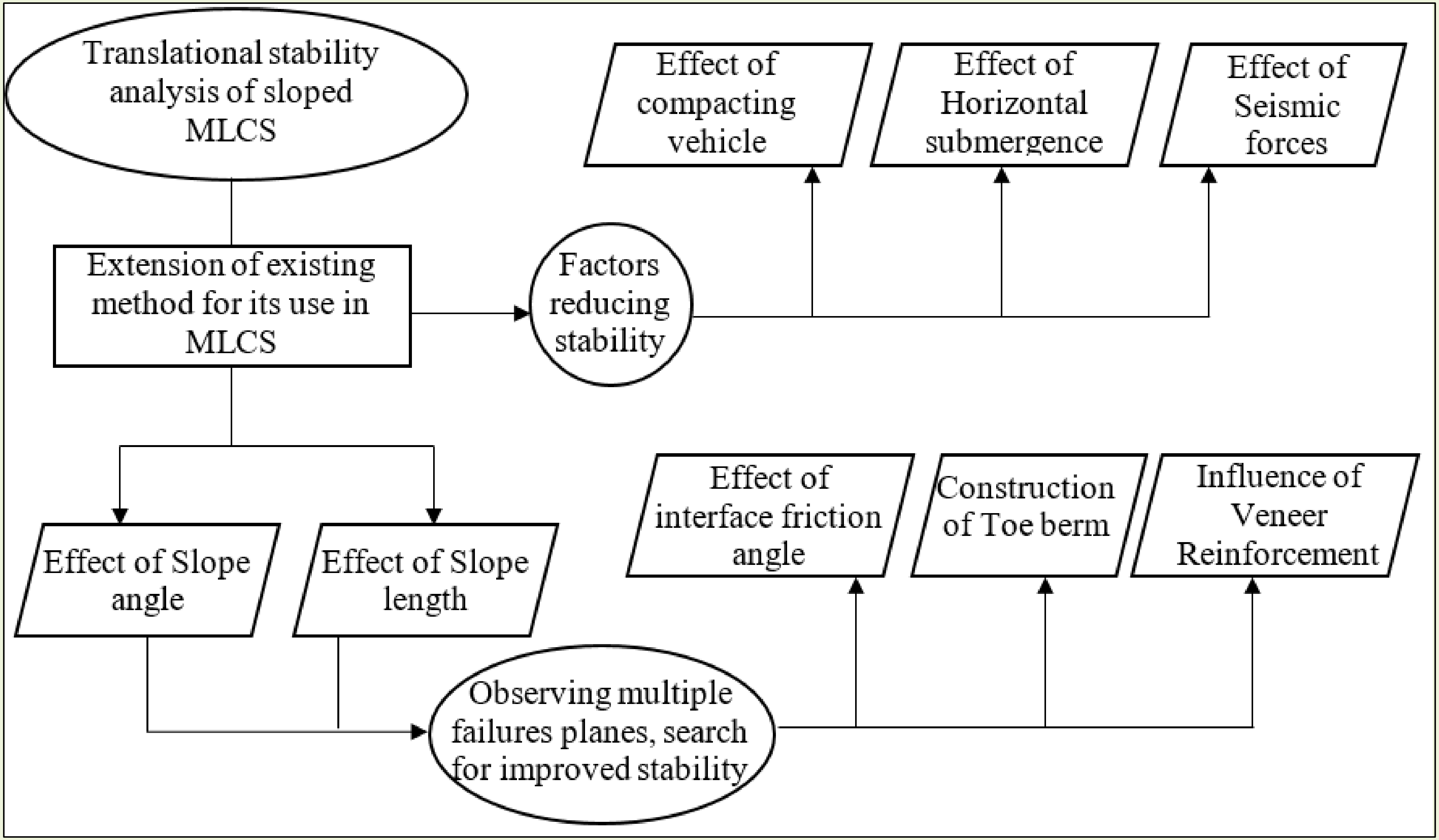




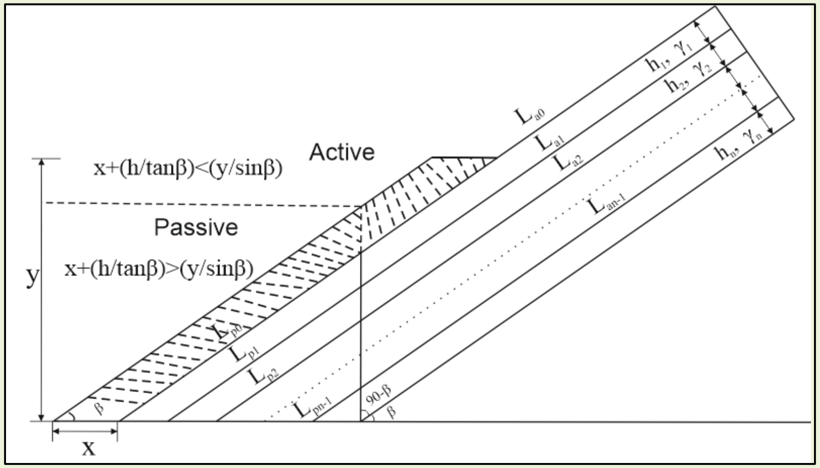


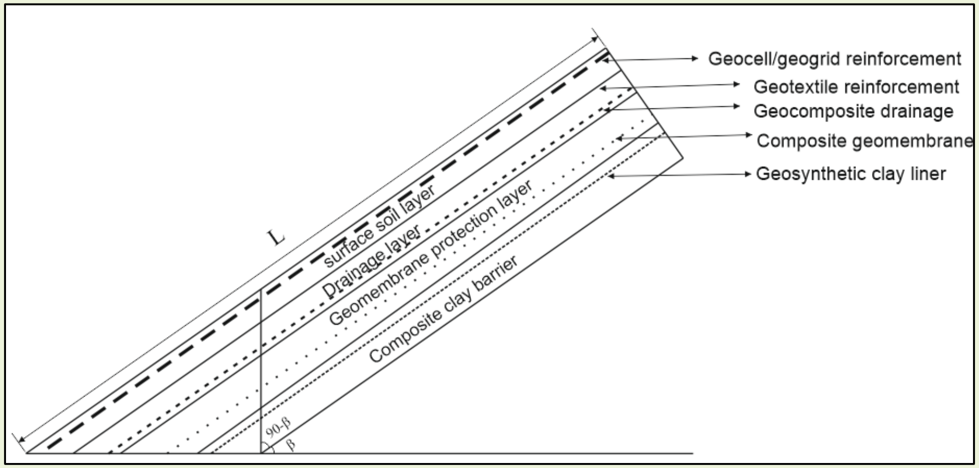


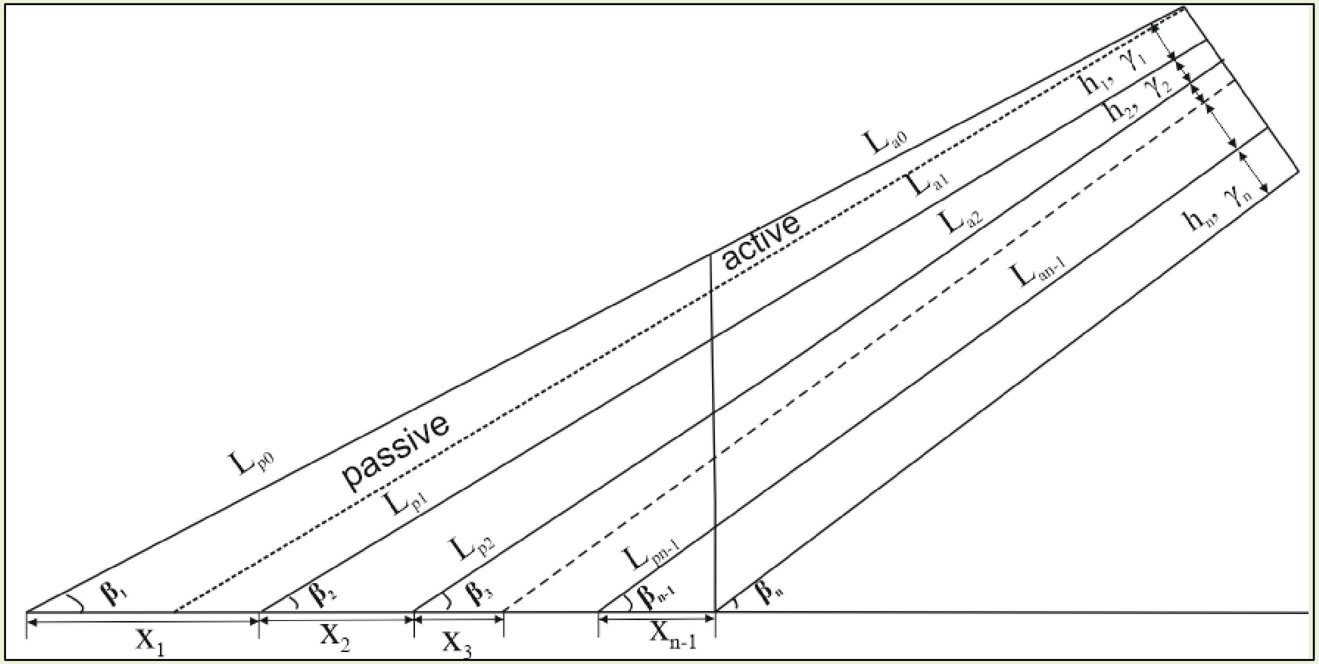
Translational Stability of MSW Landfill



Translational Stability of MSW Landfill

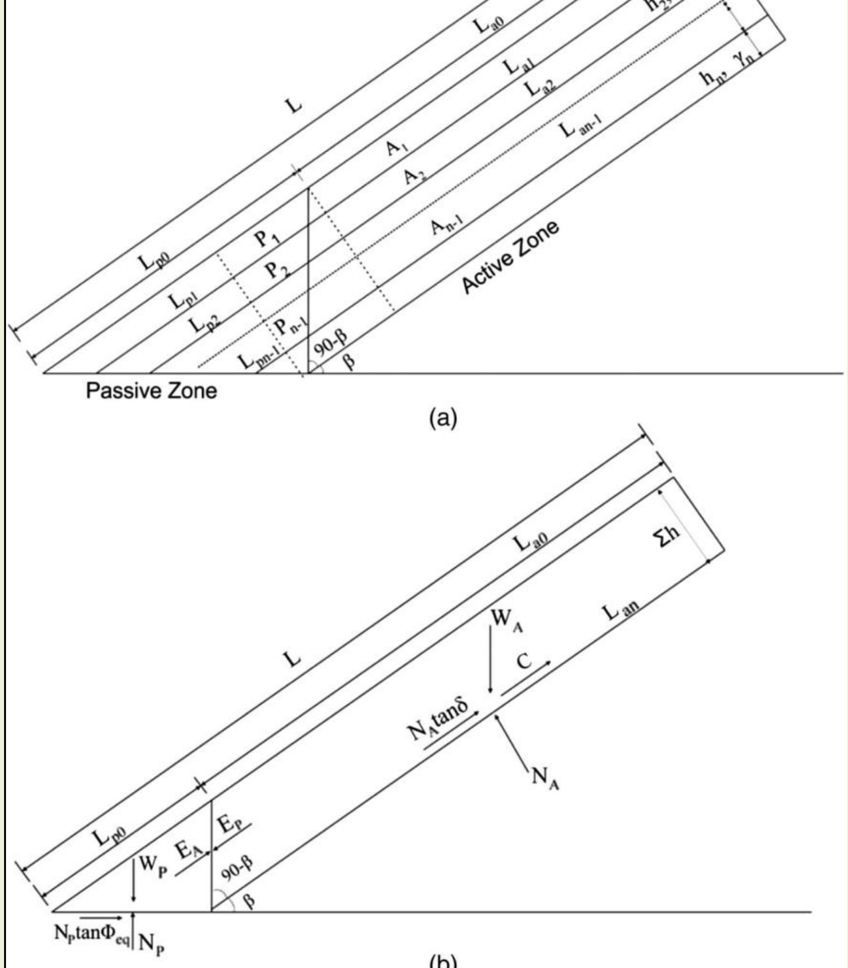


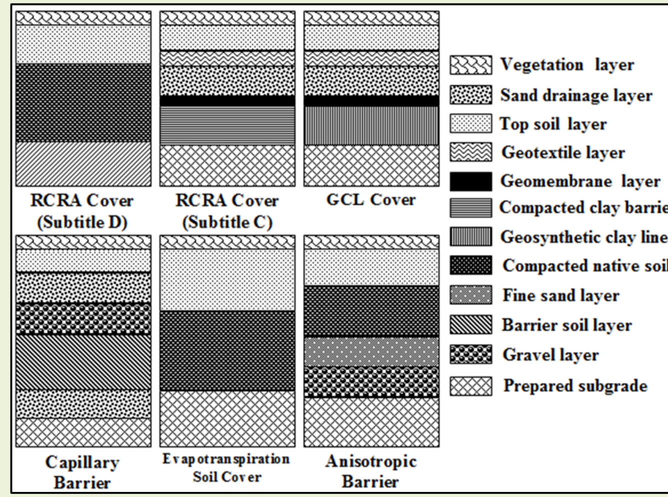




Translational Stability of MSW Landfill

Yamsani et al., IJoG, ASCE, 2019



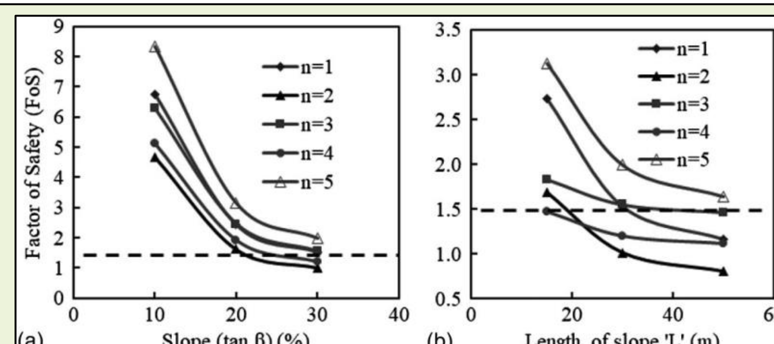


$$k_1 FoS^2 + k_2 FoS + k_3 = 0$$

$$k_1 = (W_A - N_A cos\beta)cos\beta$$

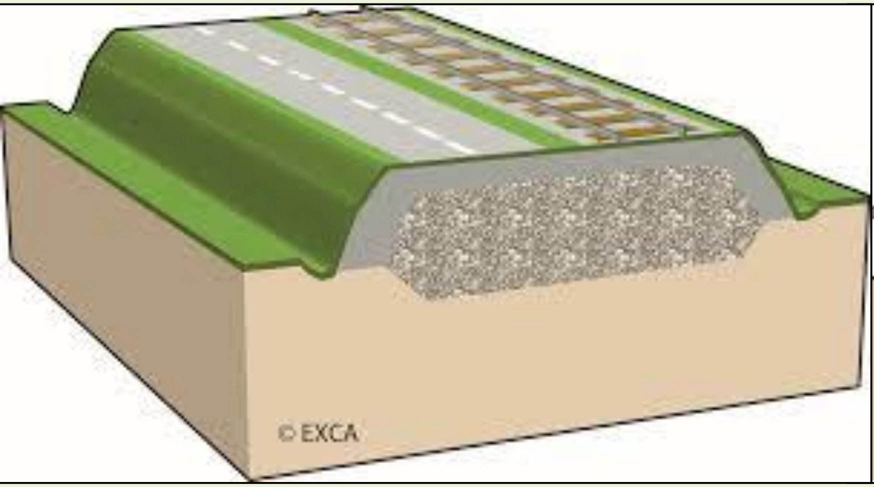
$$k_2 = -[(W_A - N_A cos\beta)sin\beta tan\delta_{eq} + (N_A tan\delta + C_a)sin\beta cos\beta + (C + W_P tan\delta_{eq})sin\beta]$$

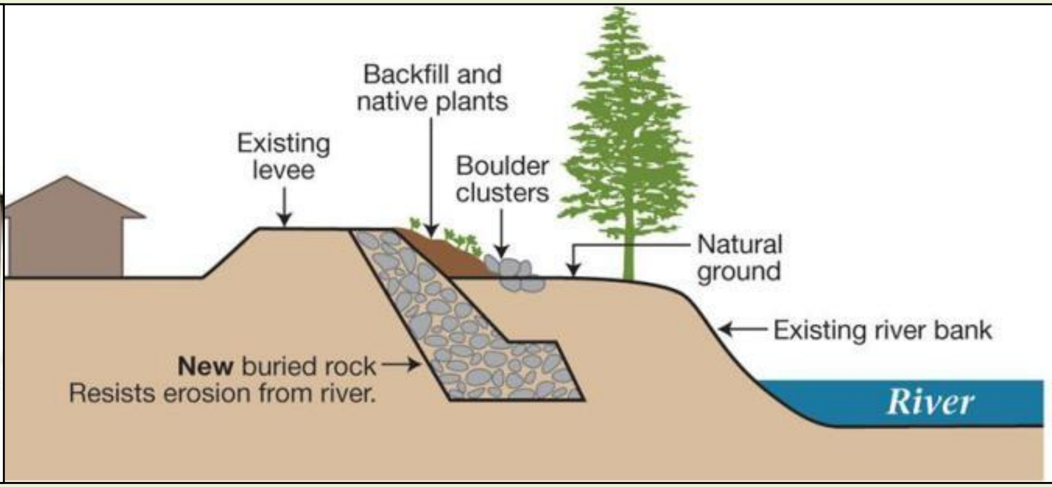
$$k_3 = (N_A tan\delta + C_a)sin^2\beta tan\delta_{eq}$$



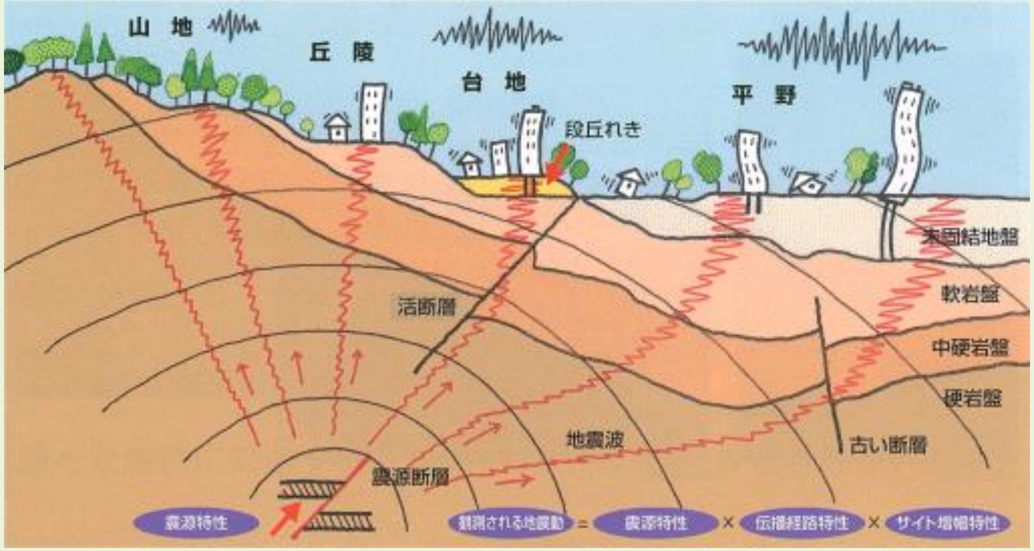
Decision on Infinite / Finite Slope Type

Mechanism **dominates** Geometry





Seismicity Induced Landslide Analyses



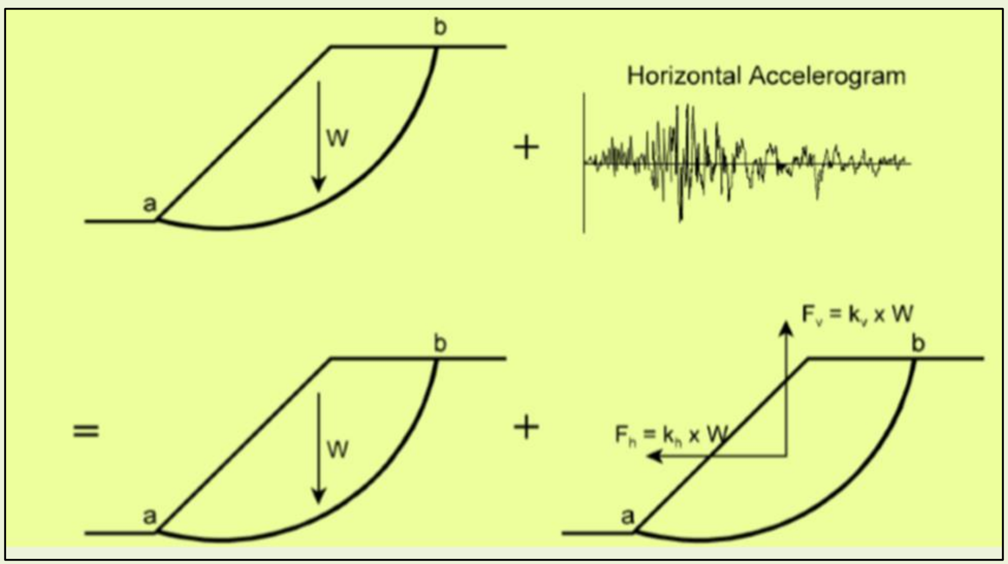
Pseudostatic Slope Stability Analysis

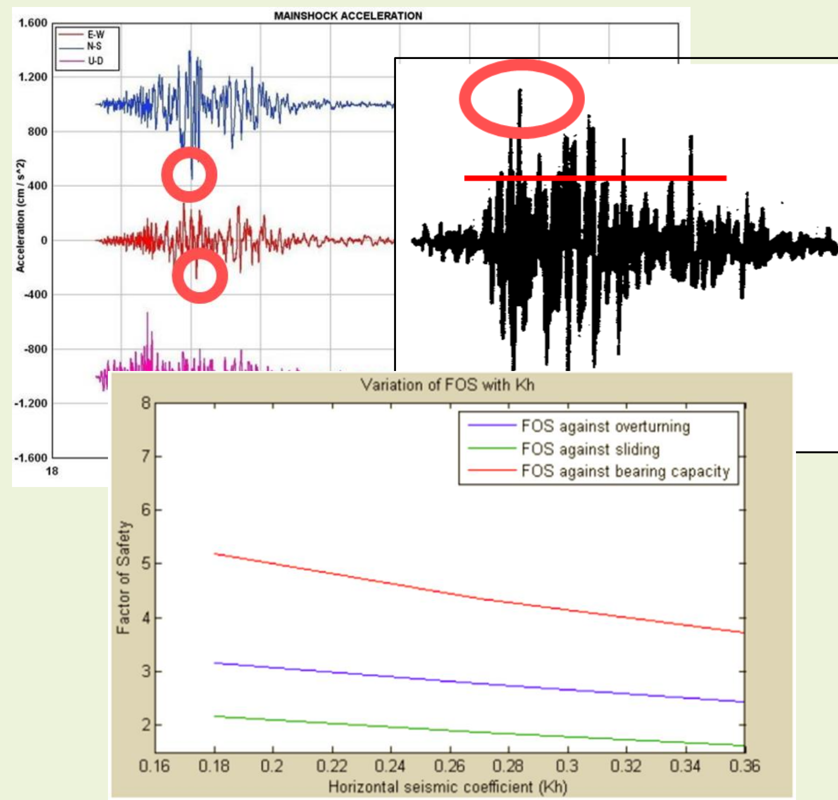
Issues in seismic slope stability analysis

- Factor of safety against failure
  - Varies with acceleration coefficient

Pseudo-static method (widely used)

- Computationally inexpensive
- Less time-consuming

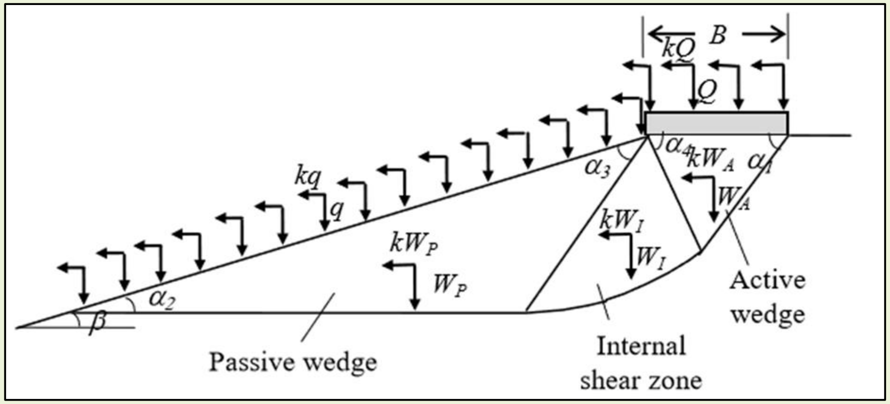


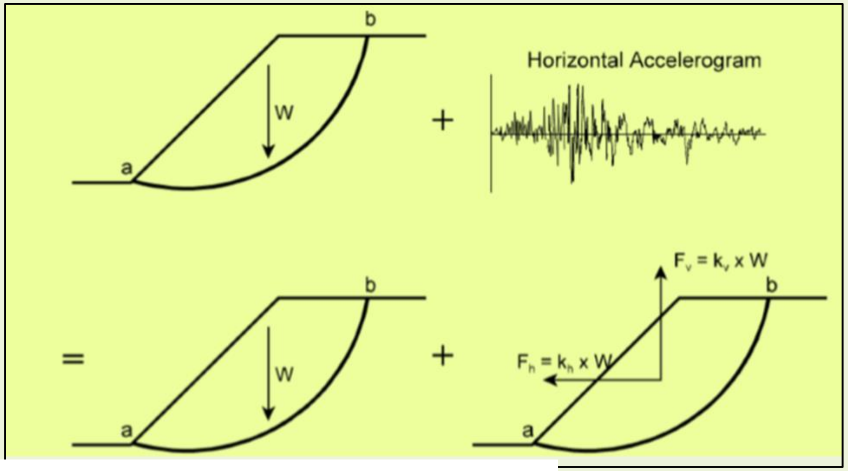


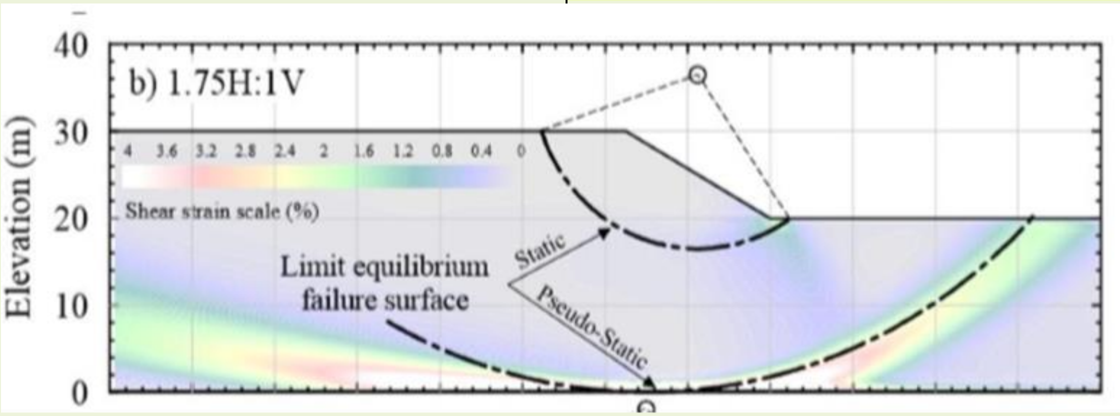
Pseudo-static Slope Stability Analysis

Issues in seismic slope stability analysis

- Location of the critical slip surface
  - Static and pseudo-static failure surfaces are not the same





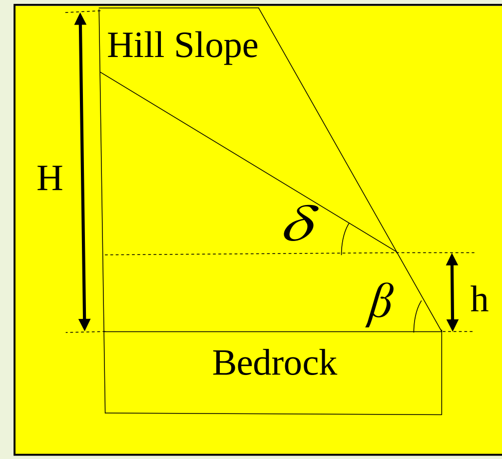


Hill-Slope Stability: Hydraulic and Seismic Effects

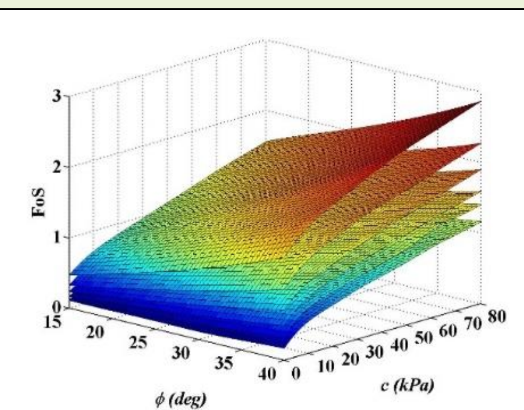
- Effect of hydraulic and pseudo-static conditions on the stability of hill slope

Chakraborty and Dey, NESGC, 2016

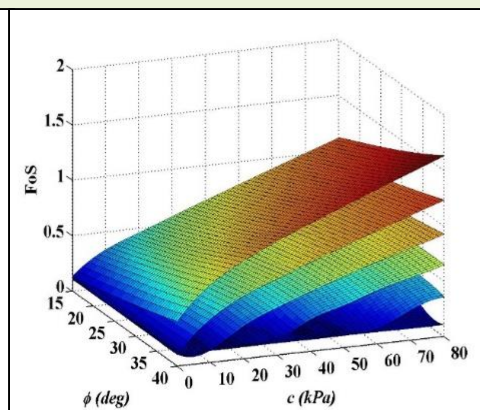
c \ φ	15	20	25	30	35	40
0	0.232	0.314	0.403	0.498	0.603	0.723
10	0.343	0.436	0.533	0.639	0.755	0.885
20	0.416	0.515	0.618	0.728	0.848	0.981
30	0.485	0.585	0.691	0.805	0.928	1.065
40	0.554	0.653	0.76	0.876	1.002	1.143
50	0.623	0.723	0.829	0.944	1.072	1.216
60	0.693	0.792	0.898	1.013	1.141	1.286
70	0.763	0.861	0.967	1.082	1.209	1.354
80	0.833	0.931	1.036	1.151	1.278	1.422



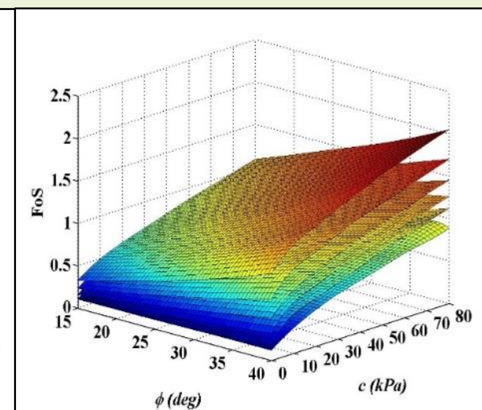
Static Dry



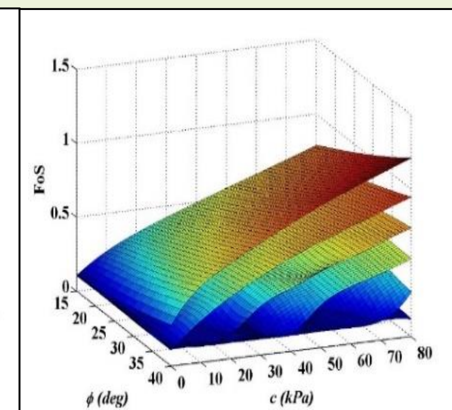
Static with water table



Pseudo-Static Dry

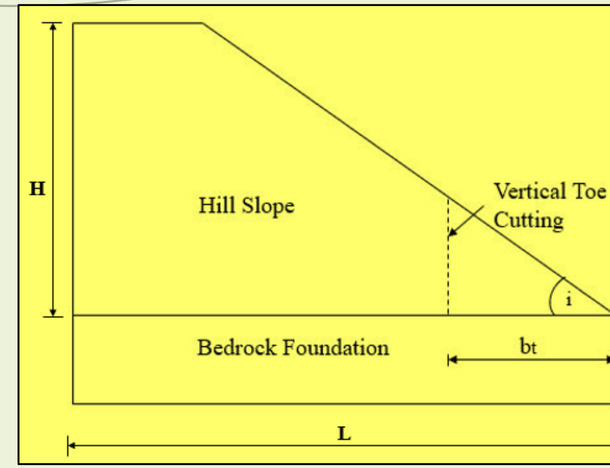


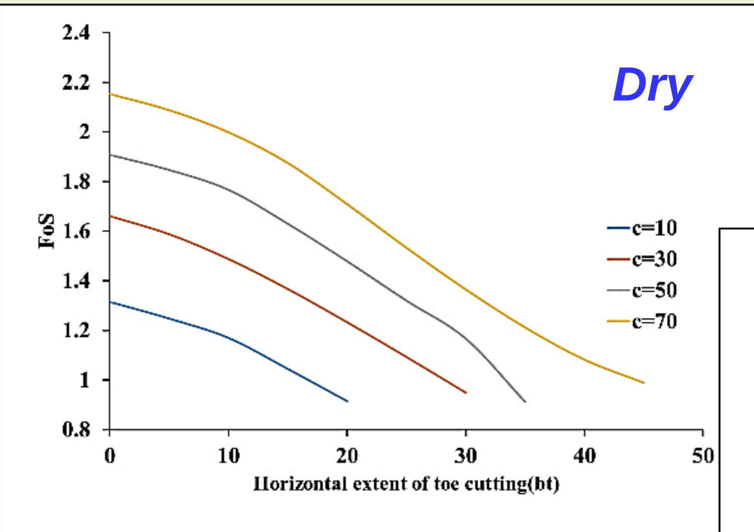
Pseudo-Static with water table



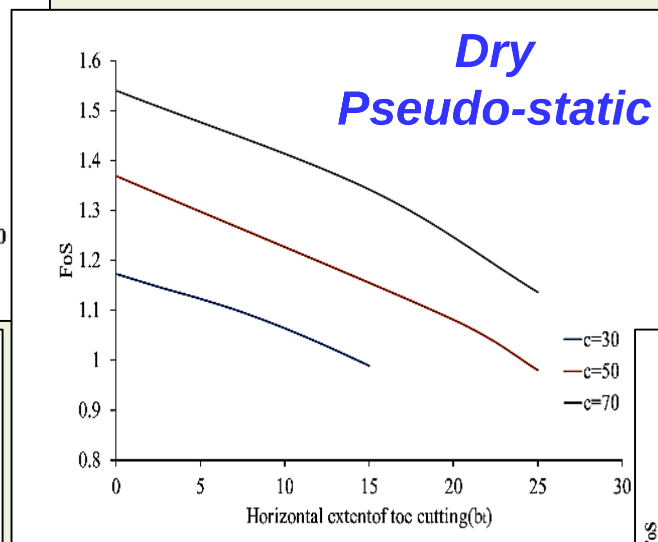
Hill-Slope Stability: Toe Cutting

- Toe-cutting (A typical slope i=30^0, φ=20^0)

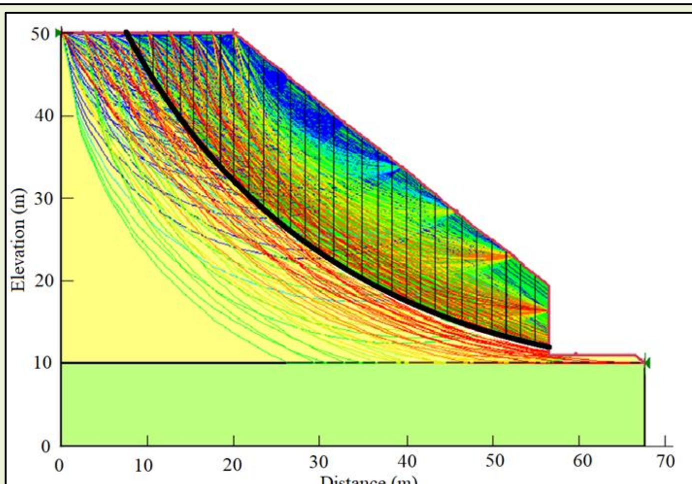


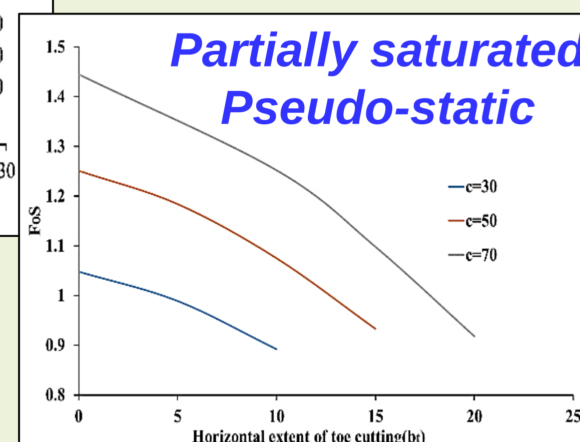


Chakraborty and Dey, Sadhana, 2021



Chakraborty and Dey, Geotechnical Applications, 2018

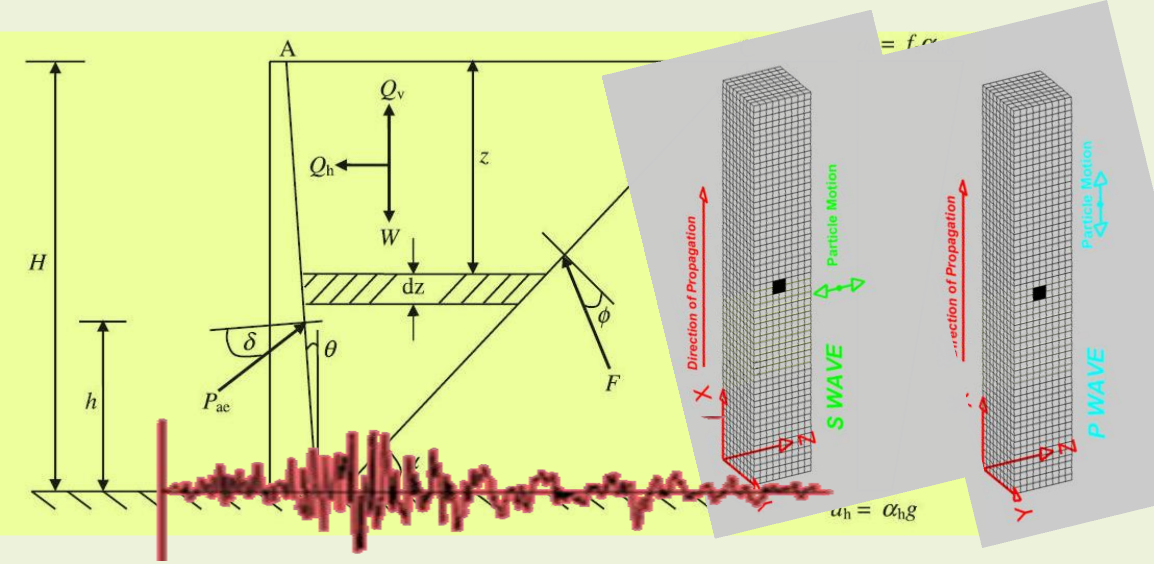


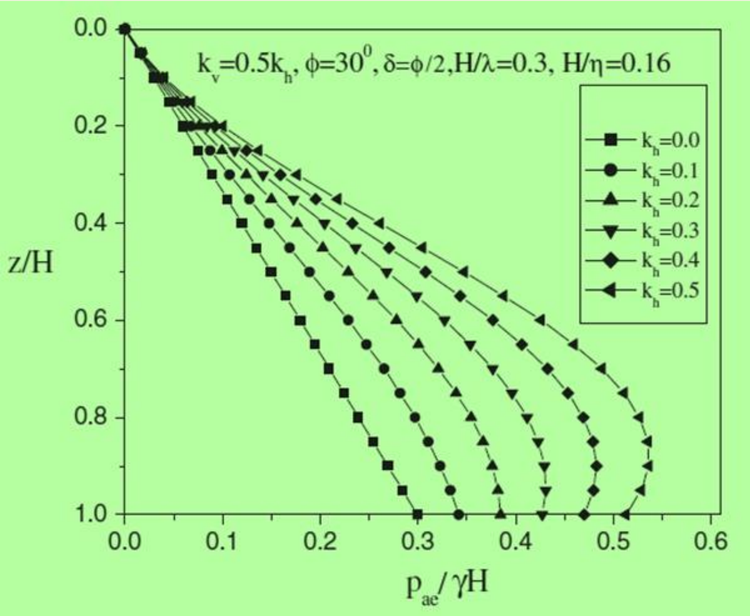


Chakraborty and Dey, ASEJ, 2022

Pseudo-dynamic Slope Stability Analysis

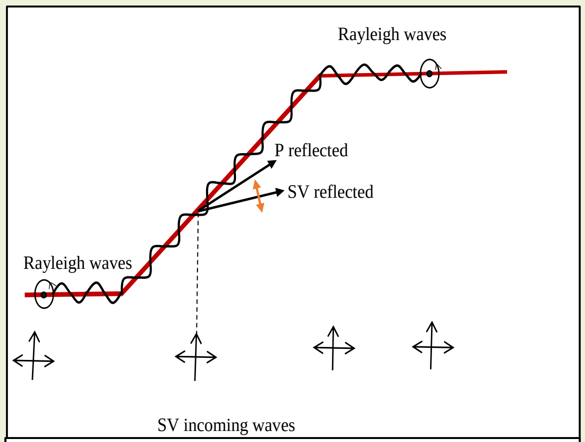
- Pseudo-dynamic analysis incorporates amplification
  - ❖ FoS governed by nature and magnitude of pre-defined amplification

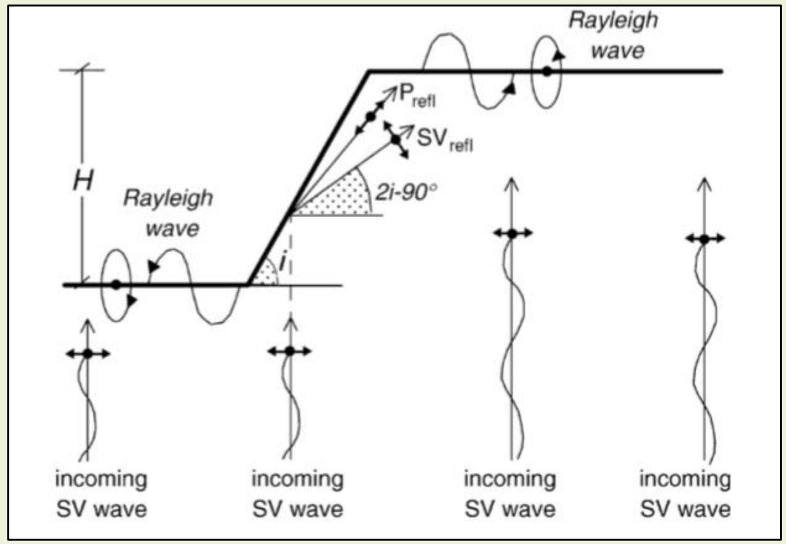


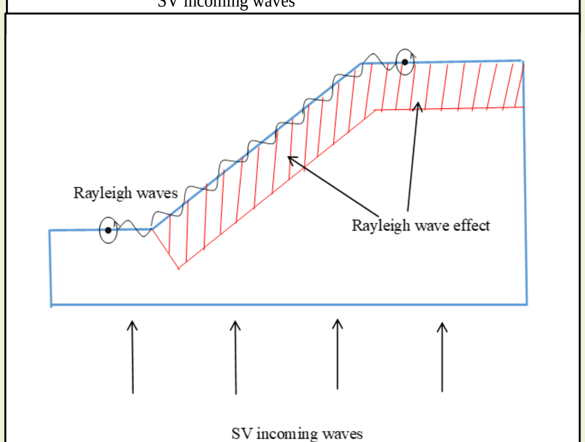


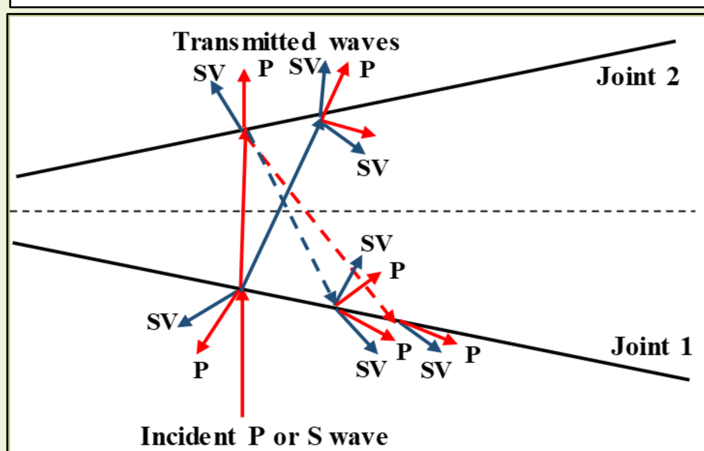
Topographic Amplification in Slopes

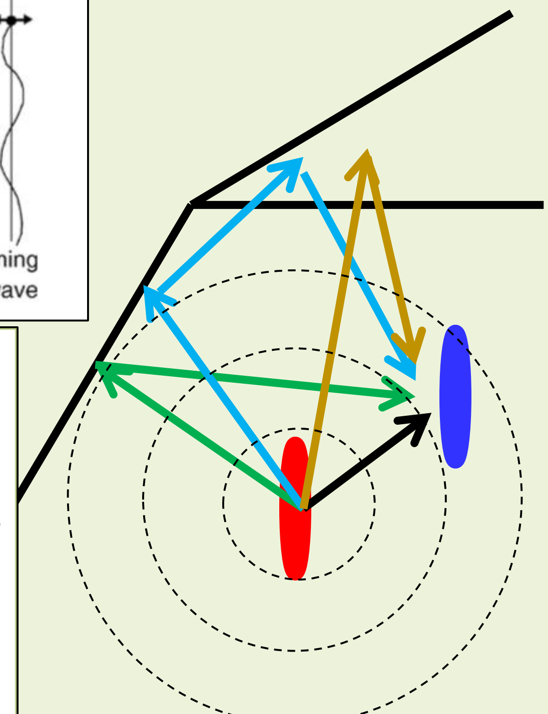
- Slope face acts as reflective boundary
  - ❖ Wave directivity
  - ❖ Wave generation





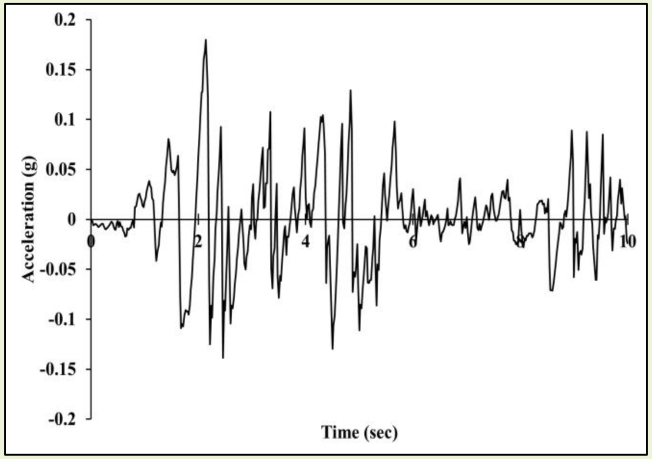


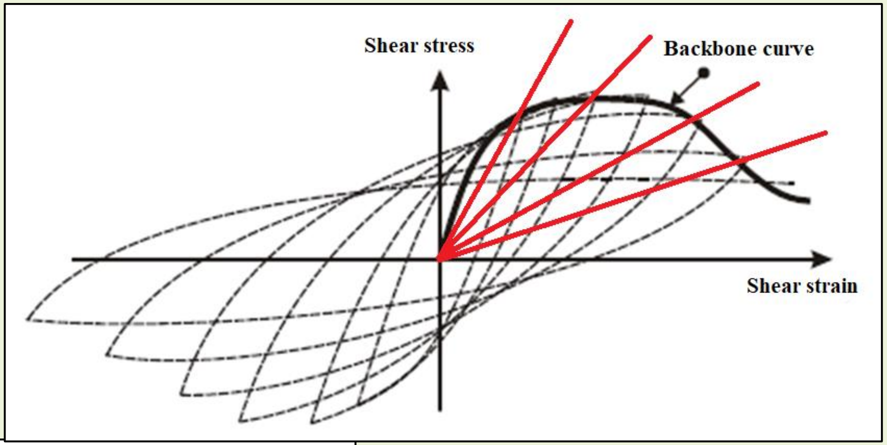


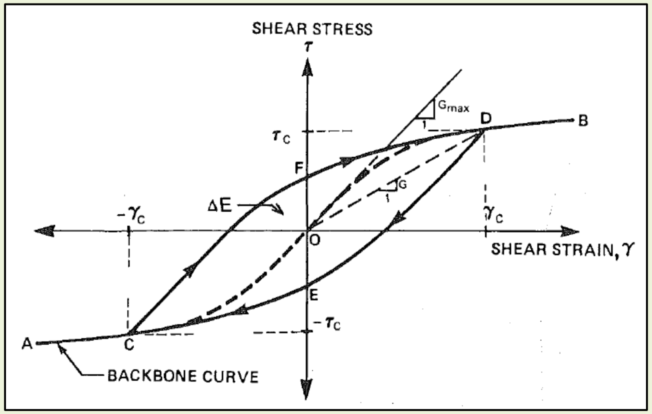


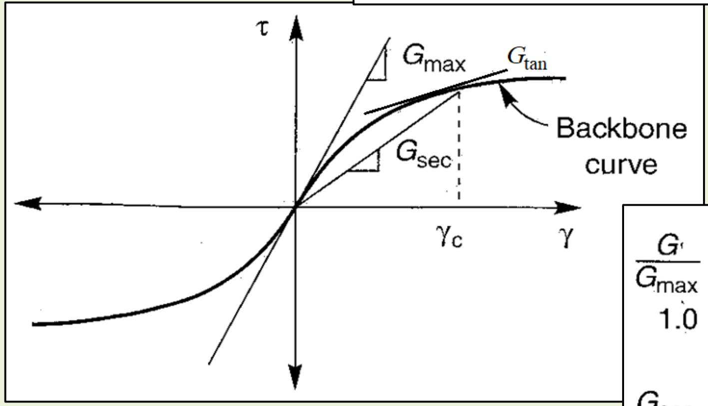
Seismic Slope Stability Analysis

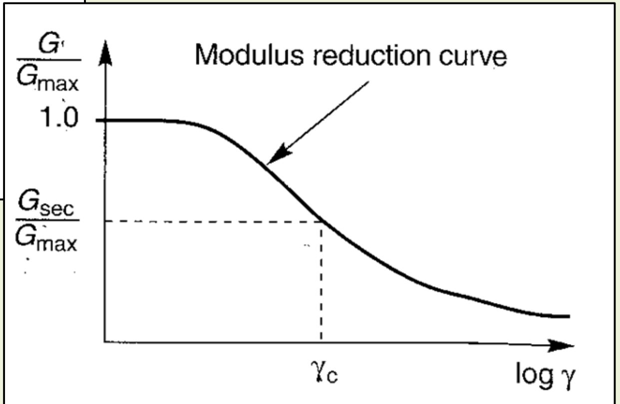
- Equivalent linear and Nonlinear dynamic time-history analysis





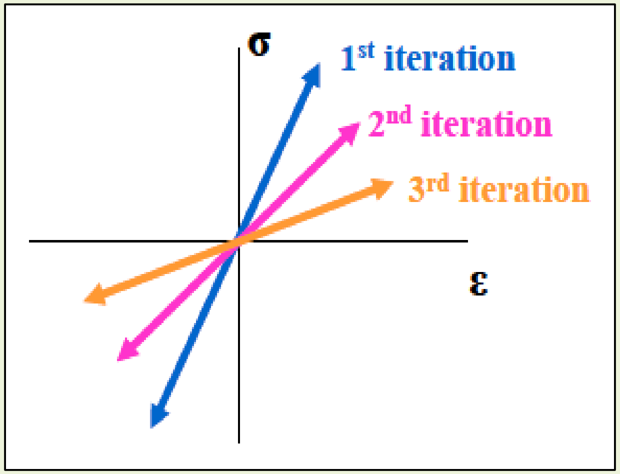


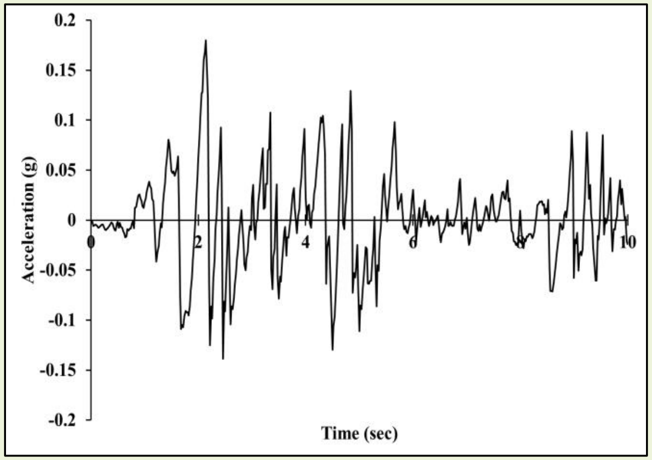


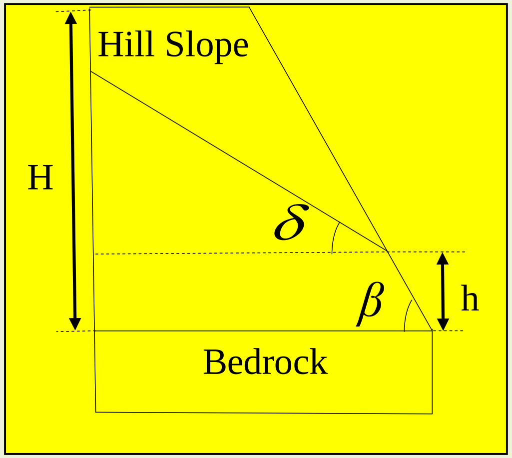


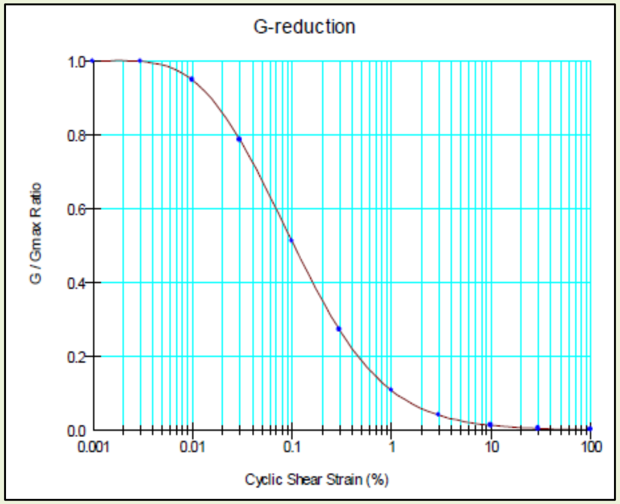
Seismic Slope Stability Analysis

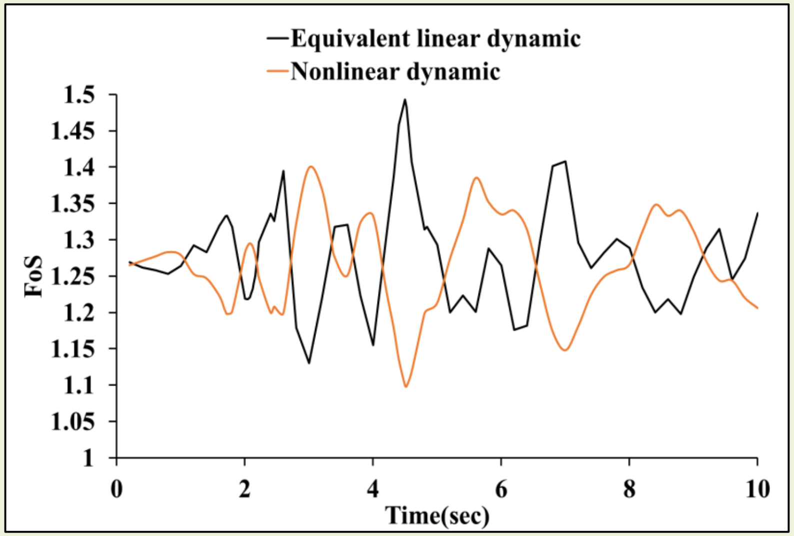
- Equivalent linear and Nonlinear dynamic analysis









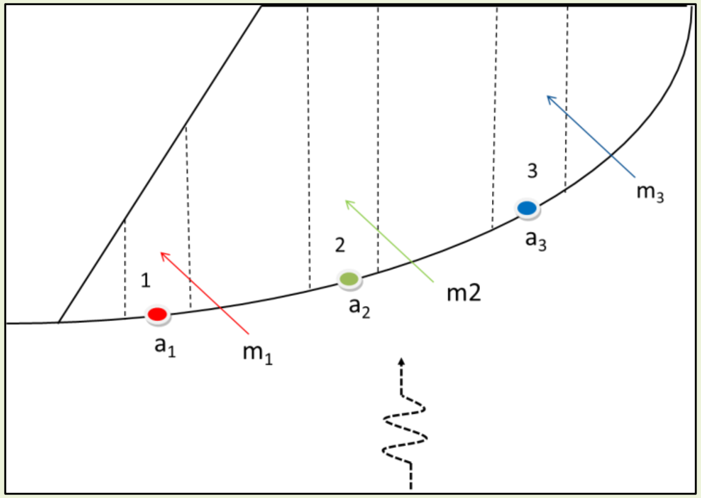


Chakraborty and Dey, EPAM, 2016

Chakraborty and Dey, Local Site Effects and Ground Failures, 2021

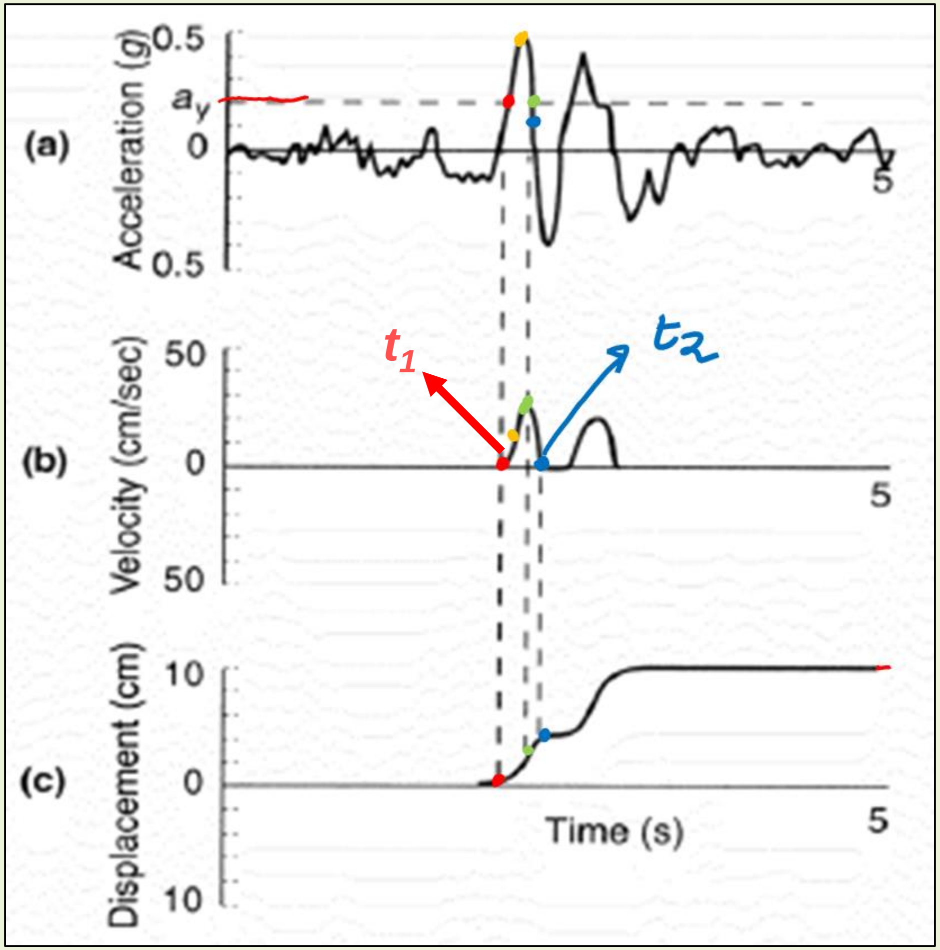
Newmark's Displacement Method

- Identify the displacement of slopes during seismic event
  - ❖ Rigid block failure analysis over a pre-assumed failure surface



$$V = \int_{t_1}^{t_2} a\,dt$$

$$S = \int_{t_1}^{t_2} V\,dt$$

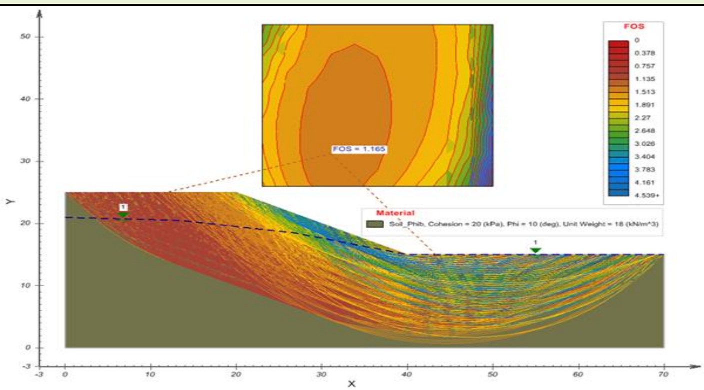


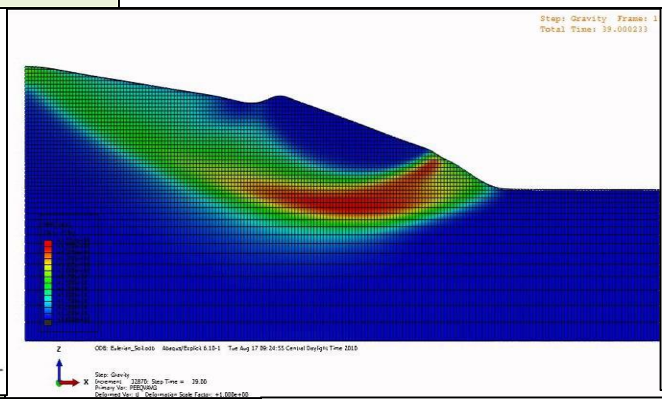
Landslide Analysis

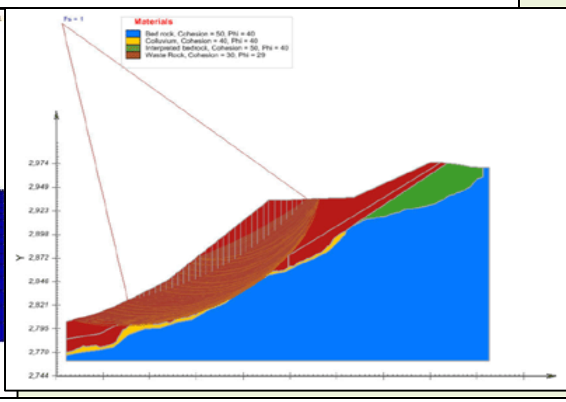
- Continuum Analysis

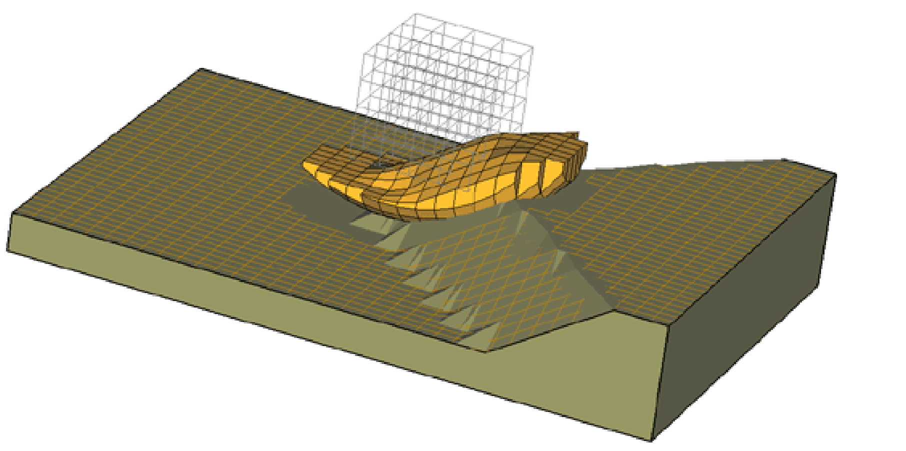
Stress-Deformation Analysis
Continuum Modelling

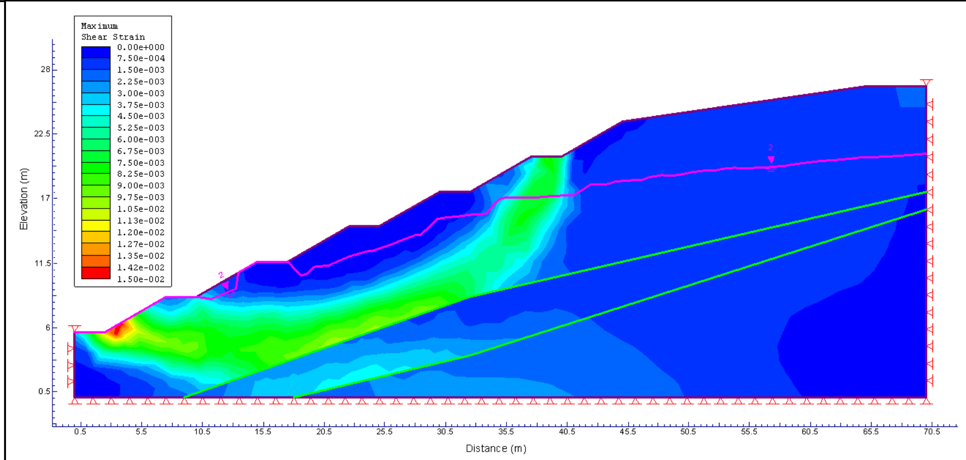
- ➢ Finite Element Method
- ➢ Finite Difference Method
  - Strength Reduction Method (Griffiths and Lane, 1999)
  - Slip Surface Stress Analysis (Wright, 1973)



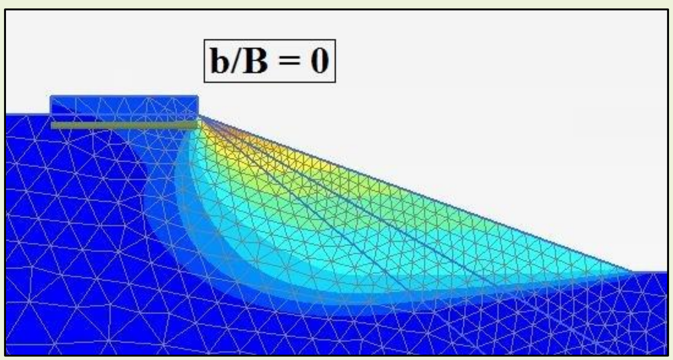


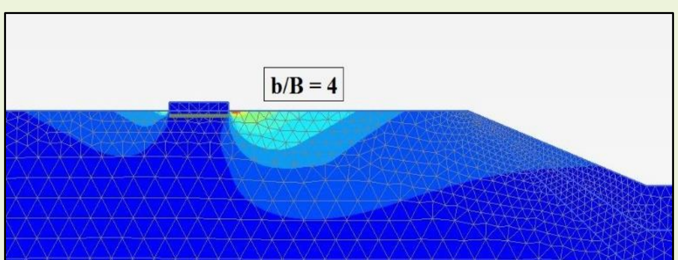


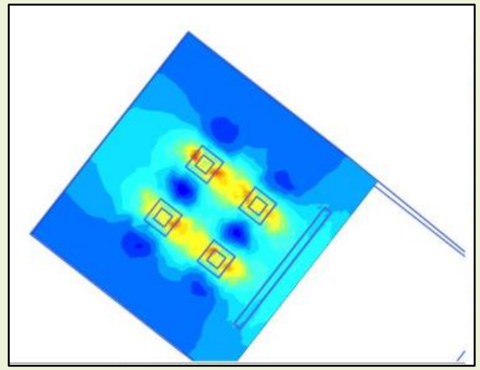


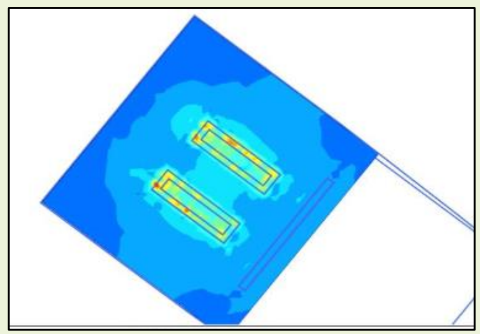


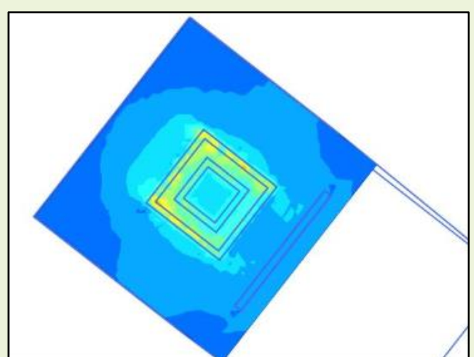
Buildings on Slopes: Foundation Interaction

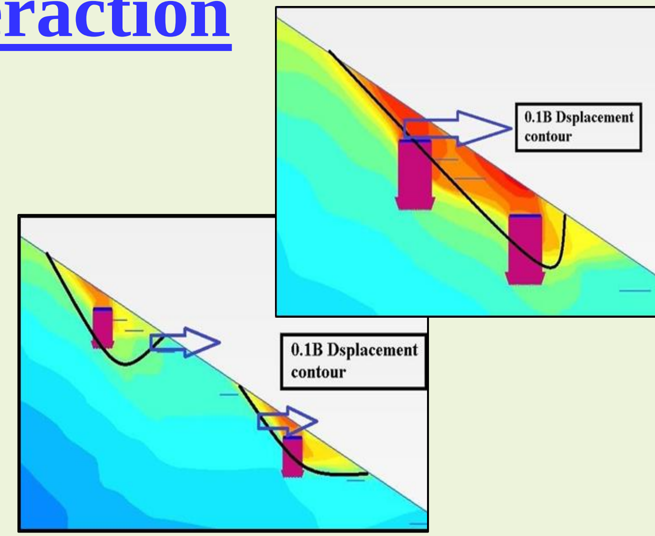


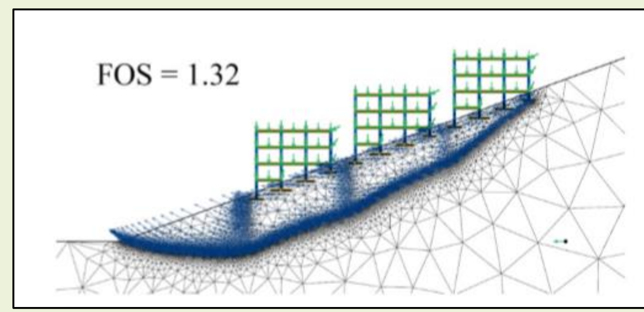


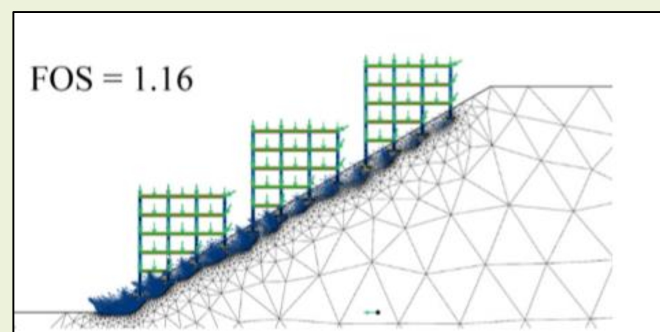












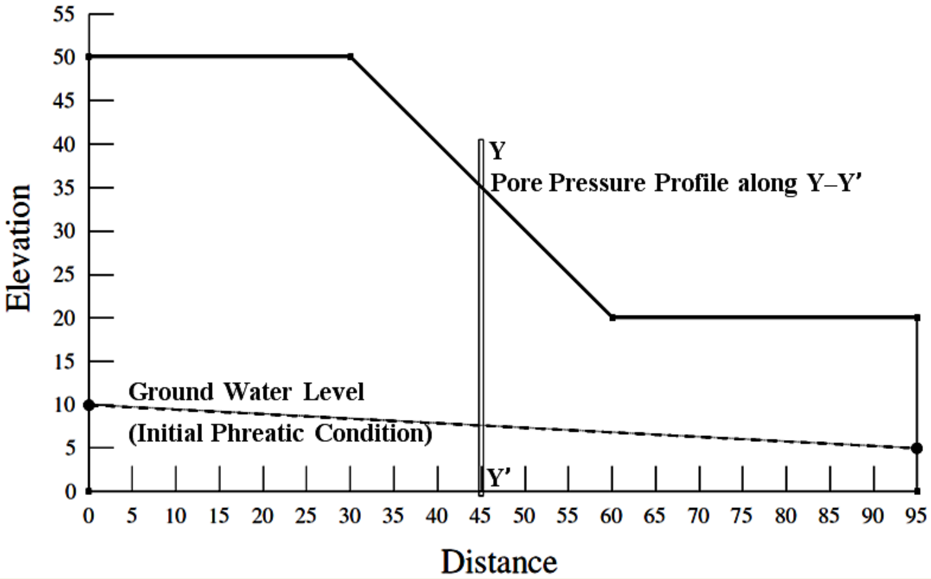
Rainfall Induced Slope Stability Analyses in a Local Scale

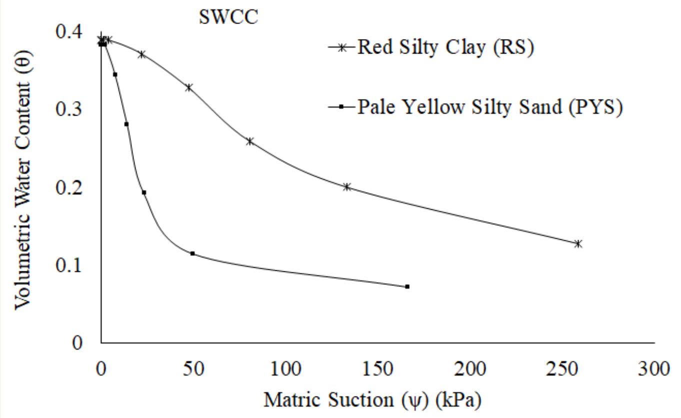
Rainfall Induced Slope Stability

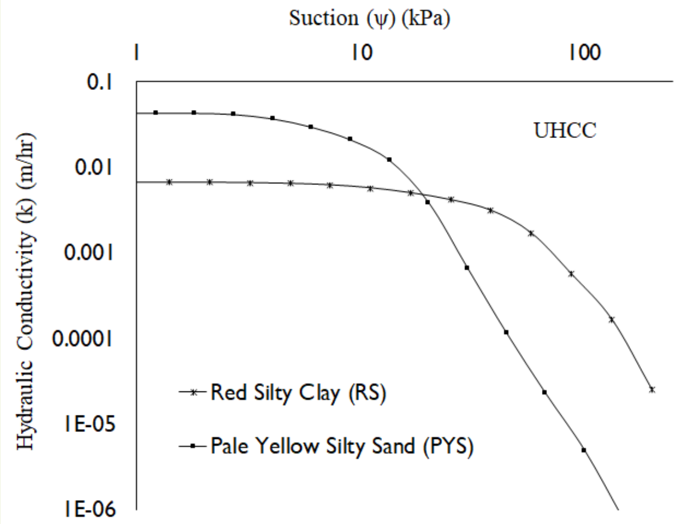
- Involves two steps
  - Transient Seepage Analysis – (SEEP/W) Finite Element Method
  - Slope stability analysis – (SLOPE/W) Morgenstern–Price Method – Limit Equilibrium Method
  - SEEP/W and SLOPE/W – modules of GeoStudio Software Suite (GeoSlope 2007)

Rainfall Induced Slope Stability

- Slope Geometry and Initial in-situ condition
  - Maximum suction to a limit of 80 kPa (in order to resemble the natural water content of the soil)



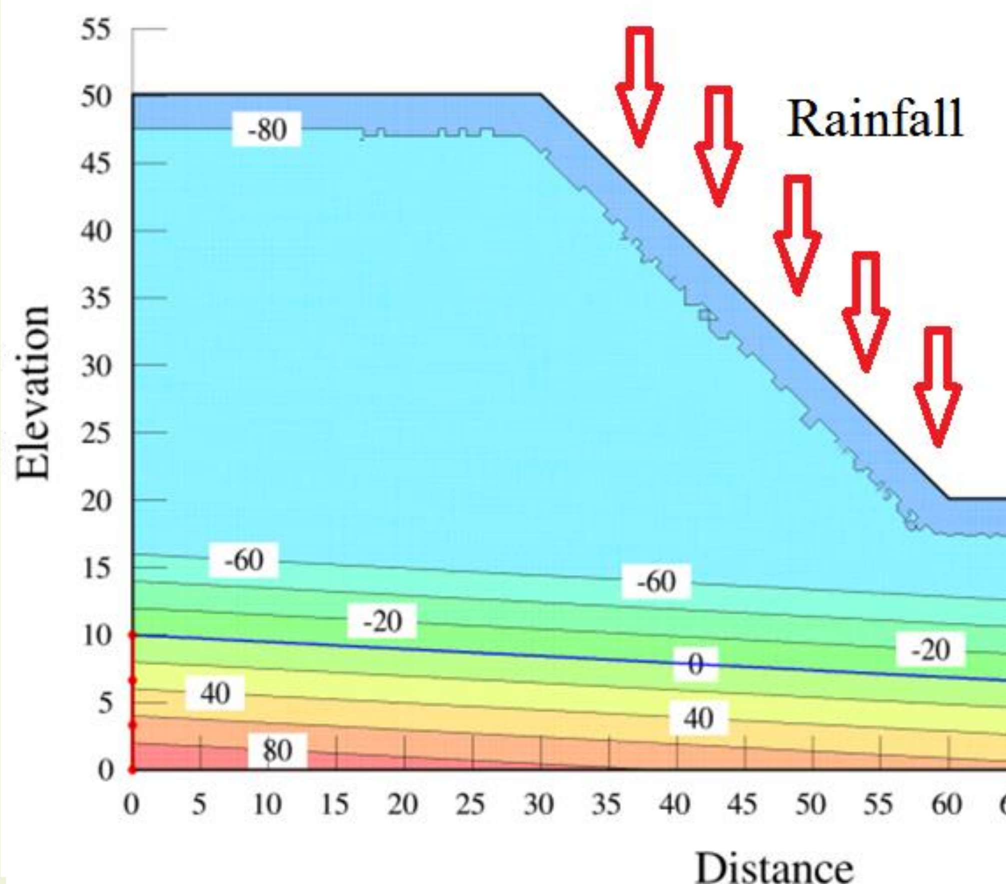




Property	(RS)	(PYS)
Φ'	31°	38.5°
c'	10 kPa	0 kPa
Φ^b	16.7°	7.5°
Residual Saturation	31 %	33 %
Co-efficient of permeability at saturation	1.86×10^{-6} m/s	1.21×10^{-5} m/s

Rainfall Induced Slope Stability

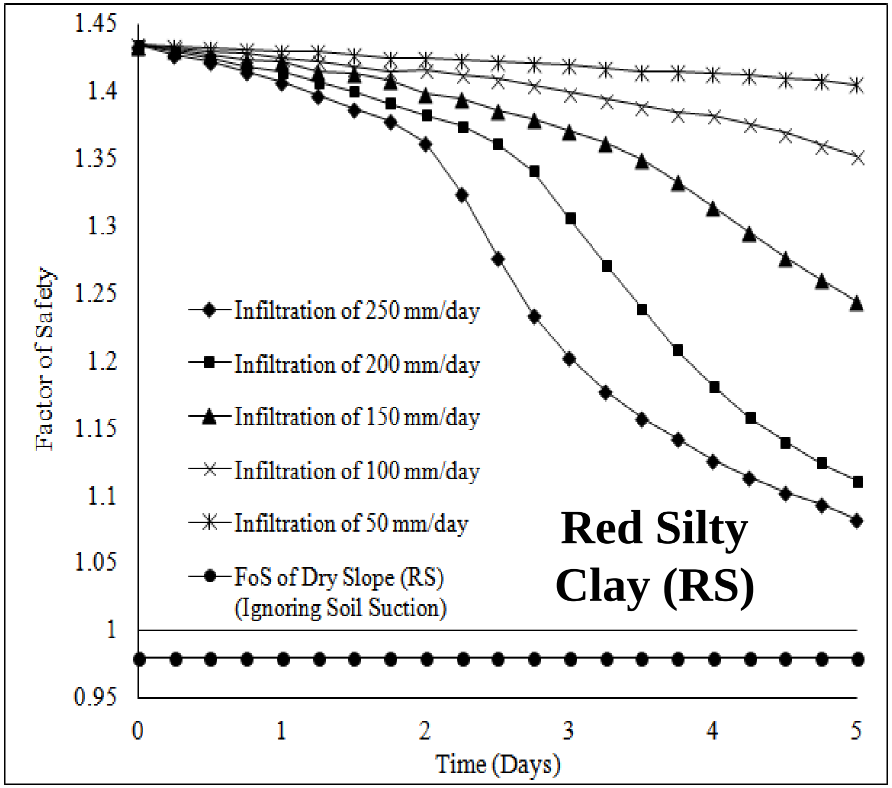
- Slope Geometry and Initial in-situ condition
  - ❖ Maximum suction to a limit of 80 kPa (in order to resemble the natural water content of the soil)



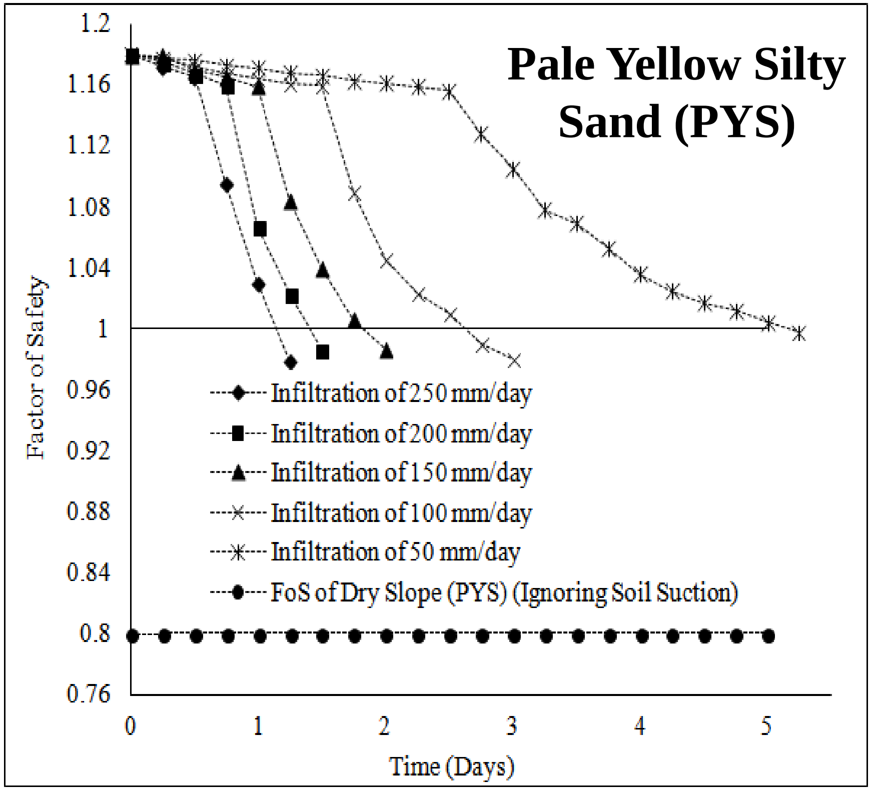
- Applied Infiltration
  - Five different rates of infiltration
    - 50 mm/day
    - 100 mm/day
    - 150 mm/day
    - 200 mm/day
    - 250 mm/day

Rainfall Induced Slope Stability

- Factor of Safety degradation with time



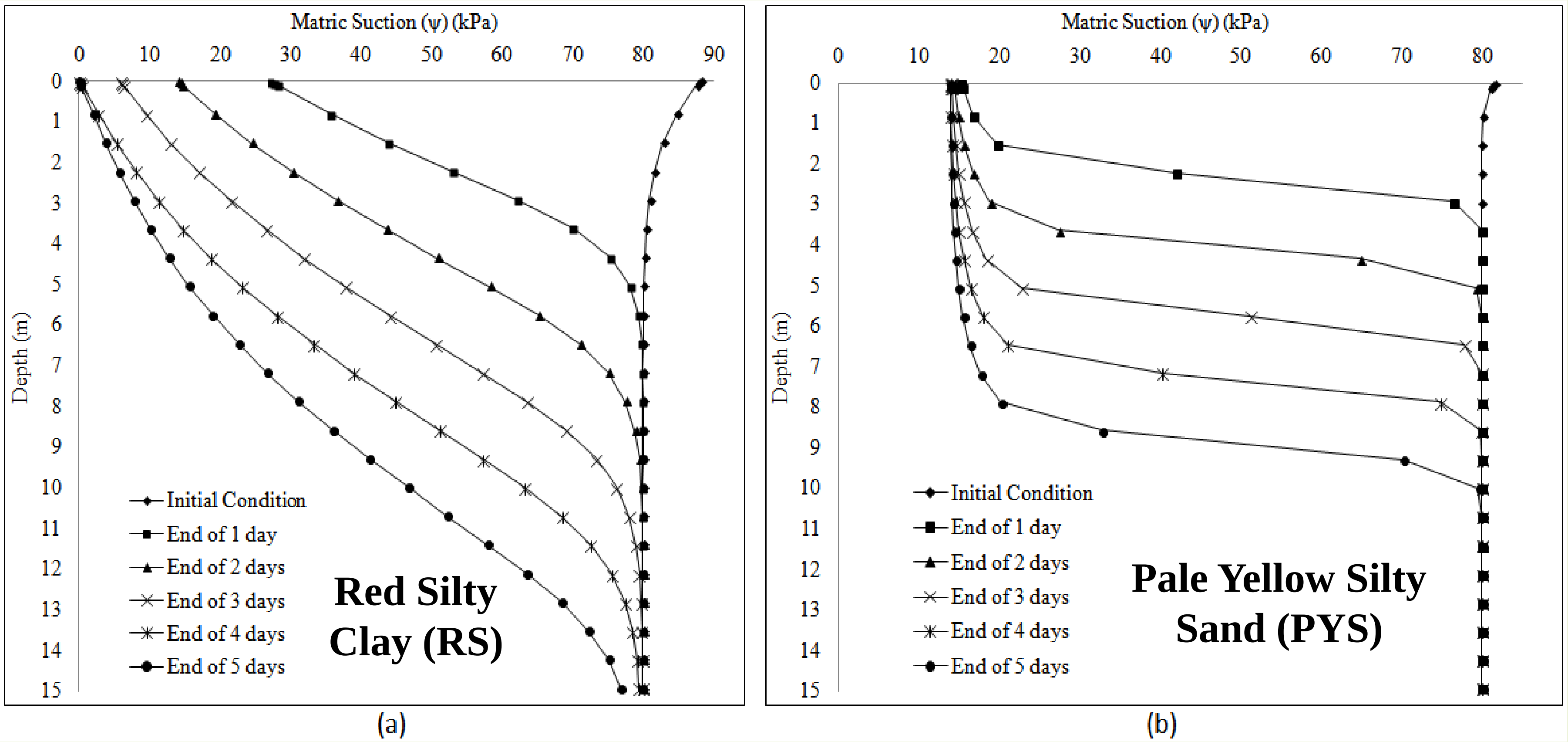
(a)



(b)

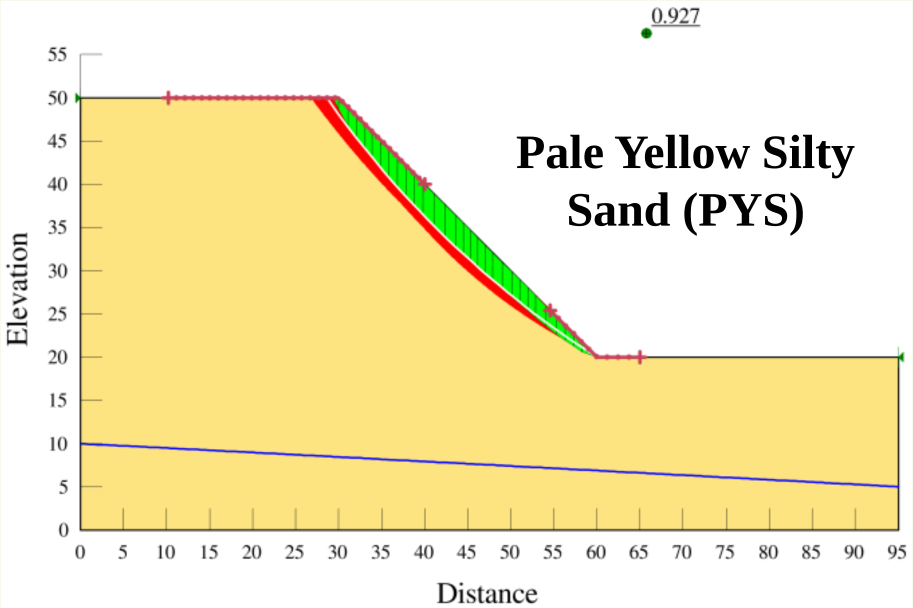
Rainfall Induced Slope Stability

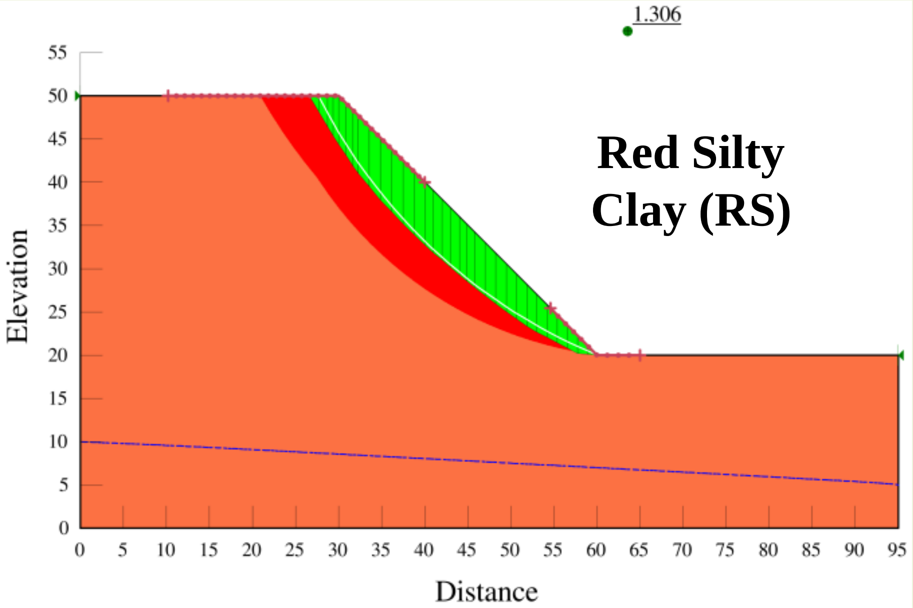
- Pore pressure profile for the two types of soil



Rainfall Induced Slope Stability

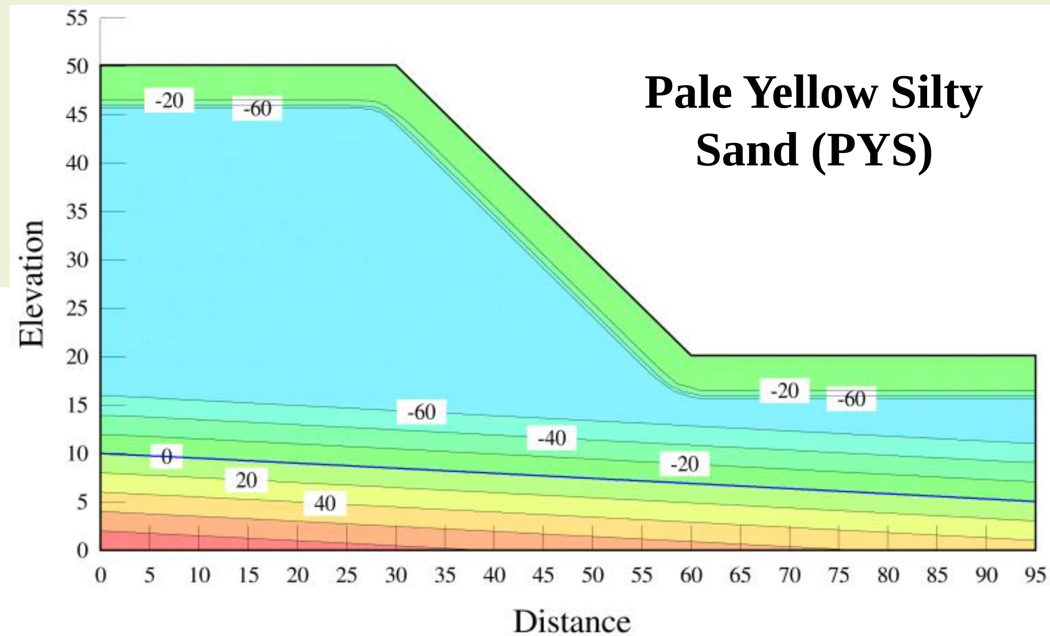
- Factor of Safety

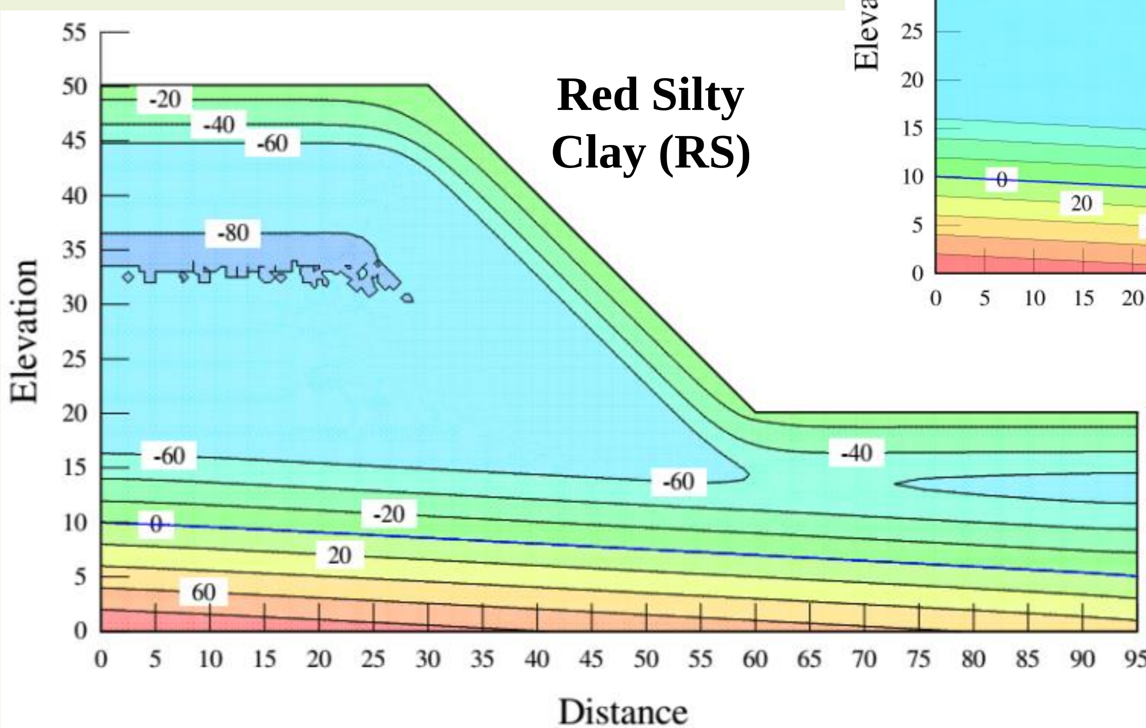




Rainfall Induced Slope Stability

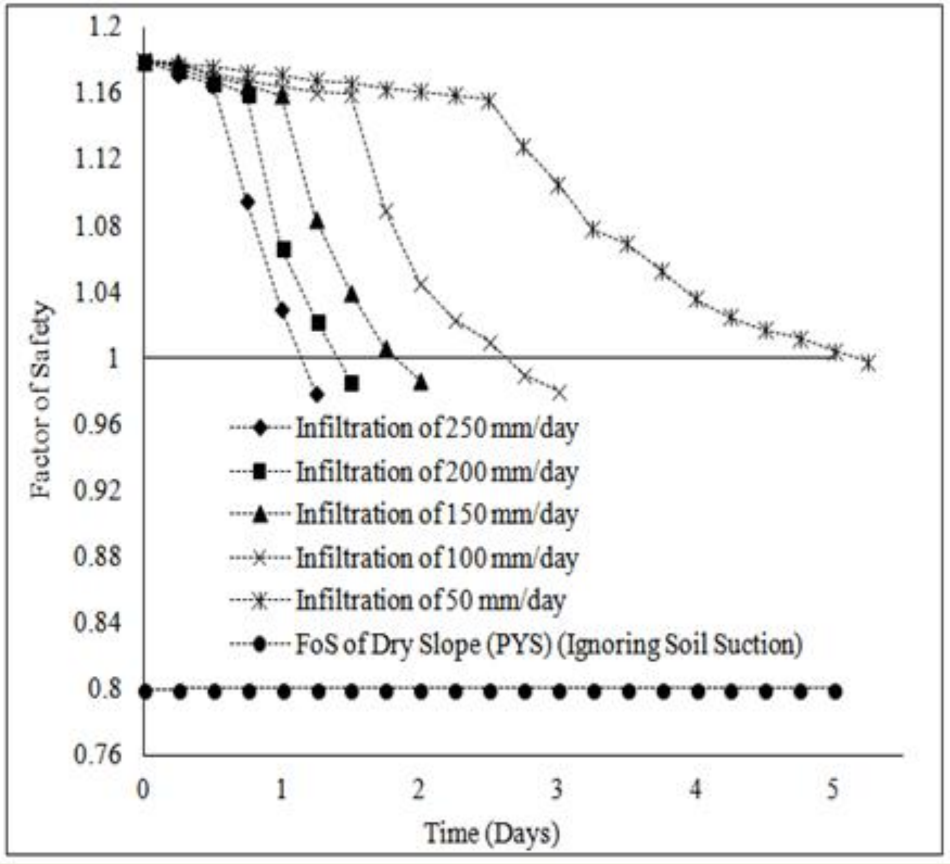
- Pore pressure profile for the two types of soil

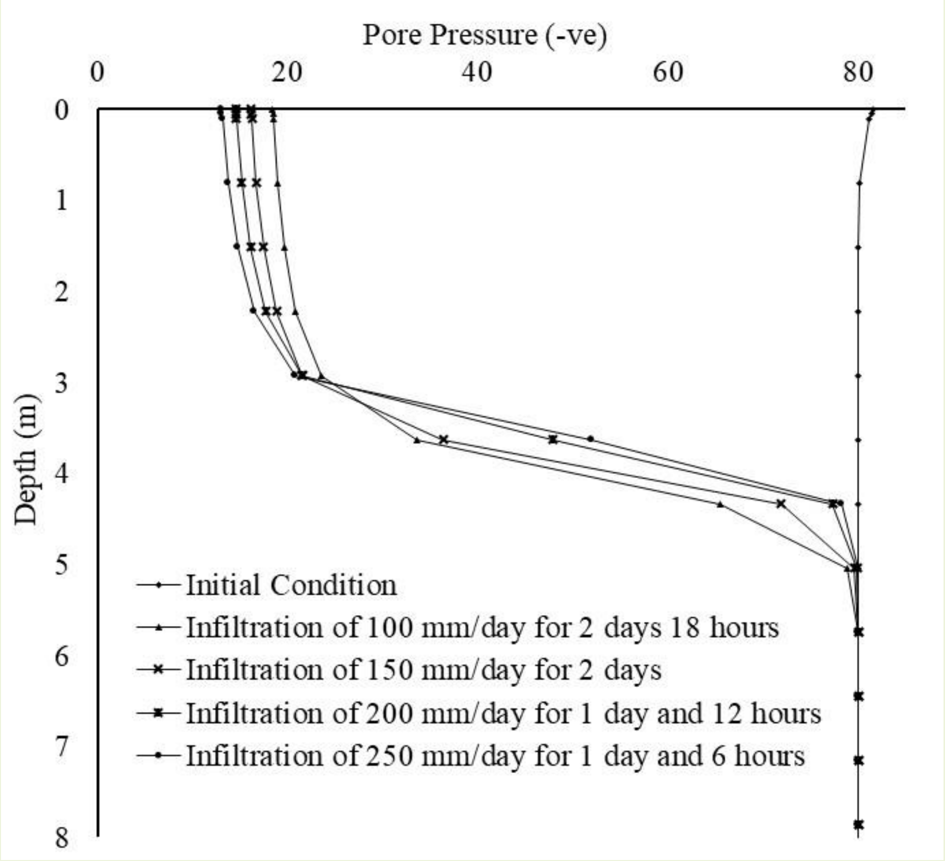




Rainfall Induced Slope Stability

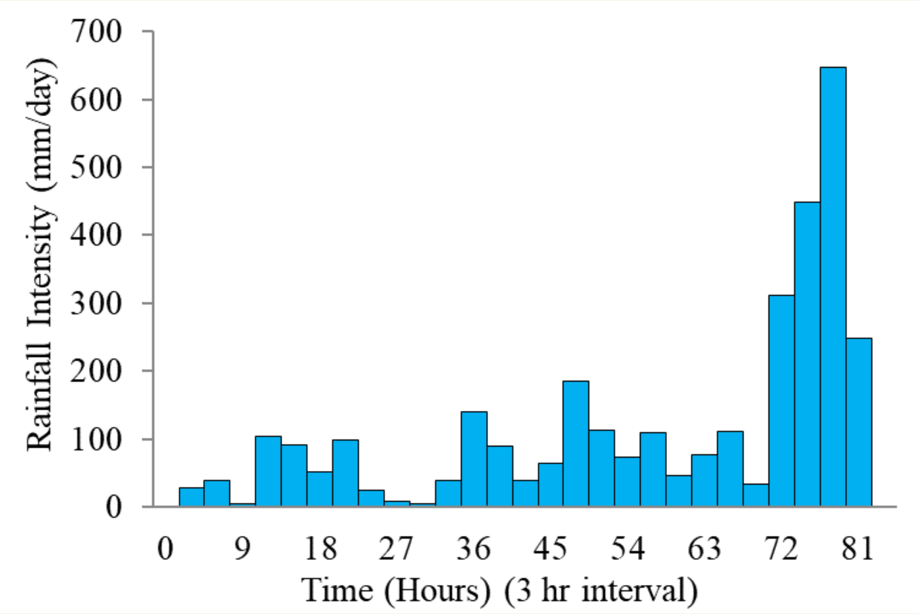
- Factor of Safety degradation with time and the pore pressures developed at the moment of the failure

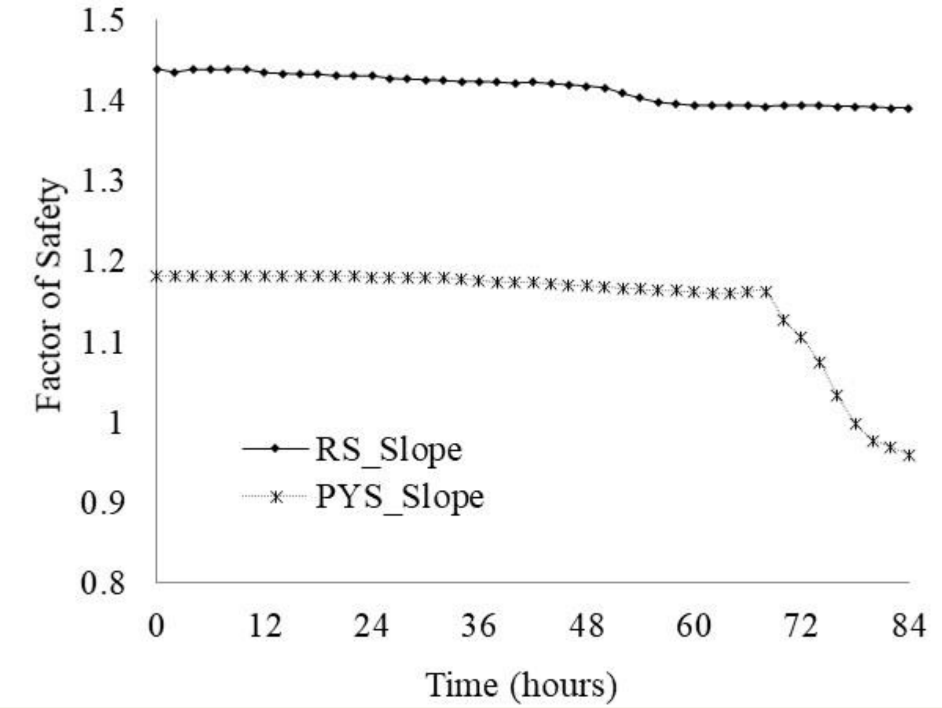




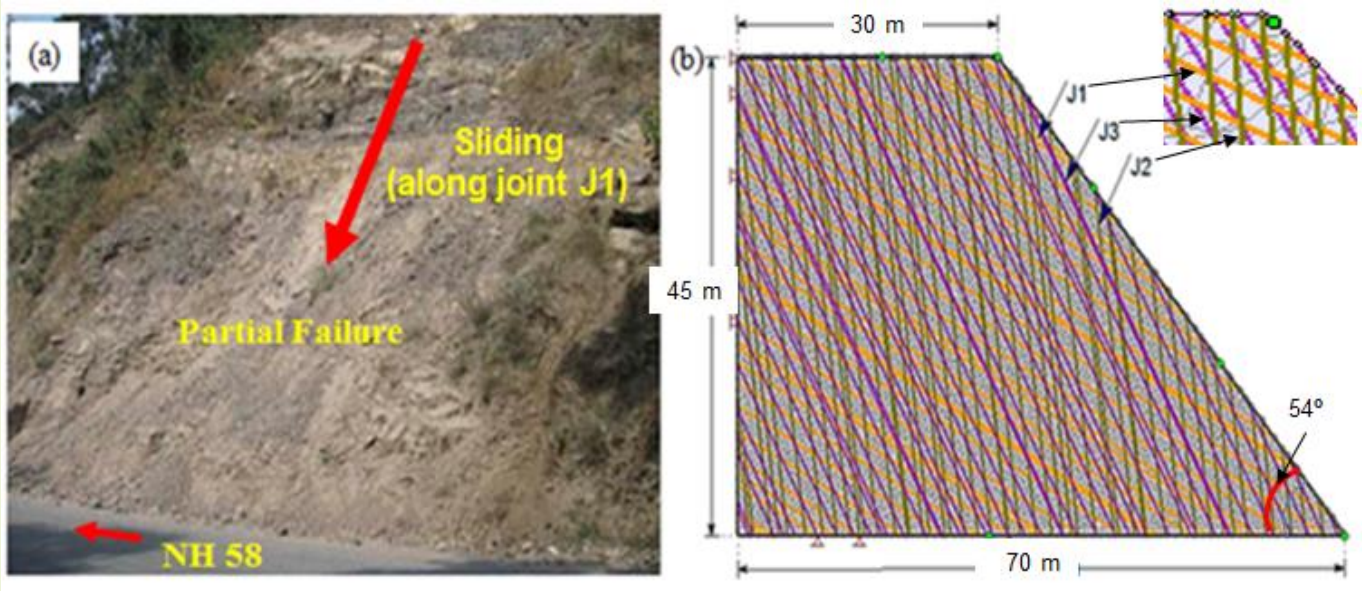
Rainfall Induced Slope Stability

- Factor of Safety degradation with time and the pore pressures developed at the moment of the failure

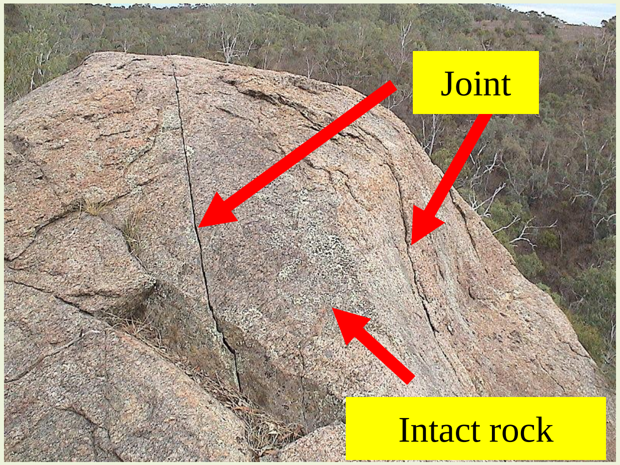


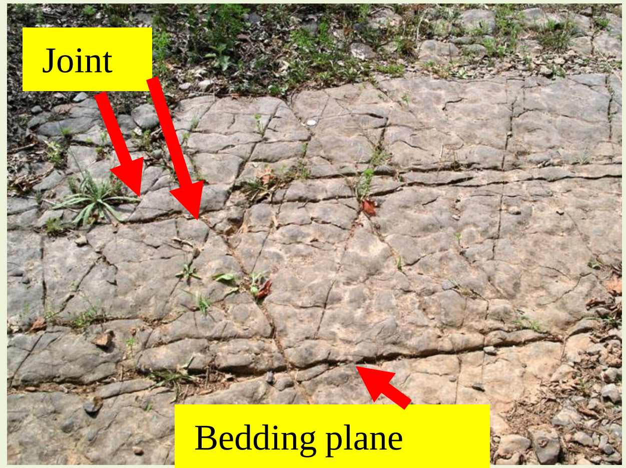


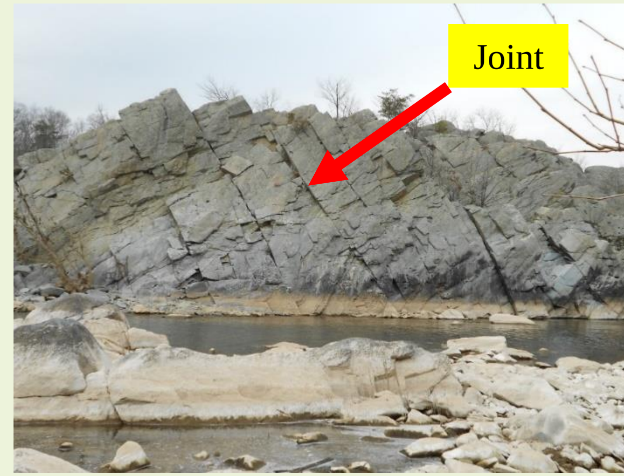
Rock Slope Stability Analyses



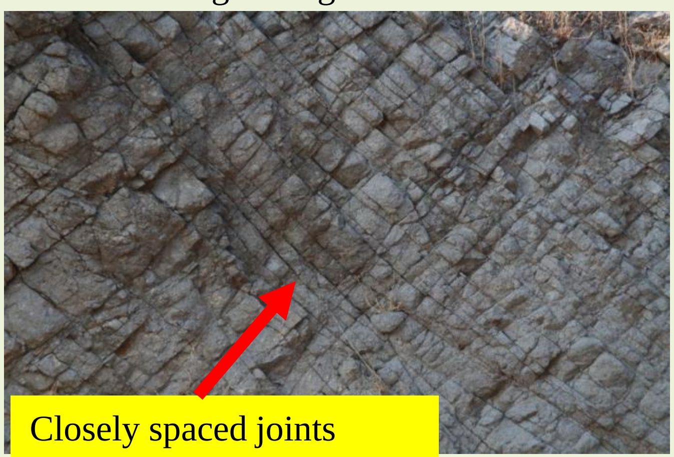
Discontinuity In Rock: Complex Structure



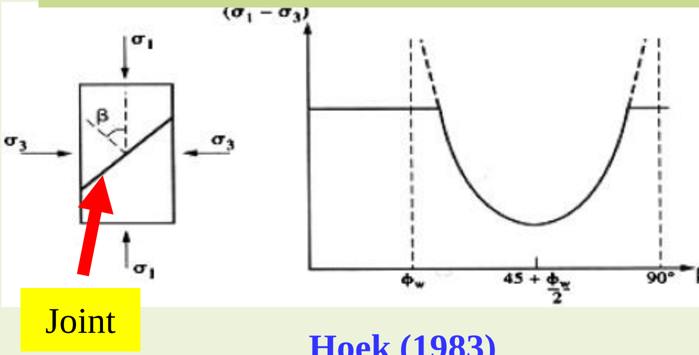




Source: Google image

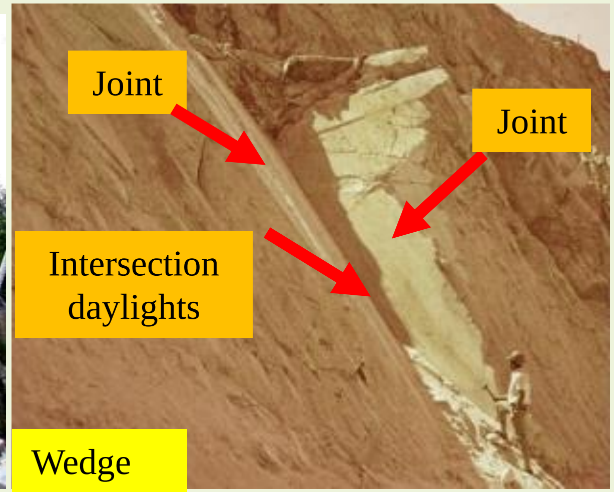


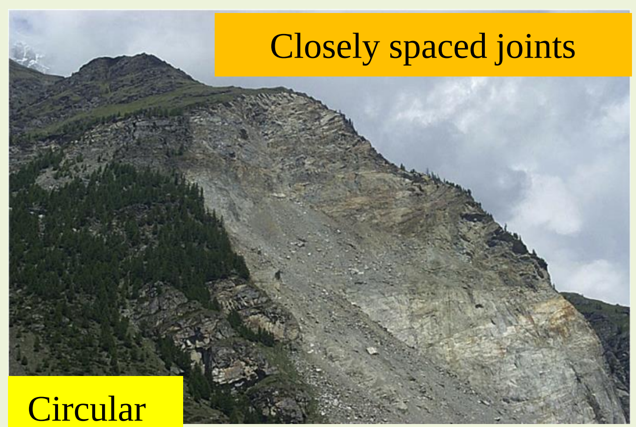
Anisotropic response of joint

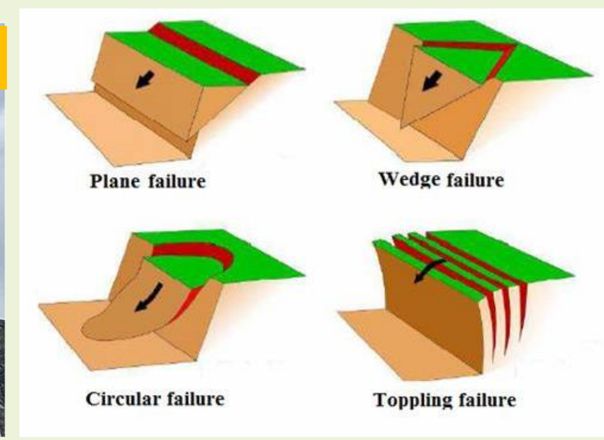


Hoek (1983)

Rock Slope Failure: An Intricate Mechanism







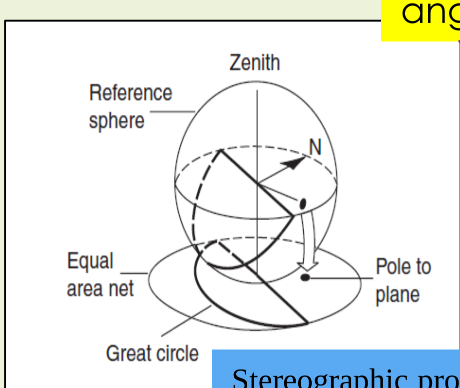
Rock Slope Stability Analysis

Rock slope stability analysis

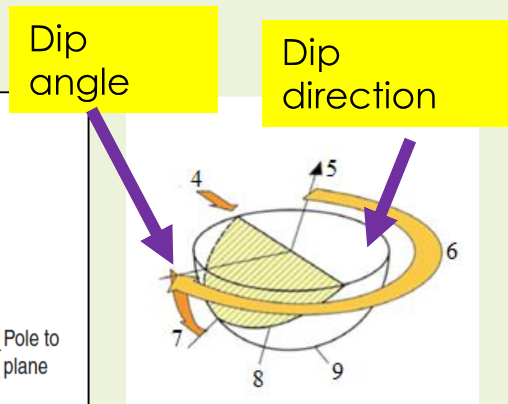
- **Conventional method**
  - **Kinematic analysis**
    - Setreonet plot
    - Friction cone
  - **Limit equilibrium analysis**
    - Planar sliding
    - Wedge analysis
    - Slip surface
- **Numerical method**
  - **Continuum modeling**
    - Finite element
    - Finite difference method
  - **Discontinuum modeling**
    - Discrete element
    - Discontinuum deformation
    - Hybrid modeling

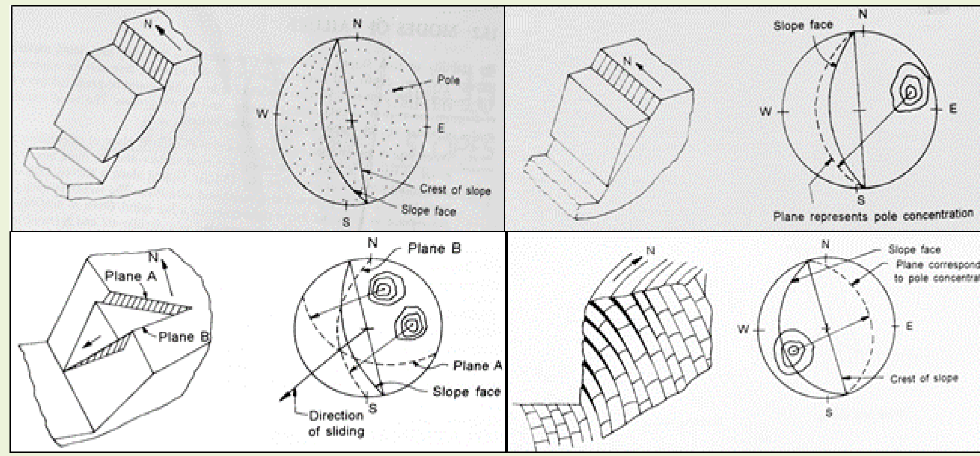
Kinematic Approach

- Possibility of translational failures to the formation of daylighting wedges or planes

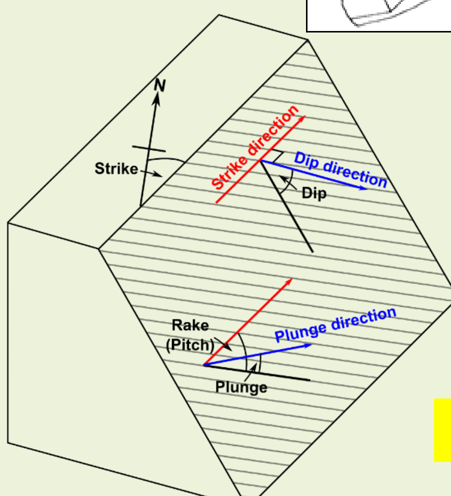


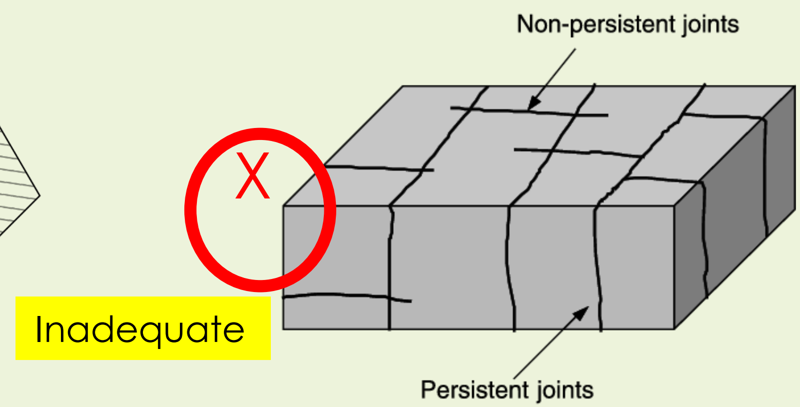
Stereographic projection





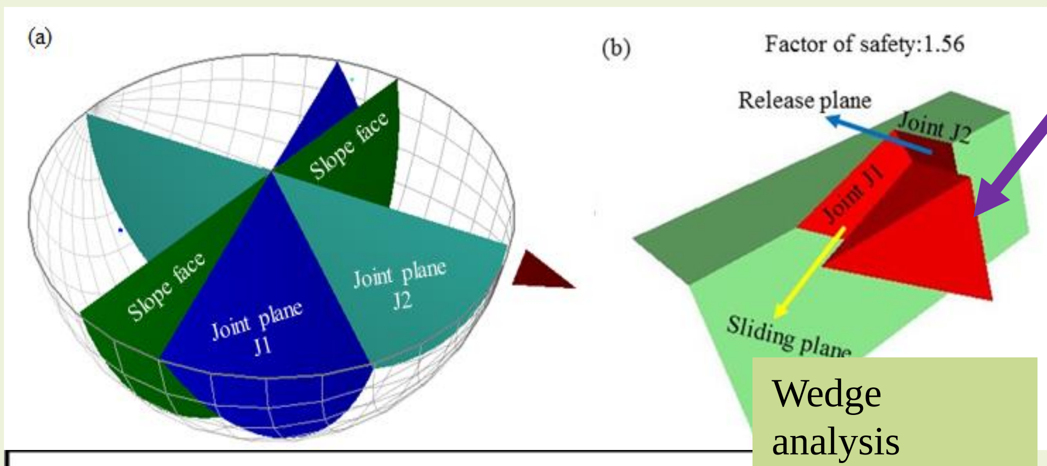
Wyllie and Mah, 2004

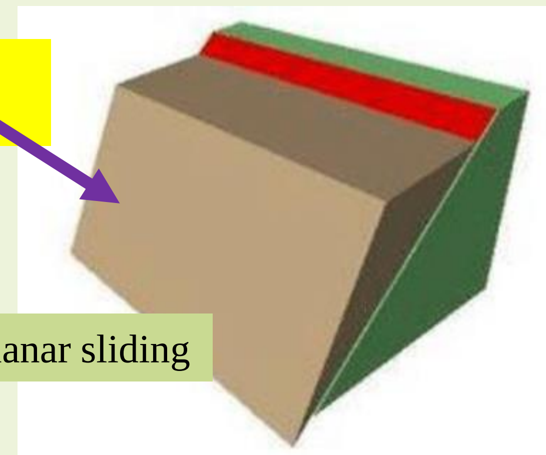


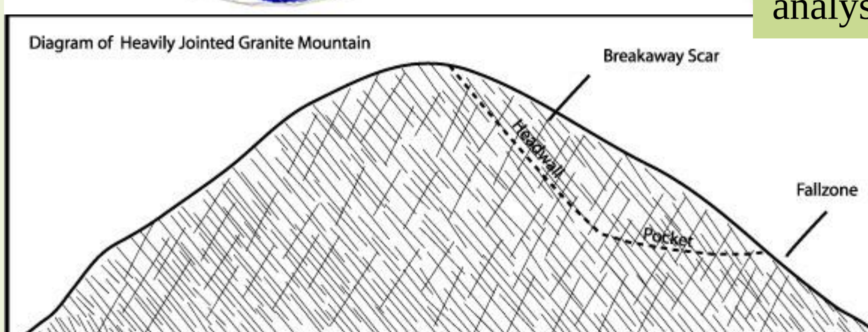


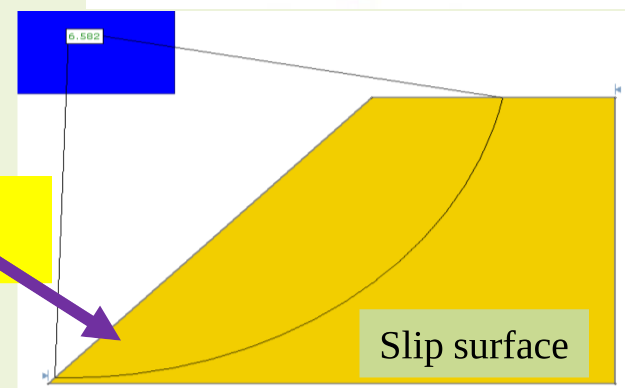
Limit Equilibrium Method

- Assumptions in this method:
  - ❖ FOS same along the predefined surface;
  - ❖ Rigid body above the slip surface;
  - ❖ Joint persistence and spacing are neglected
  - ❖ Intricate internal deformation and fracturing neglected in 2-D rigid block





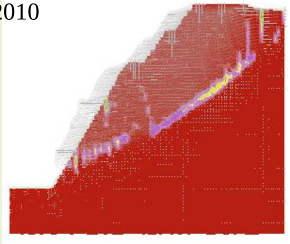


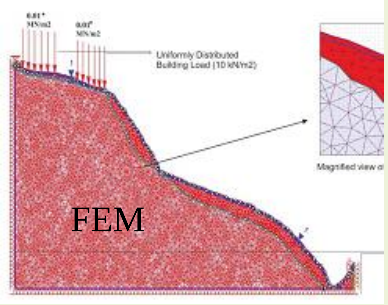


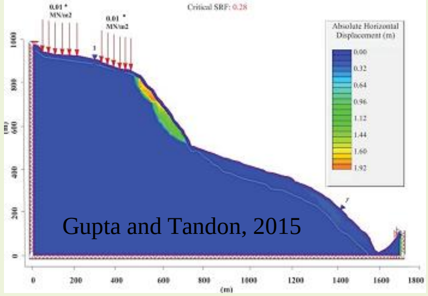
Continuum or Equivalent Continuum Approach

- Finite-difference and finite element methods
  - ❖ Equivalent continuum method used
  - ❖ Estimation of equivalent rock mass parameter
  - ❖ Homogeneous system
  - ❖ Shear strength reduction technique used to get FOS
  - ❖ Appropriate for the analysis of rock slopes that are comprised of **massive intact rock**, **weak rocks, or heavily fractured rock masses**

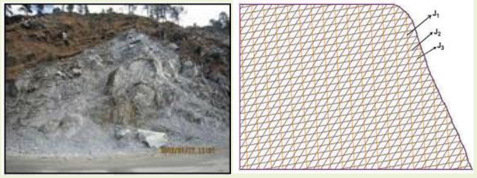
Latha and Garaga, 2010

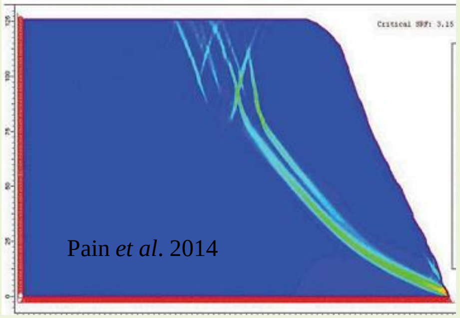






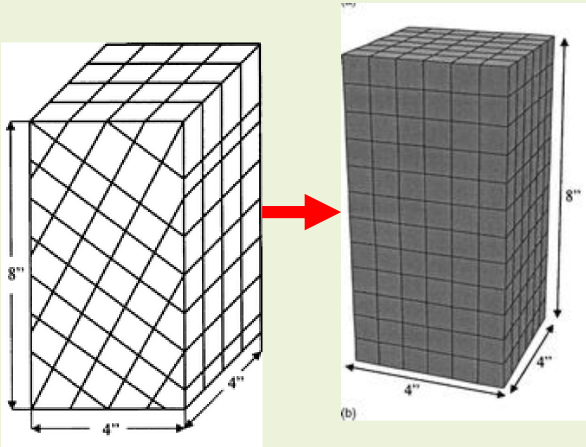
Gupta and Tandon, 2015





Pain *et al*. 2014

Equivalent continuum method



Jointed model to Rock mass

Discontinuum Modeling

- For blocky rock slopes, structural failure occurs due to anisotropy created by the joints,
- Discontinuum deformation analysis (DDA) and Discrete element method (DEM) are useful to predict the behavior of jointed rock slopes
- Consideration of stress-strain interactions, with the incorporation of explicit joints.

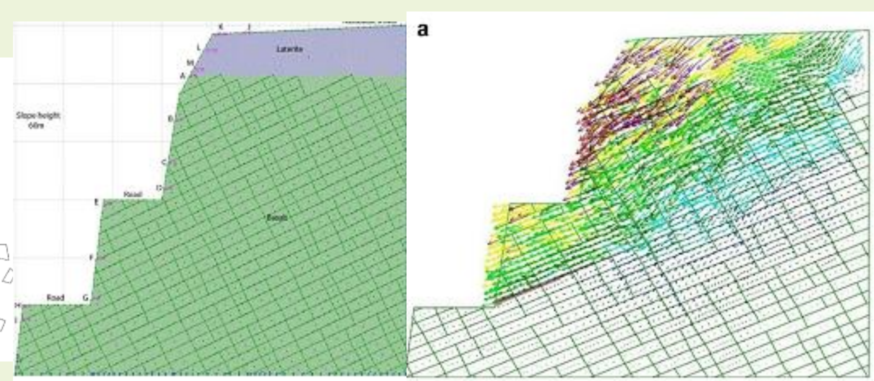
DDA formulated by **Shi and Goodman (1985, 1989)**

- working principle of DDA similar to FEM
- Isolated blocks are bounded by discontinuities to represent the jointed slope
- Advantage of being able to model large deformations and rigid body movements

Distinct element method developed by **Cundall (1971)**

- Treat a discontinuous rock mass as an assembly of quasi-rigid, and later deformable, blocks
- Interacting through deformable joints of definable stiffness
- Proficient of simulating large displacements due to slip, or opening

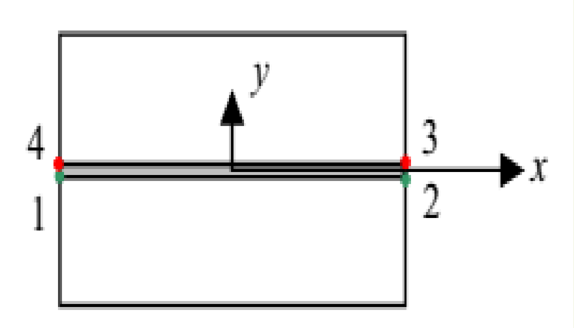
Hatzor et al. (2004)

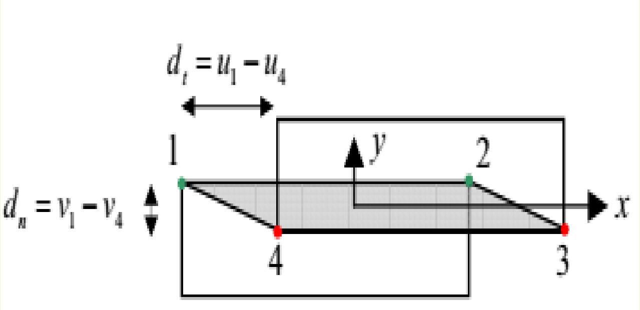


Kainthola et al. (2015)

Explicit Joint Element Model (Goodman *et al*., 1968)

- Zero thickness
- Rectangular element
  - Four nodes and eight degrees of freedom
- Normal displacement and tangential displacement
- Interface stresses related to relative displacements governed by constitutive relation
- Uncoupled tangential and normal stiffness. The shear and normal deformations are independent of each other
- If the joint normal stress is tensile in any element both stiffness is set equal to zero for the element.
  - This simulates opening of the joint.
- If the joint shear stress exceeds the shear strength then relative displacement occurs



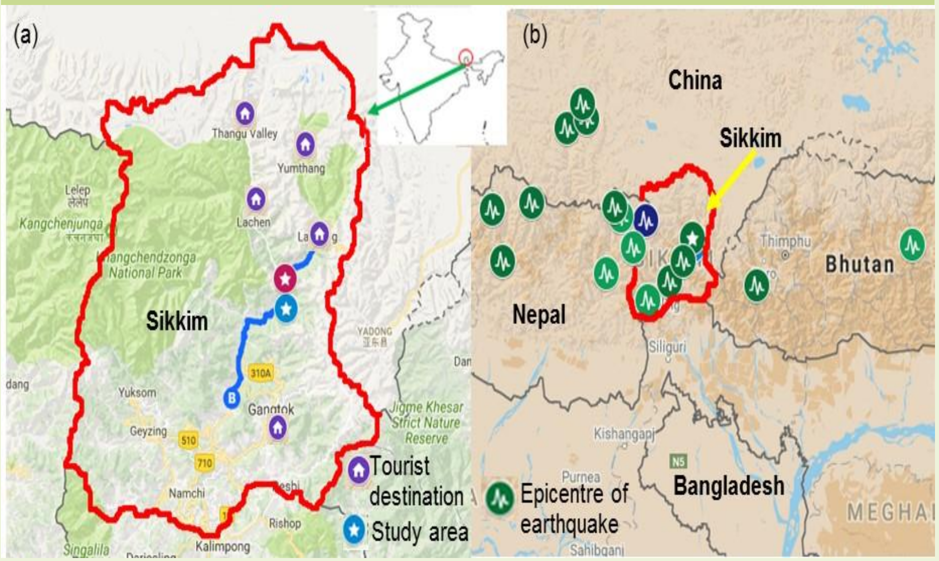


Static Stability Analysis of Jointed Rock

- A Sikkim Himalayan case study: North Sikkim Highway

IMPORTANCE OF STUDY AREA

North Sikkim Highway is one of the major transportation corridors

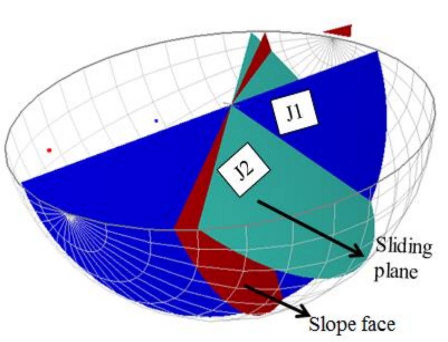


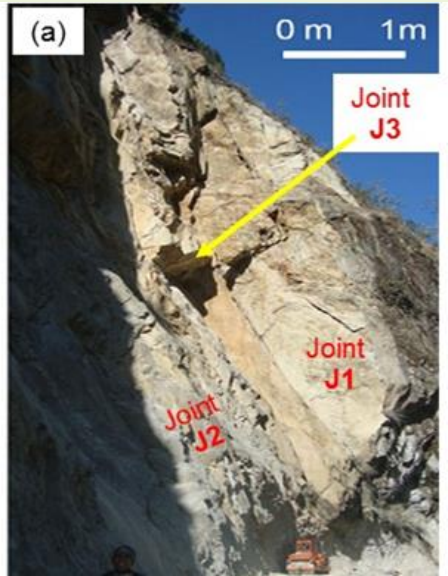
Sikkim earthquake (18th September 2011), 500 landslides were observed along this highway (Mahajan et al., 2012)

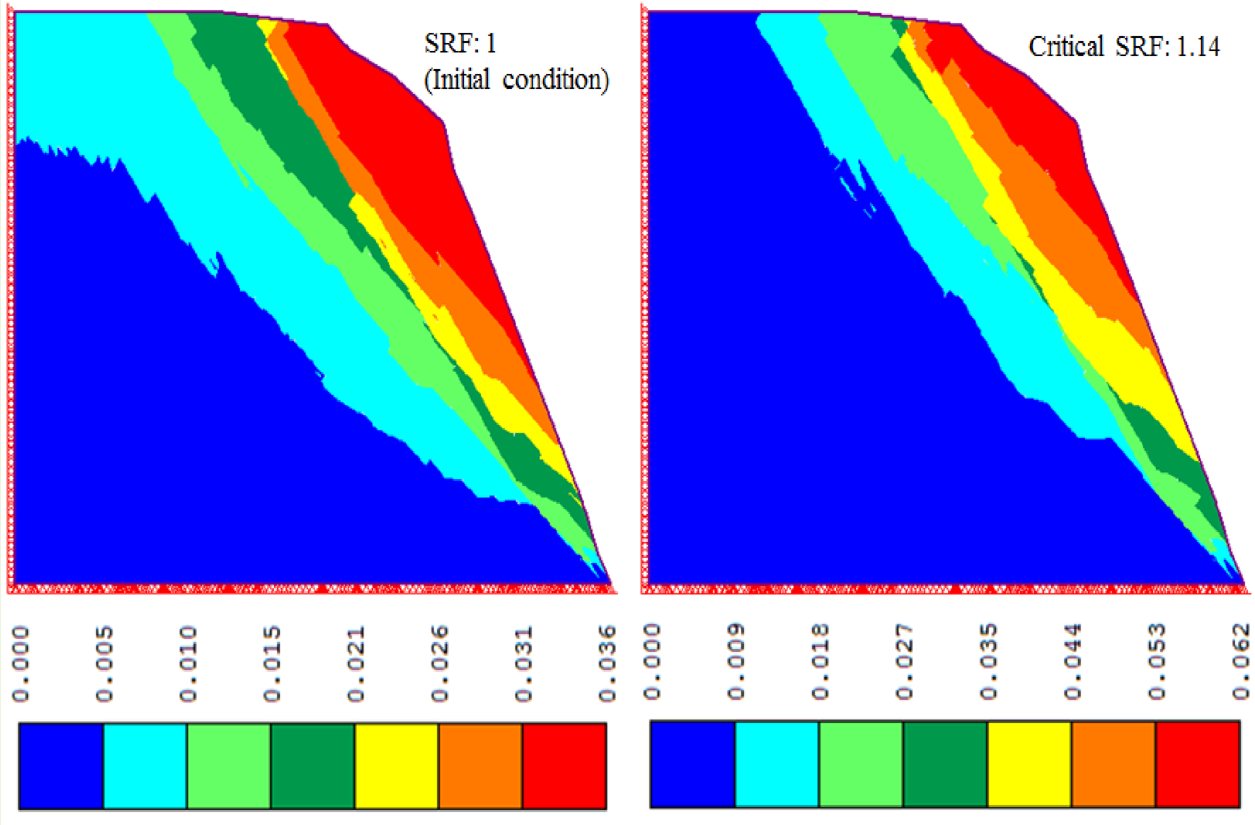
Shear Strength Reduction Technique to Assess SRF

$$c_f = \frac{c}{SRF} \qquad \phi_f = \tan^{-1}\left(\frac{\tan\phi}{SRF}\right)$$

Critical SRF 1.14 is less than minimum FOS of 1.5 **(Hoek and Bray, 1981)**







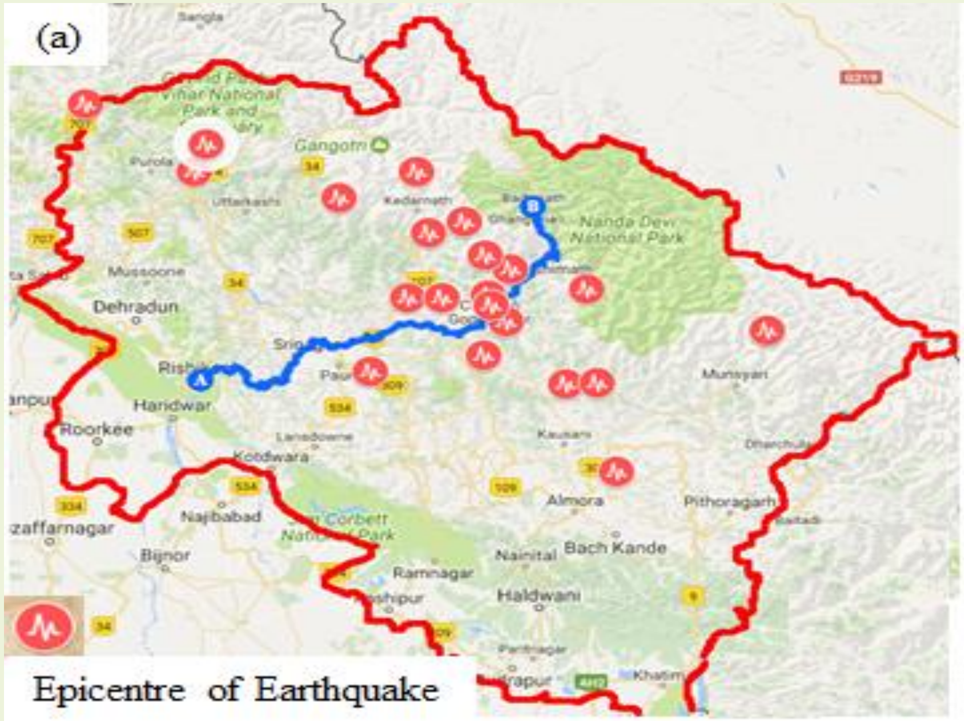
Dynamic Stability Assessment of Jointed Rock Slope

- A Garhwal Himalayan case study: National Highway-58

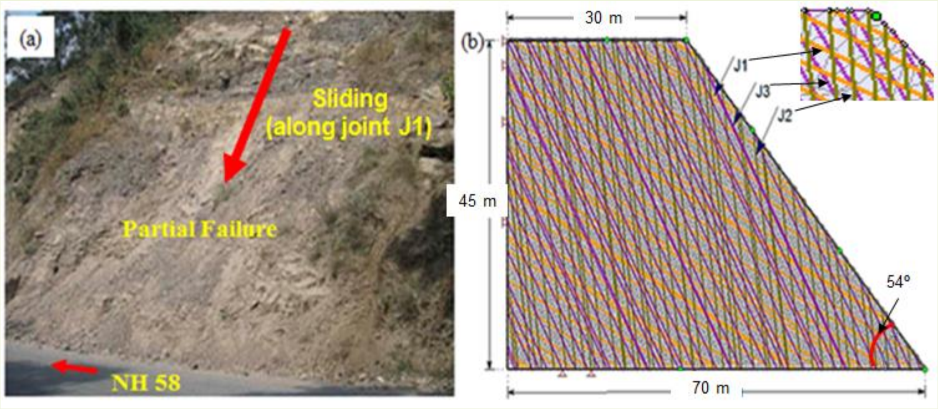
IMPORTANCE OF STUDY AREA

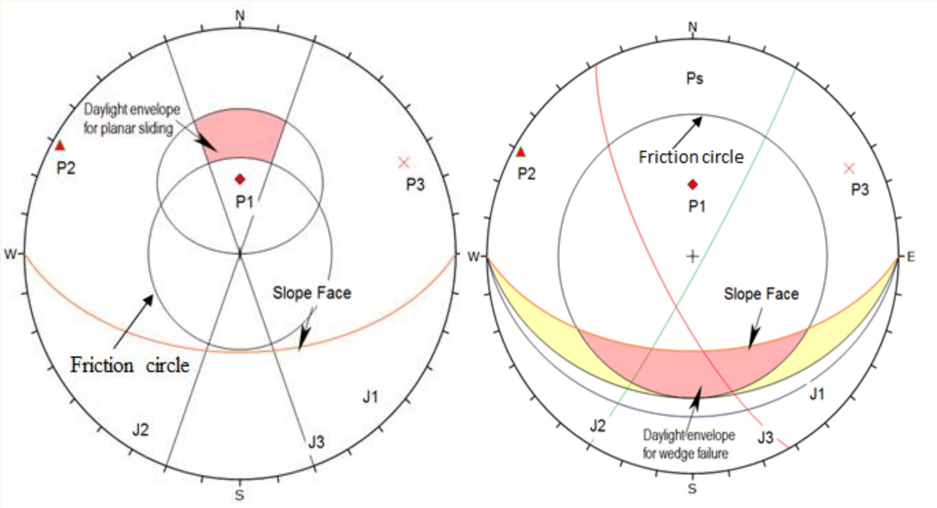
National Highway-58 in Uttarakhand, India is one of the major roads in western Himalayas

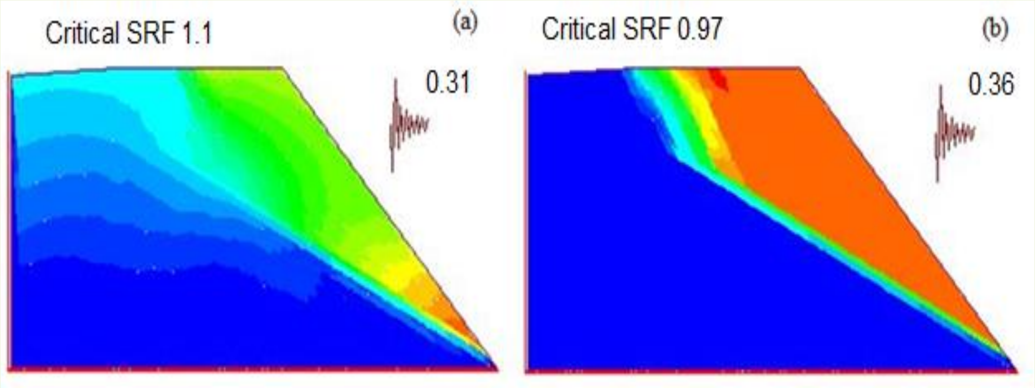
Earthquake history of Uttarakhand showing location of seismic epicenters



Pseudo-Static Slope Stability Analysis





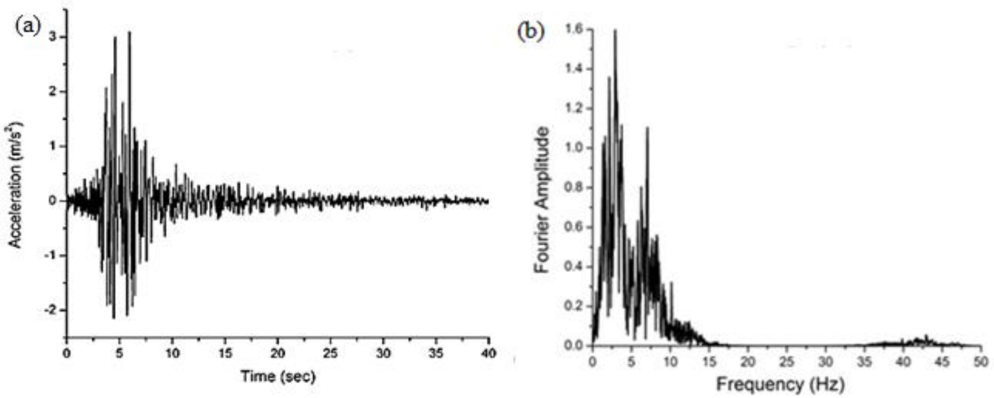


k_h (g)	0 (Static)	0.15	0.2	0.31	0.36
SRF	1.78	1.4	1.27	1.10	0.97

Jointed rock slope is vulnerable to failure when subjected to Maximum Credible Earthquake (MCE) for the region.

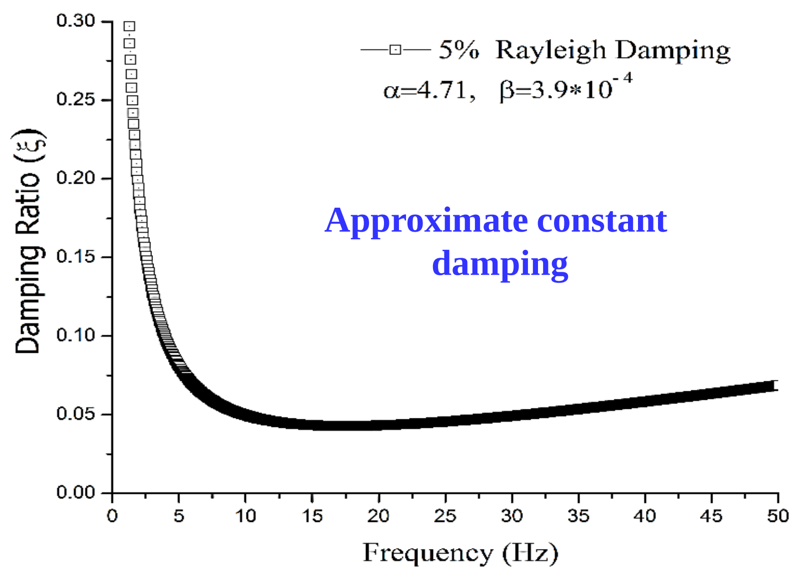
Time History Analysis

Dynamic loading: Uttarkashi earthquake (16th October 1991)

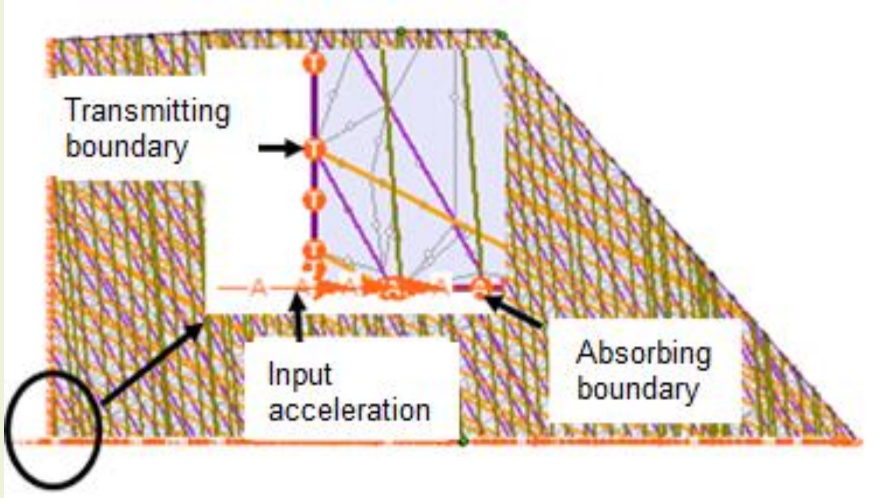


Rayleigh damping

5% damping has been used



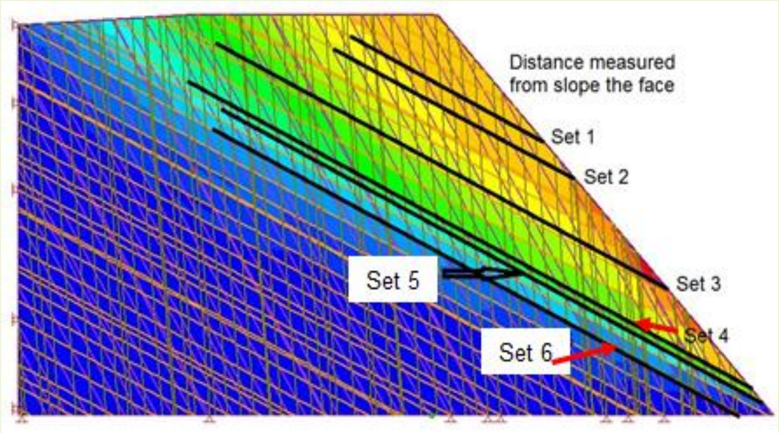
Boundary conditions: Modeling and application

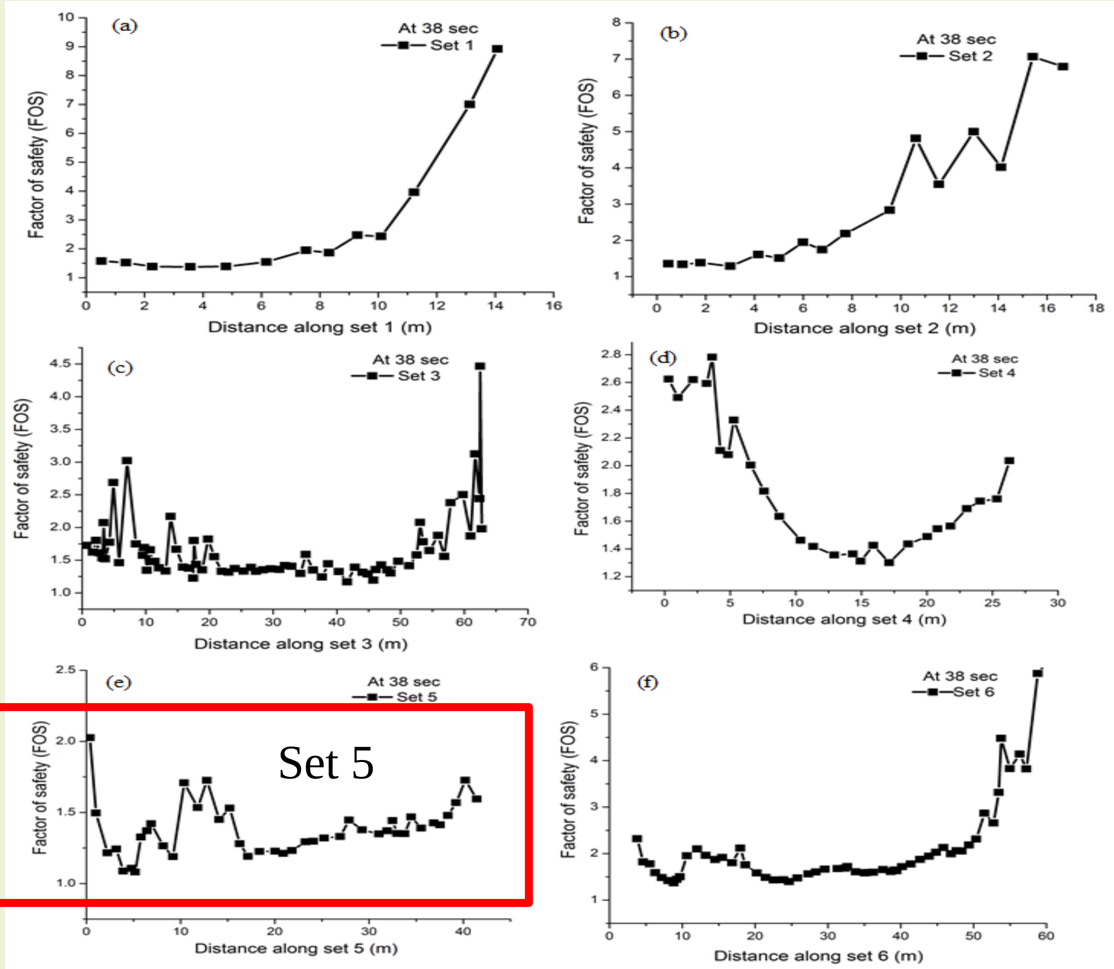


- **Compliant base convert velocity to shear stress**

$$\tau_s(t) = V_s \rho v_s(t)$$

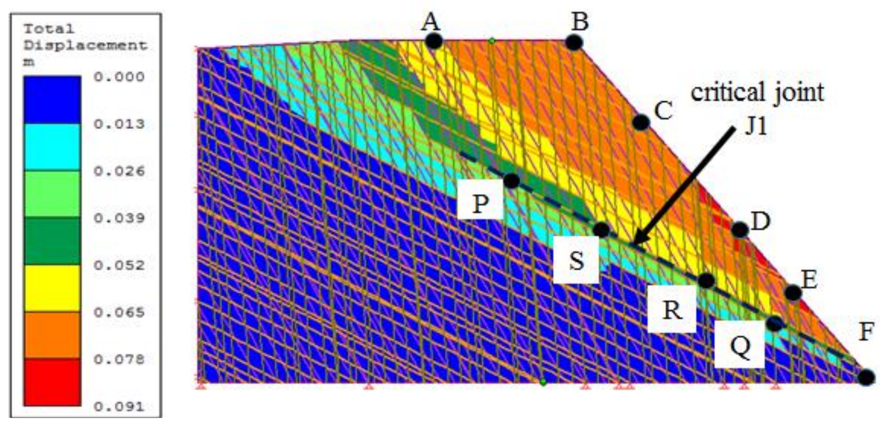
Time History Analysis Results: Which joint is failing?



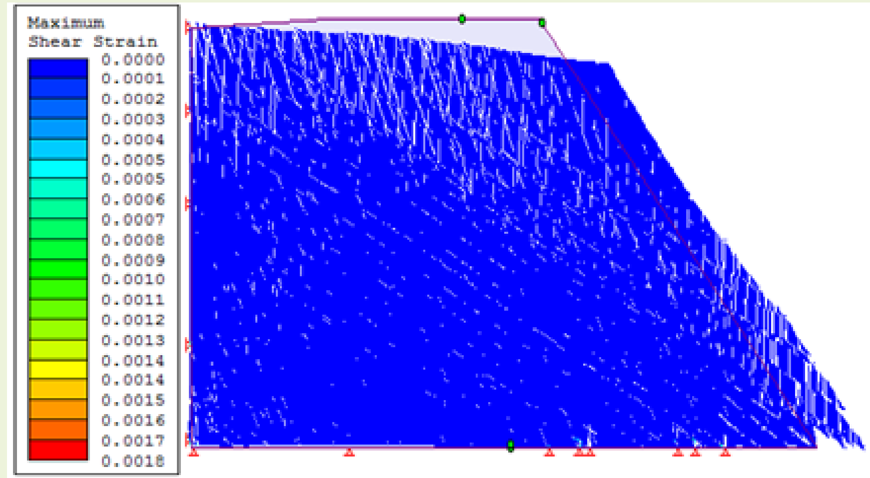


Variation of factor safety along different joint set belonging to joint class J1

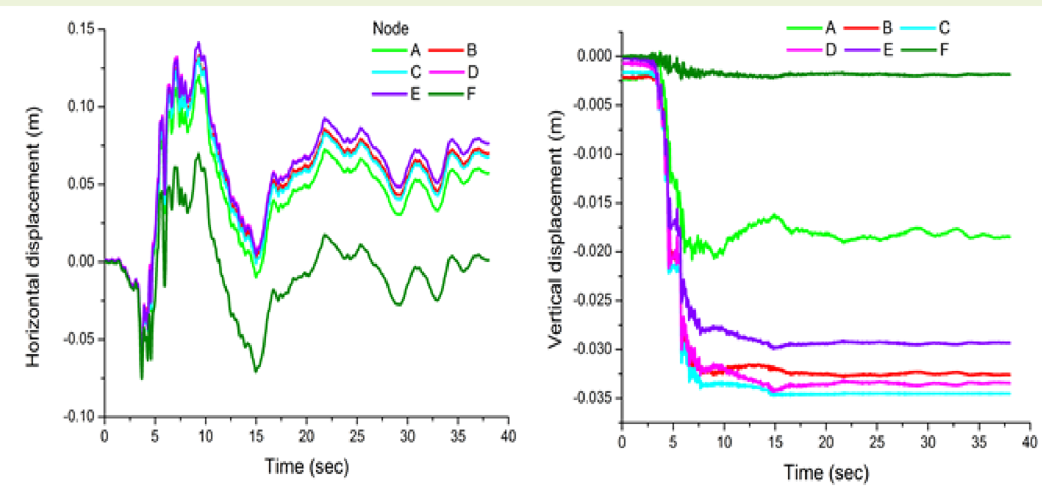
Time History Analysis Results: Which part of joint is failing?

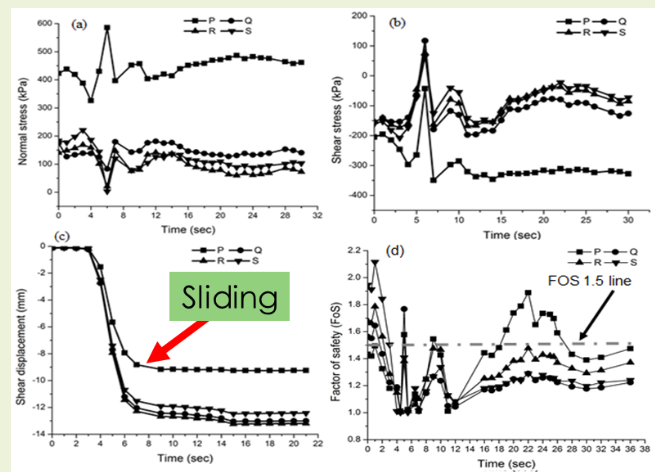


Displacement contour of the slope near the termination of seismic shaking



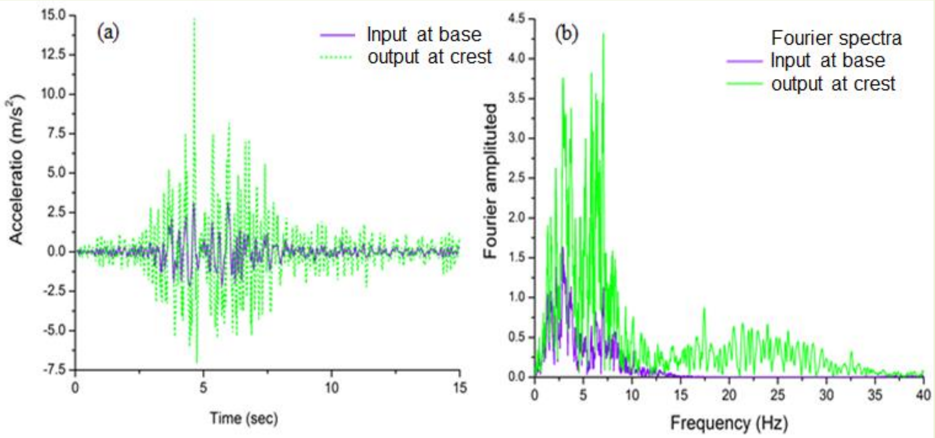
Shear strain developed after the application of dynamic load

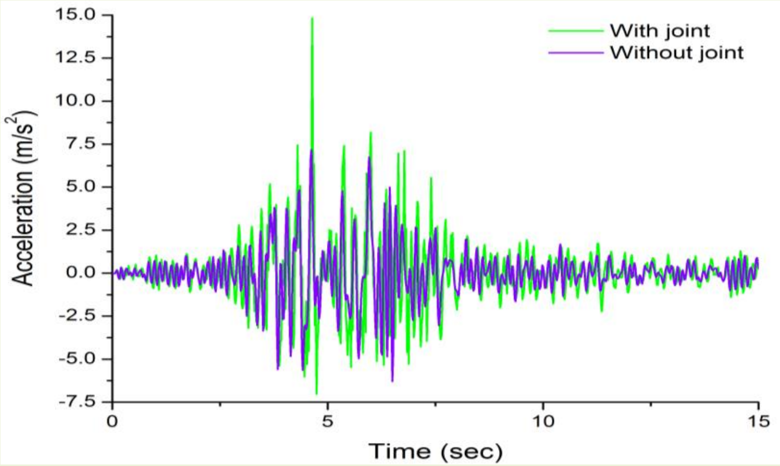




Amplification of Seismic Wave Within the Jointed Slope

- Seismic wave amplification within the rock slope is an important factor for instability of rock slope
    - ❖ Harp and Jibson, 2002; Sepulveda *et al.*, 2005; Sepulveda and Serey, 2009; Gischig *et al.*, 2015





Amplification of seismic wave

- ❑ Amplification within the rock slope mainly depends on three factors, **geometry of the slope, material contrasts and the internal fracture** of the material
- ❑ Joints can open up due to tensile stress, trapping of energy

Amplification of seismic wave in intact rock and jointed rock

- ❑ Presence of joint results in higher amplification of the seismic wave
- ❑ FEM explicit joint model accurately captured the amplification of the seismic wave

Probabilistic Approaches

Why probabilistic study??? Uncertainties……

- Einstein and Baecher in 1982 stated the following words of wisdom:
  - “In thinking about sources of uncertainty in engineering geology, one is left with the fact that uncertainty is inevitable. One attempts to reduce it as much as possible, but it must ultimately be faced. It is a well recognized part of life for the engineer. The question is not whether to deal with uncertainty, but how?”

Soil sample collected from SPT

Why probabilistic study??? Uncertainties……

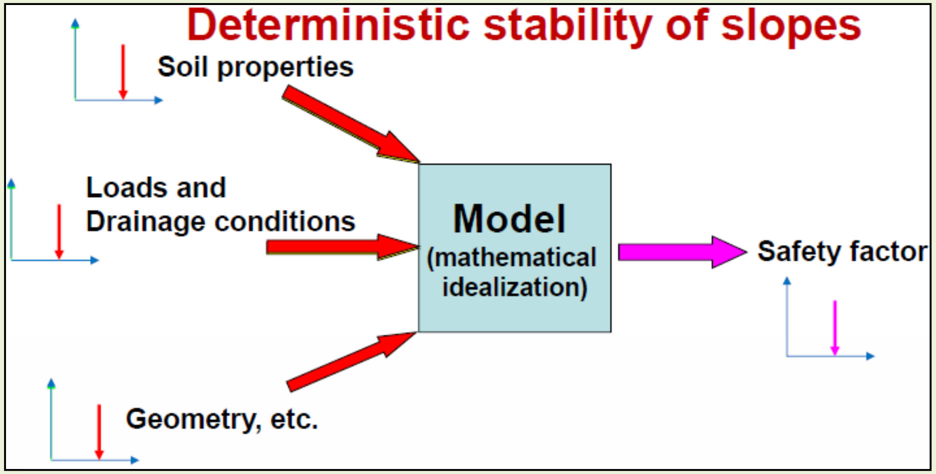
- Einstein and Baecher in 1982 stated the following words of wisdom:
  - ❖ Collective experience (both from practice and research) suggests that it may be time for a shift to an uncertainty-based perspective which may be, on the whole more convenient in terms of safety, performance and economy

Geotechnical Uncertainties

- Geological anomalies
- Inherent spatial variability of soil properties
- Lack of data availability
- Simplifying approximations adopted in geotechnical modelling
- Human errors in design and construction

Deterministic Analysis of Landslides

- Deterministic framework of analysis
  - ❖ Natural tendency to define soil property by a single value
  - ❖ Defines a specific safety factor
  - ❖ Obtaining the analytical safety factor based on soil parameters is **NOT GUARANTEED**



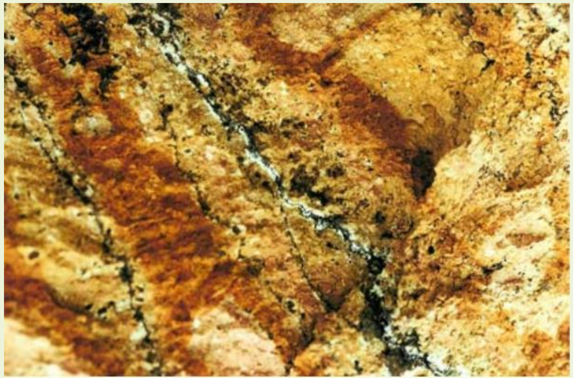
- No parameters affecting landslides are deterministic
  - ❖ All are uncertain in their determination
  - ❖ All are uncertain in their effect and functioning
    - Heterogeneity and Uncertainty are the inherent properties of soil parameters

Probabilistic Analysis

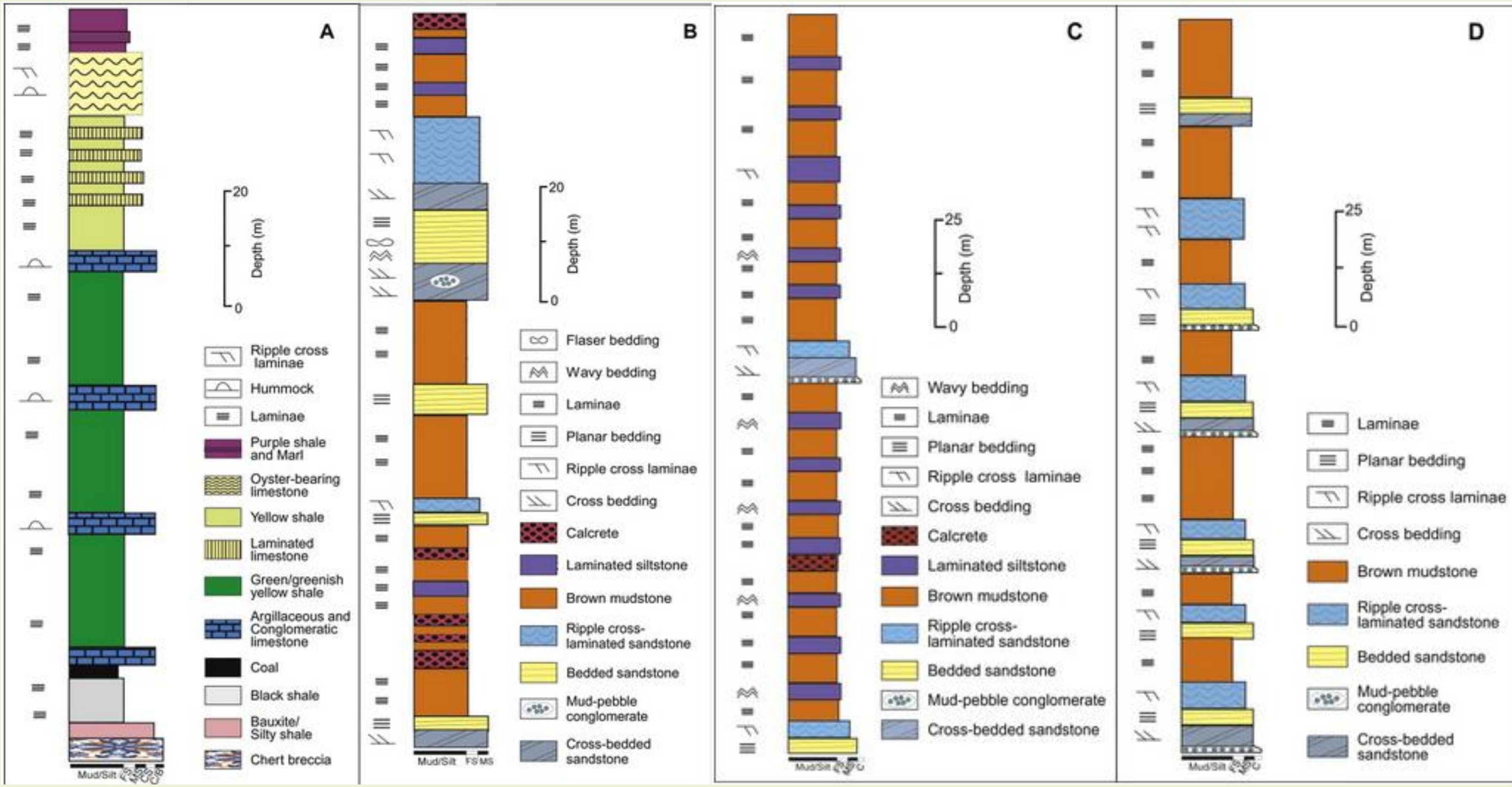
- Probabilistic Approach
  - ❖ Distributed Soil Property





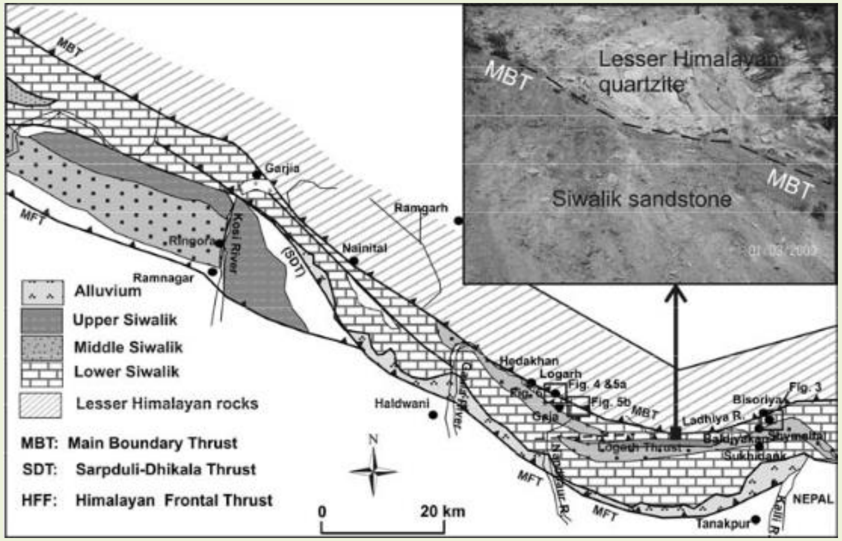


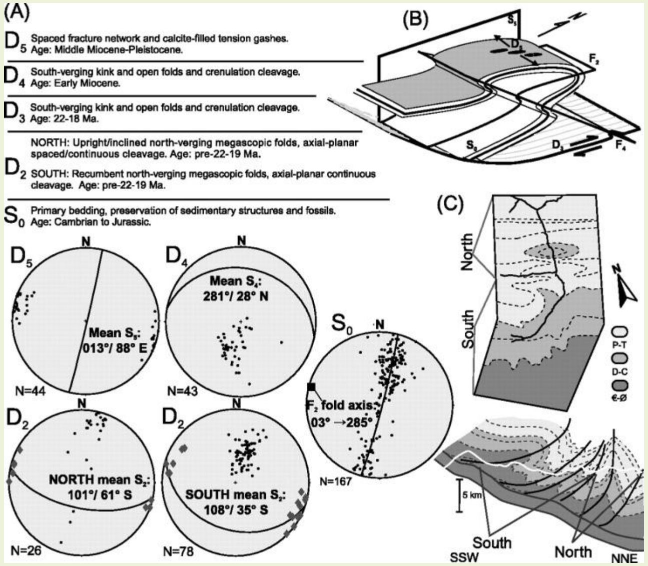

Spatial Variability of Himalayan Soil Profiles



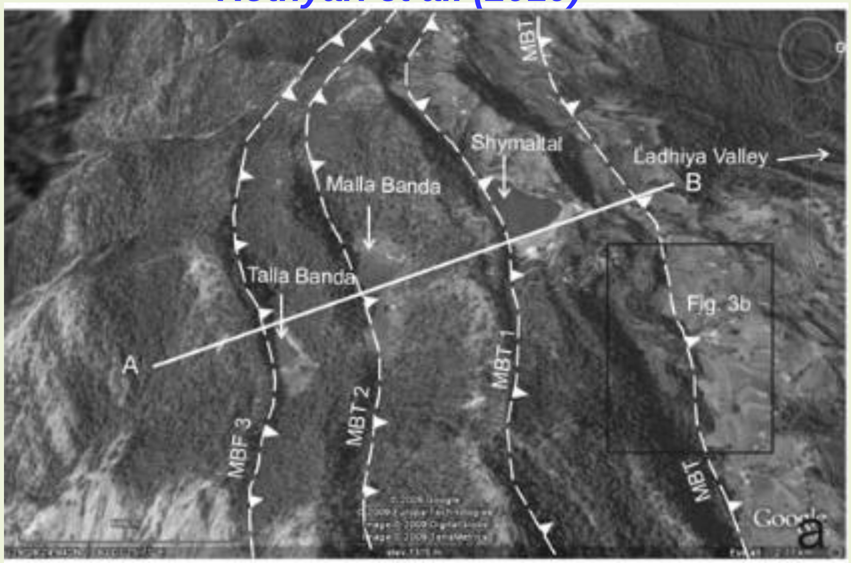
Singh (2013)

Spatial Variability in Himalayan Bedding Planes and Faulting



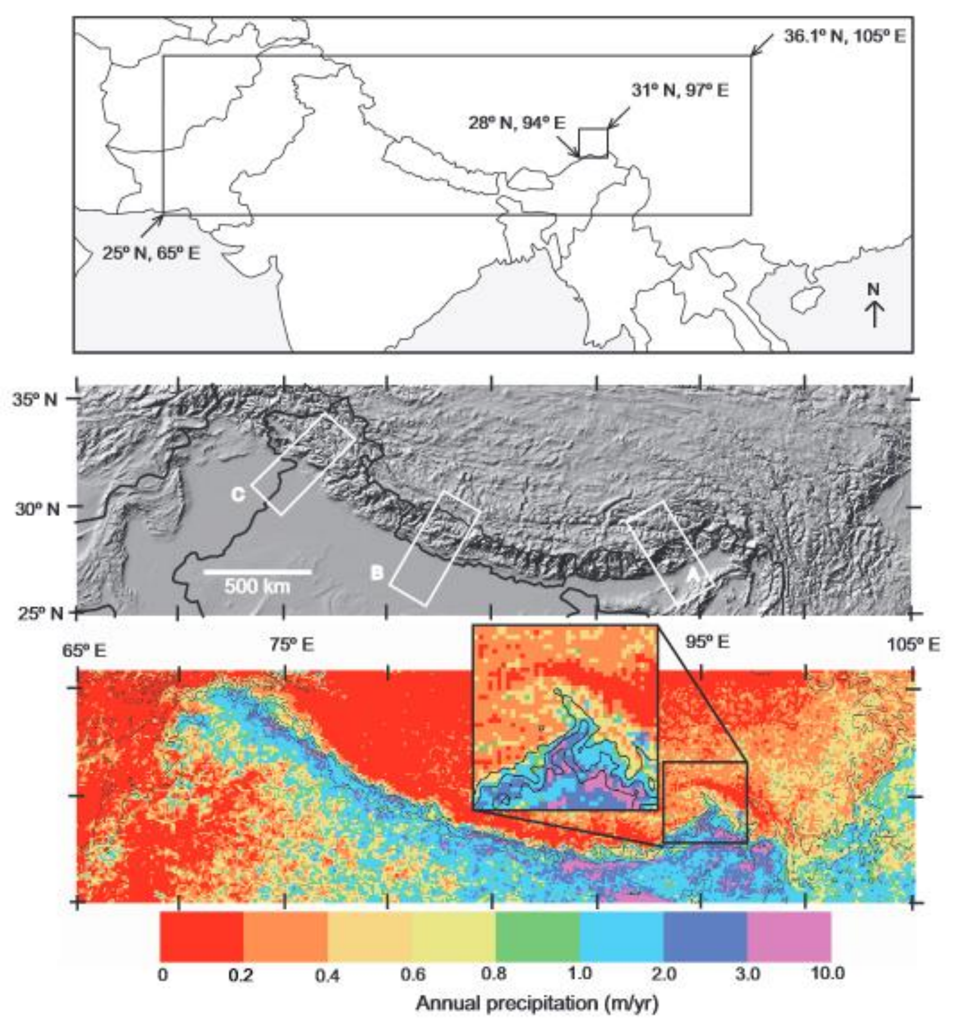


Kothyari et al. (2010)

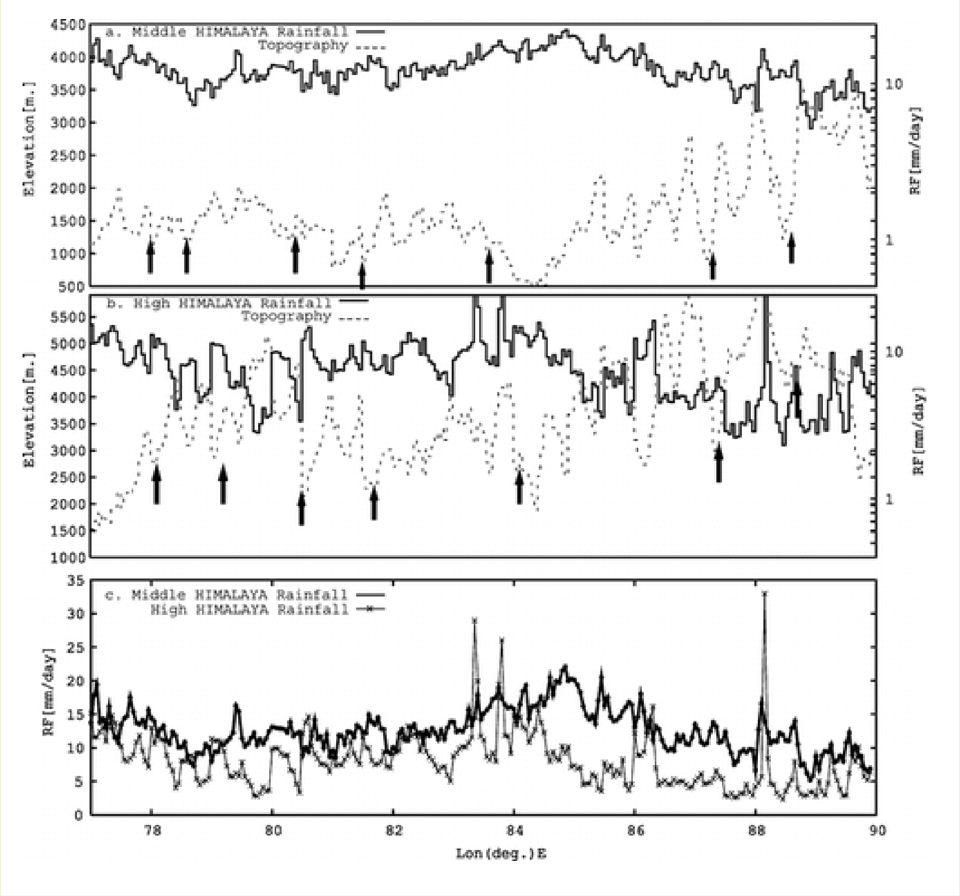


Variability of Rainfall across Himalayas

- Substantial spatial and temporal variation



Bhatt and Nakamura (2005)



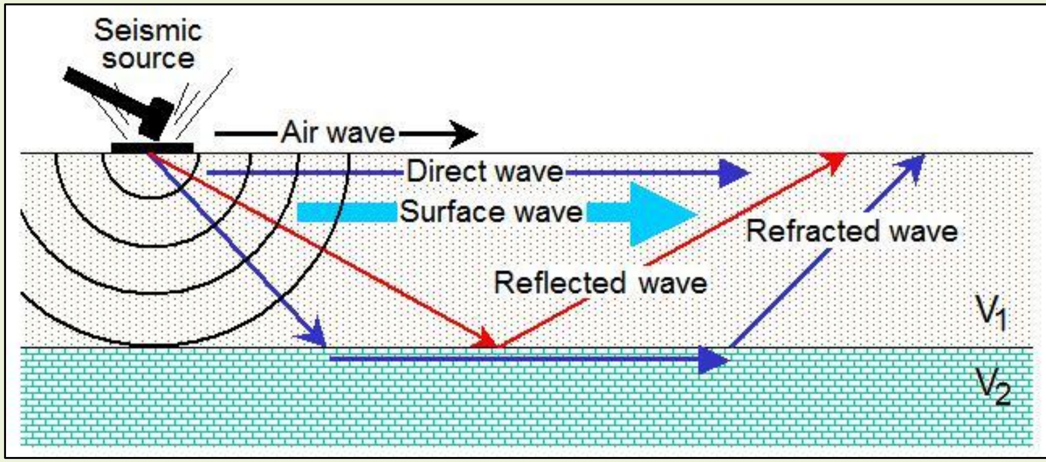
Anders et al. (2006)

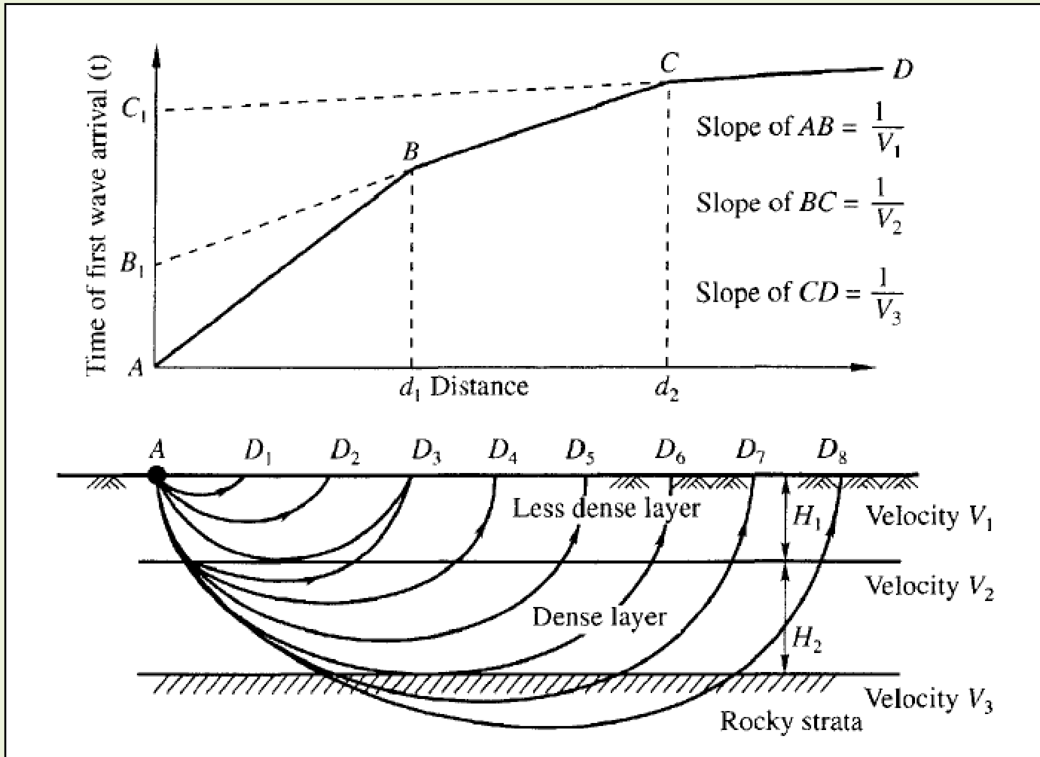
Spatial Variability of Soil Properties

- Salient variable parameters
  - ❖ Shear strength parameters
  - ❖ Permeability characteristics
  - ❖ Geological and geomorphological variability
  - ❖ Rainfall distribution
  - ❖ Seismicity and seismic amplifications

Geophysical Investigation

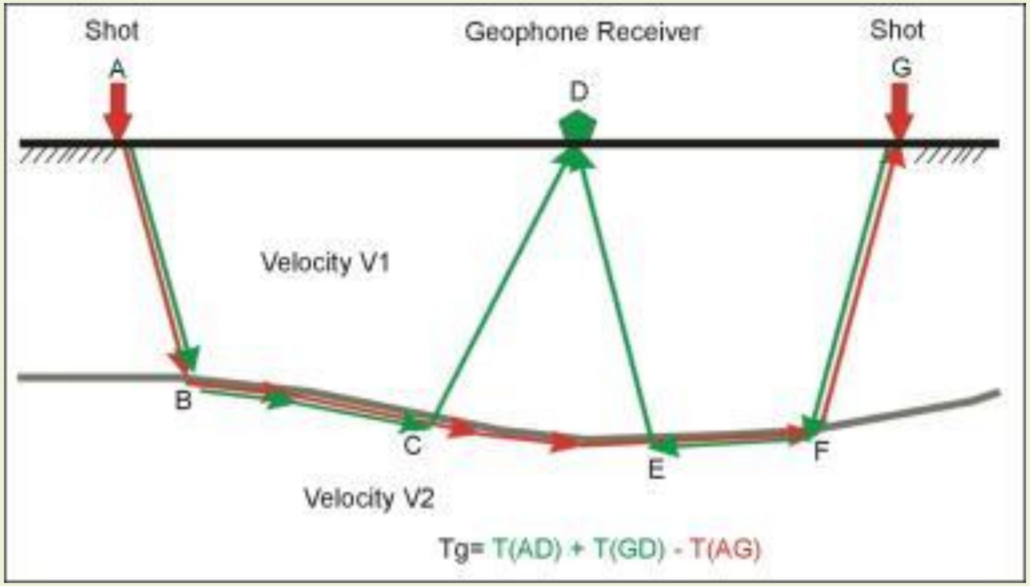
- Seismic Refraction Method (SRS)
  - *Operates on the velocity of wave propagation of the soil medium*
  - *Generates an array of reflected and refracted waves*
  - *Based on first arrival of waves in the receivers*
  - *Results*
    - Velocity of wave propagation in the medium
    - Thickness of the stratification

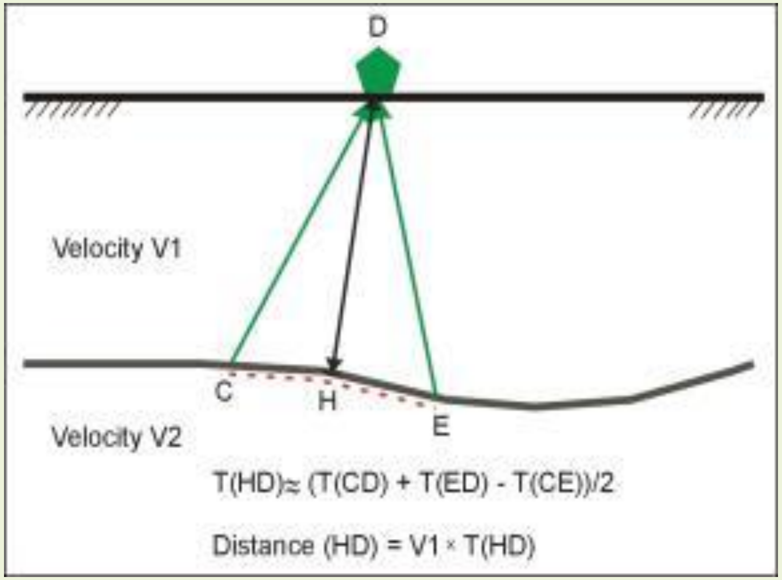




Geophysical Investigation

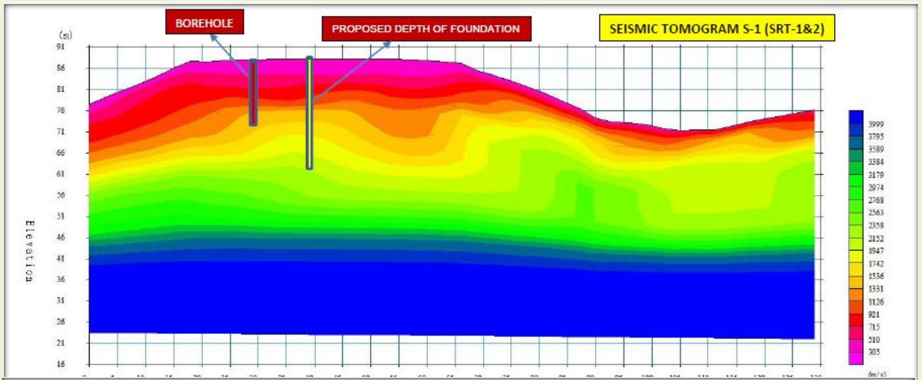
- Seismic Refraction Survey (SRS)
  - *Based on refraction of generated waves through various soil layers*
    - Restrictive limitation
      - Each of the successive soil layer should have higher velocity than the shallower layer
      - Improper for arbitrarily formed subsoil stratigraphy

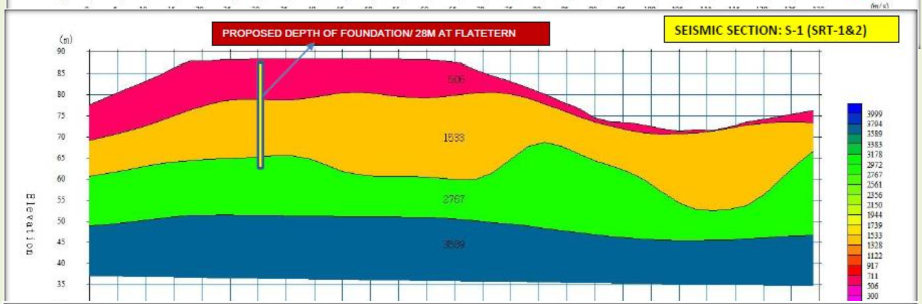


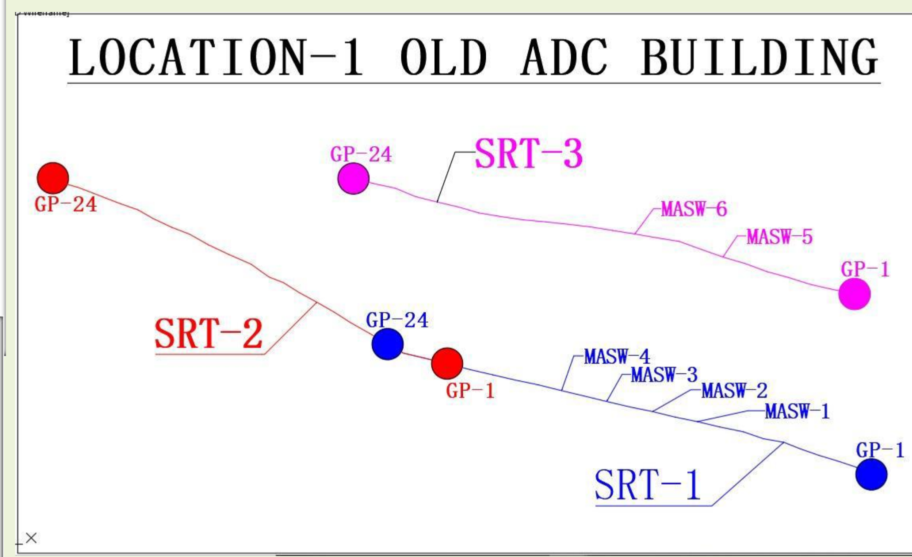


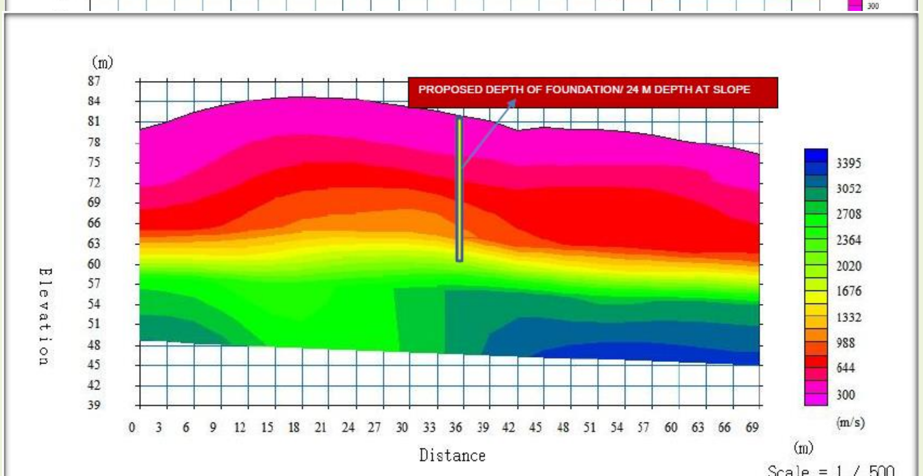
http://www.cflhd.gov

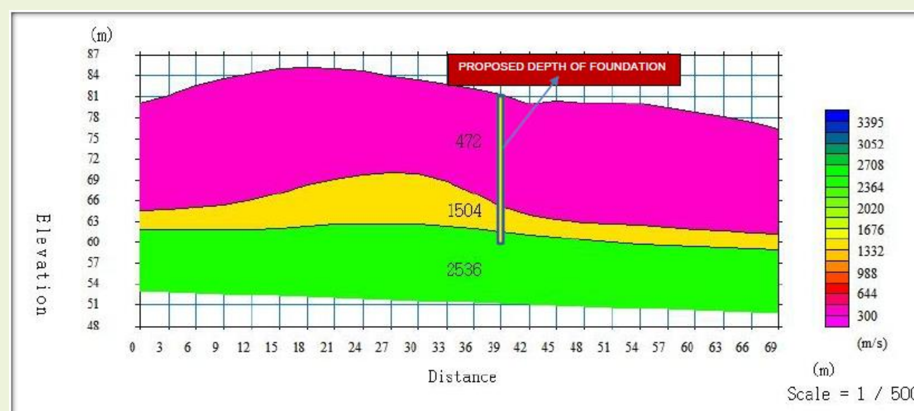
SRS at Failed RajBhawan Site, Assam





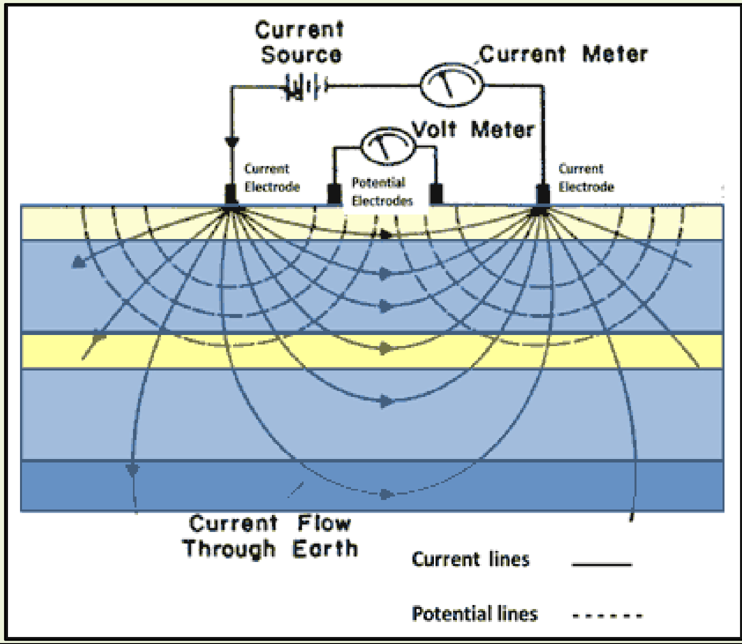


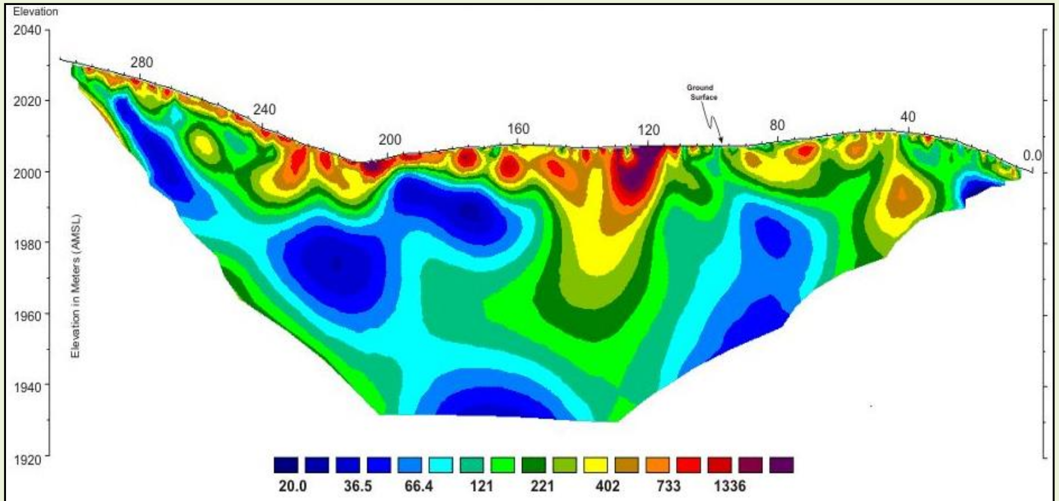


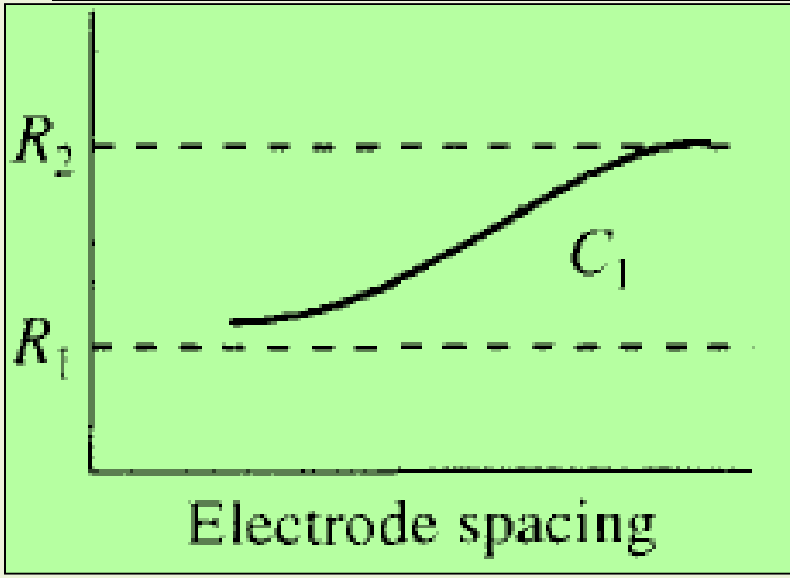


Geophysical Investigation

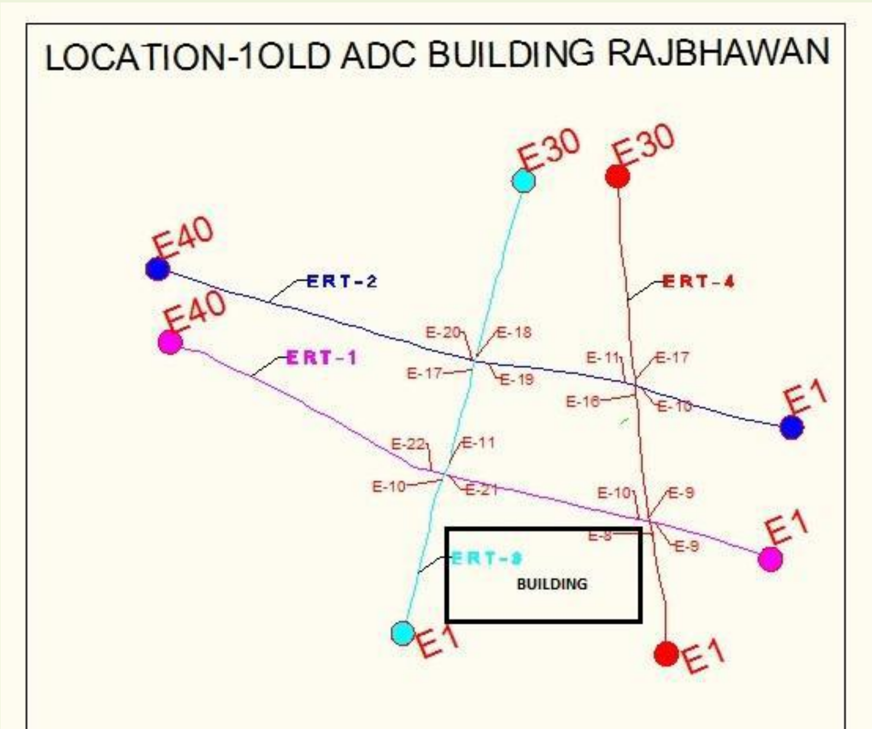
- Electrical Resistivity Tomography (ERT)
  - *Depends on the current flow generated due to the differences in the electrical resistance of different soils (dielectric constant)*
  - *Depends on salt concentration and water content of soils*
  - *Variation in apparent resistivity of soils*

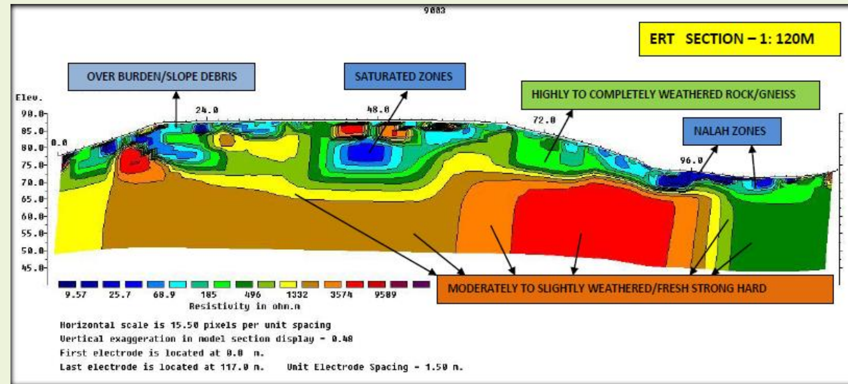


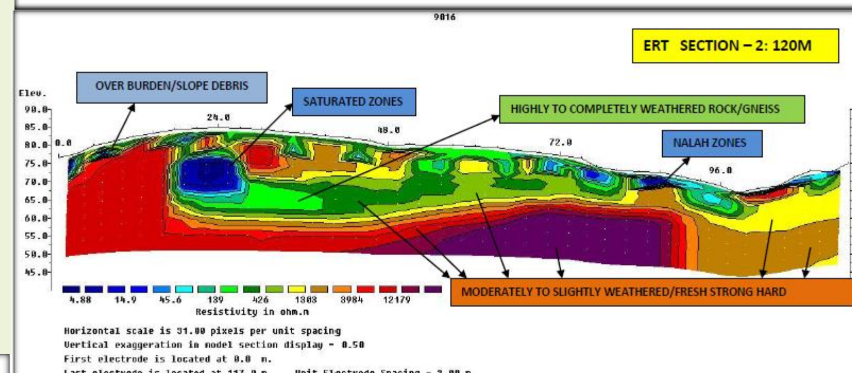


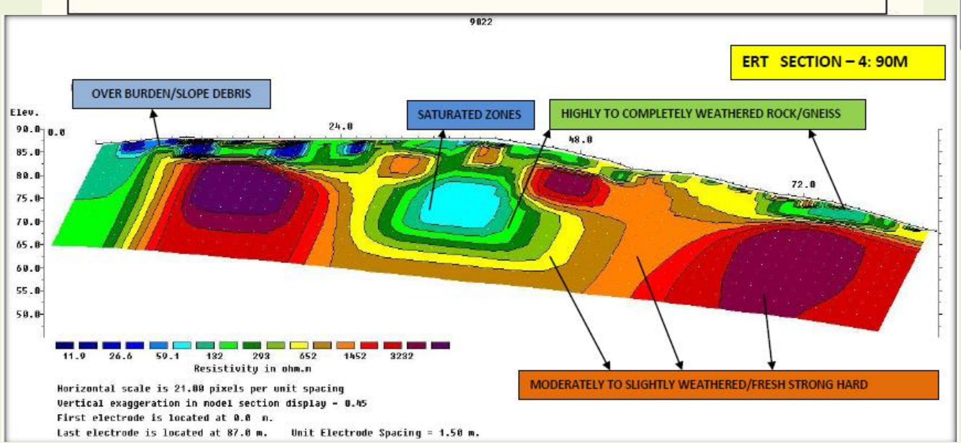


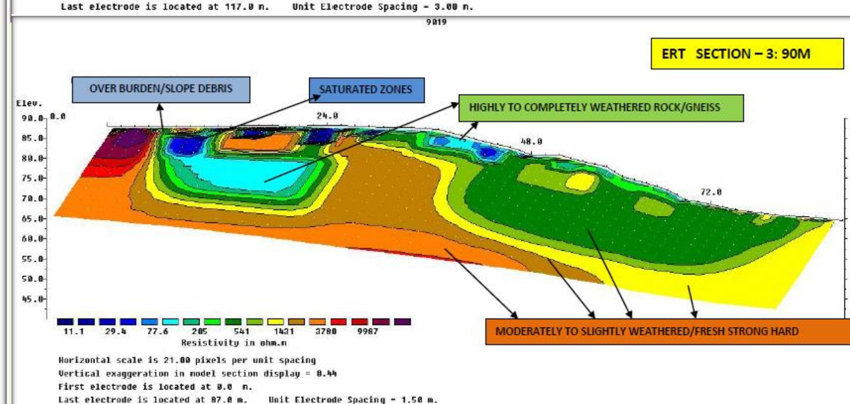
ERT at Failed RajBhawan Site, Assam





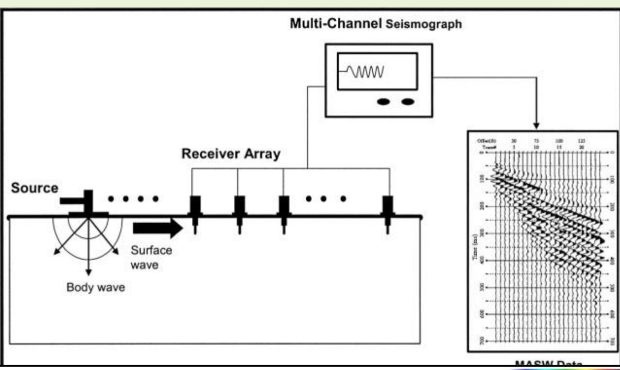


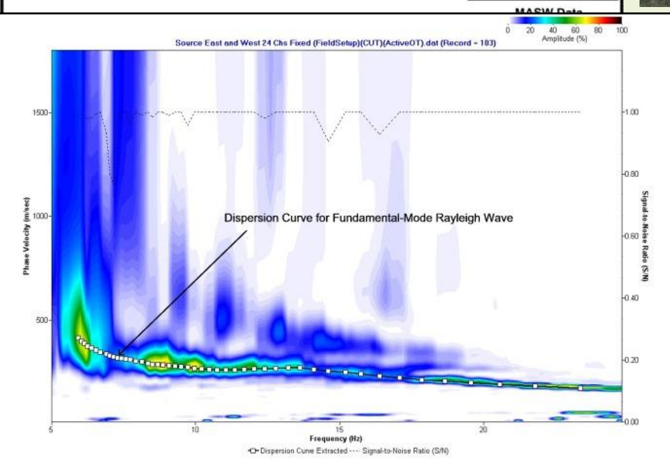


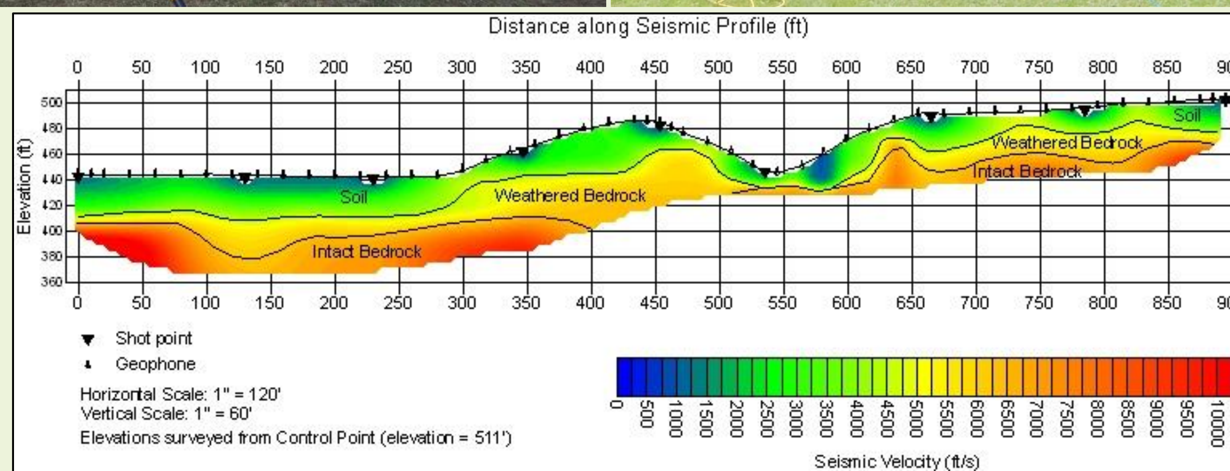


Geophysical Investigation

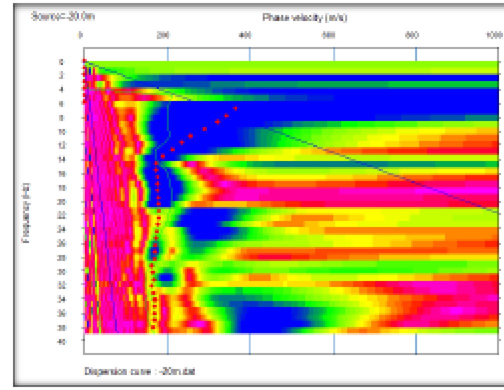
- Multichannel Analysis of Surface Waves (MASW) – Active and Passive Surveys
  - *Shear wave velocity profiling of soil substrata*
  - *Operates on the dispersive capacity of soils*

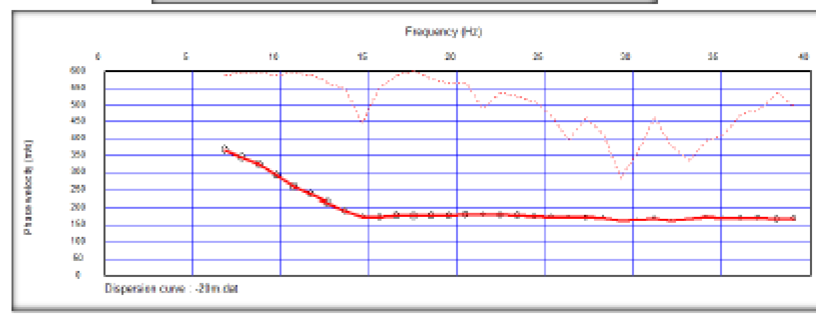


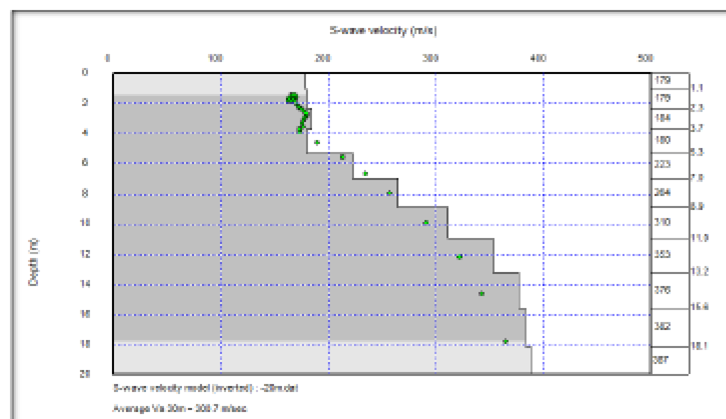




MASW Survey at a Failed Rajbhavan Site

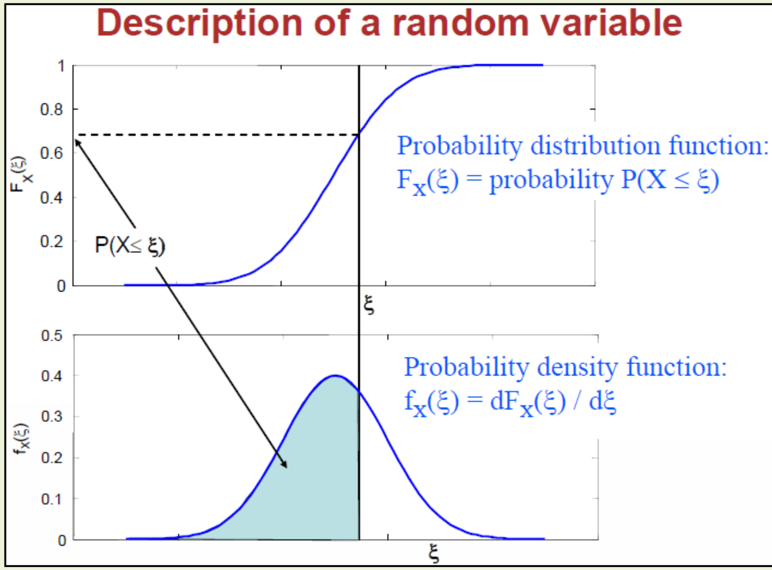


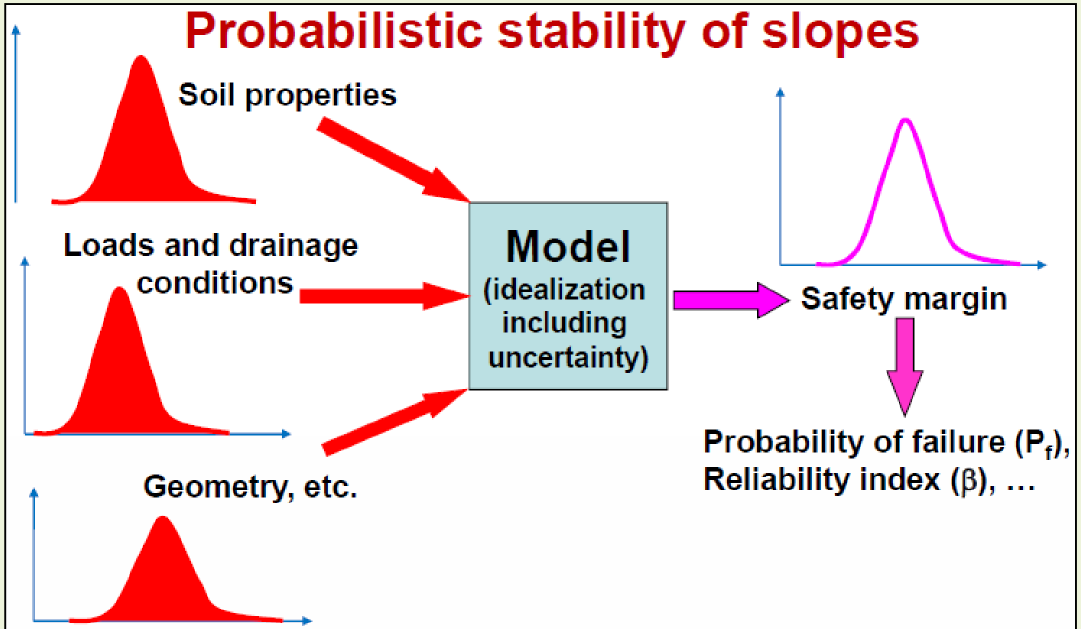


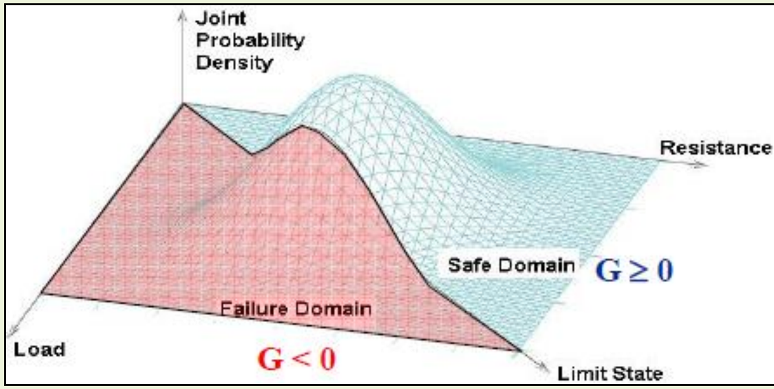


Probabilistic Analysis of Landslides

- Probabilistic framework of analysis
  - ❖ Defines a margin of safety and a probability of failure instead of a specific safety factor
  - ❖ Soil parameters are defined as random variables with a probability distribution of occurrence (single or joint probability)







Some Important Statistical Parameters of Probability

- To incorporate uncertainty in soil properties
  - Literature suggests to consider soil properties as continuous random variables
  - For example, **undrained shear strength of soil (S)** in kPa

Mean or expected value: $\mu_s = \int_{-\infty}^{\infty} s f_s(s) ds$

Variance: $\sigma_S^2 = E[(s-\mu_S)^2] = \int_{-\infty}^{\infty} (s-\mu_S)^2 f_S(s) ds$

Standard deviation: $\sigma_s = \sqrt{\sigma_s^{\,2}}$

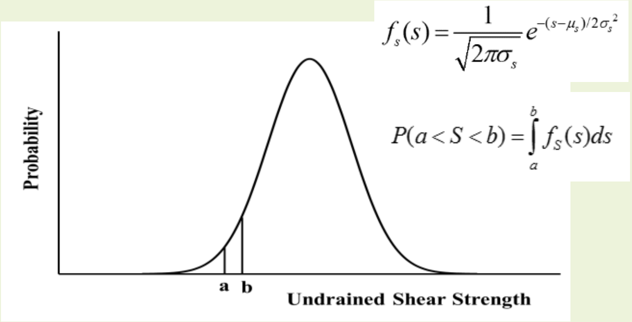
Coefficient of variation (COV): $COV = \frac{\sigma_s}{\mu_s}$

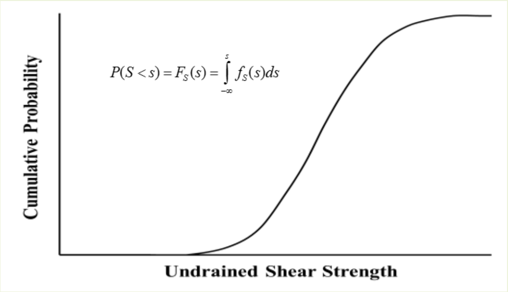
- **Multiple random variables:**
  - For example, drained shear strength of soil
    - Cohesion, *c* and angle of internal friction, φ
    - If *C* and *Φ* both are random variable

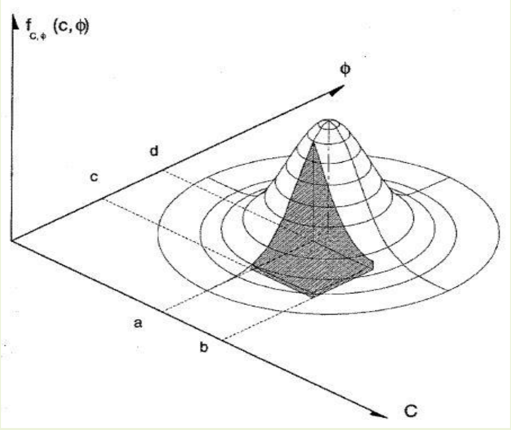
Joint probability density function, $P(a < C < b, c < \Phi < d) = \int_a^b \int_c^d f_{C,\Phi}(c,\phi) d\phi dc$

Covariance: $Cov[C,\Phi] = E[(C-\mu_c)(\Phi-\mu_\phi)] = E[C\Phi] - \mu_c \mu_\phi$

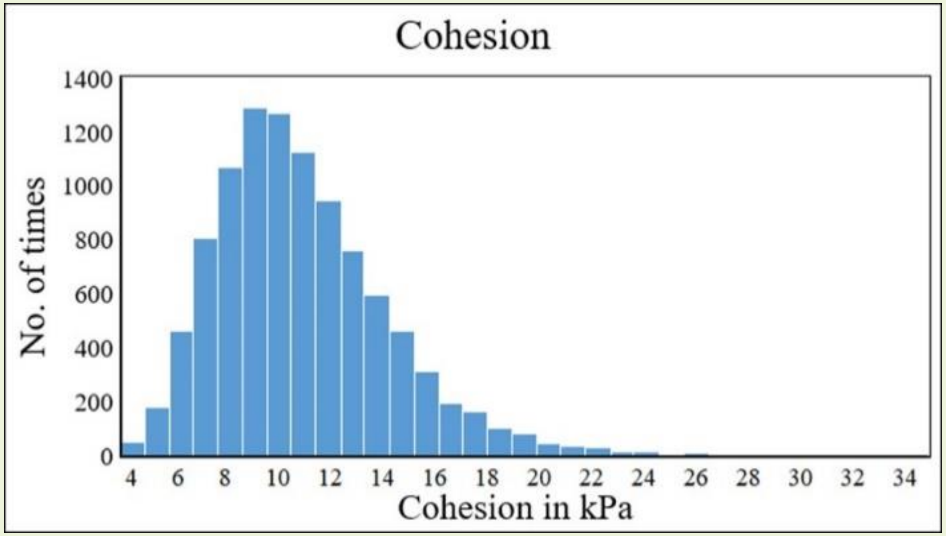
Cross-correlation coefficient: $\rho_{c\varphi} = \frac{Cov[C,\Phi]}{\sigma_c \sigma_\phi}$ $-1 \le \rho \le 1$

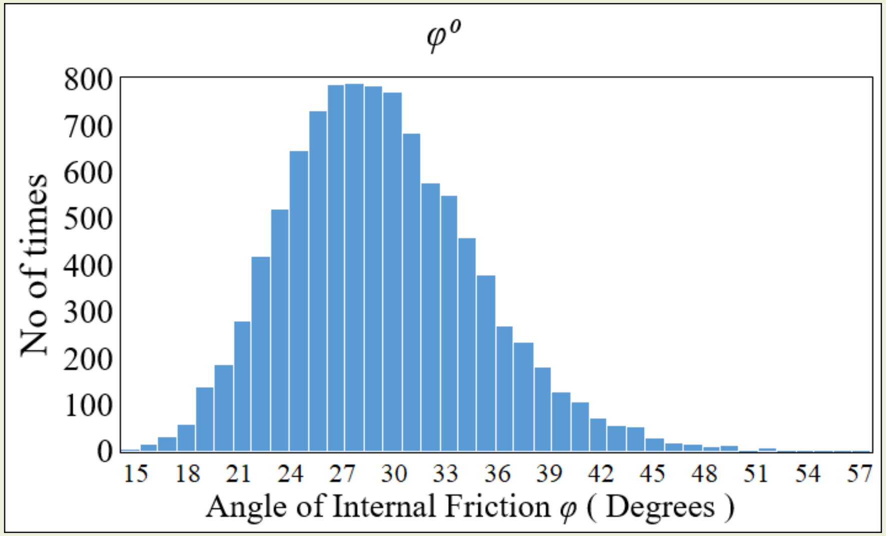


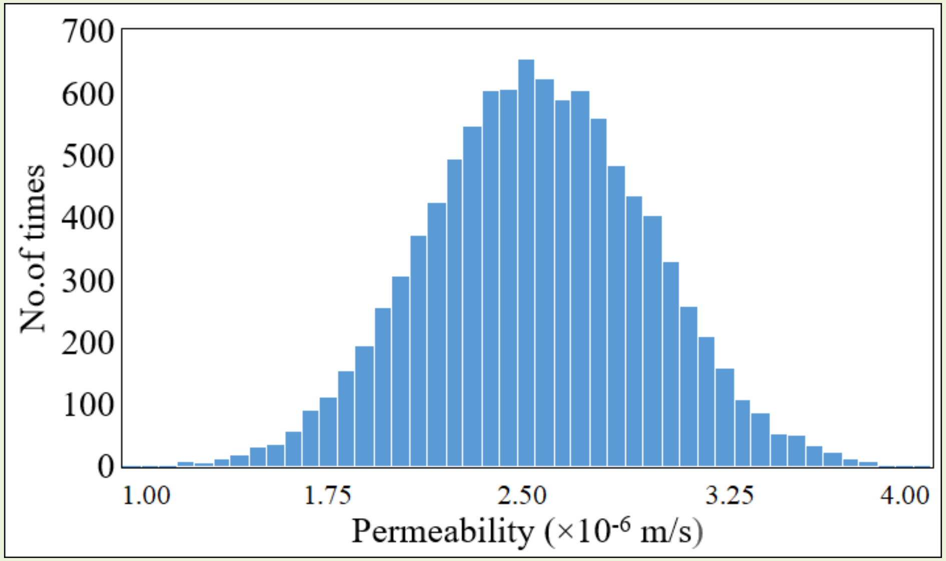


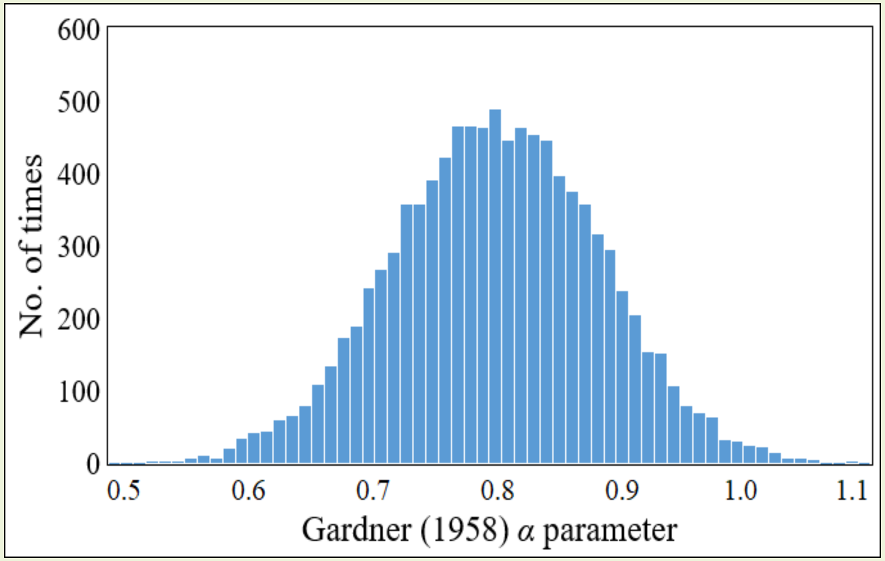


Probabilistic Analysis









Statistical Distributions

- Devore - Probability and Statistics for Engineers and Scientists (Cengage Learning, USA)
- Bury – Statistical Distributions in Engineering (Cambridge University Press, London)
  - Discrete Probability Distributions
    - Binomial
    - Poisson
    - Hypergeometric
    - Negative binomial
  - Continuous Probability Distributions
    - **Normal / Gaussian**
    - **Truncated Normal / Gaussian**
    - Exponential
    - Gamma
    - Weibull
    - **Lognormal**
    - Beta
    - Extreme value distributions

Probabilistic Approaches for Slope Stability Analysis
Random Variable Approach

1. Approximate method

- *FORM, MVFOSM, SORM*
- Reliability index (β) is estimated by solving an optimisation problem
    - Failure probability is evaluated using $P_f = \Phi(-\beta)$
- Besides the simplicity of FORM, it gives accurate results for slopes with small failure probability
- FORM is incapable of considering inherent spatial variability in soil properties (Griffiths et al., 2007)
    - Either over-estimation or under-estimation of the probability of slope failure under different conditions

2. Monte Carlo Simulation based method

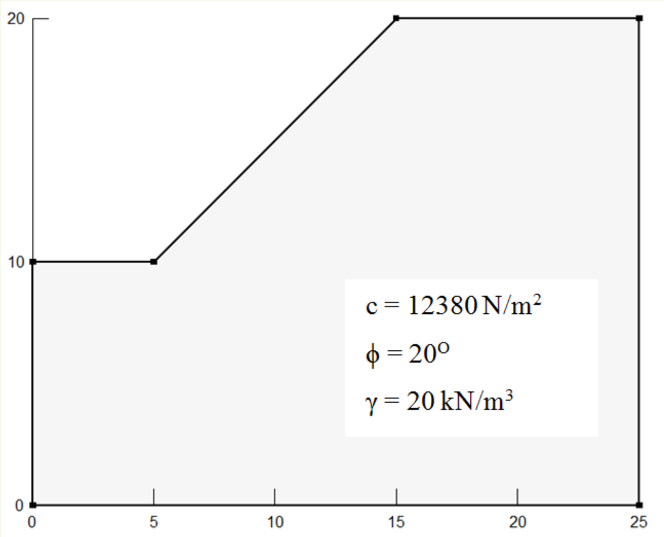
- The total number of failures occurring in all the trial values of random variable is counted, and the failure probability is estimated as

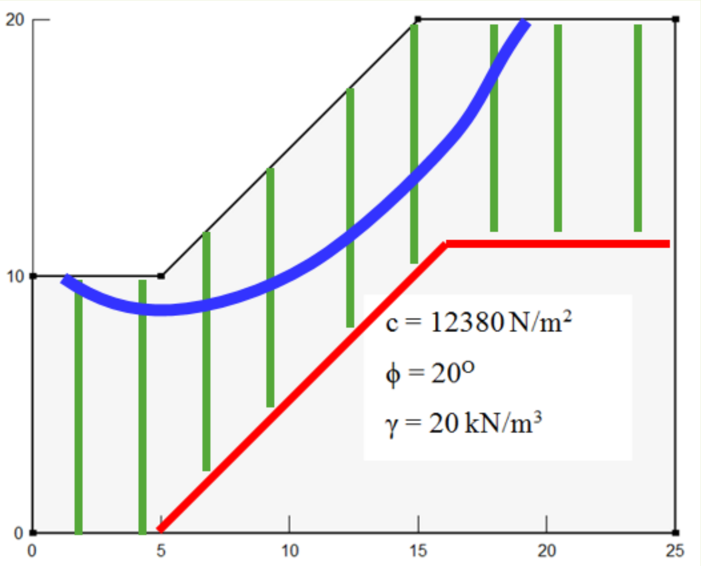
$$P_f = \frac{n_f}{N}$$

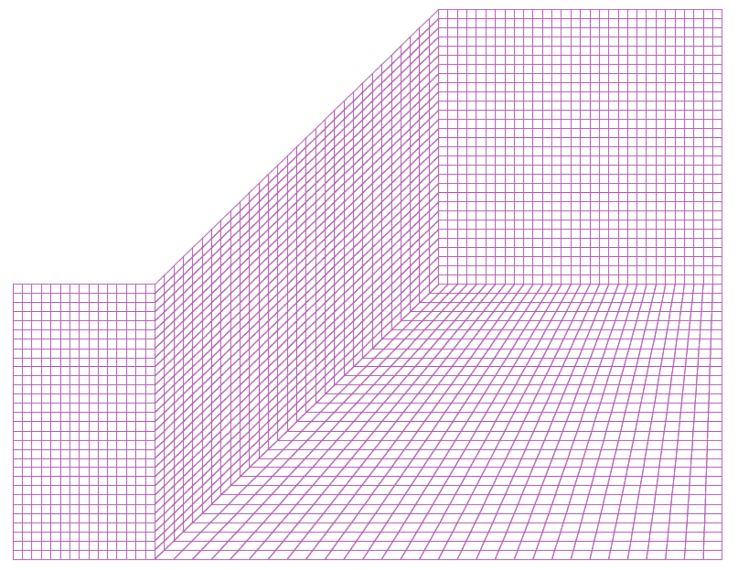
Probabilistic Slope Stability Analysis

- Slope Geometry and soil parameters

Method adopted	Factor of Safety
Limit Analysis (Chen, 2007)	1.0
Ordinary Method of Slices	0.987
Bishop's Simplified	1.025
Janbu's Simplified	0.98
Spencer's Method	1.022
Morgernstern-Price Method	1.022
Strength Reduction Method in $FLAC^{2D}$	1.01



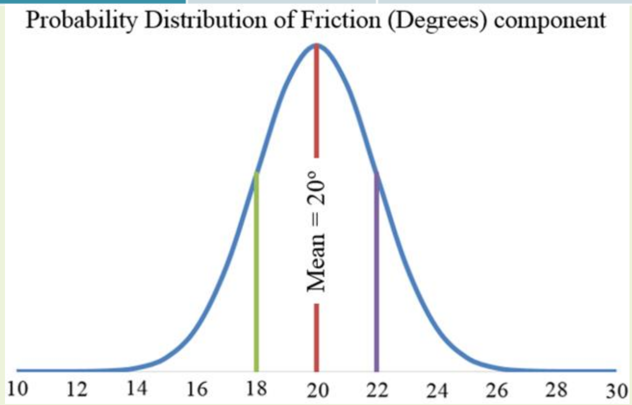


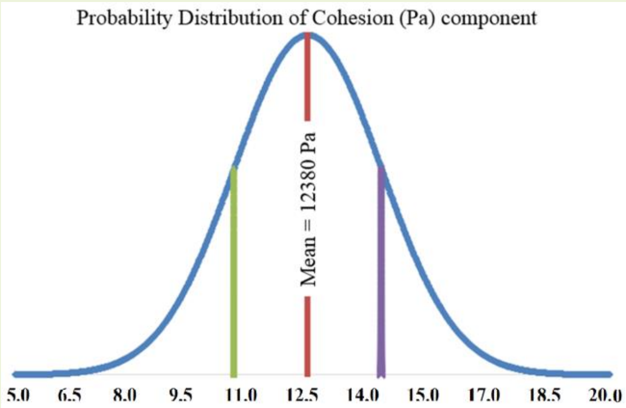


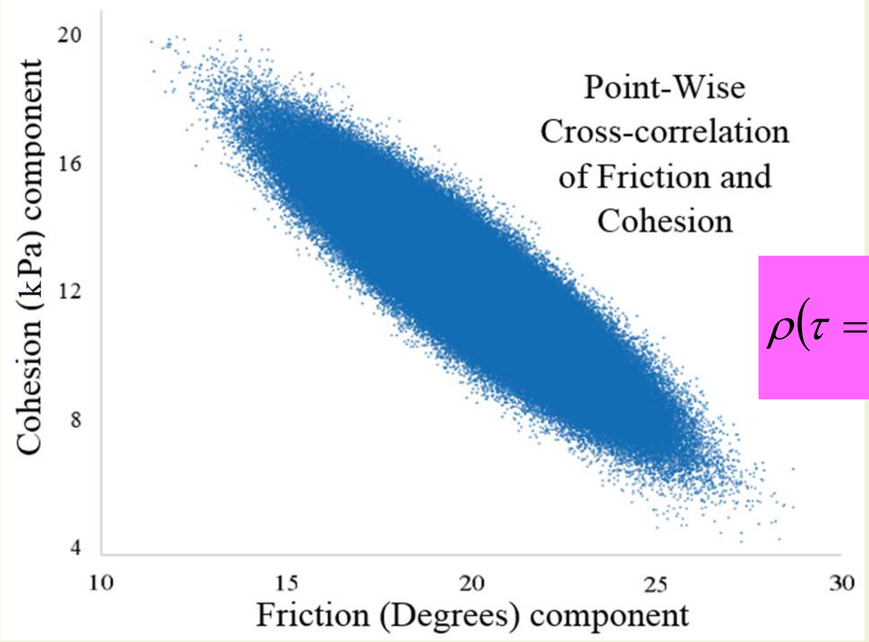
Probabilistic Slope Stability Analysis

- Soil parameters as Random Variables
  - ❖ Cohesion and Angle of internal friction
    - Normal Distribution
    - Negatively cross-correlated
    - Cross-correlation coefficient: -0.7 (Wolff 1985; Cherubini, 2000)

Property	Cohesion, c	Angle of Internal Friction, ϕ
Expected Value or Mean	12380 Pa	20^{o}
Coefficient of Variation	15 %	10 %
Standard Deviation	1857 Pa	2^{o}







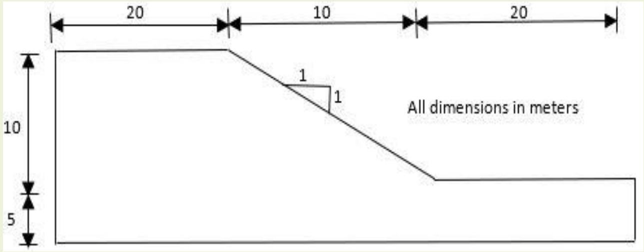
$$\rho(\tau = 0) = \begin{bmatrix} \rho_c & \rho_{c\phi} \\ \rho_{\phi c} & \rho_\phi \end{bmatrix}$$

Effect of variation of Coefficient of variation (CoV) and Coefficient of cross-correlation

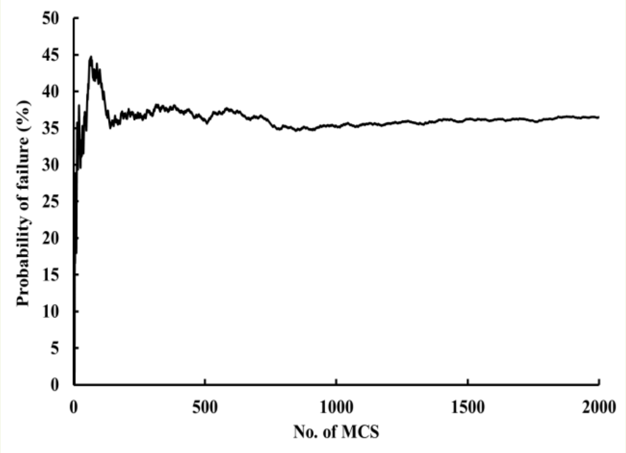
- Slope/W module of Geostudio v2018
- Morgenstern-Price LEM
- Only the shear strength parameters c and φ are modelled as random variables
- Characterized by a Lognormal distribution with no spatial variation of soil Mean cohesion (c) = 45 kPa and angle of internal friction (φ) = 20^0
    - CoV is varied from 0.05 to 1
    - 2000 number of MCS
- Unit weight (γ) = 20 kN/m^3

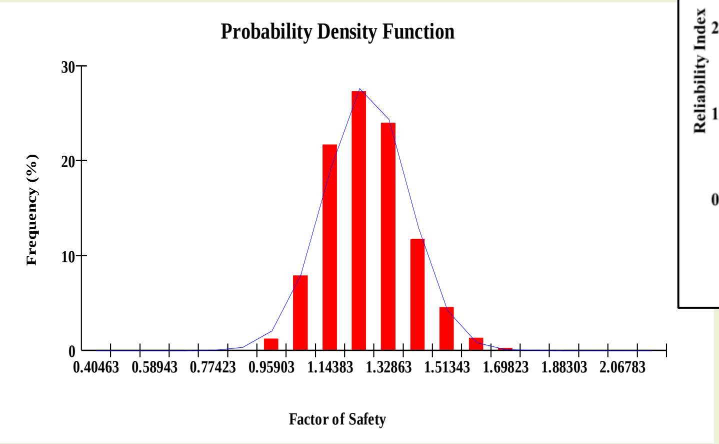
❑ **Undrained condition**

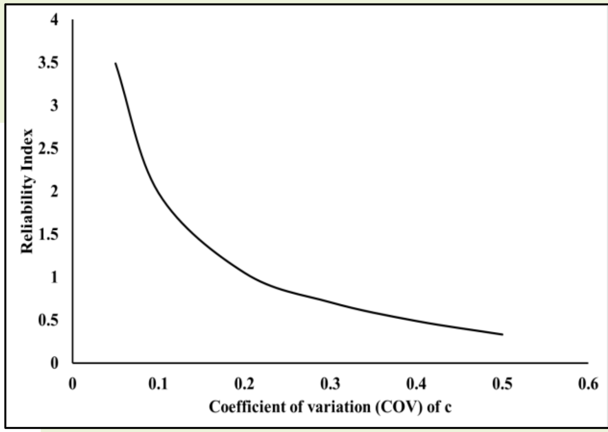
- Deterministic (Morgenstern-Price LEM) FoS = 1.3



Schematic of slope geometry considered for present study



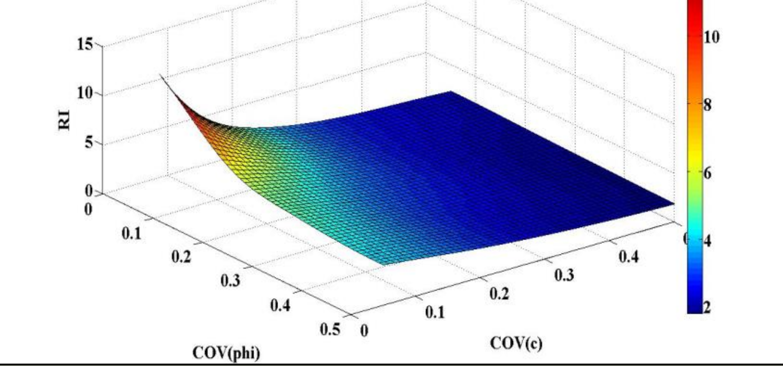




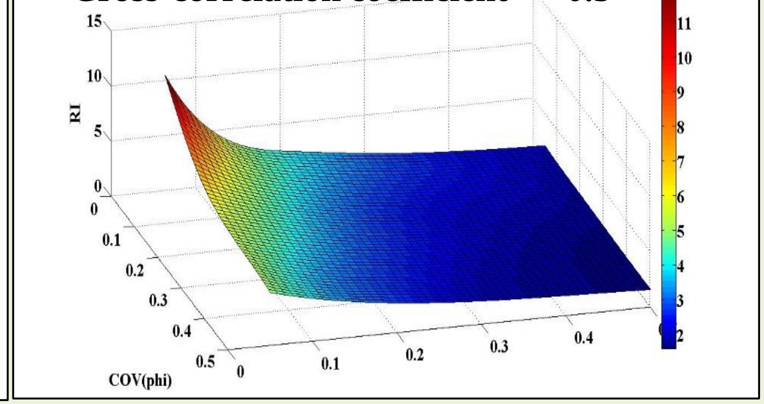
Effect of variation of Coefficient of variation (CoV) and Coefficient of cross-correlation

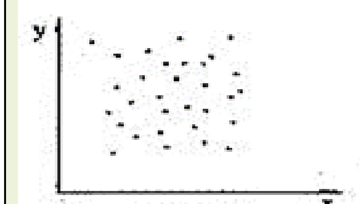
- **Drained condition**
  - Deterministic (Morgenstern-Price LEM) FoS = 2.1

Cross-correlation coefficient=0

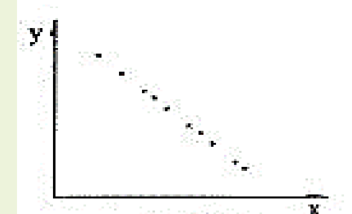


Cross-correlation coefficient = +0.5

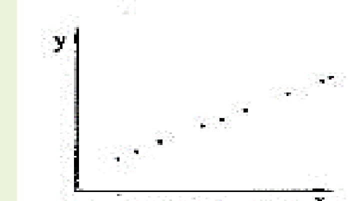




a) ρ=0

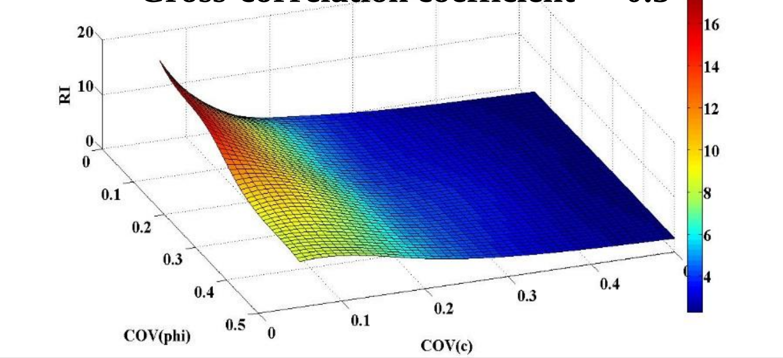


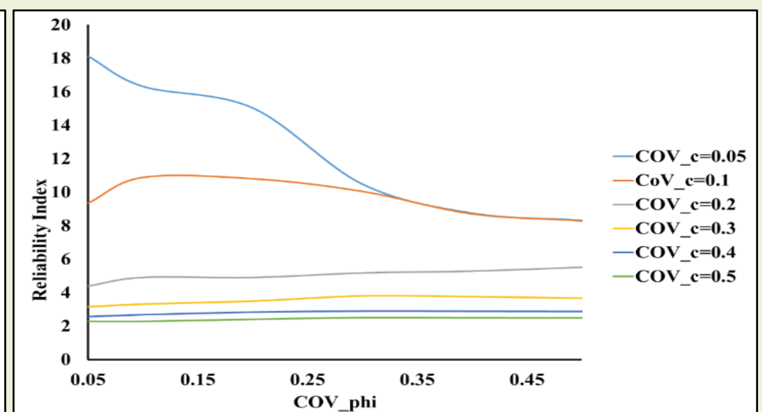
c) ρ=−1



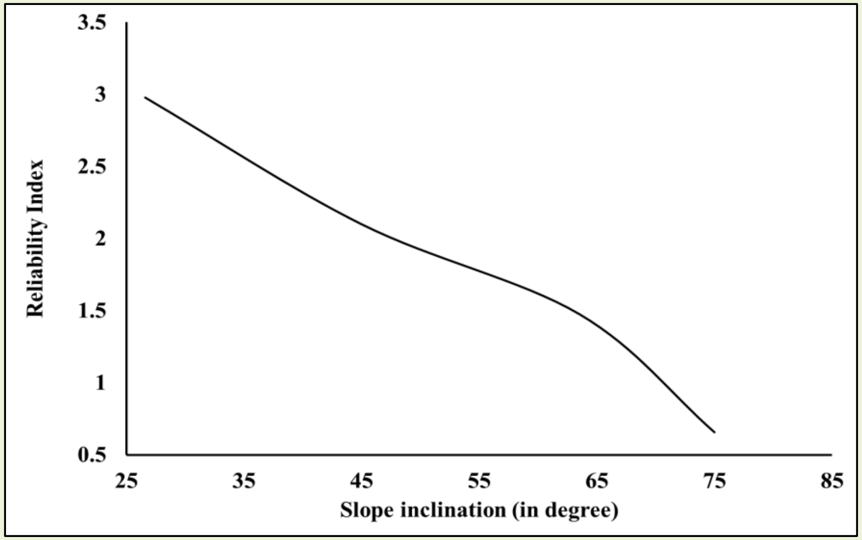
d) ρ=+1

Cross-correlation coefficient = -0.5

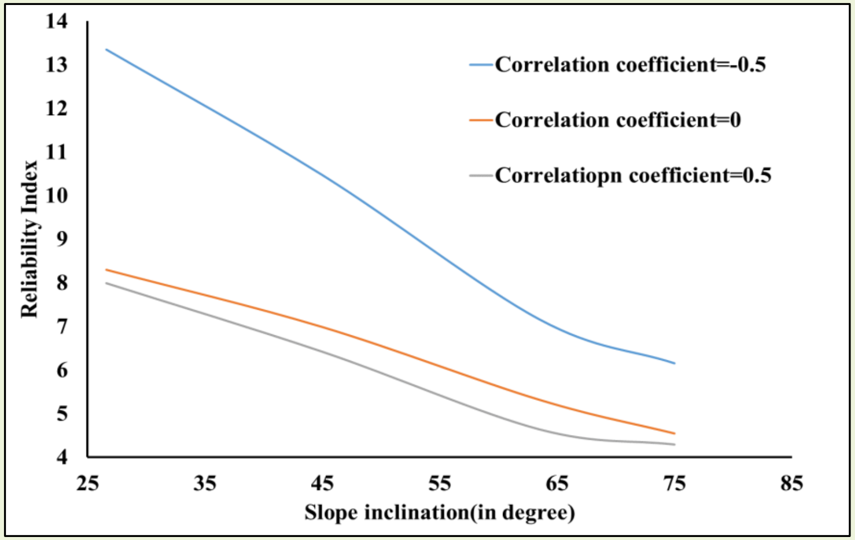




Effect of variation of slope inclination



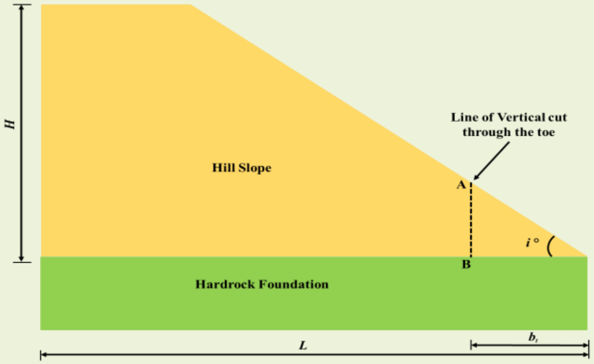
Undrained condition



Drained condition

Toe-excavated hill slopes

- Present study deals with only vertical toe excavation
- Slope/W module of Geostudio v2018
- Deterministic study (LE based Morgenstern-Price method)
    - *c* and *φ* values are varied from 0-70 kPa and 15°-40° respectively
- Probabilistic Study (LE based Morgenstern-Price and MCS)
    - Mean *c* = 40 kPa and mean *φ* = 27.5º, Log-normal pdf, CoV (0.2 - 0.4)
- Slope height (*H*) = 20 m, 30 m and 40 m
- Different slope inclinations (such as, *i* = 30°, 40°, 50°, 60°)
- The range of parameters considered for this exercise typically represents the commonly encountered hillslope materials in the NE region of India
- A typical monograph (comprising a set of tables)
- *Slopes considered safe from deterministic analysis can also be subjected to failure*
    - E.g., for *H* = 20 m, *i* = 40º and a CoV = 0.4 and b_t = 5 m
        - Deterministic FoS = **1.505**
        - High *Pf* of **8.74%**



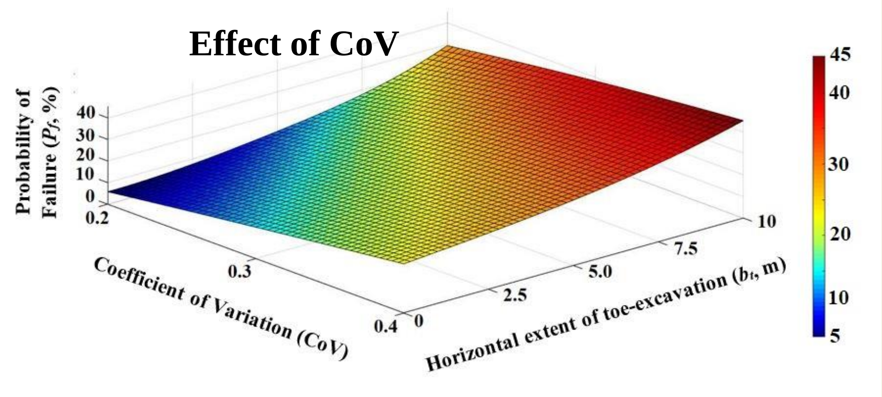
Reliability Index, β	Probability of failure, $P_f = \Phi(-\beta)$	Performance level
1	0.16	Hazardous
1.5	0.07	Unsatisfactory
2	0.023	Poor
2.5	0.006	Below average
3	0.001	Above average
4	0.00003	Good
5	0.0000003	High

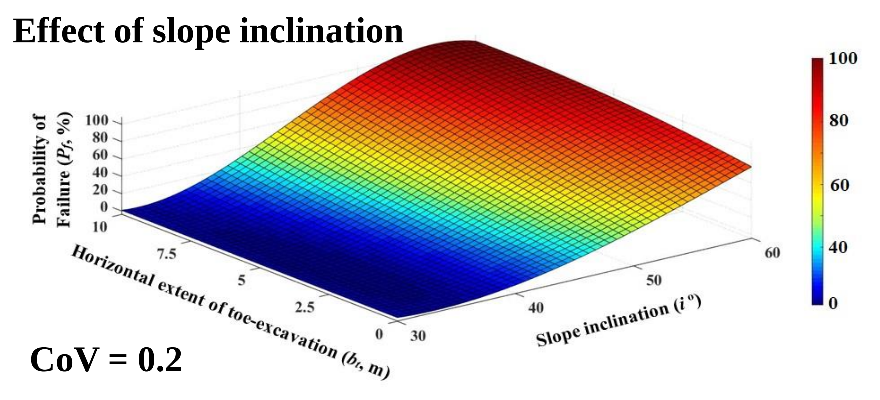
Note: Φ(.) is standard normal cumulative distribution function.

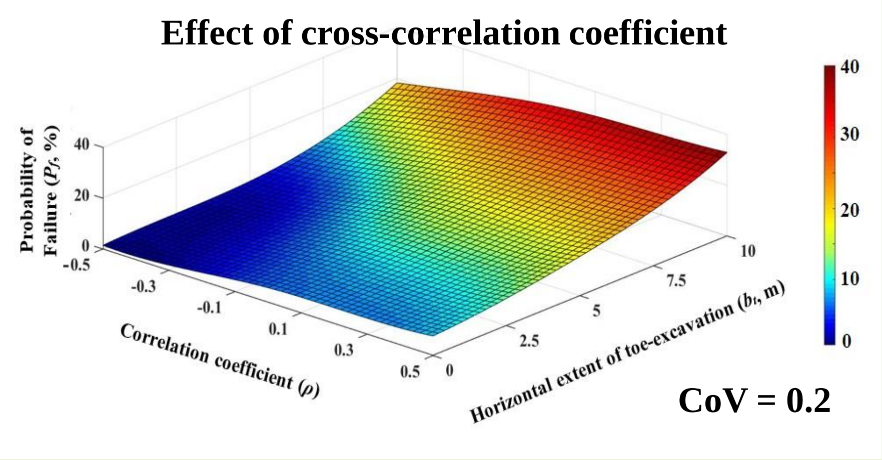
U.S. Army Corps of Engineers (1997)

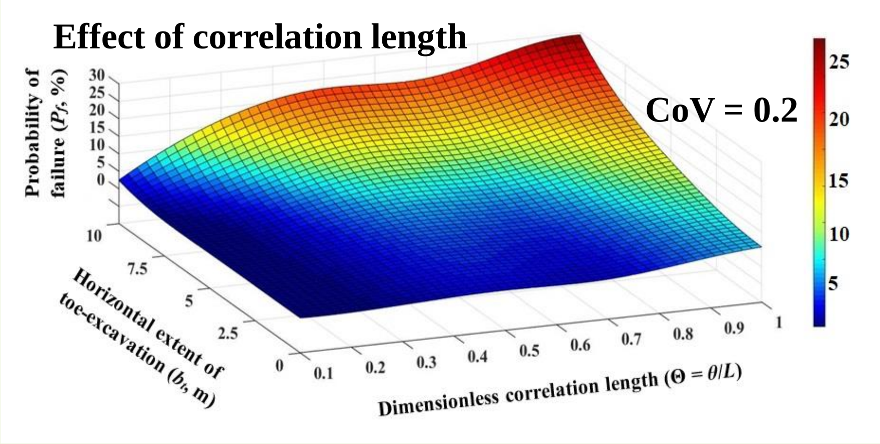
Toe-excavated hill slopes

- For a typical slope section (having 40 m height and 40° inclination)





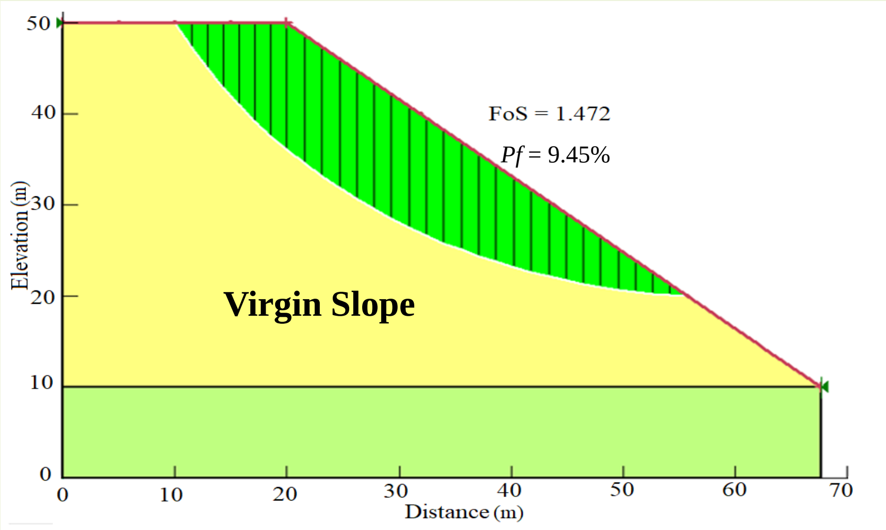


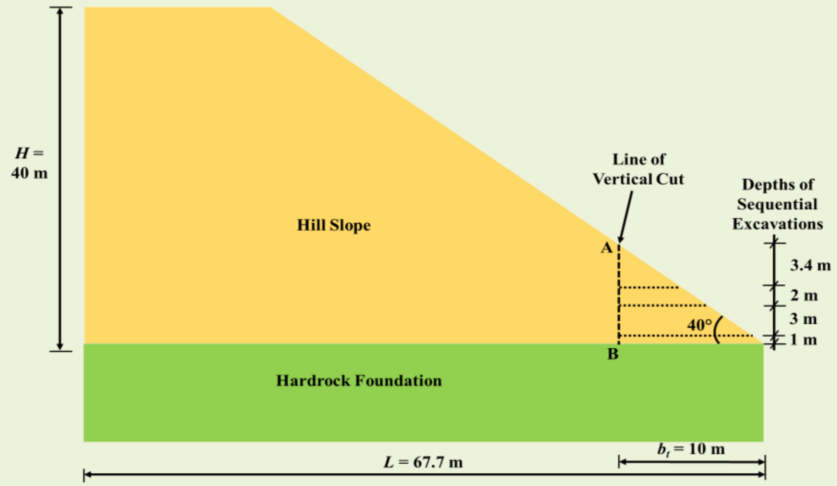


Probabilistic Assessment of Toe-excavated Hill Slope Supported By Sheet Pile Wall And SPAR System

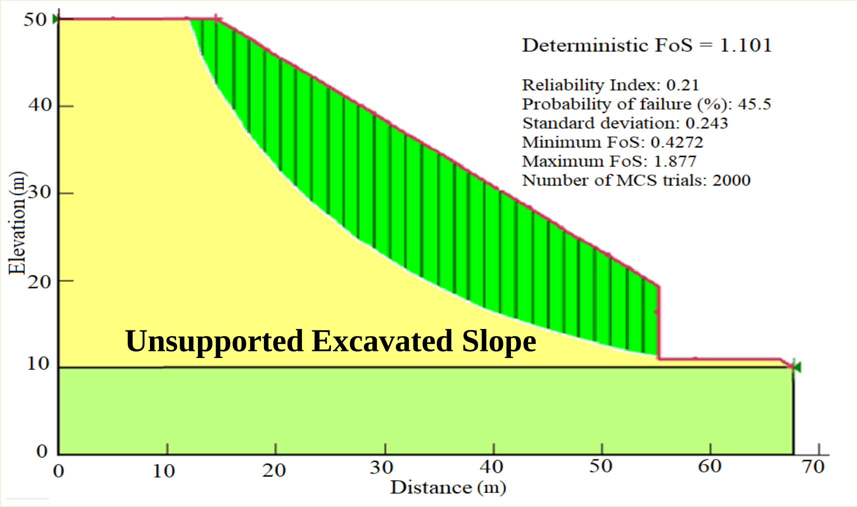
Probabilistic Analysis of Toe-Excavated System

- Sigma/W coupled with Slope/W
- Mean c = 40 kPa, Mean φ = 27.5°
- Unit weight (γ) = 18 kN/m^3 (deterministic)
- The FEM based stability analyses of the virgin slope
    - Deterministic FoS of 1.472
    - Probability of failure (9.45%) for CoV = 0.4
- Due to excavation (b_t = 10 m) deterministic FoS reduced from 1.472 to 1.101 and P_f increases from 9.45% to 45.5%



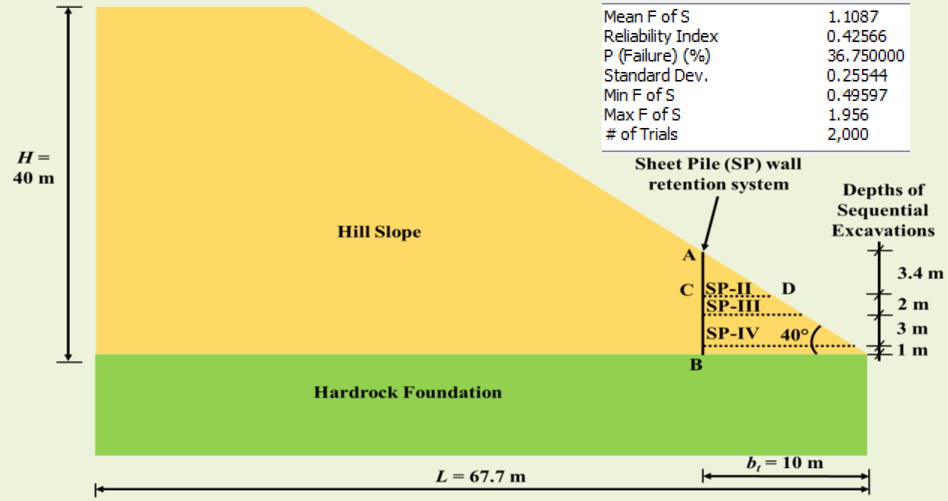


Schematic diagram of slope excavation

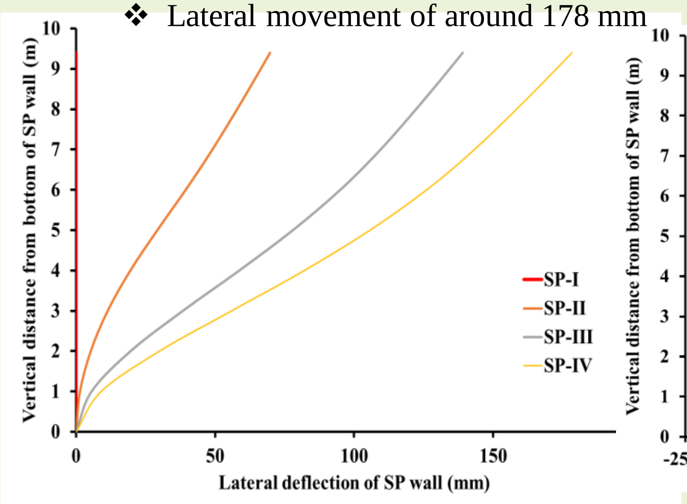


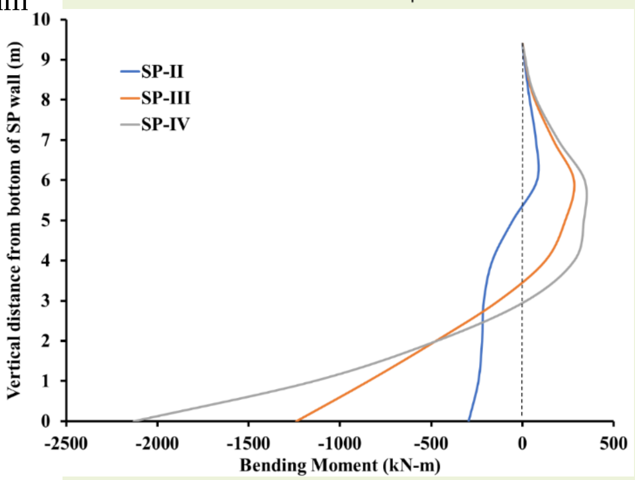
Probabilistic Analysis of Toe Excavated Slope with Sheet Pile Retention Systems

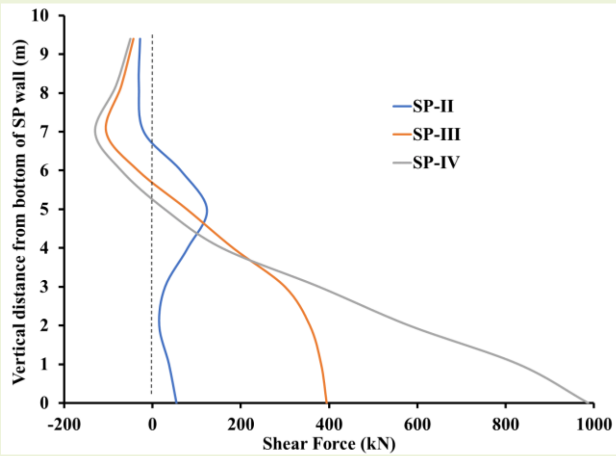
- Sigma/W coupled with Slope/W
- Mean c = 40 kPa, Mean φ = 27.5º, CoV = 0.4
- Unit weight (γ) = 18 kN/m^3 (deterministic)
- Deterministic FoS = 1.163 and P_f = 36.8%
- In comparison to the unsupported slope
  - Marginal increase in the deterministic FoS and a meagre decrease in the P_f



❖ Lateral movement of around 178 mm



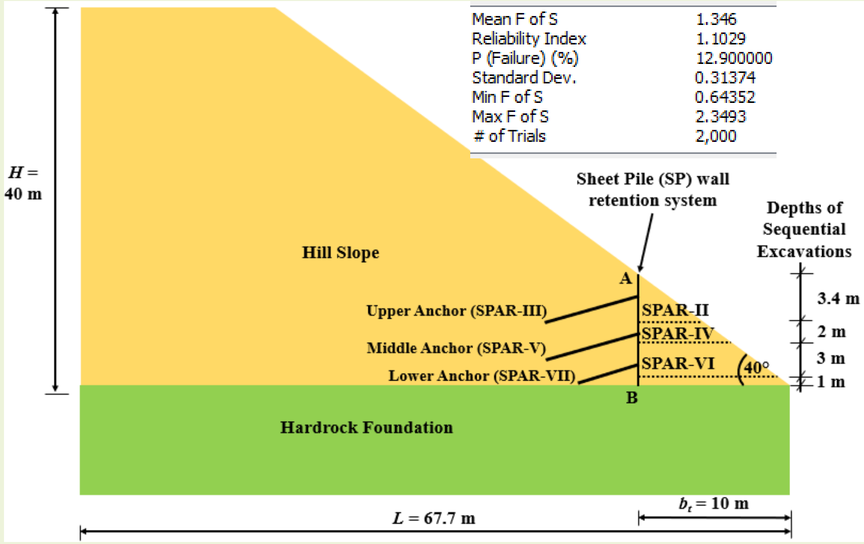


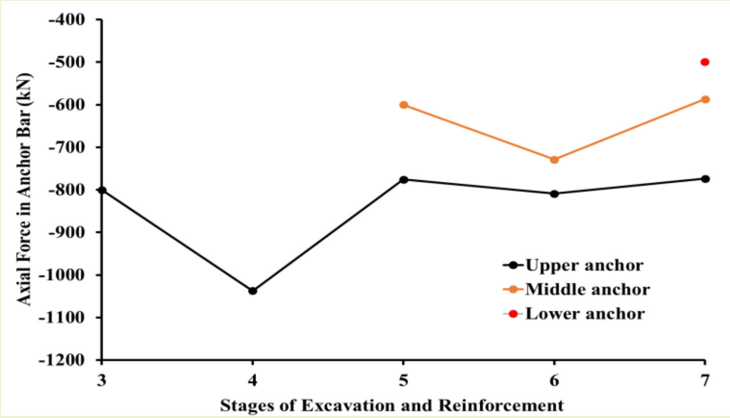


Probabilistic Analysis of Toe-excavated Slope with Sheet Pile Anchor Retention Systems

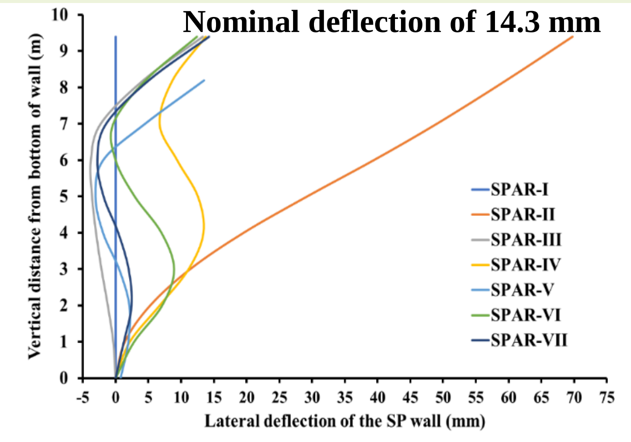
Retention Component	Material Model	Axial modulus (kPa)	Cross-sectional area (m^2)	Moment of inertia (m^4)
Sheet pile wall	Structural beam element	$2x10^8$	0.002	0.0005
Anchor	Structural bar element	$2x10^8$	0.00126	-

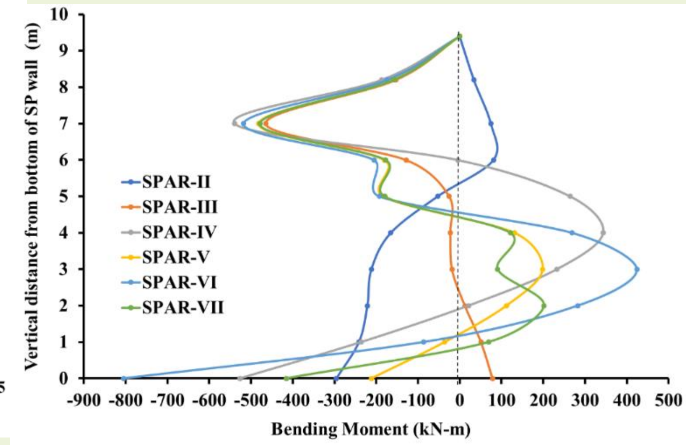
- First layer of anchors (length 8.1 m)
    - Inclination of 20° with the horizontal
    - Pre-stressed (800 kN)
    - At a depth of 2.4 m from the top
- Second layer of anchors (length 8.1 m)
    - Inclination of 20° with the horizontal
    - At the mid-height of the second layer of excavation
    - Pre-stressed (600 kN)
- Third layer of anchor (length 5.9 m)
    - Inclination of 20° with the horizontal
    - At the mid-height of the excavation
    - Pre-stressed (500 kN)

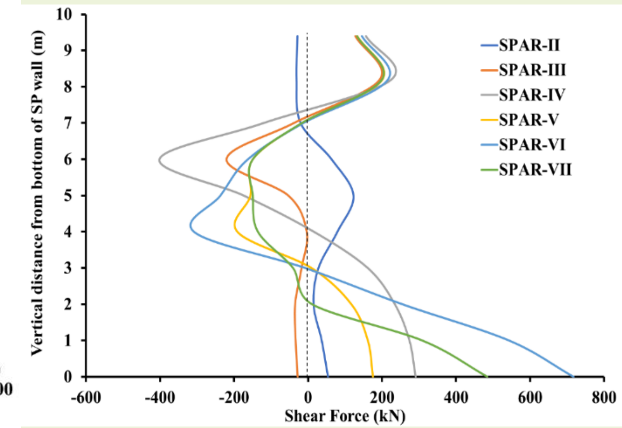


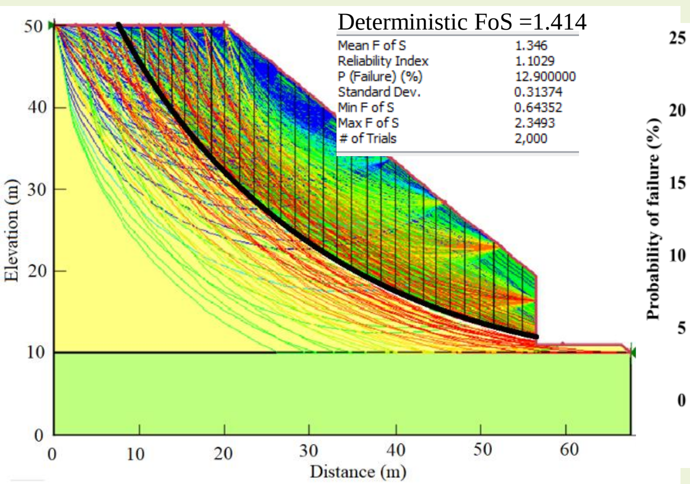


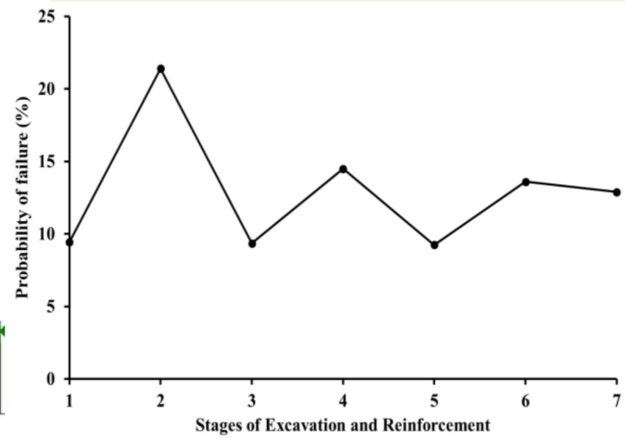
Probabilistic Analysis of Toe-excavated Slope with Sheet Pile Anchor Retention Systems

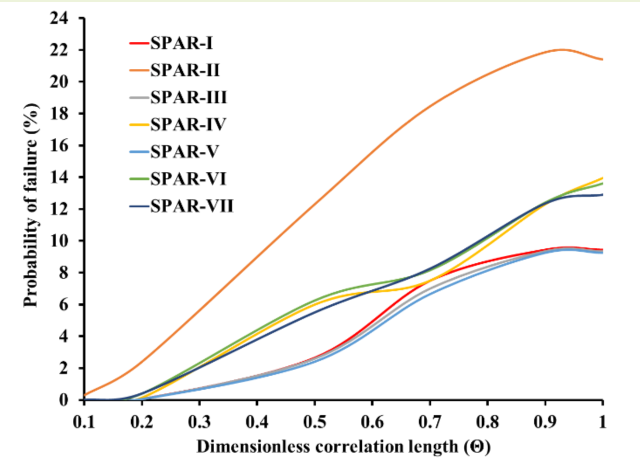








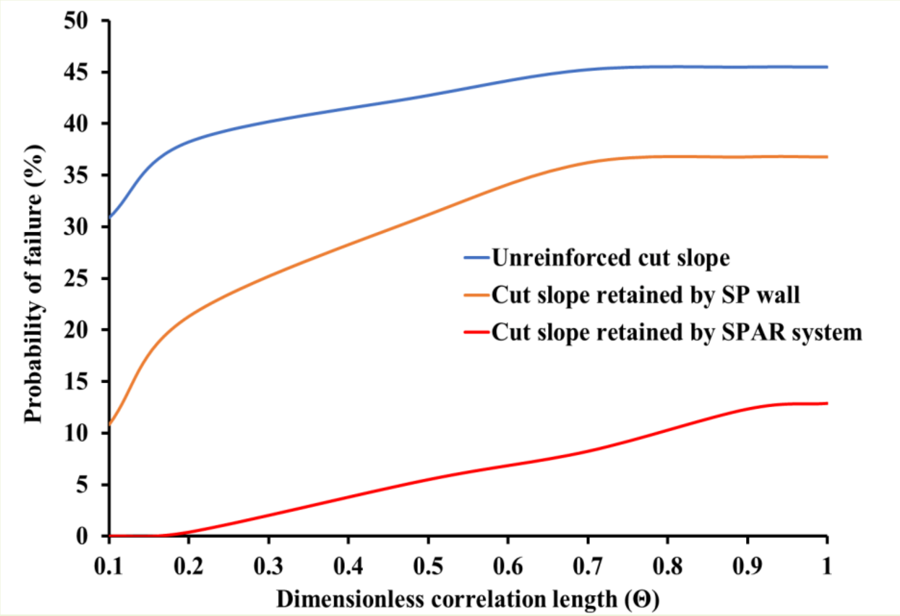




Probabilistic Analysis of Toe-excavated Slope with Sheet Pile Anchor Retention Systems

Without spatial variation	Deterministic FoS	P_f (%)
Virgin	1.472	9.45
Unsupported excavation	1.101	45.5
Excavation with SP wall	1.163	36.8
Excavation with SPAR system	1.414	12.9

- SPAR retention measure substantially reduces the P_f of the cut slope
- P_f is substantially influenced by the correlation length
- For the cut slope retained by the SPAR system, depending on Θ, P_f varies from **zero to 12.9%**
- The results indicate that the cut slope retained by SPAR has negligible probability of failure for a large range of Θ
    - Up to a value of **Θ = 0.2, the chosen slope geometry is absolutely stable without any chance of failure**



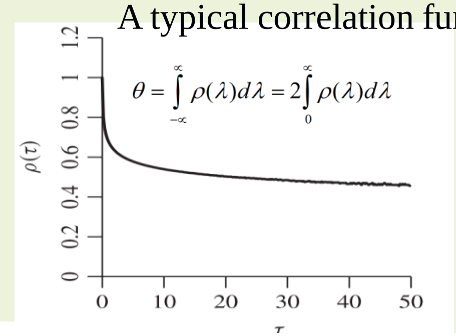
Random Finite Element Analysis For Toe Excavation Induced Slope Instability

Random Field Theory: Correlation Function and Correlation Length

Stationarity or statistical homogeneity:

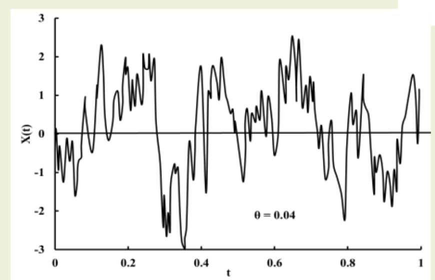
- The mean, covariance and higher order moments are constant in space
- The correlation between two points only depends on the relative distance between them does not depend on their orientation relative to each other

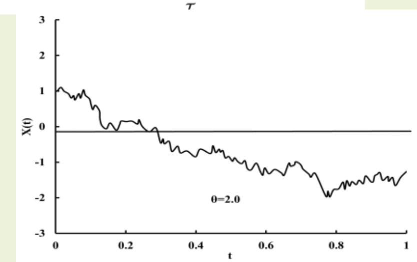
A typical correlation function



➢ Upon the simplifying assumptions that the random field is stationary, we need to know three parameters in order to characterized the field:
  - Mean
  - CoV
  - How rapidly the field varies in space

❖ The last can be characterized using a **correlation function**

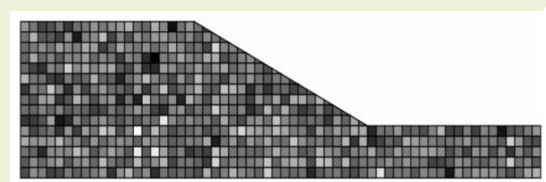




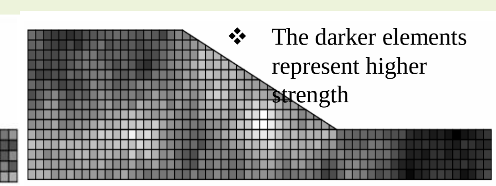
➢ The correlation function represents the variation of spatial correlation as a function of spatial separation length between two locations

➢ Correlation function characterized by ***correlation length*** or ***scale of fluctuation*** (Vanmarcke, 1977)

➢ The correlation length (θ) represents the spatial range over which the soil property shows a relatively strong spatial correlation



Slope with Low Correlation Length



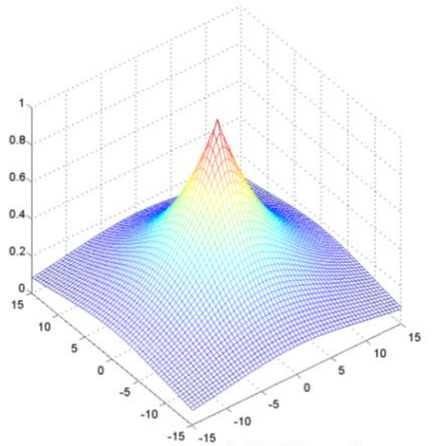
Slope with High Correlation Length

Sample realizations of *X(t)* for two different SoF(Griffiths and Fenton, 2007)

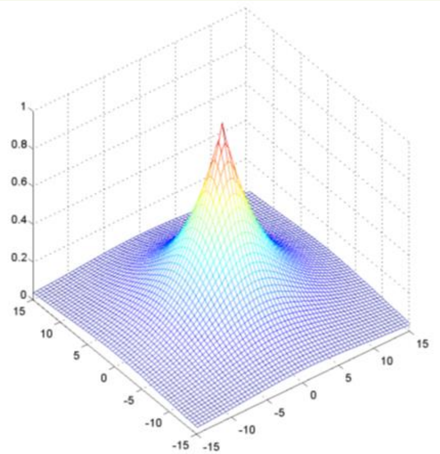
Probabilistic Slope Stability Analysis

- Spatial Correlation Structure:
  - ❖ Ellipsoidal Markovian correlation

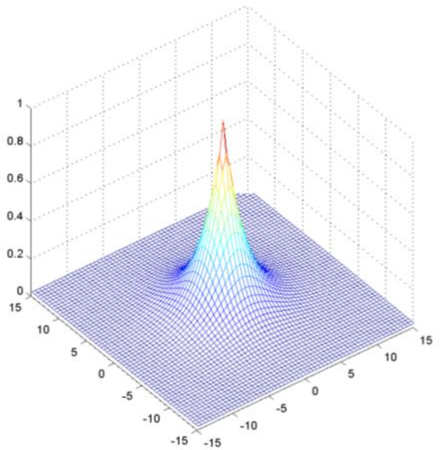
$$\rho(\tau) = \exp\left\{-\sqrt{\left(\frac{2\tau_x}{\theta_x}\right)^2 + \left(\frac{2\tau_y}{\theta_y}\right)^2}\right\}$$



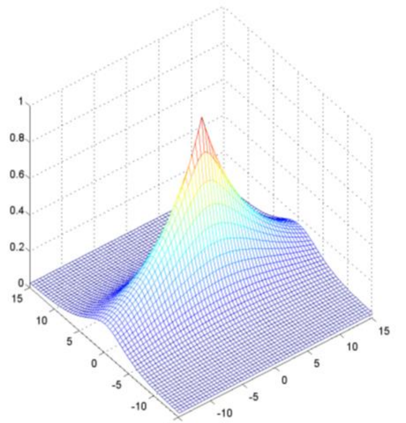
$\Theta_x = \Theta_y = 15.0$m over a field of dimension 15 m



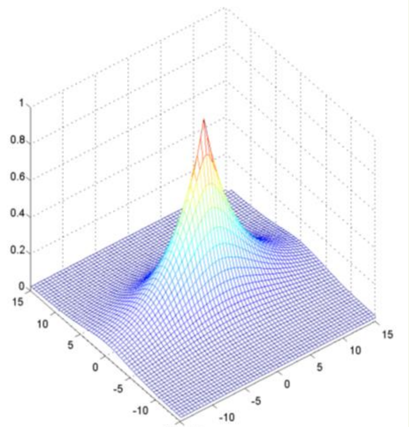
$\Theta_x = \Theta_y = 10.0$m over a field of dimension 15 m



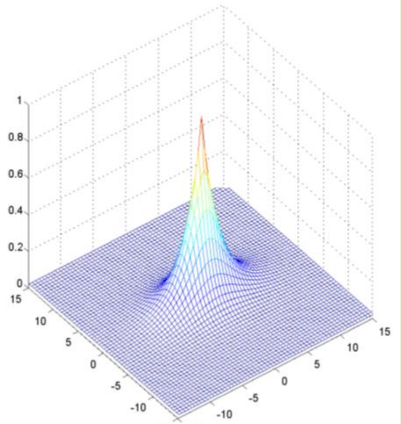
$\Theta_x = \Theta_y = 5.0$m over a field of dimension 15 m



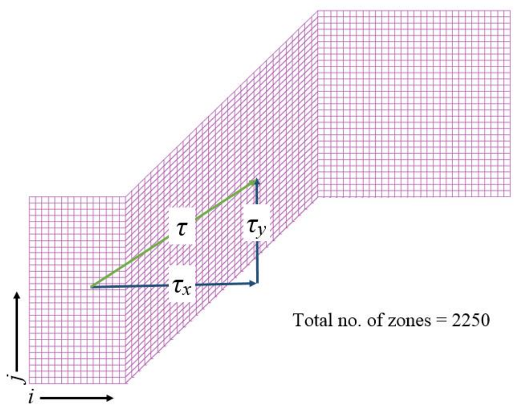
$\Theta_x = 15$m; $\Theta_y = 5.0$m over a field of dimension 15 m



$\Theta_x = 10$m; $\Theta_y = 5.0$m over a field of dimension 15 m

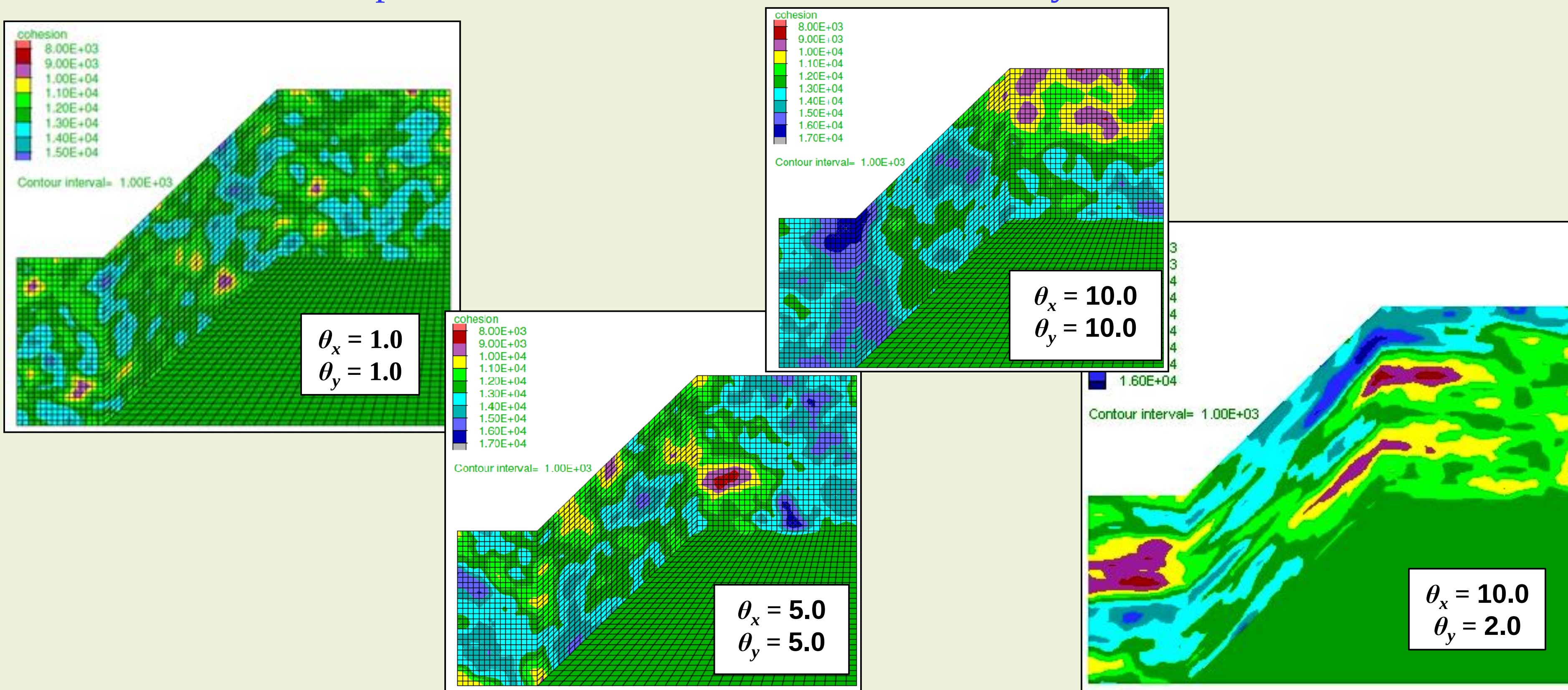


$\Theta_x = 5$m; $\Theta_y = 3.0$m over a field of dimension 15 m



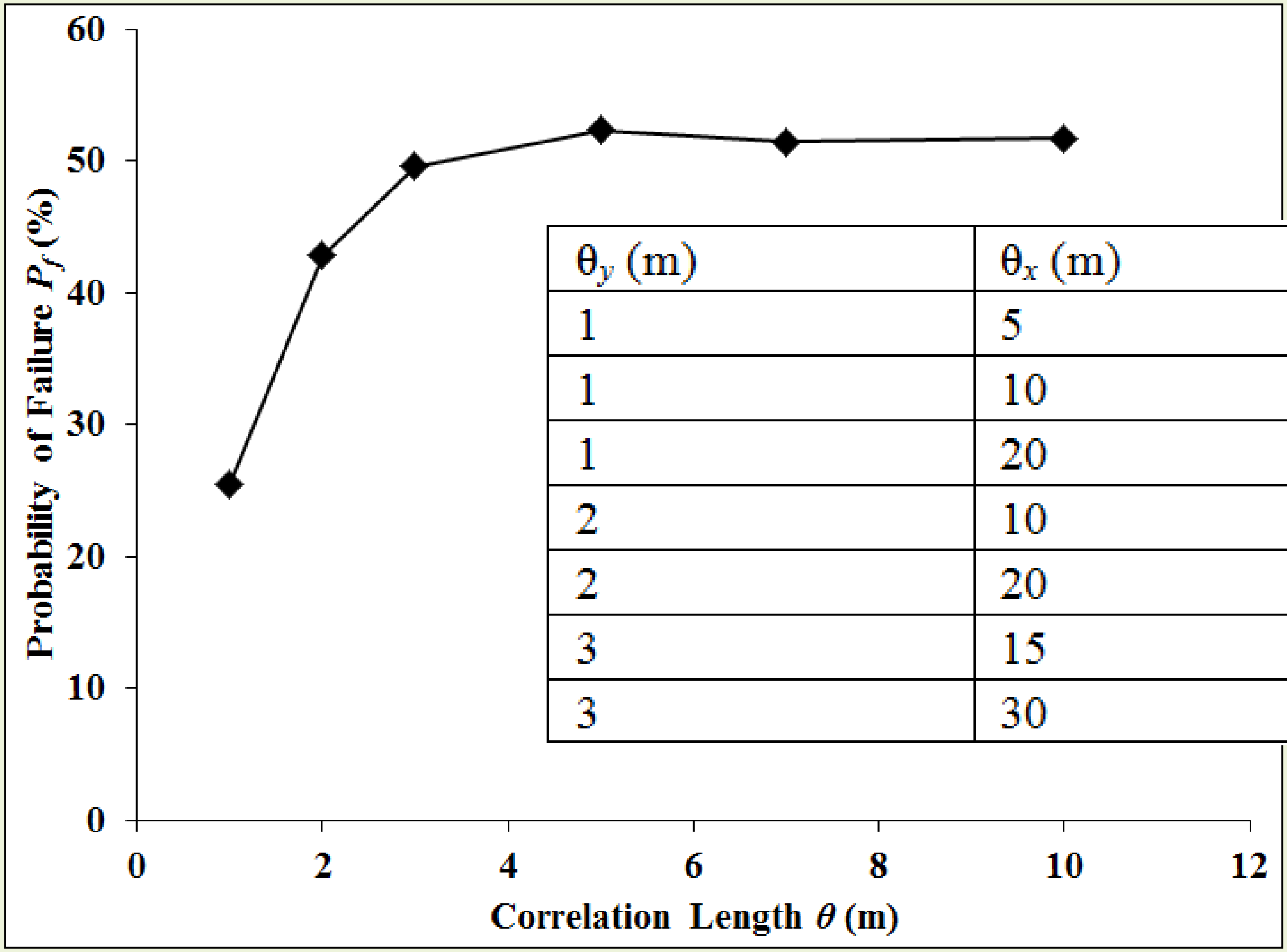
Probabilistic Analysis of Landslides

- A typical example of parameter distribution
  - ❖ Simulation of spatial variability of soil shear strength parameters (c,φ)
    - Isotropic correlation – Formation of parameter pockets
    - Anisotropic correlation – Formation of stratified layers



Probabilistic Slope Stability Analysis

- Probability of failure depends on correlation length



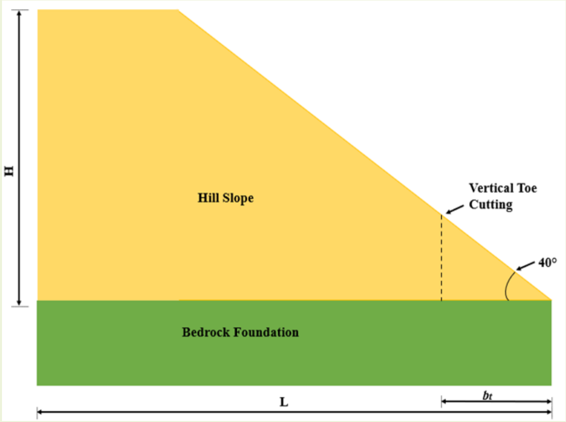
θ_y (m)	θ_x (m)	P_f (%)
1	5	43.2
1	10	45.1
1	20	46.3
2	10	45.7
2	20	48.5
3	15	47.5
3	30	53.1

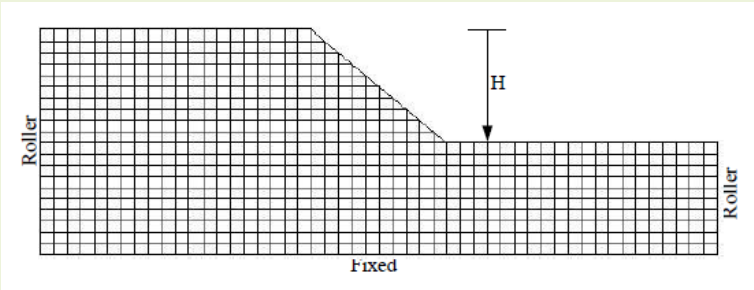
Random Finite Element Method (RFEM)

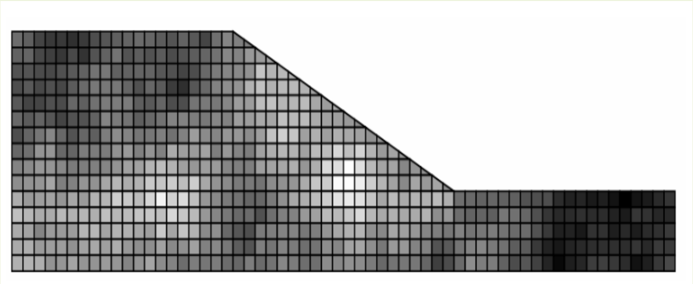
- A typical 2H:1V slope section, having a height (*H*) of 40 m and a crest length (*H*/2) of 20 m
- The vertical cut of horizontal width (b_t) 10 m
- A random field is overlaid upon a FE mesh, each mesh behaves as a random variable
- The set of random variables is characterised by joint pdf
- Completely accounts for *spatial correlation* and *local averaging*
- *No presumptions* regarding the location and shape of critical slip surface
- 2D spatial variation of the shear strength parameters in the slope domain in *Rslope2d* is characterized by an exponentially decaying ***(Markovian) correlation function***

$$\rho(k) = \exp\left(-\frac{2|k|}{\theta}\right)$$

- Number of MCS
  - 4000 in Rslope2d

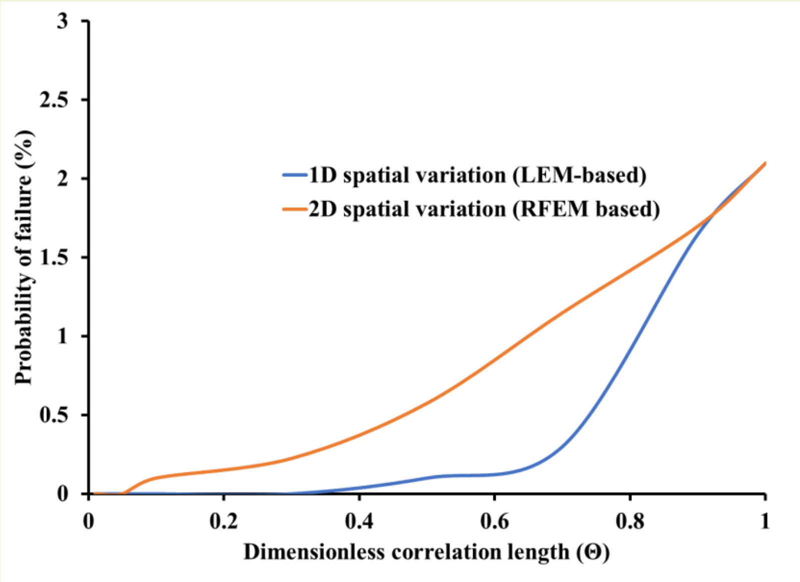


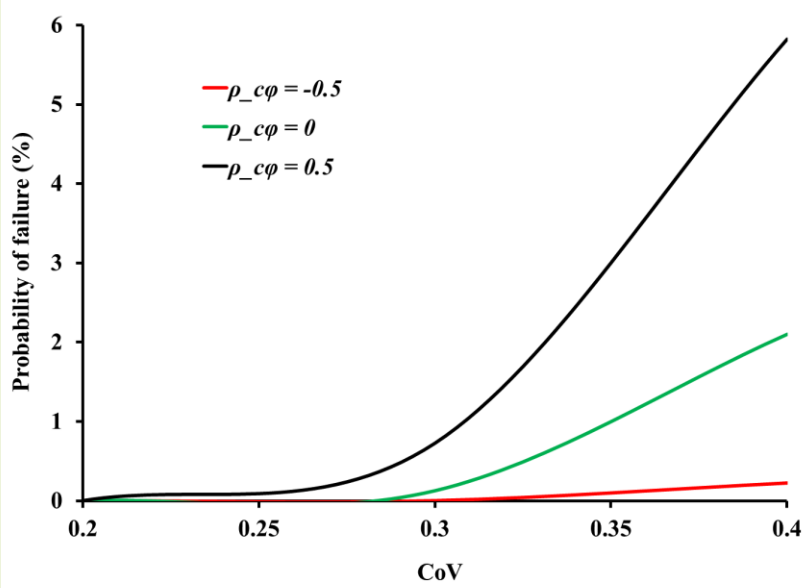




Random Finite Element Method (RFEM)

- LEM based probabilistic study
  - Slope section is safe with a low value of P_f having a performance level ‘above average’, for Θ up to 0.7
- RFEM analysis shows
  - Slope section is safe, having a low value of P_f with a performance level ‘above average’, for Θ up to 0.5
- P_f of the cut slope for Θ = 1 and CoV = 0.4, are 0.23%, 2.1% and 5.83% for $\rho_{c\varphi}$ values of -0.5, 0 and 0.5 respectively



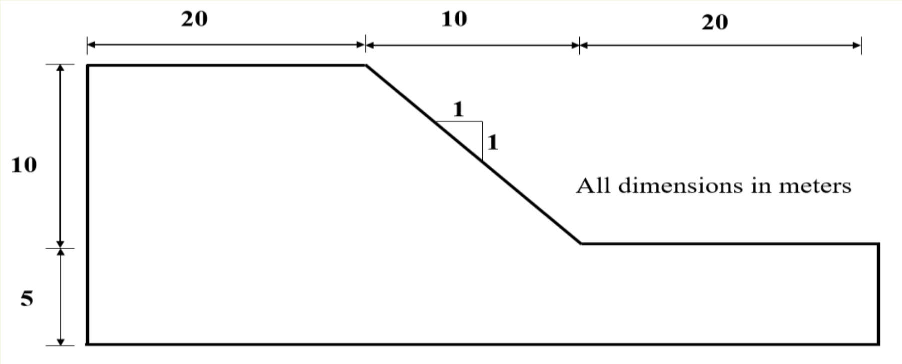


Rslope2d

Probabilistic Assessment of Seismic Response of Cut Slopes

Randomness in Earthquake Coefficients

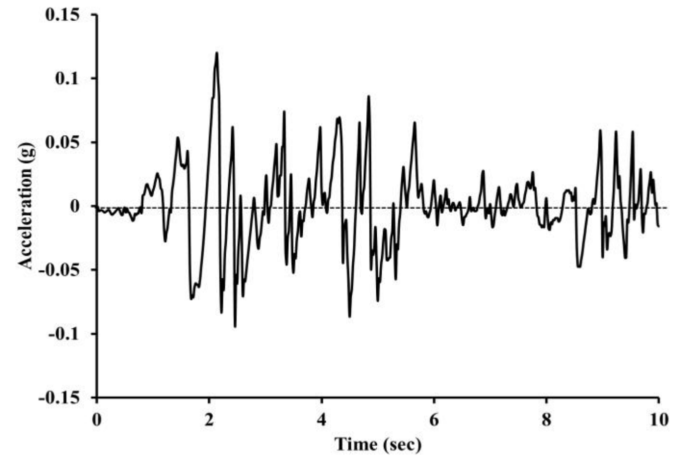
- Horizontal pseudo-static force, $F_h = \frac{a_h W}{g} = k_h W$
- Vertical pseudo-static force, $F_v = \frac{a_v W}{g} = k_v W$
- The mean cohesion (c) = 45 kPa
    - Log-normal pdf with a CoV value of 0.1
    - Unit weight of soil (γ) = 20 kN/m^3



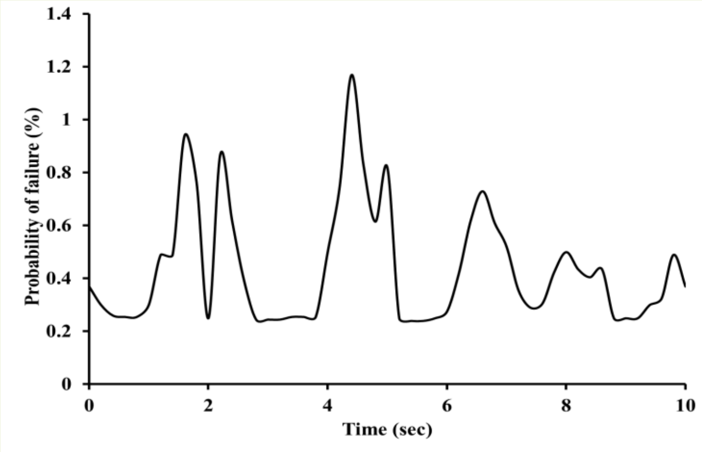
Pseudo-static acceleration coefficients	$k_h = 0.18, k_v = 0.09$		$k_h = 0.16, k_v = 0.08$		$k_h = 0.12, k_v = 0.06$	
	Constant	Random	Constant	Random	Constant	Random
Deterministic FoS	0.791	0.791	0.826	0.826	0.905	0.905
RI	-2.475	-2.128	-1.983	-1.777	-1.013	-0.899
P_f (%)	99.25	98.15	97.2	96.4	86.1	83.55
Pseudo-static acceleration coefficients	$k_h = 0.10, k_v = 0.05$		$k_h = 0, k_v = 0$			
	Constant	Random				
Deterministic FoS	0.947	0.947	1.263			
RI	-0.523	-0.449	1.916			
P_f (%)	72.35	69.65	1.25			

Non-linear Dynamic Approach

- For dynamic analysis, the Poisson's ratio (v), damping ratio (ξ) and maximum shear modulus (G_{max}), for the slope material, is considered to be 0.334, 0.1 and 5 MPa respectively.
- The maximum P_f is approximately 1.17%
- A pseudo-static analysis of the same slope section (for k_h = 0.12, k_v = 0.06) gave a high P_f value of 86.1%



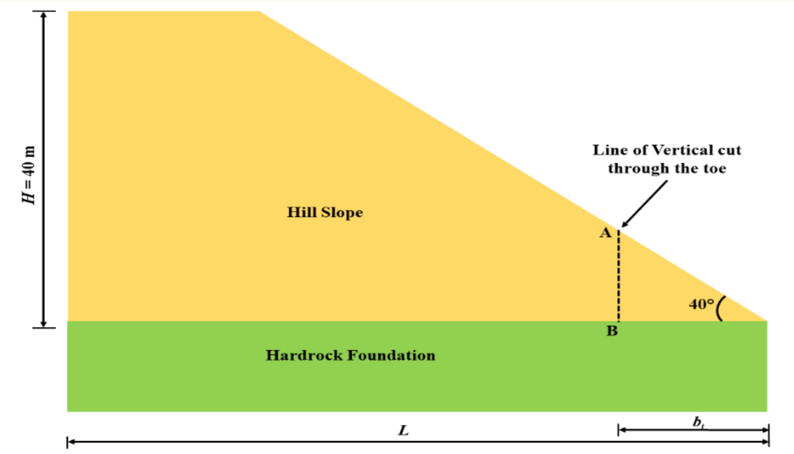
A typical earthquake time history recorded during the 1971 San Fernando earthquake

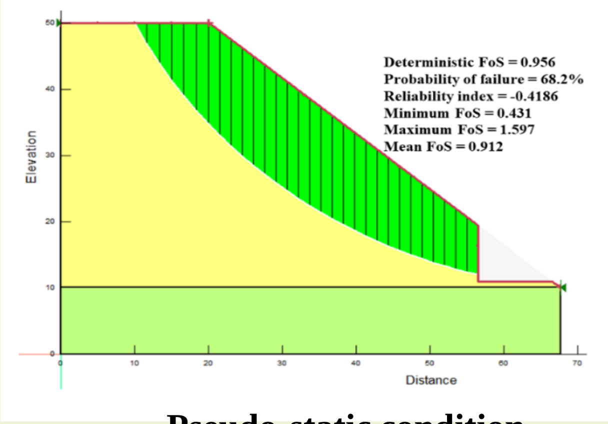


Variation of probability of failure with time during earthquake occurrence

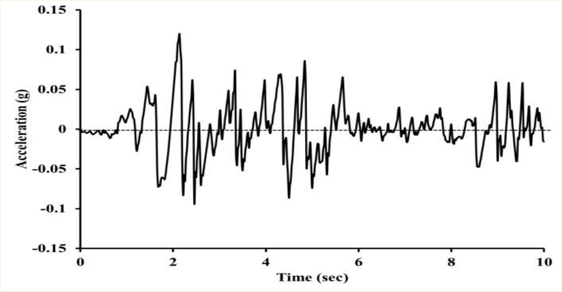
Analysis of Toe Excavation Induced Slope Instability under Earthquake Condition

- **Pseudo-static Approach**
  - The horizontal and vertical pseudo-static acceleration coefficients is considered in this section as **0.12g and 0.06g,** respectively; corresponding to Zone-IV (IS 1893 Part 1: 2002) and a P_f = **68.2%** is obtained
- **Non-Linear Dynamic Approach**
  - A maximum probability of failure of **51.2%** occurred during the entire duration of earthquake motion

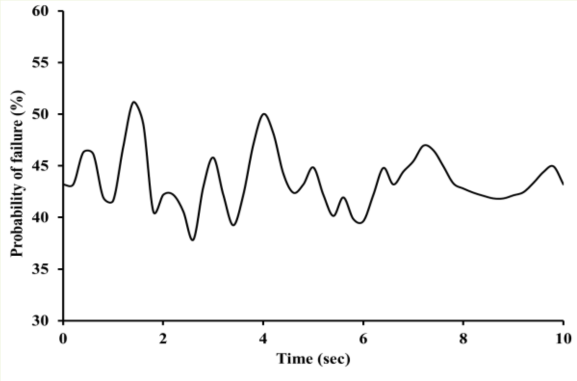




Pseudo-static condition



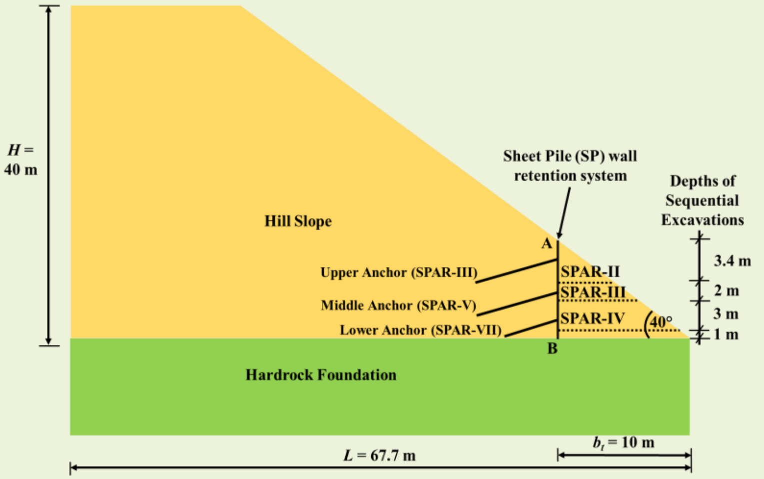
Earthquake time history

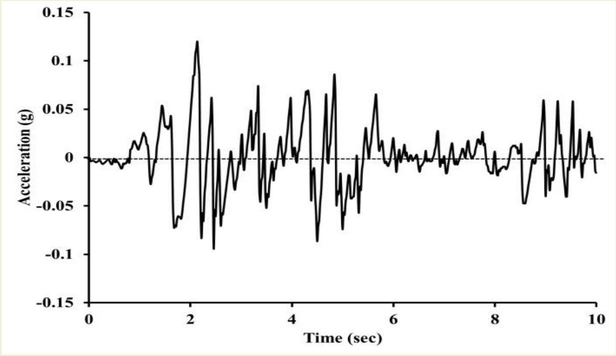


Variation of *Pf* with time

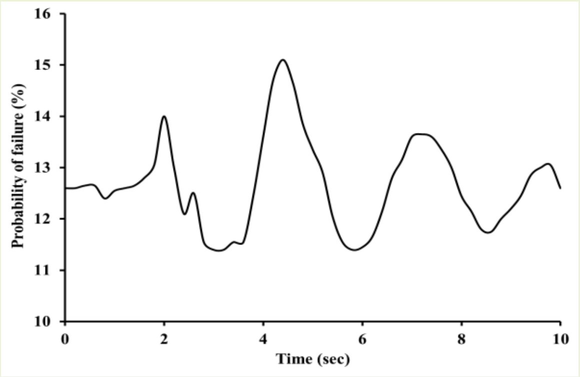
Analysis of Toe Excavation Induced Slope Instability under Earthquake Condition

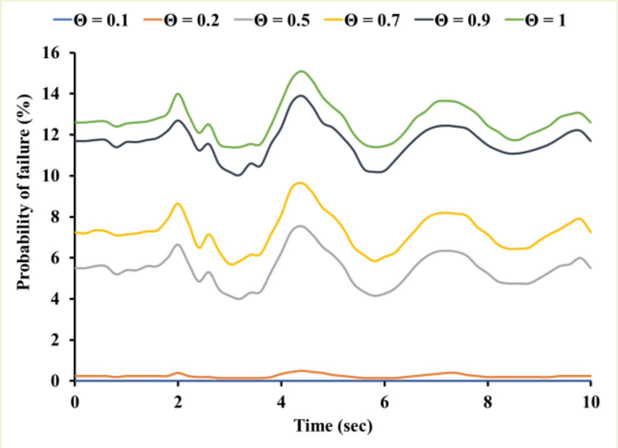
- **SPAR System**
  - The cut slope structure reinforced with SPAR shows a P_f value of as high as **15.1%**
  - Low P_f for a Θ up to 0.2 under dynamic excitation, and hence safe upon excavation under static as well as dynamic condition





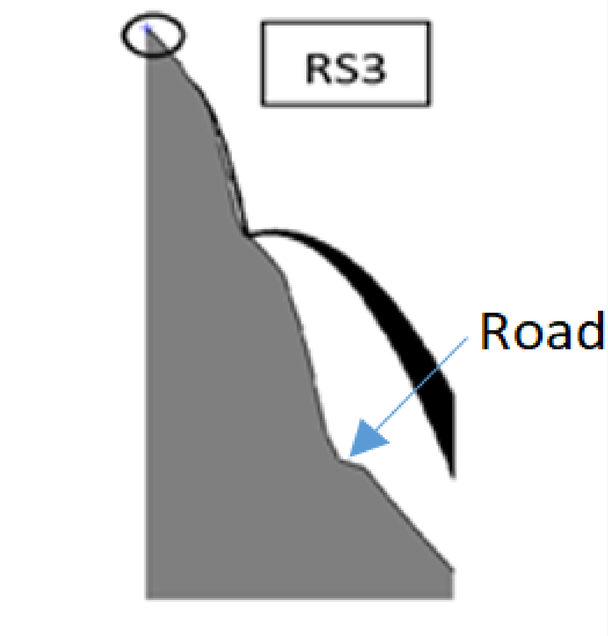
Earthquake time history





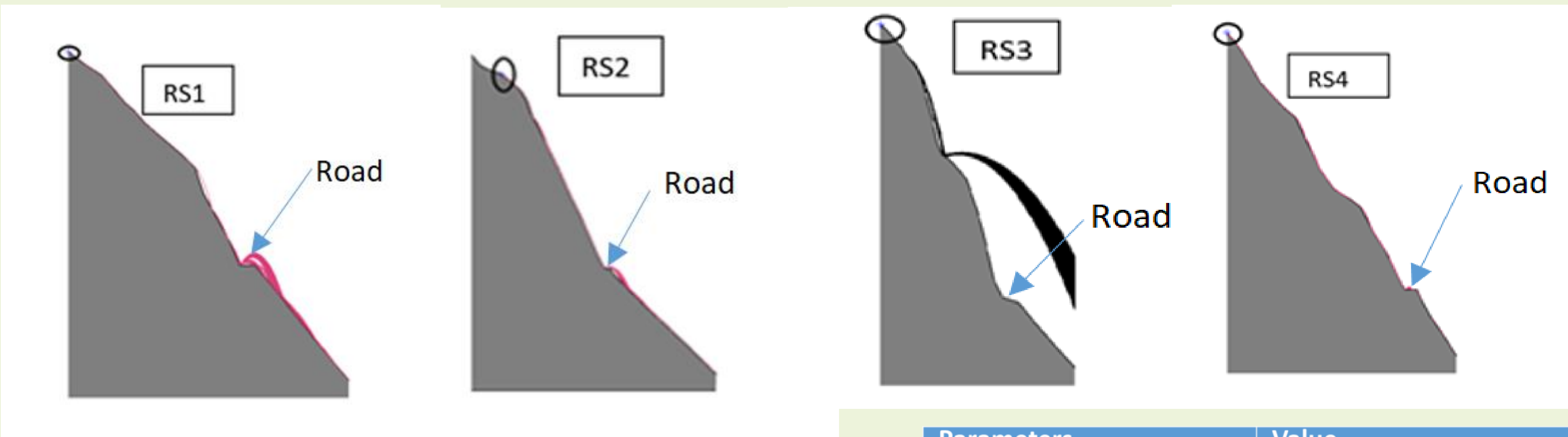
Variation of probability of failure with time

ROCKFALL



Rockfall Analysis using Rocfall, Rocscience

Theng slope along the North Sikkim Highway that connects Chungtang town to Tung

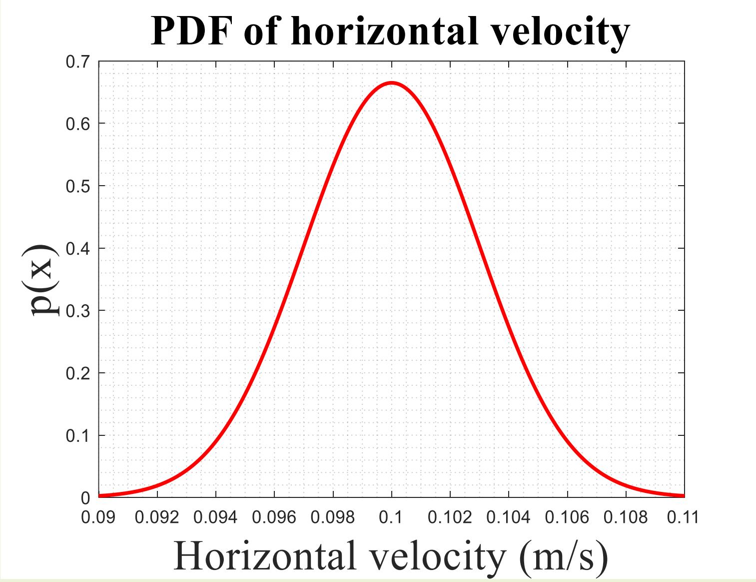


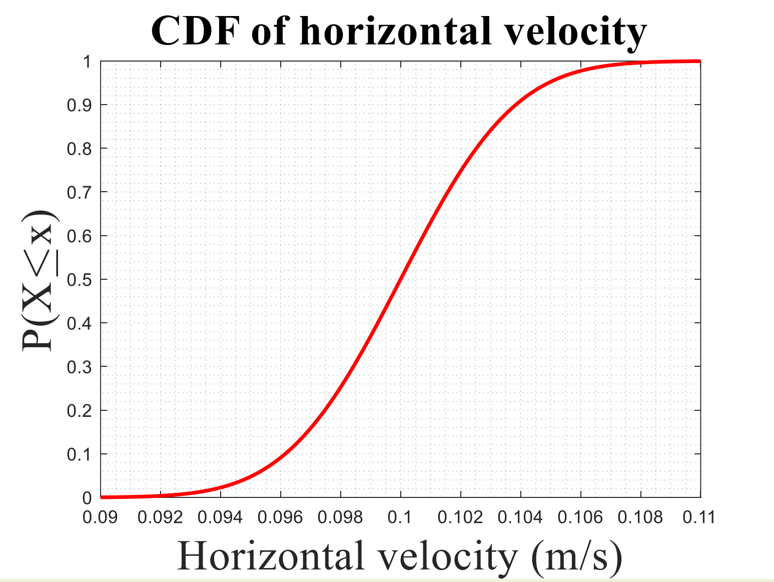
Slope Designation	Height of the slope (m)	Angle of the slope (°)	Friction angle (°)
RS1	141	35-60	35
RS2	346	45-75	30
RS3	258	50-80	30
RS4	244	45-65	35

Parameters	Value
Tangential restitution	0.65
Friction angle	30°
Slope roughness	0
Number of rocks thrown	500
Vertical velocity	0
Rotational velocity	0
Initial Rotation	0

Stochastic Parameters

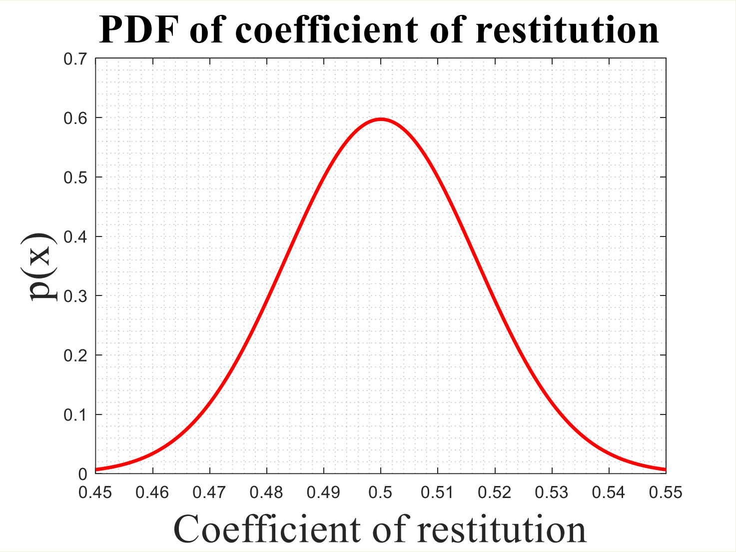
Stochastic parameters	Type of distribution	Mean	Standard deviation	Maximum	Minimum
Horizontal velocity	Truncated normal distribution	0.1	0.01	0.11	0.09

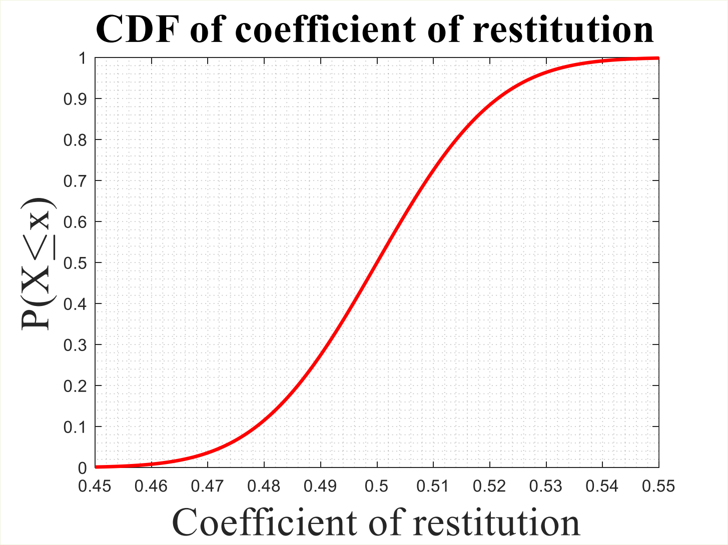




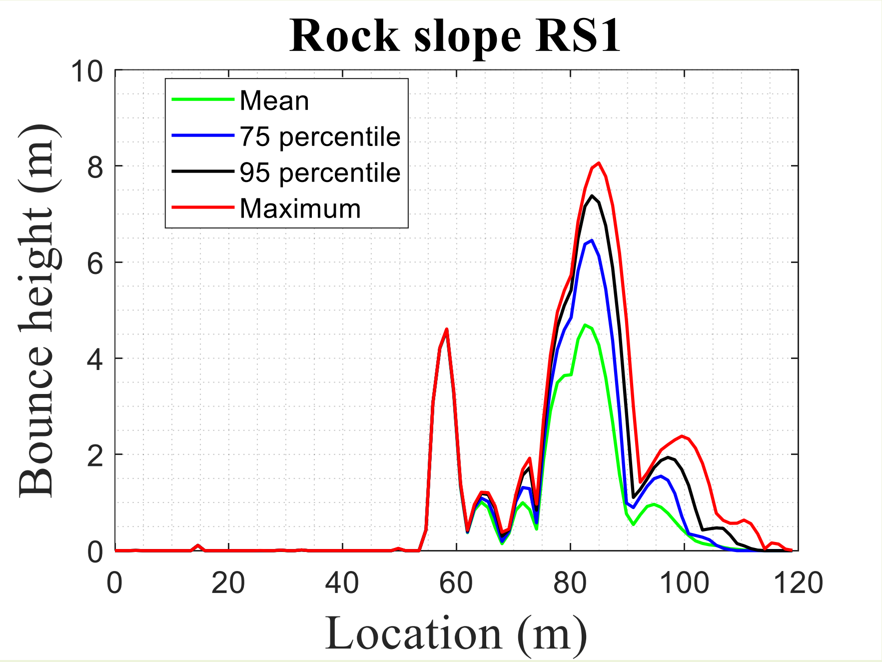
Stochastic Parameters

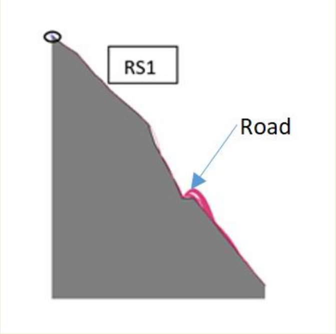
Stochastic parameters	Type of distribution	Mean	Standard deviation	Maximum	Minimum
Coefficient of restitution	Truncated normal distribution	0.5	0.05	0.55	0.45

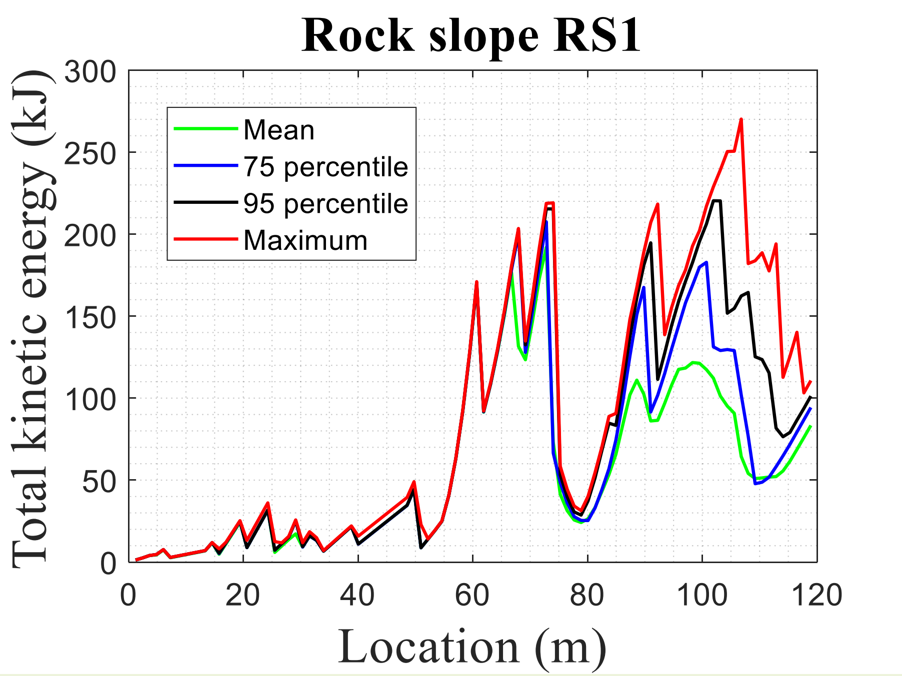




Results from Stochastic Analysis







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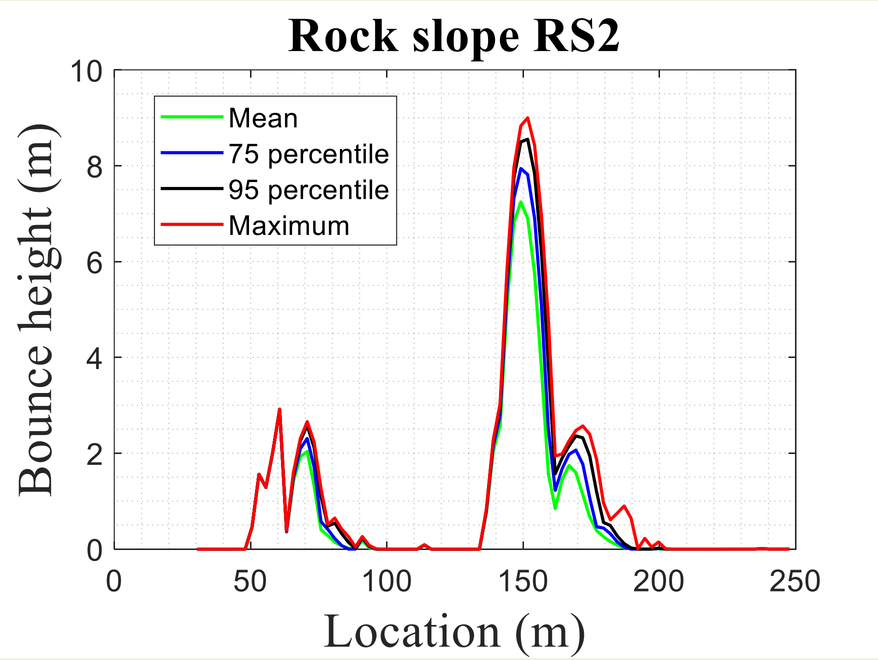

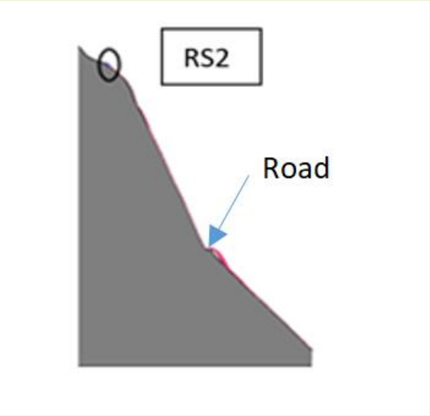

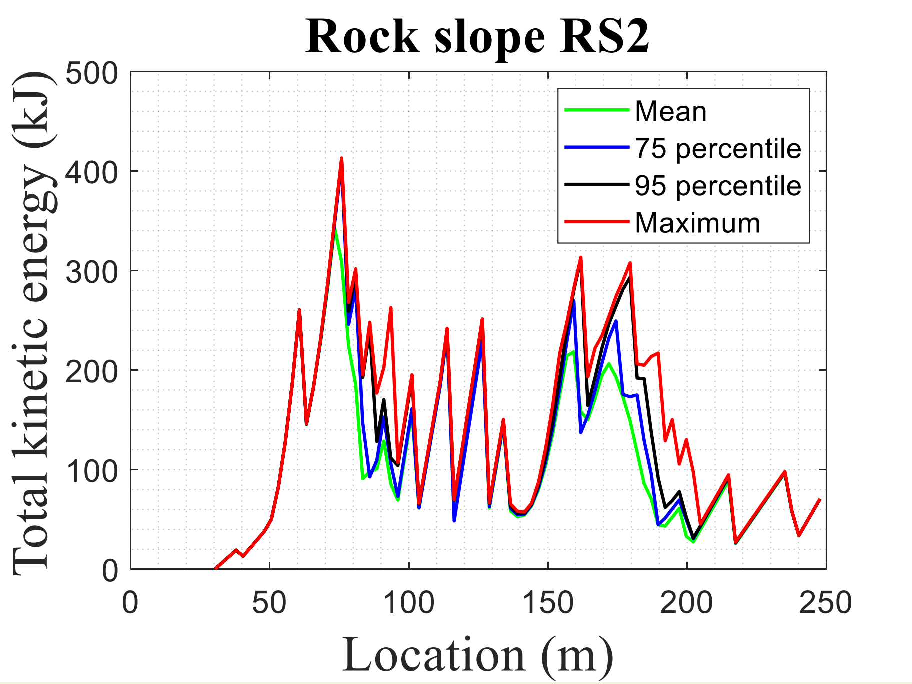

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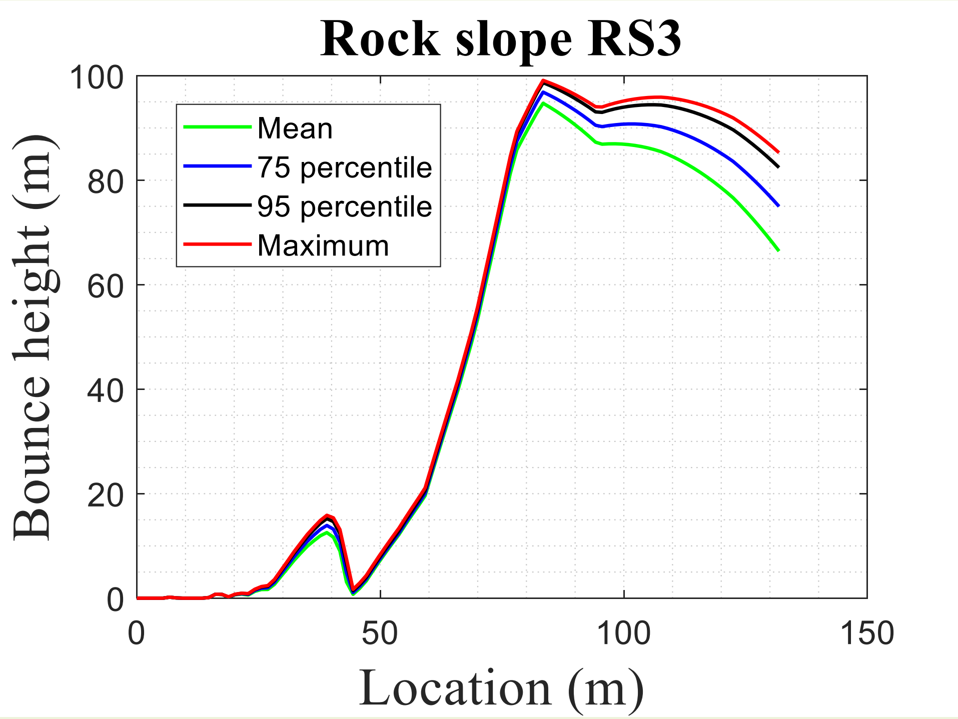

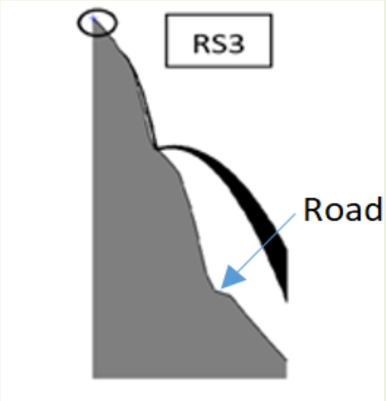

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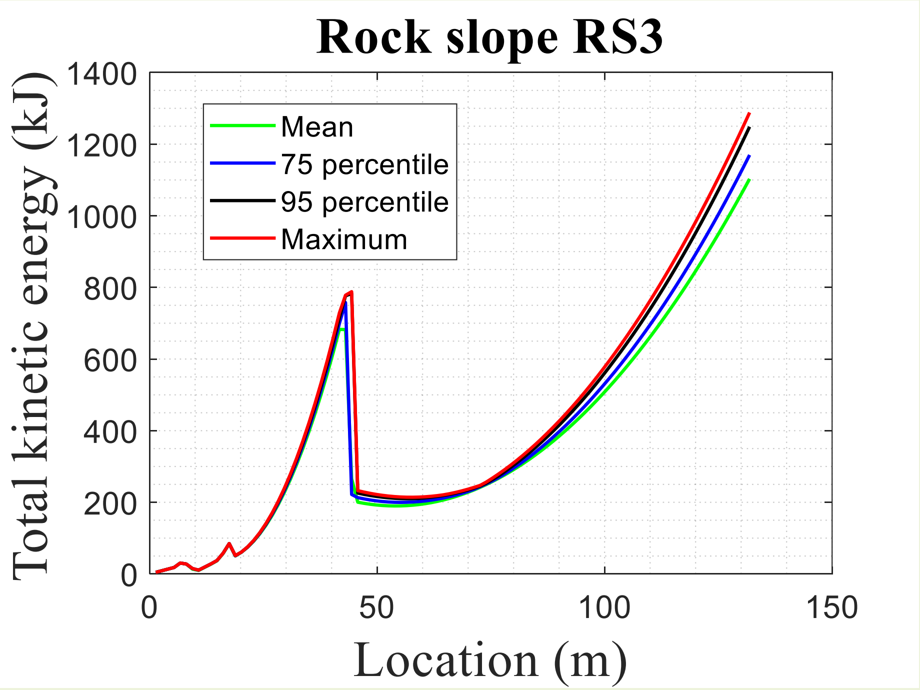
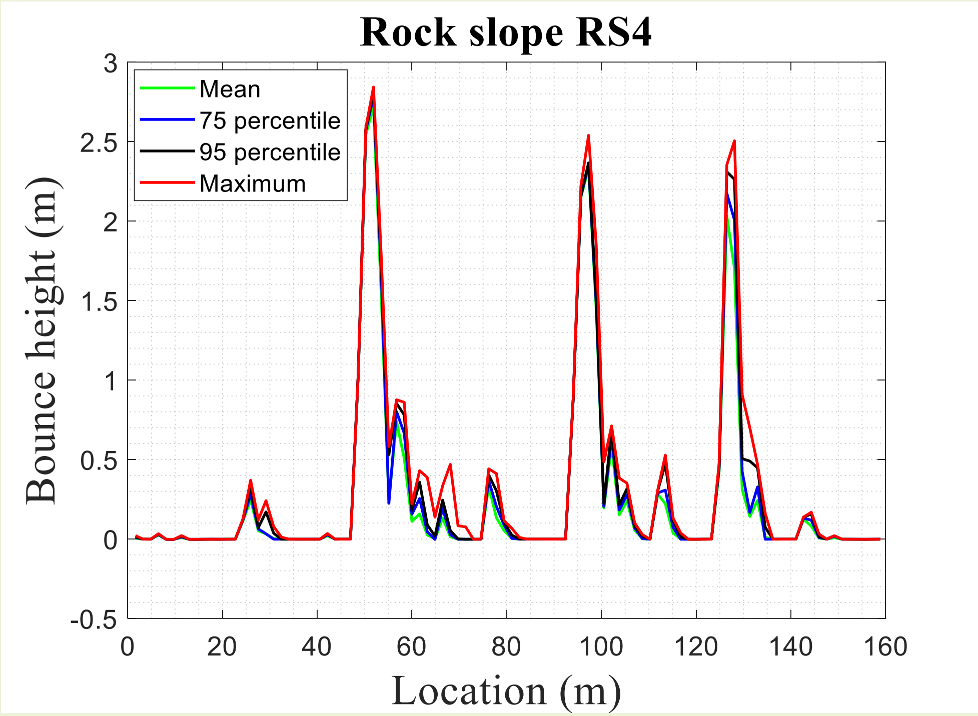
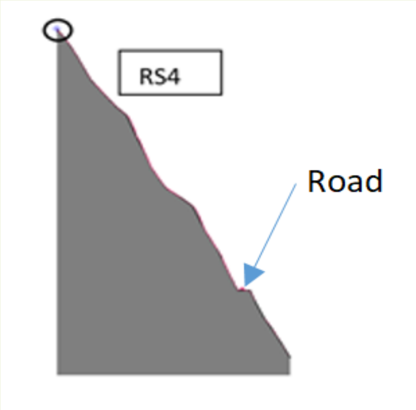


Results from Stochastic Analysis





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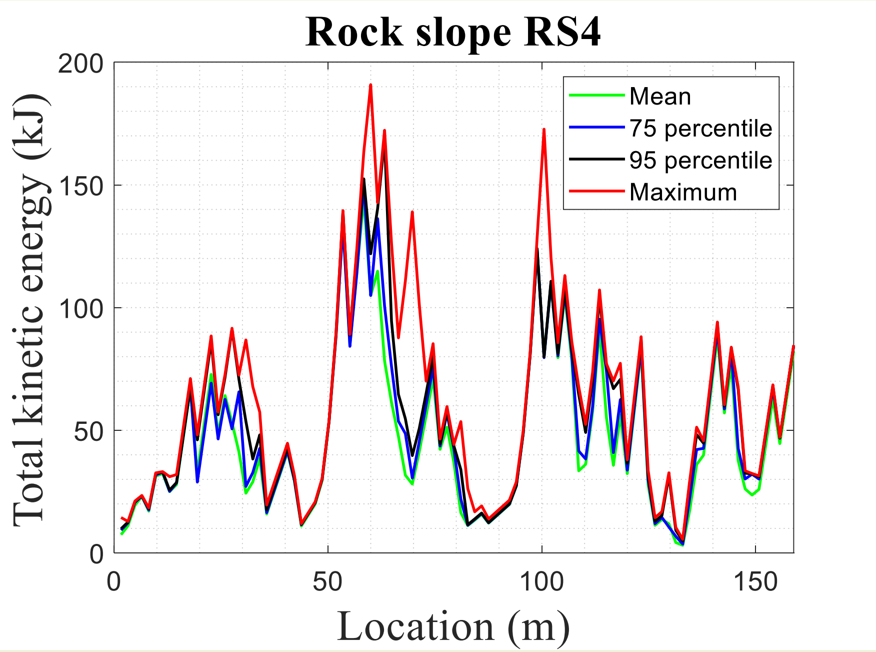


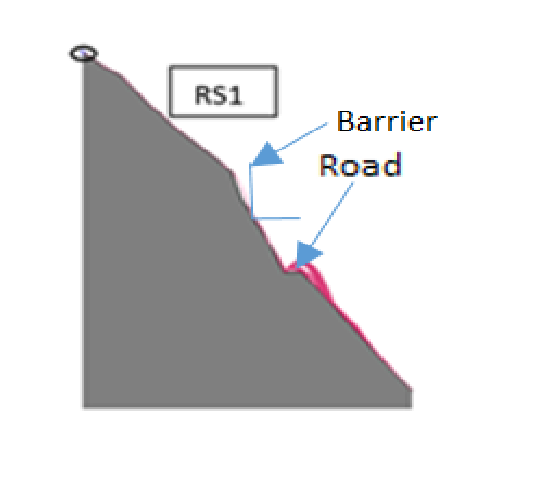
Results from Stochastic Analysis

- Maximum values of parameters as a function of height of slope

Rock slope section	Location of maximum bounce height	Location of maximum kinetic energy
RS1	0.37 H	0.41 H
RS2	0.3 H	0.72 H
RS3	0.3 H	-NA-
RS4	0.69 H	0.55 H

Rockfall Mitigation Systems

- Essential for preventing any damage to life and property
- Designed in the software Rocfall
- Two variable sensitivity analysis is performed for finding optimum location of barrier
- Variable used for sensitivity analysis
  - ❖ Location of barrier
  - ❖ Inclination of barrier



Optimal Barrier Configuration

Rock slope section	Optimum location of barrier from left side of slope section (m)	Optimum inclination of barrier	Impact energy on barrier (kJ)
RS1	64	30°	124
RS2	129.35	30° to 90°	73.91
RS3	50.38	50°	214.16
RS4	120.35	30° to 90°	43.78

Regional Scale Analysis

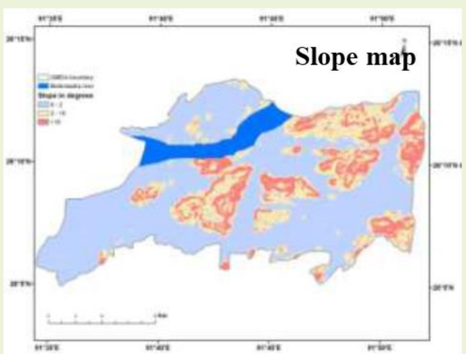
Rainfall Induced Landslide Hazard Zonation Mapping of Guwahati, Assam

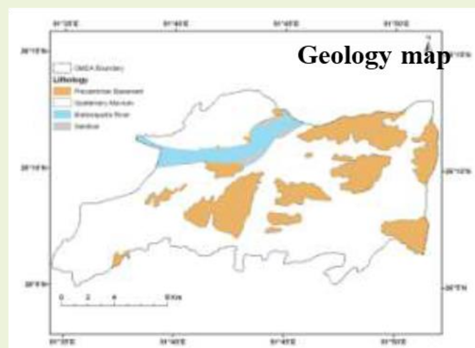
Landslide Studies for Guwahati City

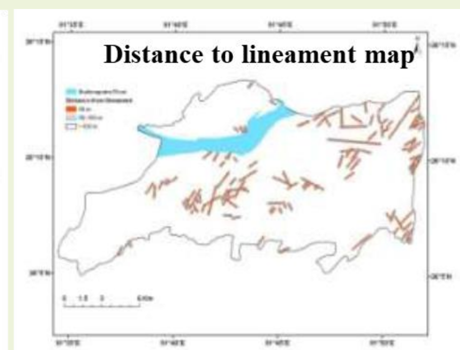
- Landslide Studies concerning Guwahati city:
  - Saikia *et. al*., 1996, 2002
  - Combined Landslide Hazard Evaluation Factor (LHEF)
    - Rainfall intensity
    - Earth Cutting
    - Soil erosion – Weathering
    - Geological formation
    - Drainage density
    - Land use – land cover – human interference
    - Slope Angle – relative relief
    - Soil Characteristics – Geotechnical properties
    - Geotechnical factors – Slope stability analysis of homogenous slopes with GWT
  - Landslide susceptibility map

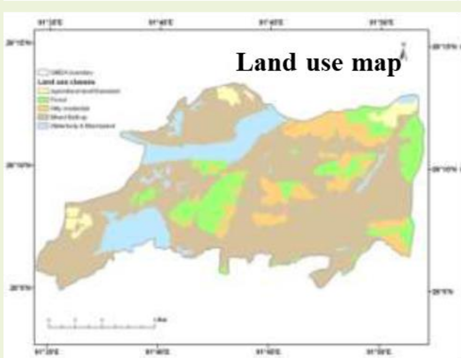
Landslide Studies for Guwahati City

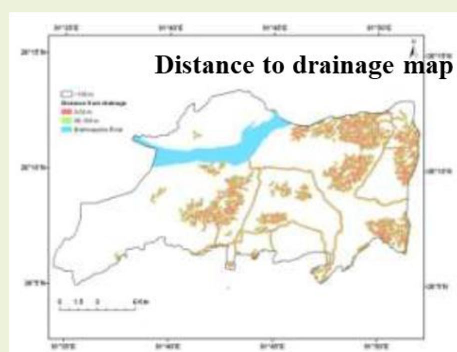
- Landslide Studies concerning Guwahati city
  - Phukon et. al., 2013
  - Analytical Hierarchical Process (AHP) (Saaty, 1980)
  - Five probable causal factors that triggered the past landslides were considered and used for pair-wise comparison
  - Landslide susceptibility map

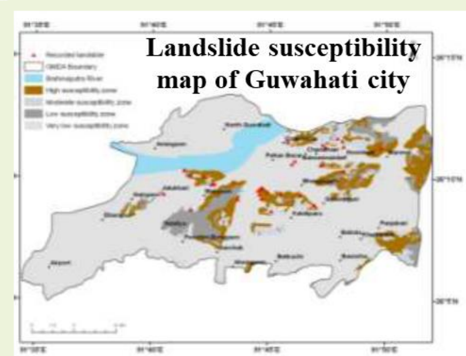






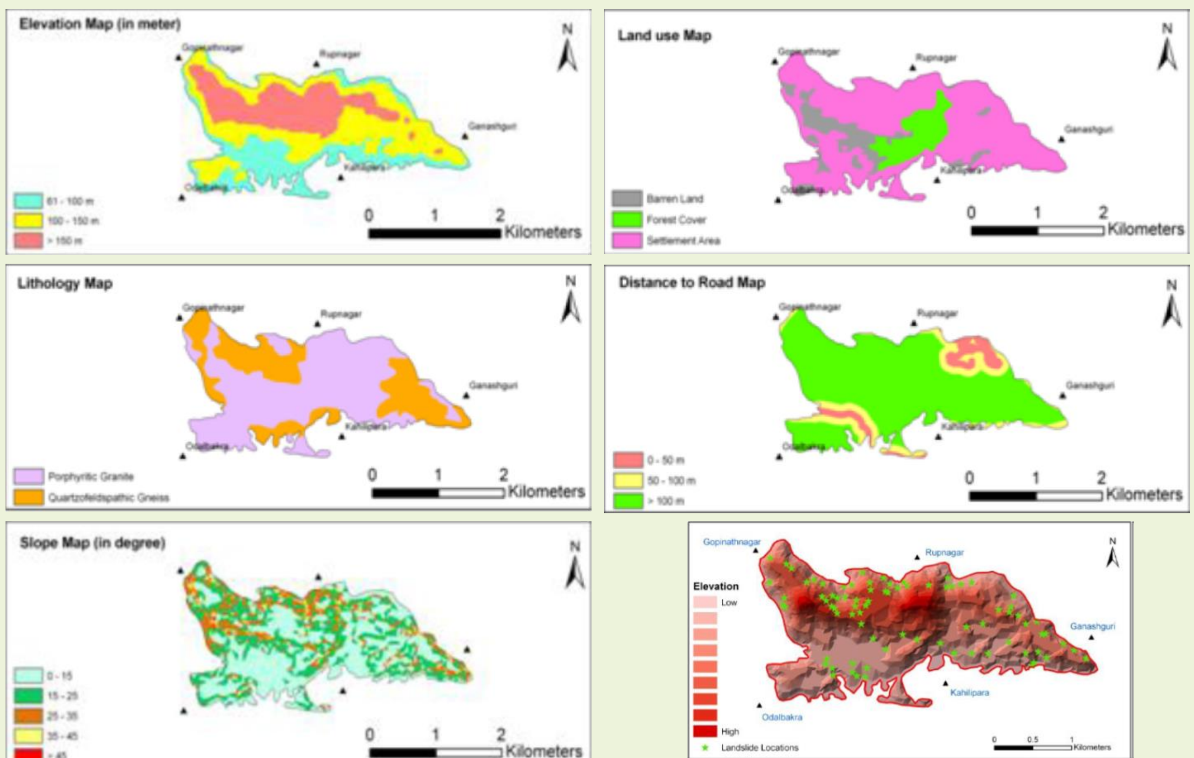






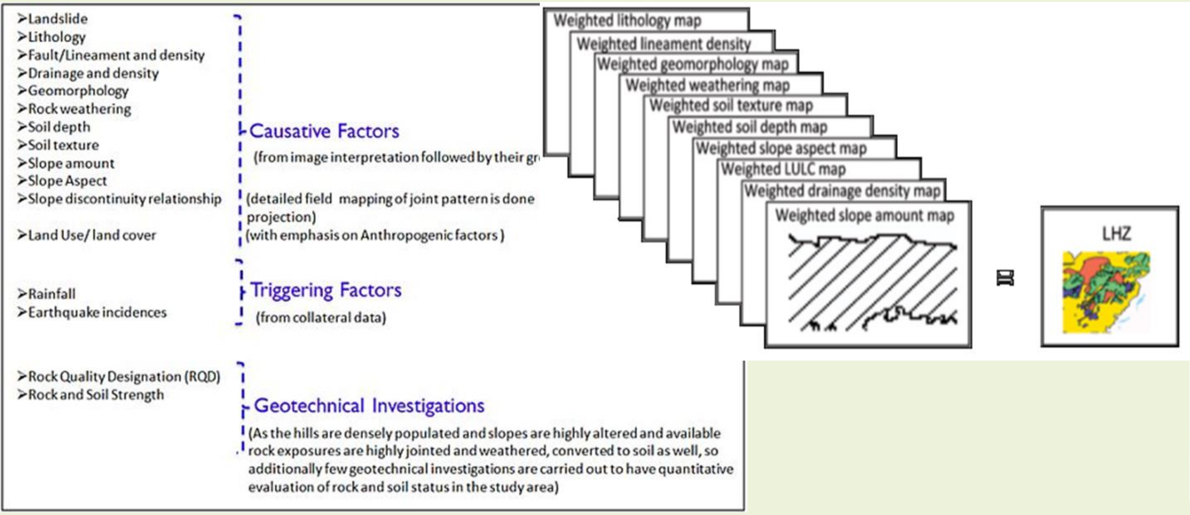
Landslide Studies for Guwahati City

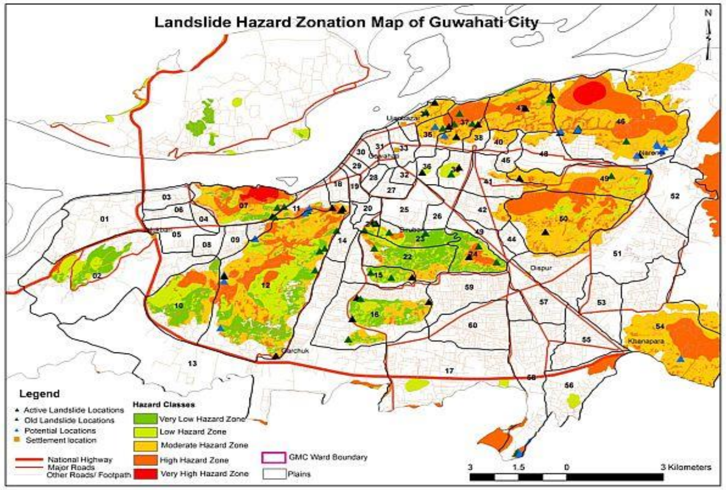
- Landslide Studies concerning Guwahati city
  - Dutta and Sarma, 2013
  - Landslide Susceptibility Zoning
  - Of the Kalapahar hillock within Guwahati city
  - Different thematic maps, as causative factors were used for the analysis



Landslide Studies for Guwahati City

- Landslide Studies concerning Guwahati city
  - Bhusan *et al*. 2014
  - Landslide Hazard Zonation (LHZ) map of Guwahati city
  - Analytical Hierarchical Process (AHP) (Saaty, 1980)
  - Various thematic parameters
  - Depending on their role in causing slope instability
  - Based on the database prepared from satellite images acquired during 2009-2011





Landslide Studies for Guwahati City

- Congregation of thematic maps to develop
  - ❖ Landslide Susceptibility map
  - ❖ Landslide Hazard Zonation map
    - Semi – heuristic method
    - Weight factors based on lithology
      - Soil and Rock given almost similar weights
    - Hydrogeology – surface indications
      - Dry – Damp – Wet – Dripping – Flowing

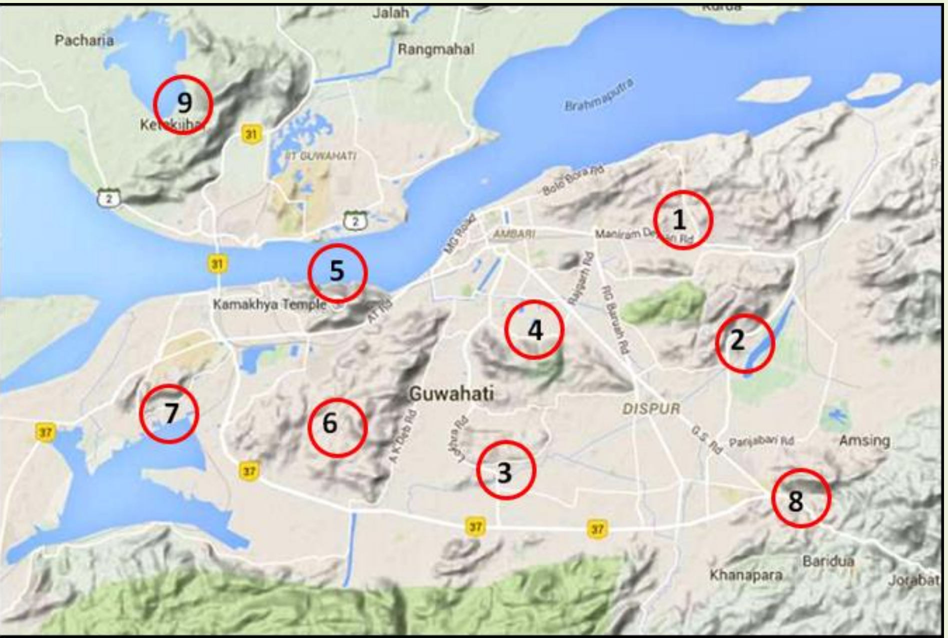
- **What are/were missing?**
  - ❖ **A strong geotechnical perspective**
  - ❖ **Landslide triggering rainfall patterns**
  - ❖ **Influence of antecedent conditions**
  - ❖ **Temporal recurrence and likelihood**

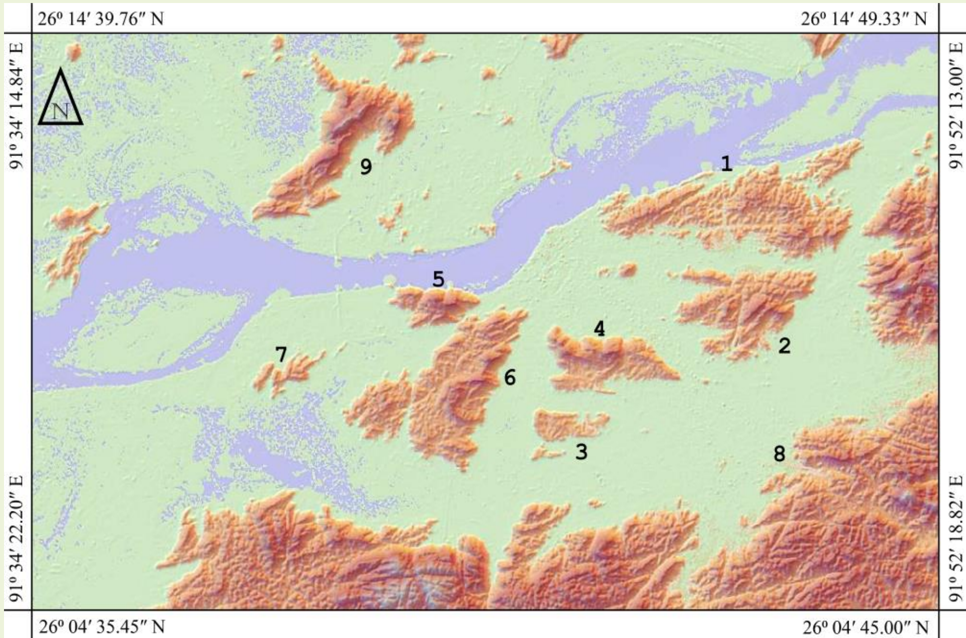
Study Area - Guwahati City

- Geomorphology
  - ❖ Three prominent geomorphological feature
  - ❖ Residual hills altitude ranging 100–300 meter above MSL
  - ❖ Low-lying alluvial plains varying altitudes of 49–56 meter
  - ❖ Marshy wetlands

8 major hill series:

(1) Nabagraha and Sunsali hill series
(2) Japorigog hill
(3) Sonaighuli and Jutikuchi hill series
(4) Narakashur hill
(5) Nilachal hill
(6) Fatasil hill
(7) Jalukbari hill
(8) Khanapara hill
(9) Agyathuri hills



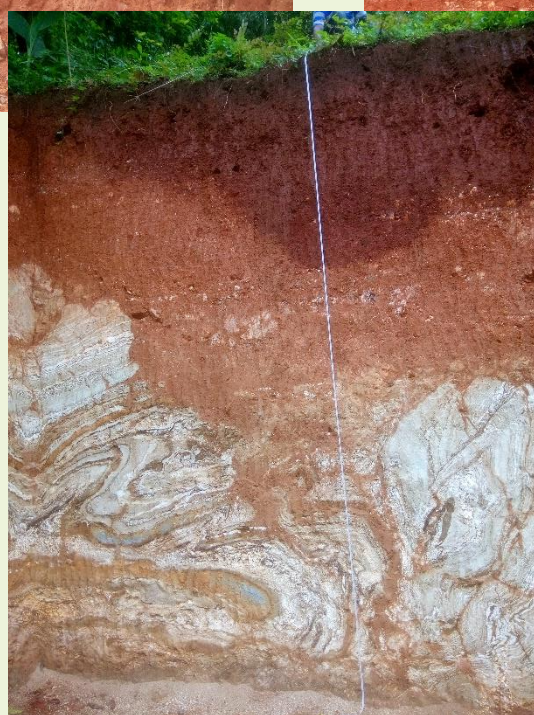


Characterization of Hillslope Soils

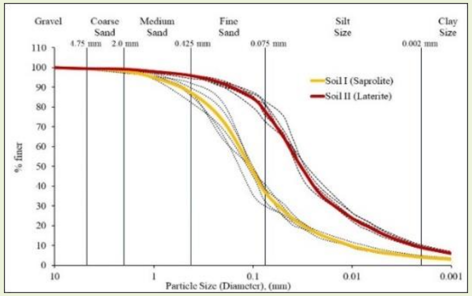
Characterization of Hillslope Soils

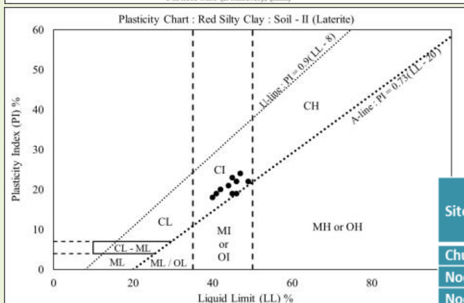
- Sample collection



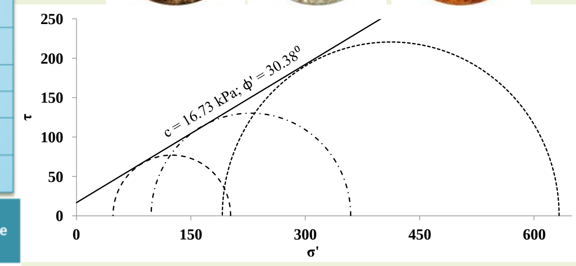





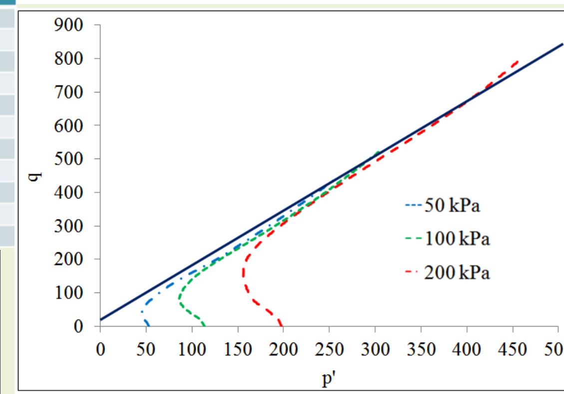


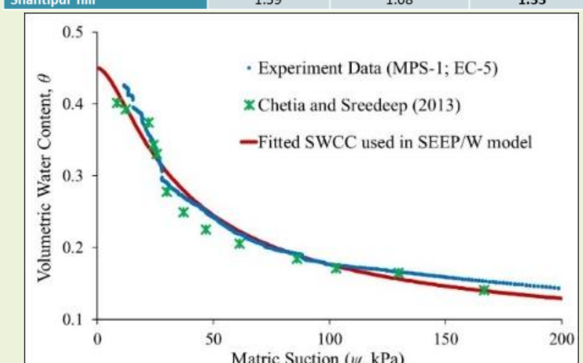


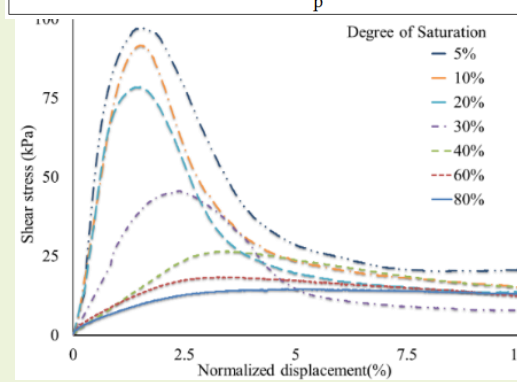
Soil Characteristics	Das and Saikia (2010; 2011) – SOIL 1	Das and Saikia (2010; 2011) – SOIL 2	Chetia and Sreedeep (2013)	Experimental Results – SOIL 1	Experimental Results – SOIL 2
Referred as	RSC	PGSS	RSC_CS	RSC_EXP1	PGSS_EXP2
Specific Gravity	2.44	2.64	2.62	2.68	2.68
In-situ bulk density	1.65	1.79	--	1.92	1.77
In-situ dry density	1.49	1.63	--	1.50	1.57
Liquid Limit	49	39	46	47	35*
Plastic Limit	27	Non – Plastic	27	27	Non – Plastic
Fines Content	72.7	7.45	74	77.8	36.75
Natural Moisture Content	11.00	10.00	--	27.72	12.69
In-situ Volumetric Water Content	16.60	16.52	--	41.68	15.39
Void Ratio	0.78	0.62	--	0.78	0.71
Porosity	0.44	0.38	--	0.44	0.41
In-situ degree of Saturation	38	43	--	95	47.79
Saturated Permeability (m/s)	1.86×10^{-7}	1.2×10^{-6}	--	10^{-6}	10^{-5}



Site name	Maximum infiltration rate $\times10^{-6}$(m/s)	Minimum infiltration rate $\times10^{-6}$(m/s)	Average infiltration rate $\times10^{-6}$(m/s)
Chunsali hill	0.955	0.867	0.911
Noonmati hill 1	1.75	0.160	0.955
Noonmati hill 2	7.36	6.70	4.02
Kailash nagar hill 1	2.12	1.83	1.97
Kailash nagar hill 2	0.828	0.614	0.721
Shree nagar Kailash nagar hill	0.566	0.462	0.514
Punnya nagar hill	4.59	4.48	4.53
Jyoti ban	17.5	11.1	1.43
Indupur kharghuli	113.0	9.00	10.1
Kamakhya hill	0.661	0.58	0.623
Shantipur hill	1.59	1.08	1.33





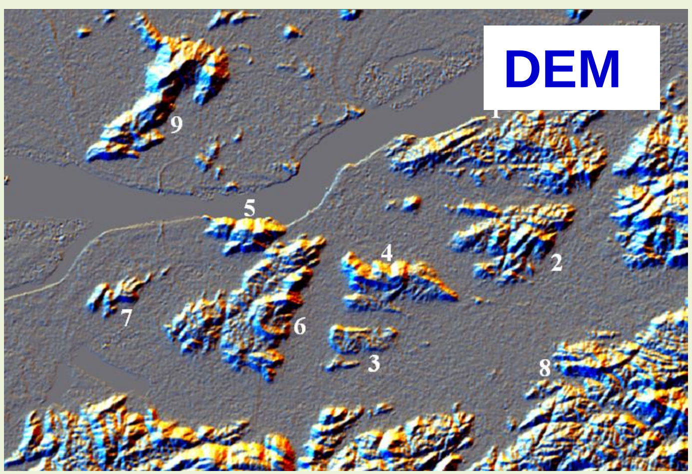


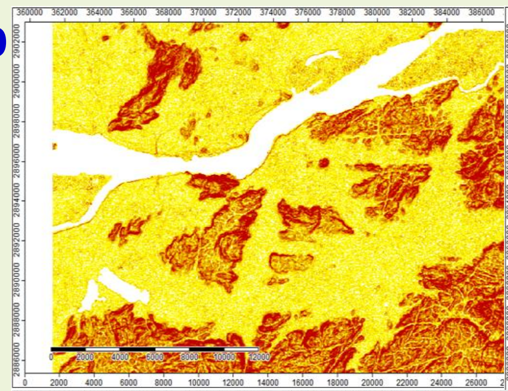
Regional Scale: Landslide Susceptibility - Hazard

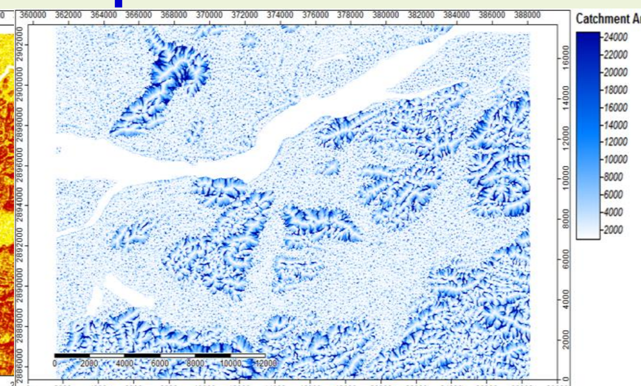
- Regional Scale Analysis
  - ❖ Landslide Hazard Zonation and Landslide Susceptibility Studies
    - SHALSTAB, TRIGGRS, SINMAP, Physically Based Models
    - GIS platform for Digital Elevation Models (DEM)

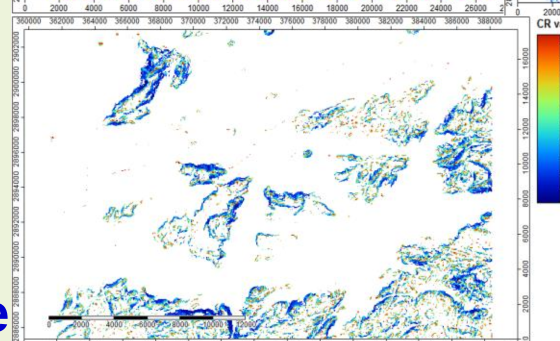
Map of Catchment Area

Slope Map





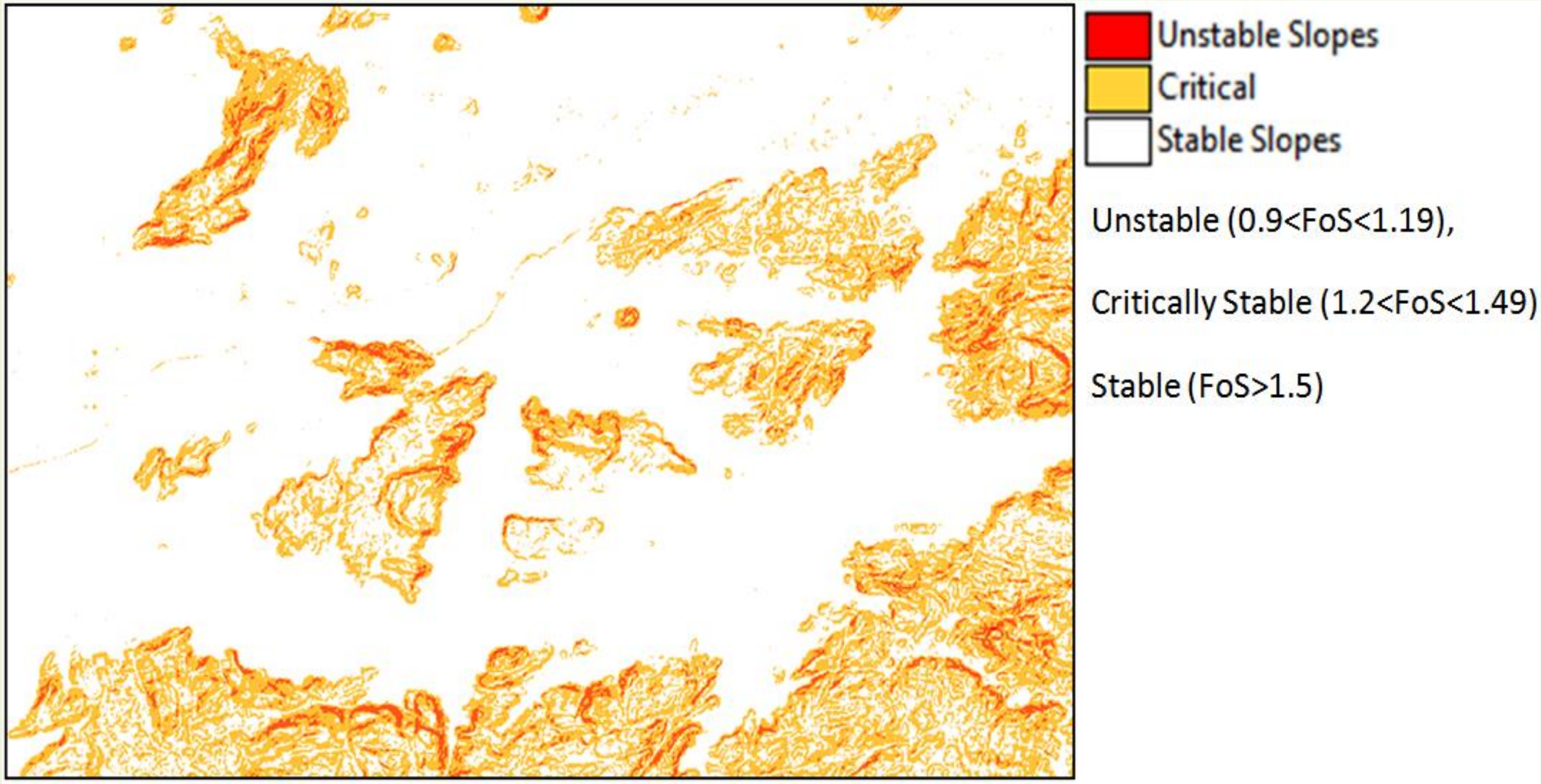




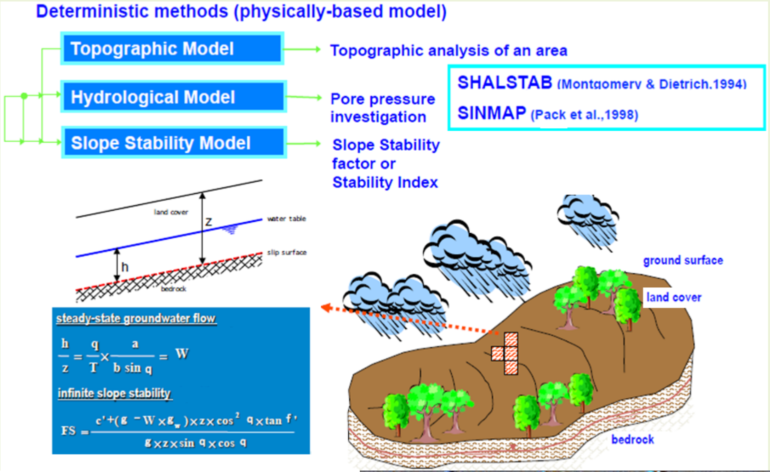
Steady-State Recharge Map

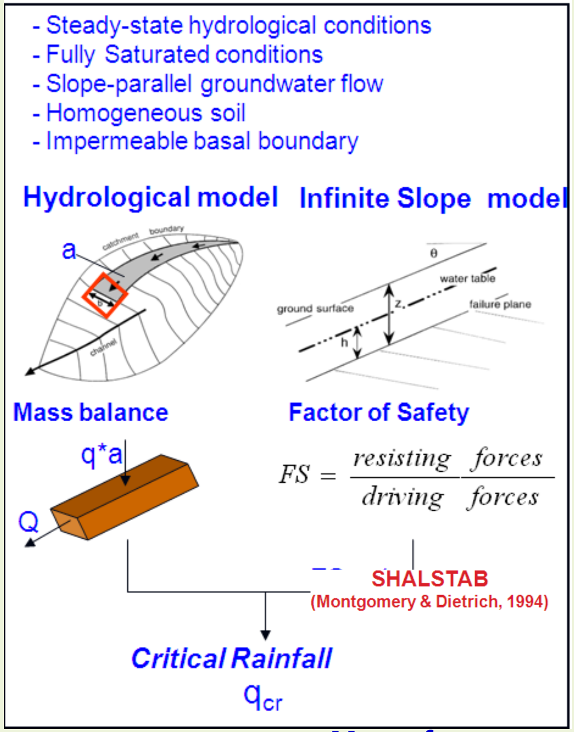
Regional Scale: Landslide Susceptibility - Hazard

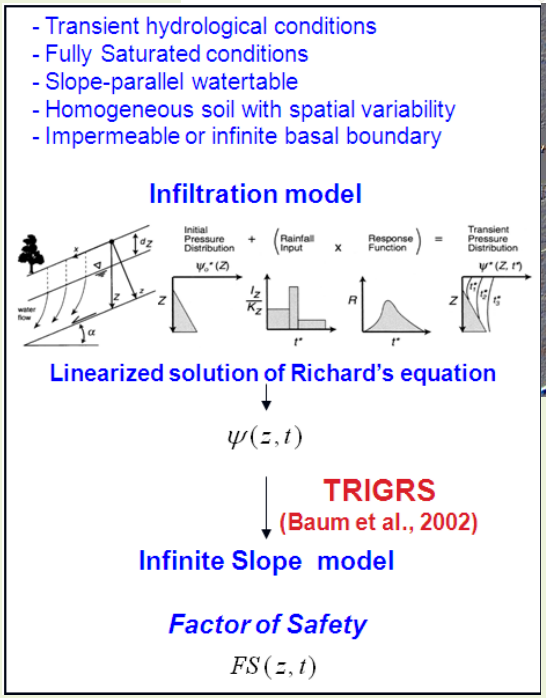
- Regional Scale Analysis
  - Landslide Hazard Zonation and Landslide Susceptibility Studies
    - SHALSTAB, TRIGGRS, SINMAP, Physically Based Models
    - GIS platform for Digital Elevation Models (DEM)

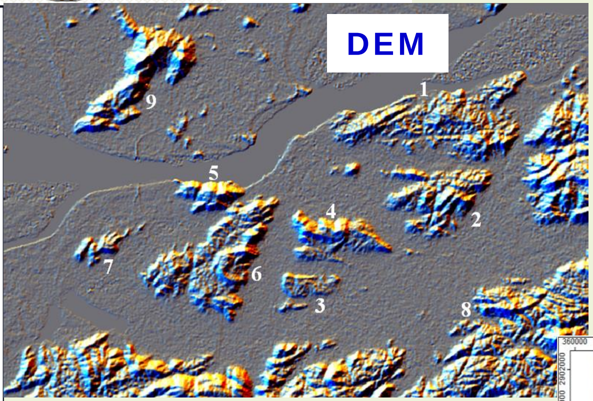


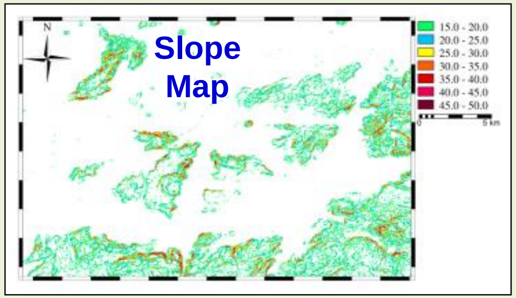
Regional Scale: Landslide Susceptibility - Hazard

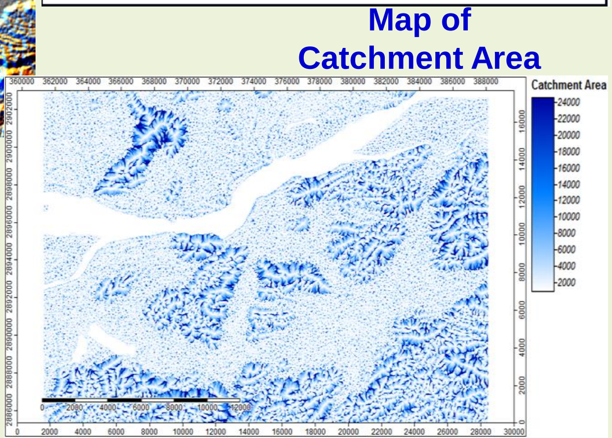




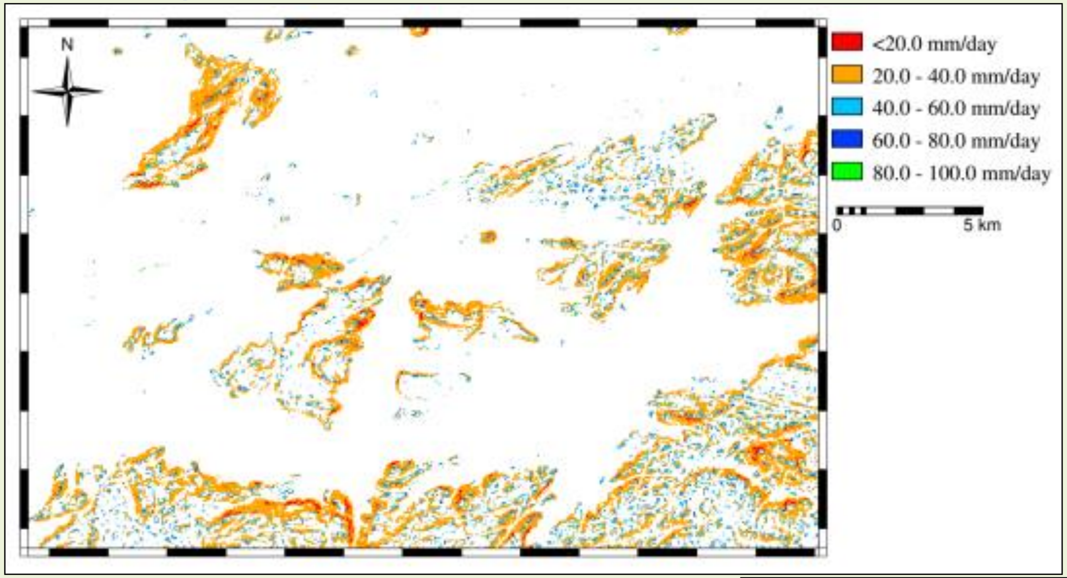




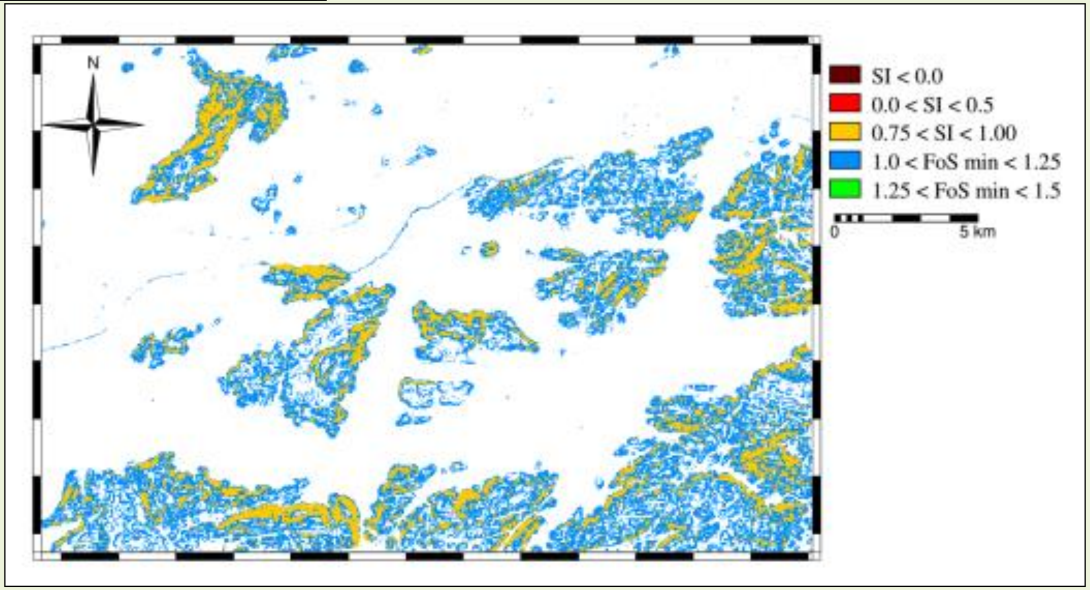




Regional Scale: Landslide Susceptibility - Hazard

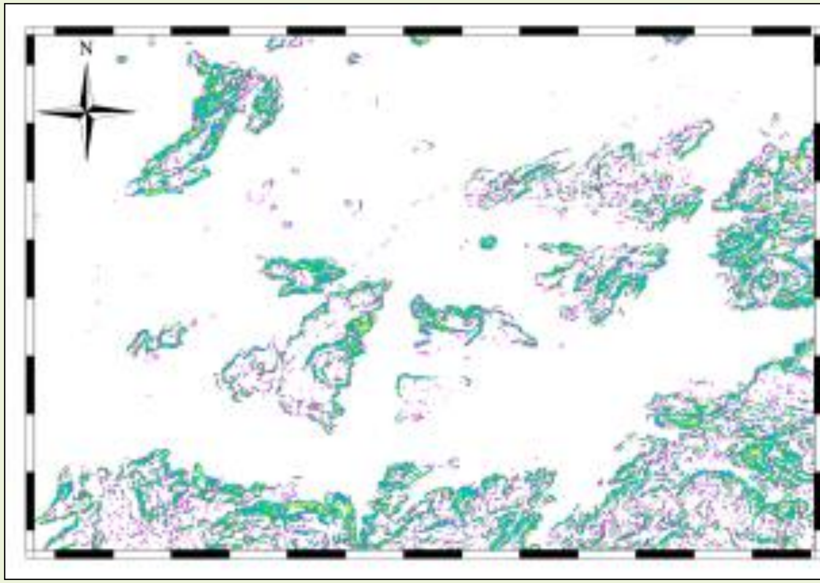


Steady-state recharge map required to initiate instability (SHALSTAB output)



Stability Index (SI) Map (SINMAP output)

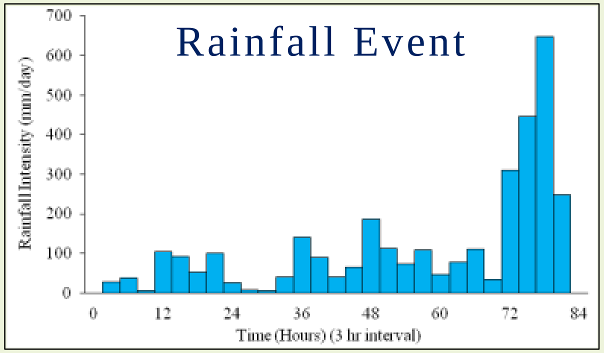
Regional Scale: Landslide Susceptibility - Hazard

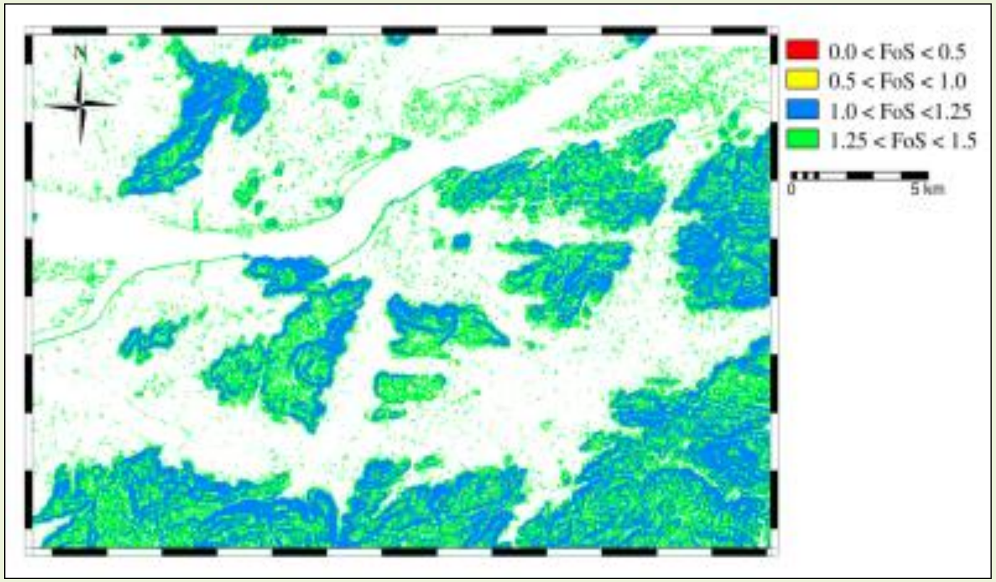


Very stable initial condition

Suction within the unsaturated soil renders very high shear strength to the hillslopes

The stability of the slopes decreases to a marginally stable condition due to rainfall infiltration





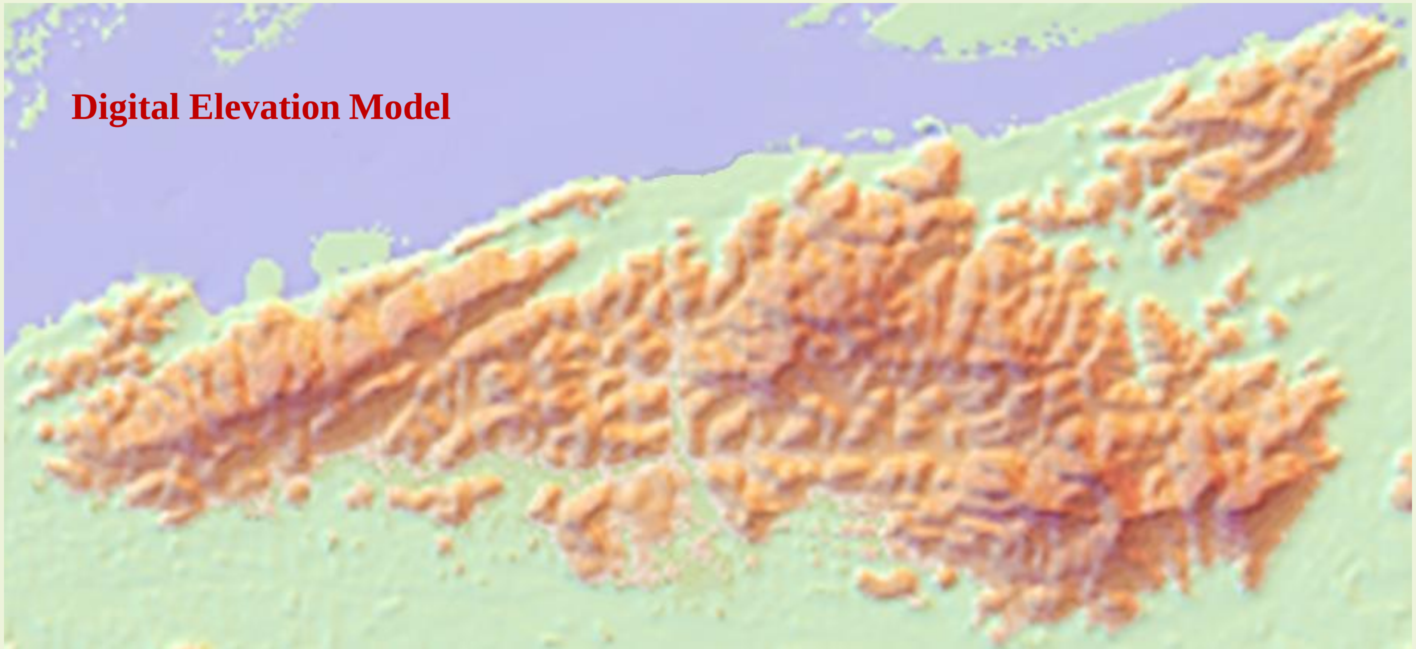
Addresses the possibility to simulate different rainfall scenarios and its effect on the stability condition of the study region

TRIGRS model for Guwahati city (Regional scale)

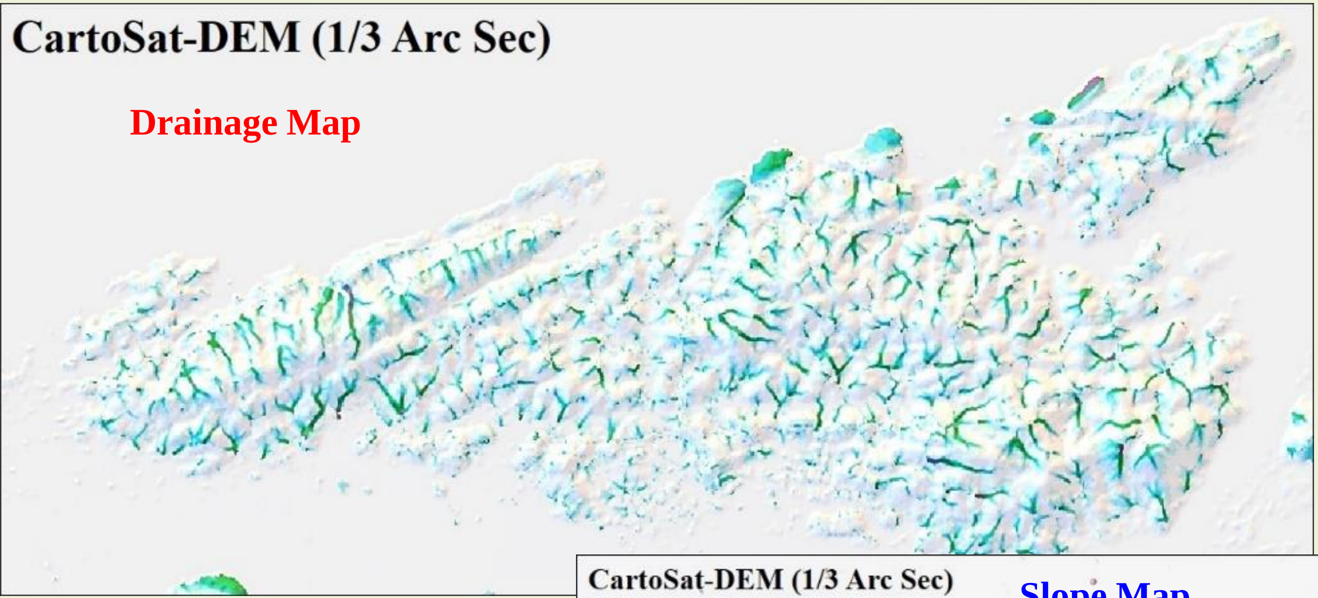
- Transient Rainfall Infiltration and Grid-Based Regional Slope-Stability Model (TRIGRS) - **(Baum et al., 2002; Savage *et al*., 2004)**
  - FORTRAN code
  - Transient pore pressure response to rainfall infiltration
  - Temporal and spatial distribution of shallow rainfall-induced landslides
  - Decrease in the factor of safety values
  - Infiltration process is approximated as one-dimensional vertical flow
  - Each cell of the grid is considered as a vertical soil column
  - Simple runoff routing process
  - Drain excess surface water to adjacent downslope cells
  - Implementation of complex storm events

Topographical Data – DEM

- ALOS World 3D 1-arc second resolution digital surface model (DSM)
  - ❖ Japan Aerospace Exploration Agency (JAXA) - Advanced Land Observing Satellite (ALOS)
- CartoDEM 1/3-arc second resolution
  - ❖ Indian Space Research Organisation - National Remote Sensing Centre

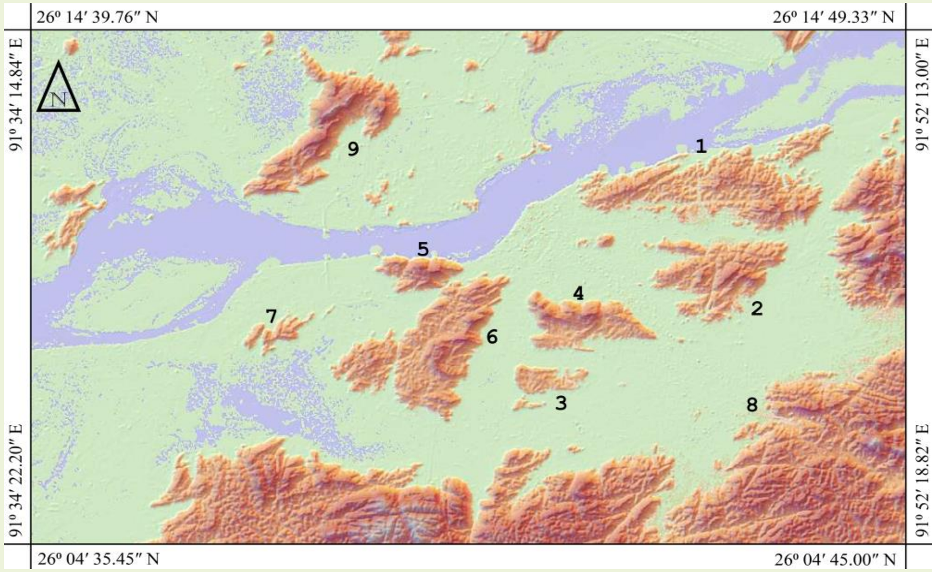


Topographical Data – DEM

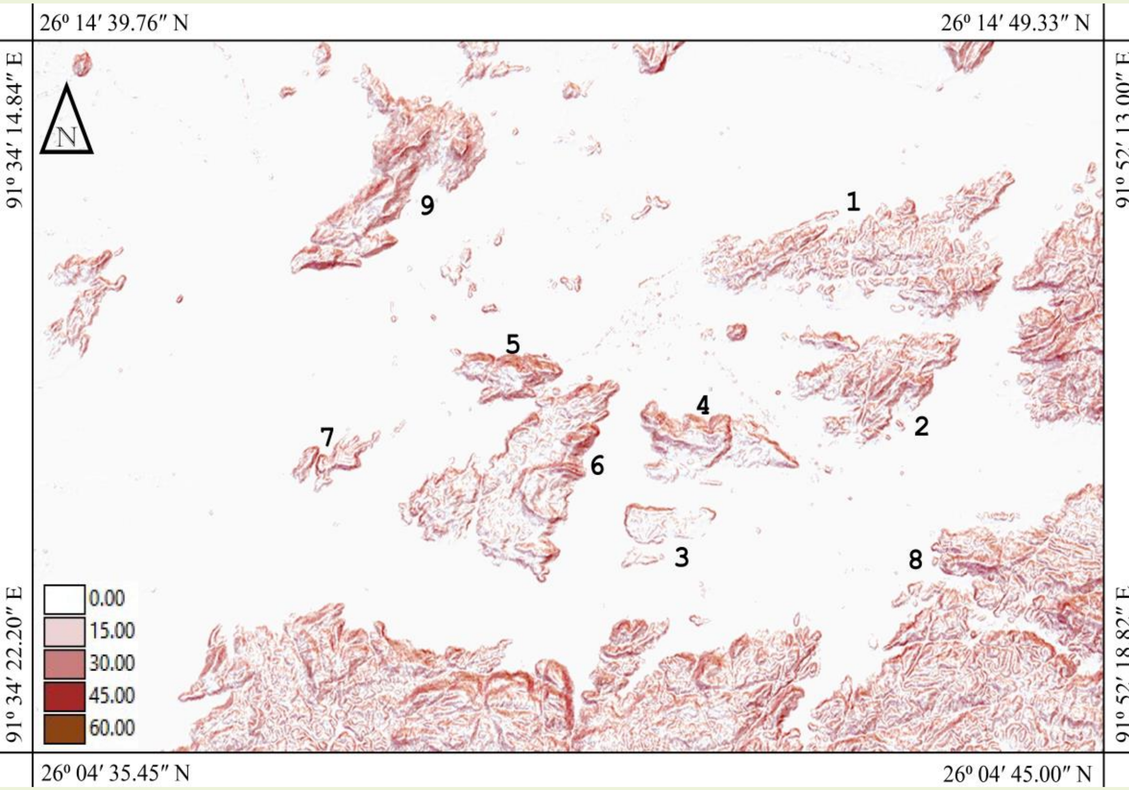


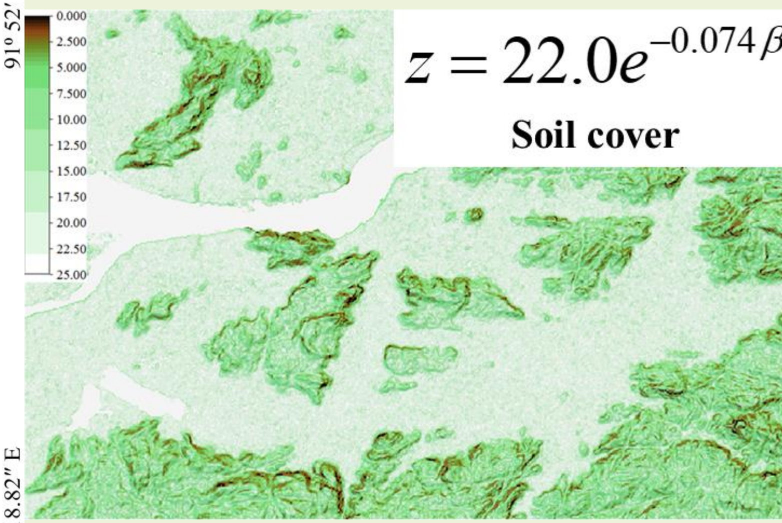
TRIGRS model for Guwahati city (Regional scale)

- Input data (ALOS–3D DEM 1 Arc Sec)
  - Thematic data
    - Digital Elevation Model – Topography of study area
    - Slope map
    - Aspect map
    - Depth of Soil formation map
    - Ground water level map
  - Rainfall – Applied surface infiltration
  - Soil Parameters
    - Cohesion (N/m^2)
    - Angle of Internal Friction (ϕ^0)
    - Saturated Permeability (k_{sat})
    - Soil Diffusivity (D_o)
    - Saturated Volumetric Water Content, θ_s
    - Residual Volumetric Water Content, θ_r
    - α – parameter (Gardner, 1958)



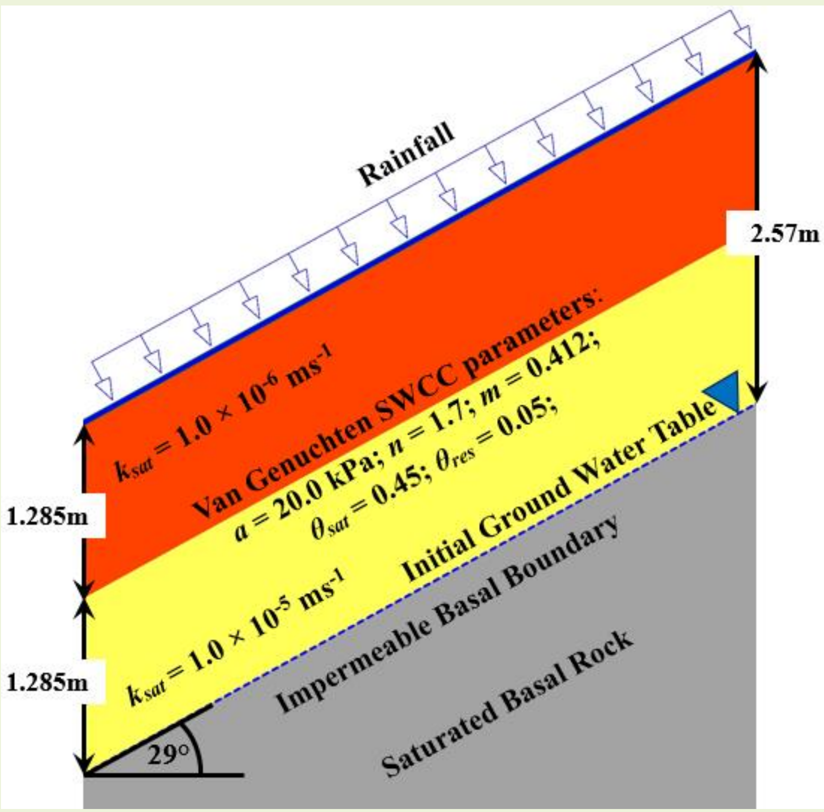
TRIGRS model for Guwahati city (Regional scale)

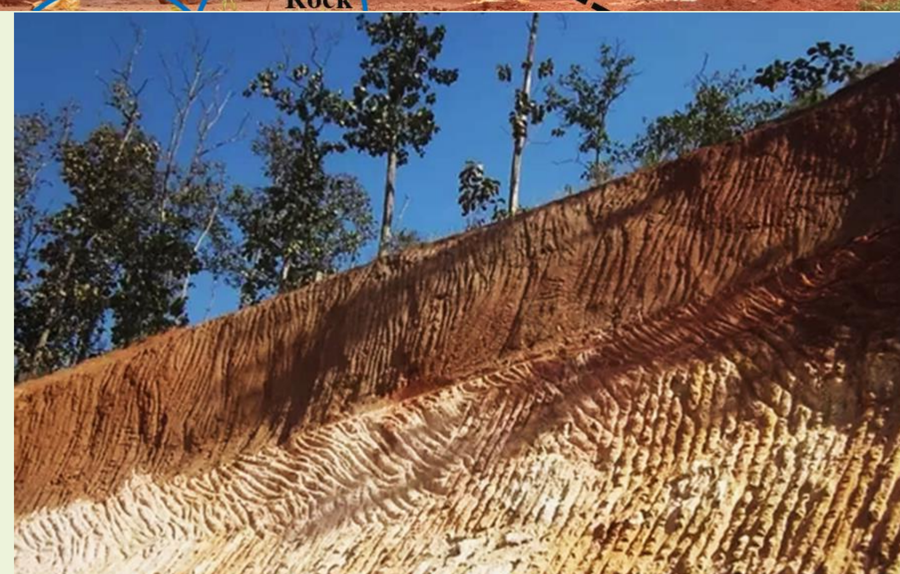




TRIGRS model calibration

- TRIGRS – SEEP/W comparative analysis





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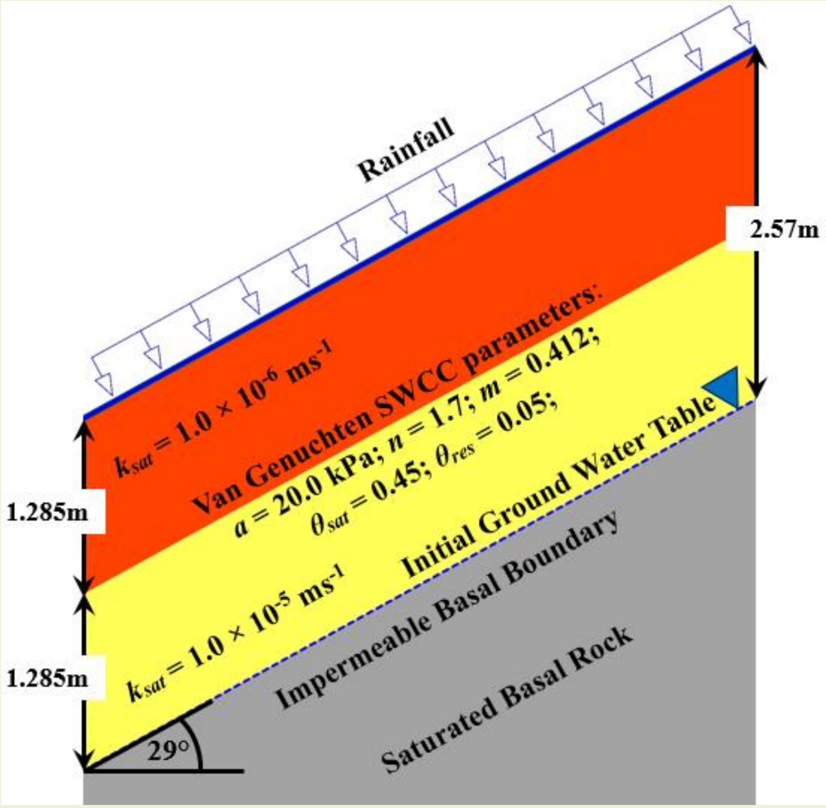

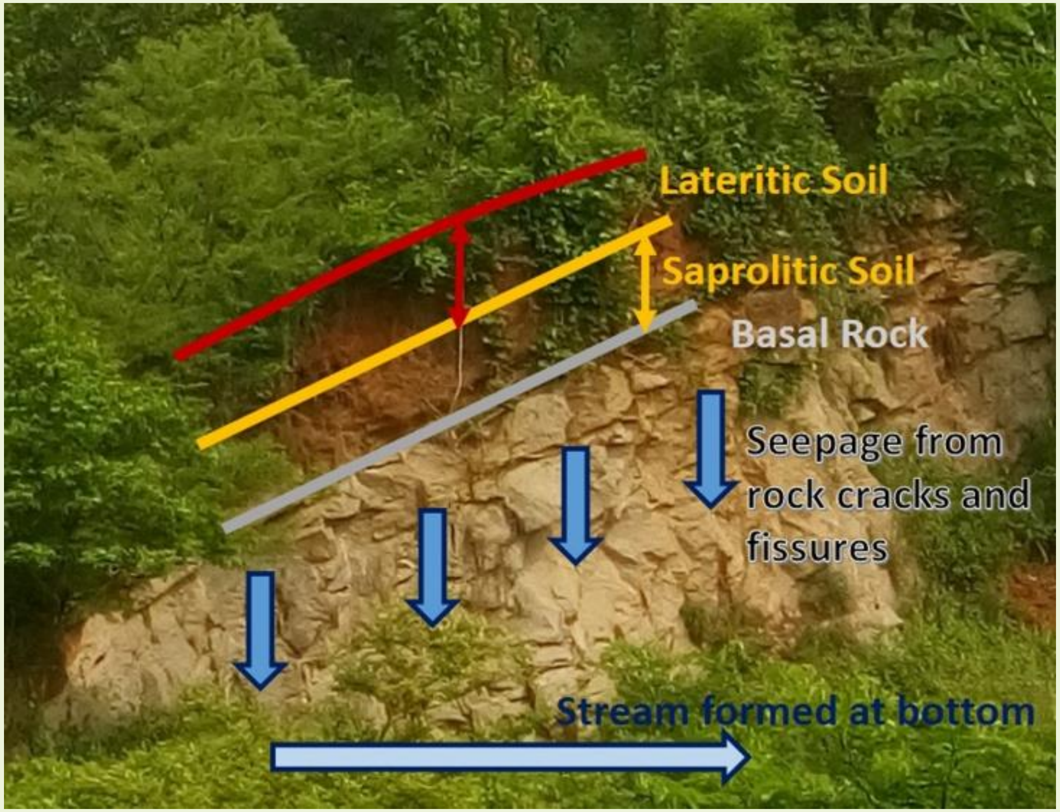

TRIGRS model calibration

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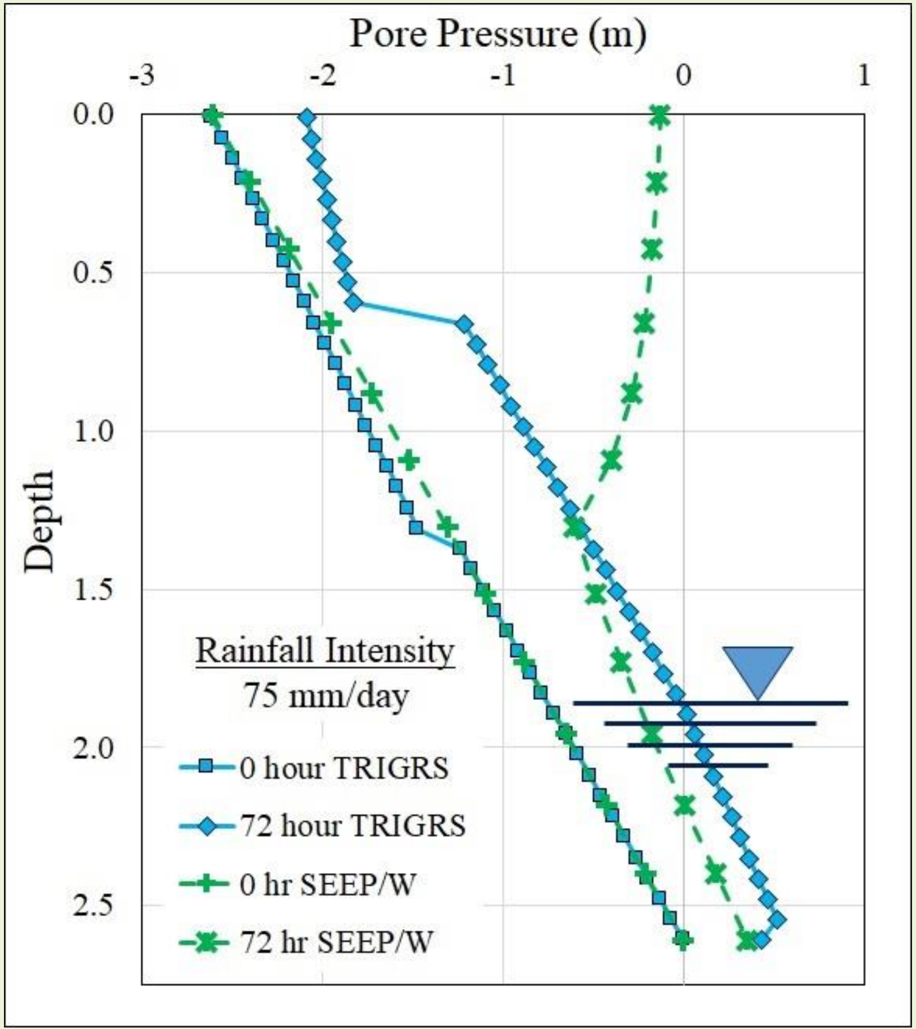

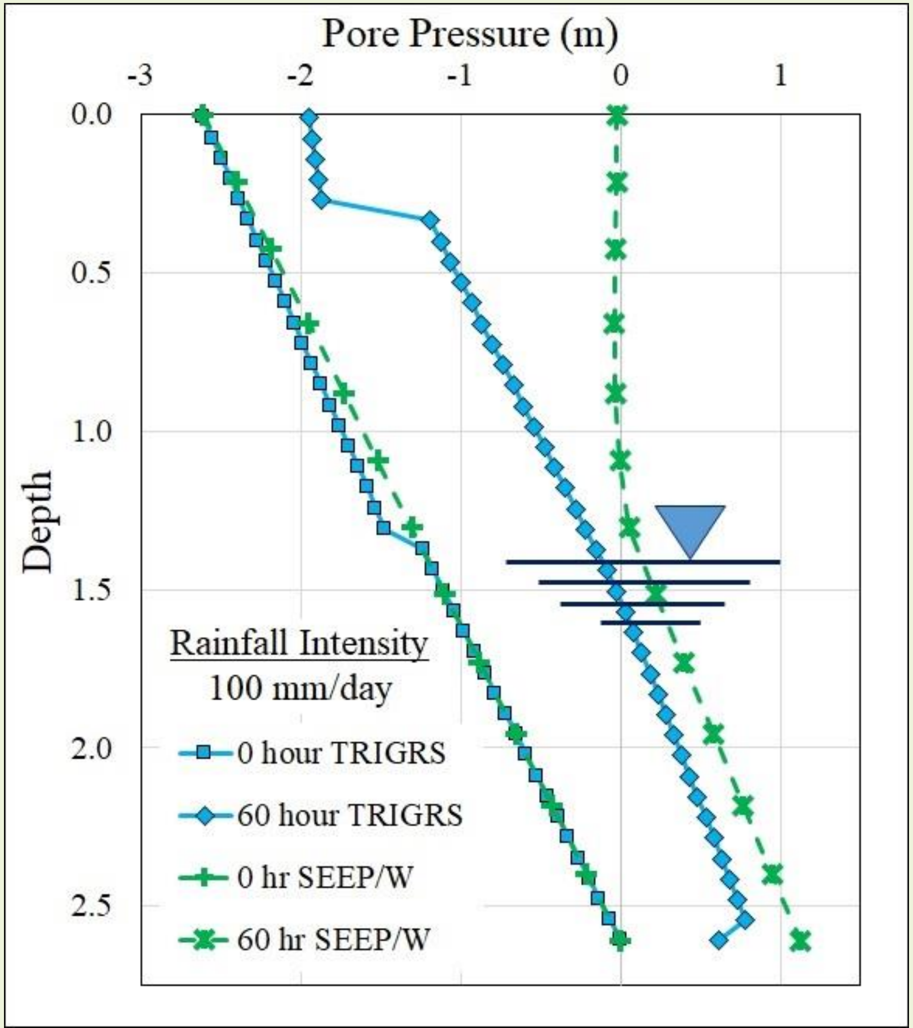

TRIGRS model calibration

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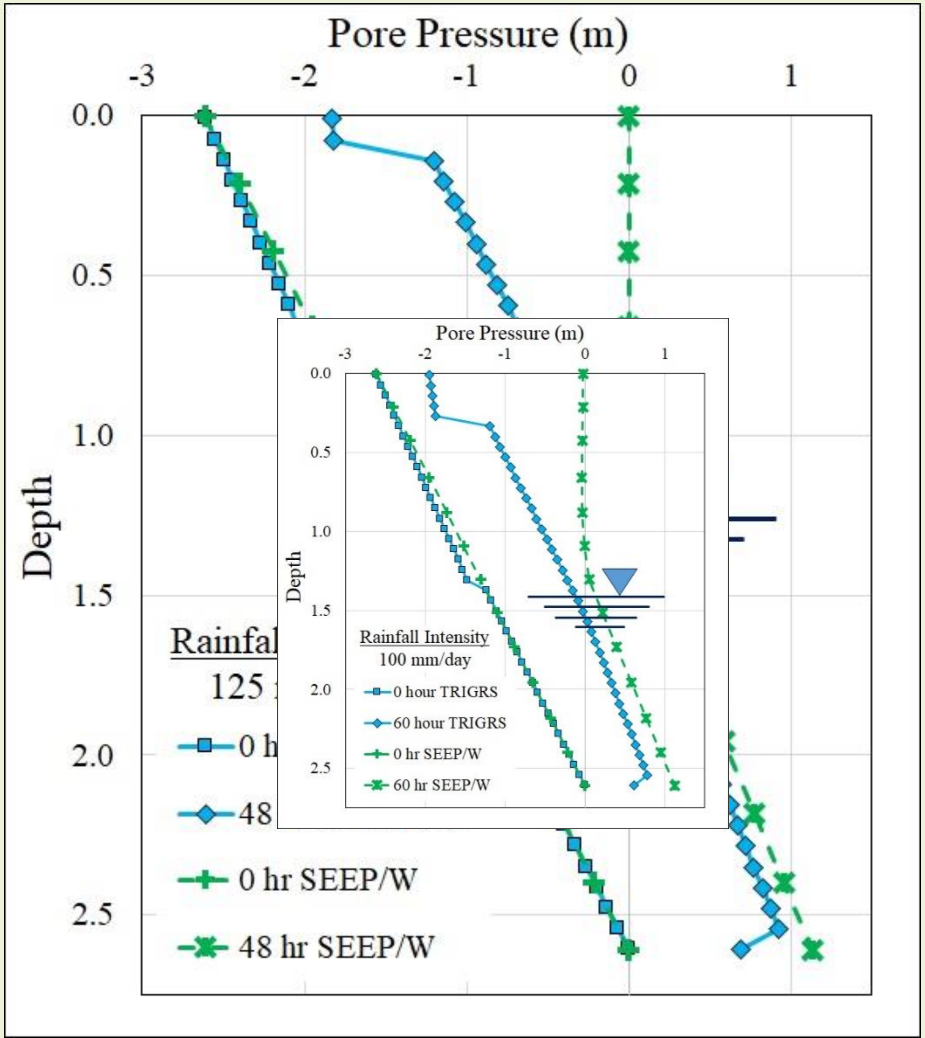
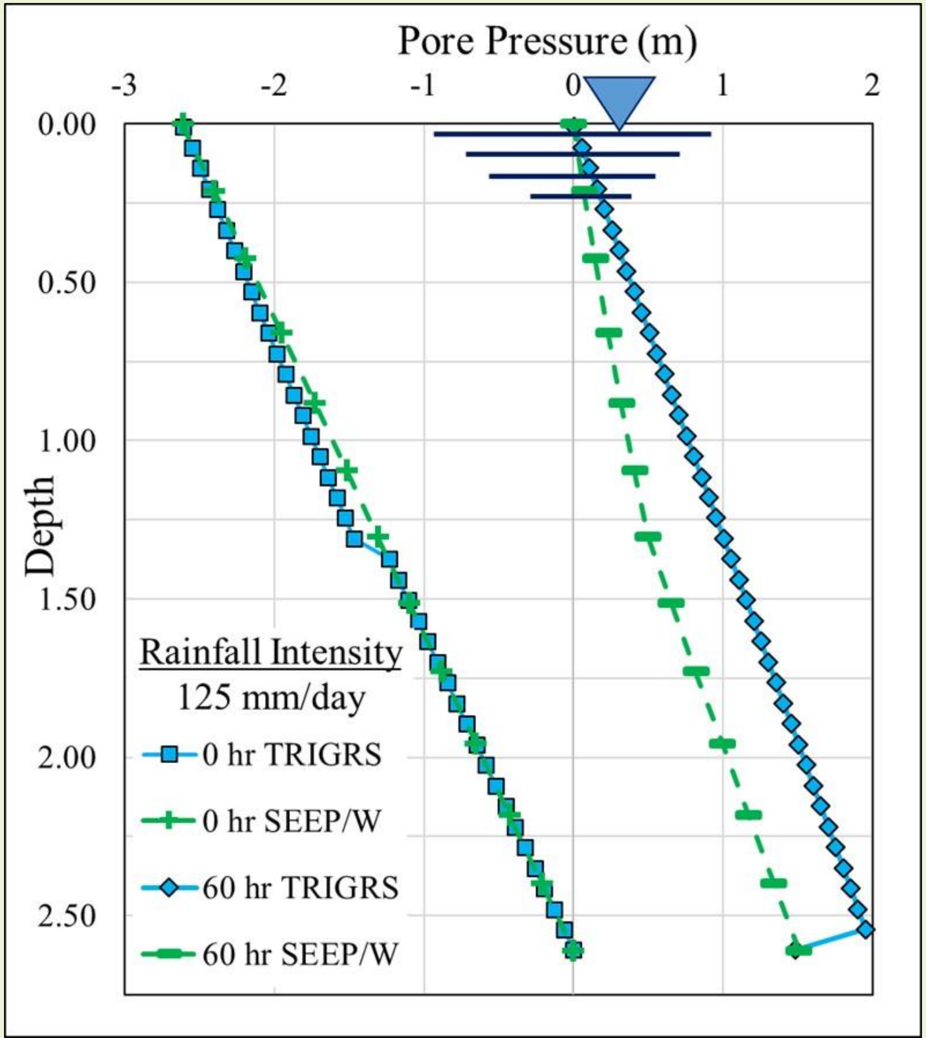
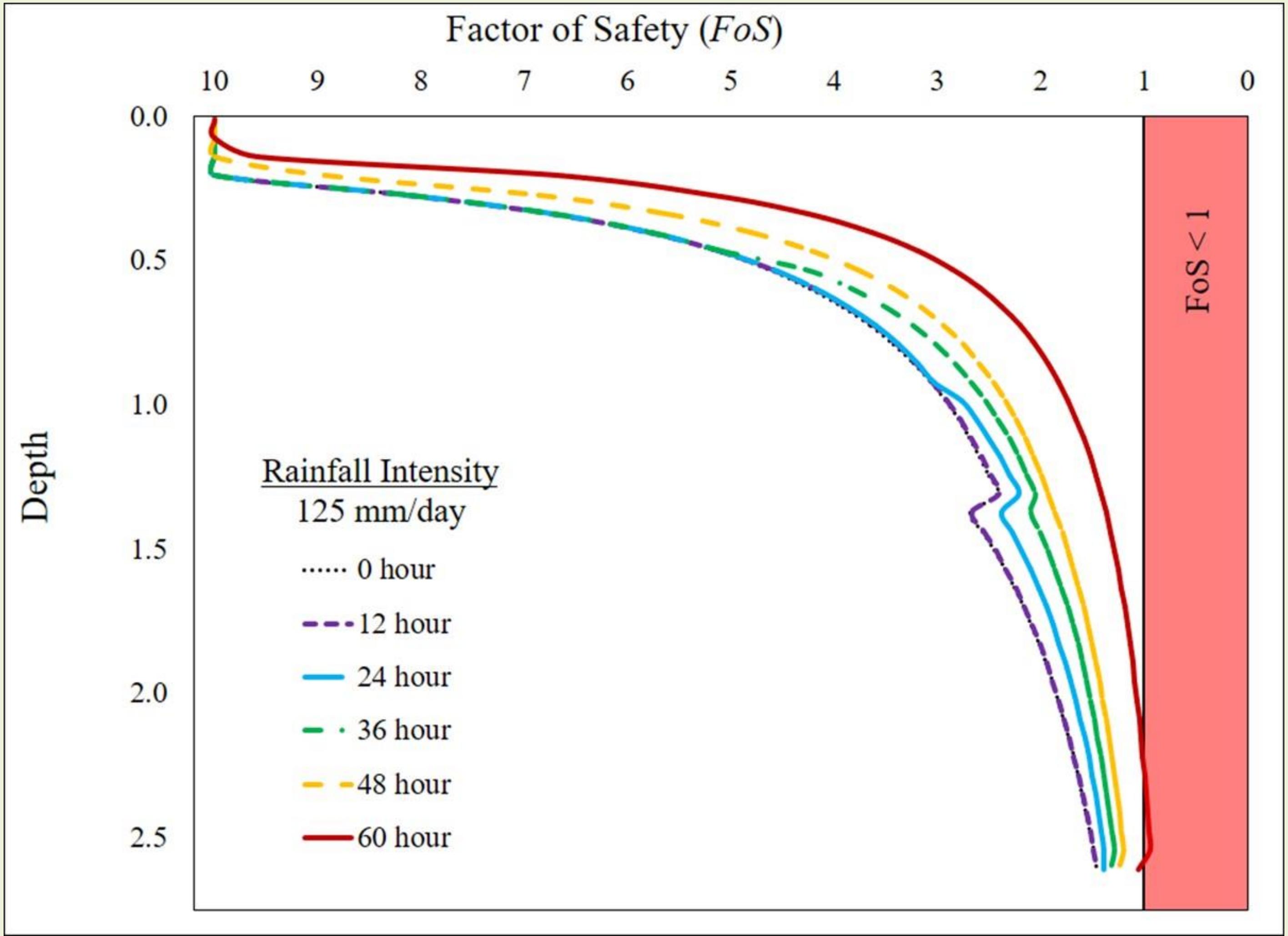




TRIGRS model calibration

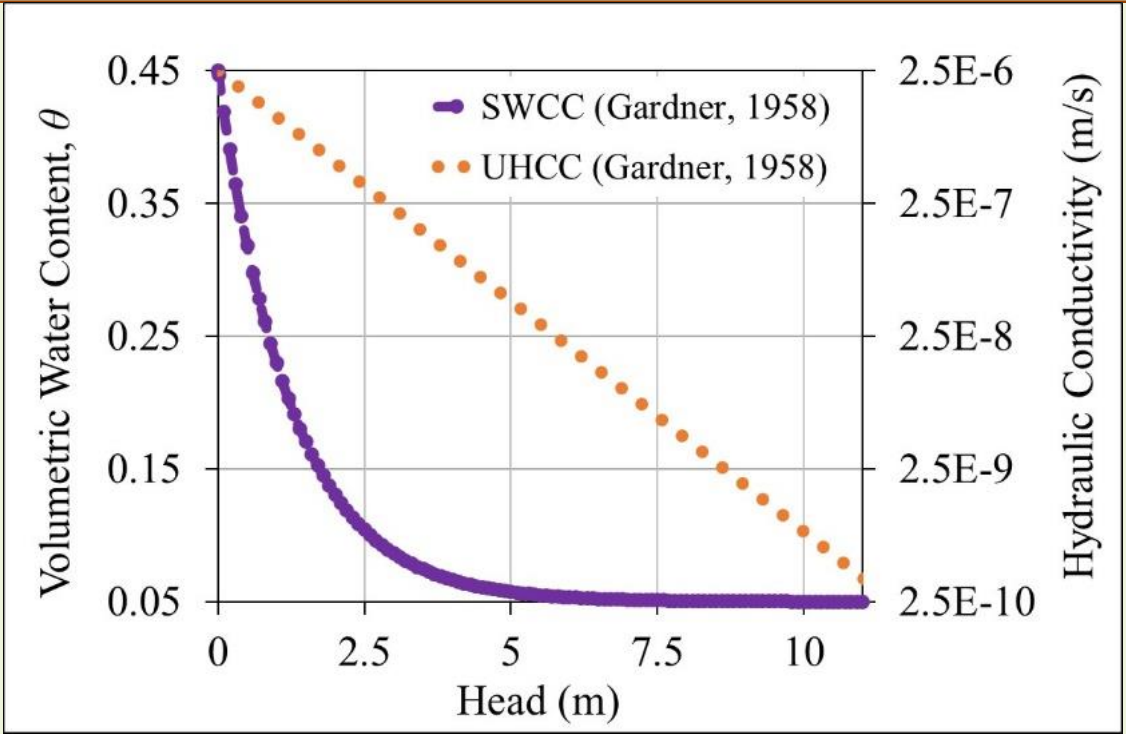
- TRIGRS – SEEP/W comparative analysis



TRIGRS model for Guwahati city (Regional scale)

- Calibrated Soil Parameters

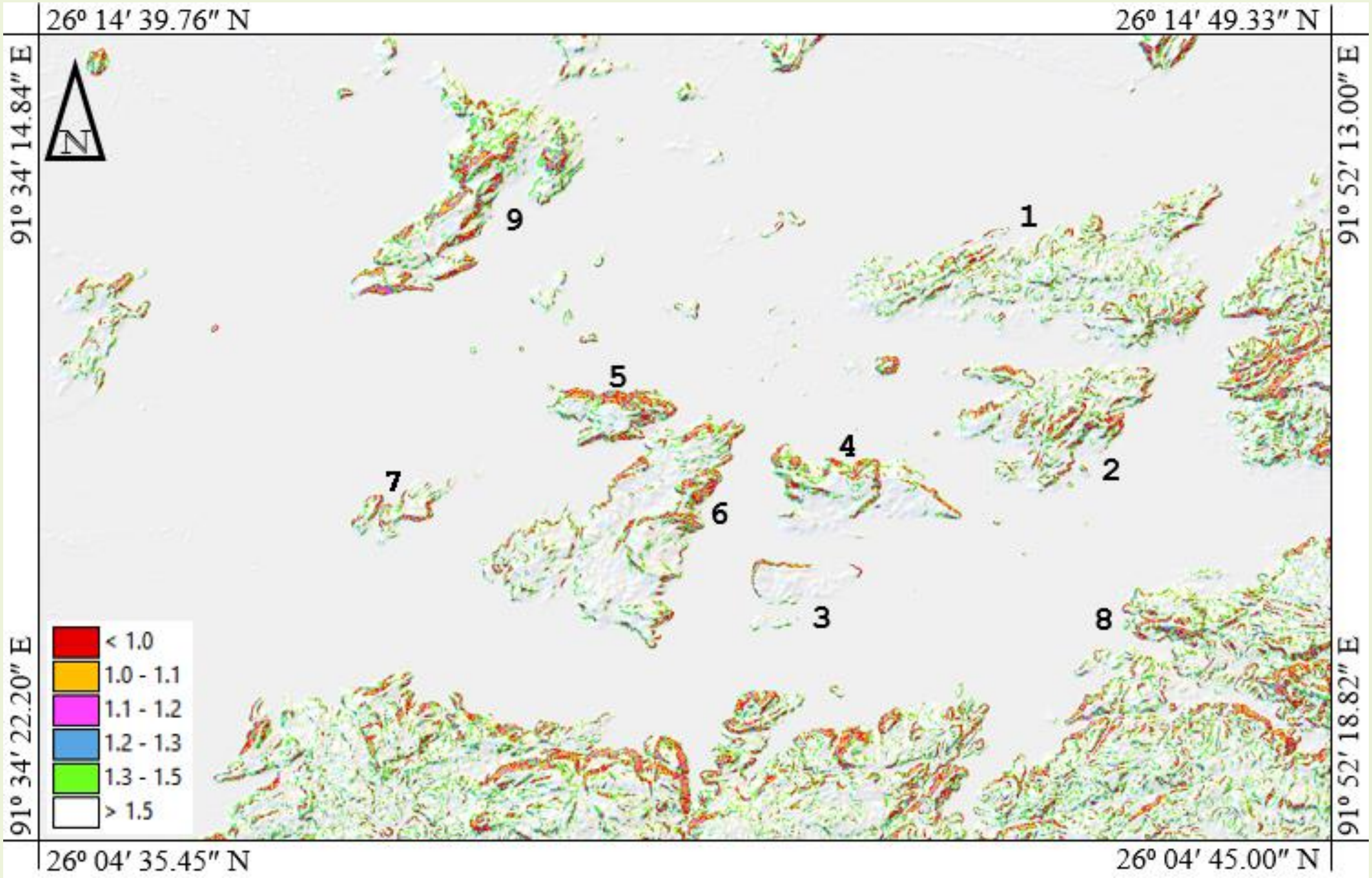
c' (kPa)	ϕ' (º)	γ_s (kN/m³)	k_s (m/s)	D_o (m/s)	θ_s	θ_r	α
10	27º	18.5	2.5×10^{-6}	2.5×10^{-5}	0.45	0.05	0.8



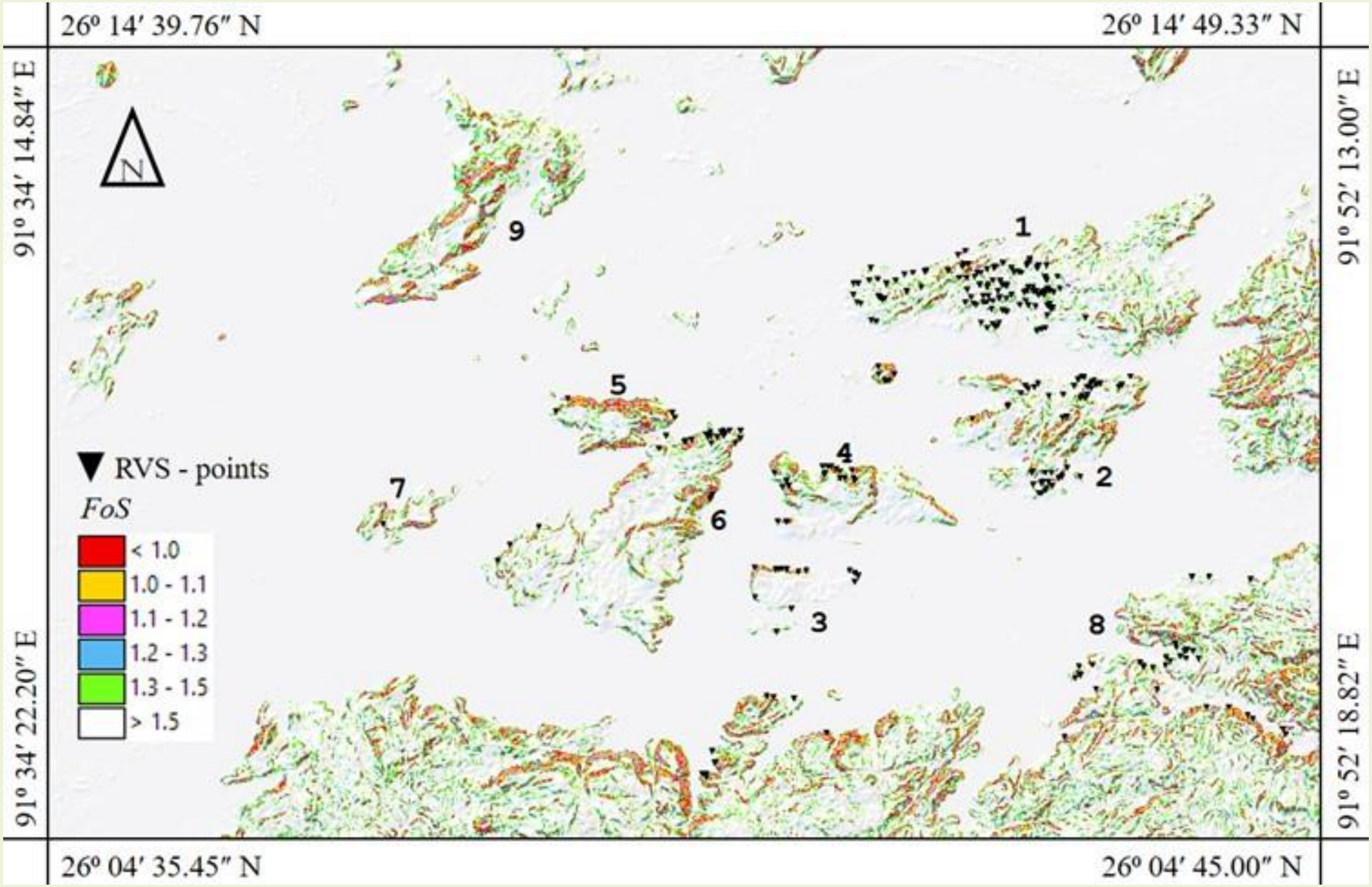
TRIGRS model for Guwahati city (Regional scale)

- Output
  - Factor of Safety map of the study area
  - Evaluation and Validation of the FoS map
- Landslide Inventory
  - "Rapid Visual Screening Potential Landslide Areas of Guwahati" (Goswami, 2013)
  - July, 2012 – Assam State Disaster Management Authority (ASDMA)
  - Location of landslide occurrences in the month of June, 2012
  - Landslide prone areas in the form of GPS Latitude-Longitude coordinates
  - 347 locations – referred as RVS-points

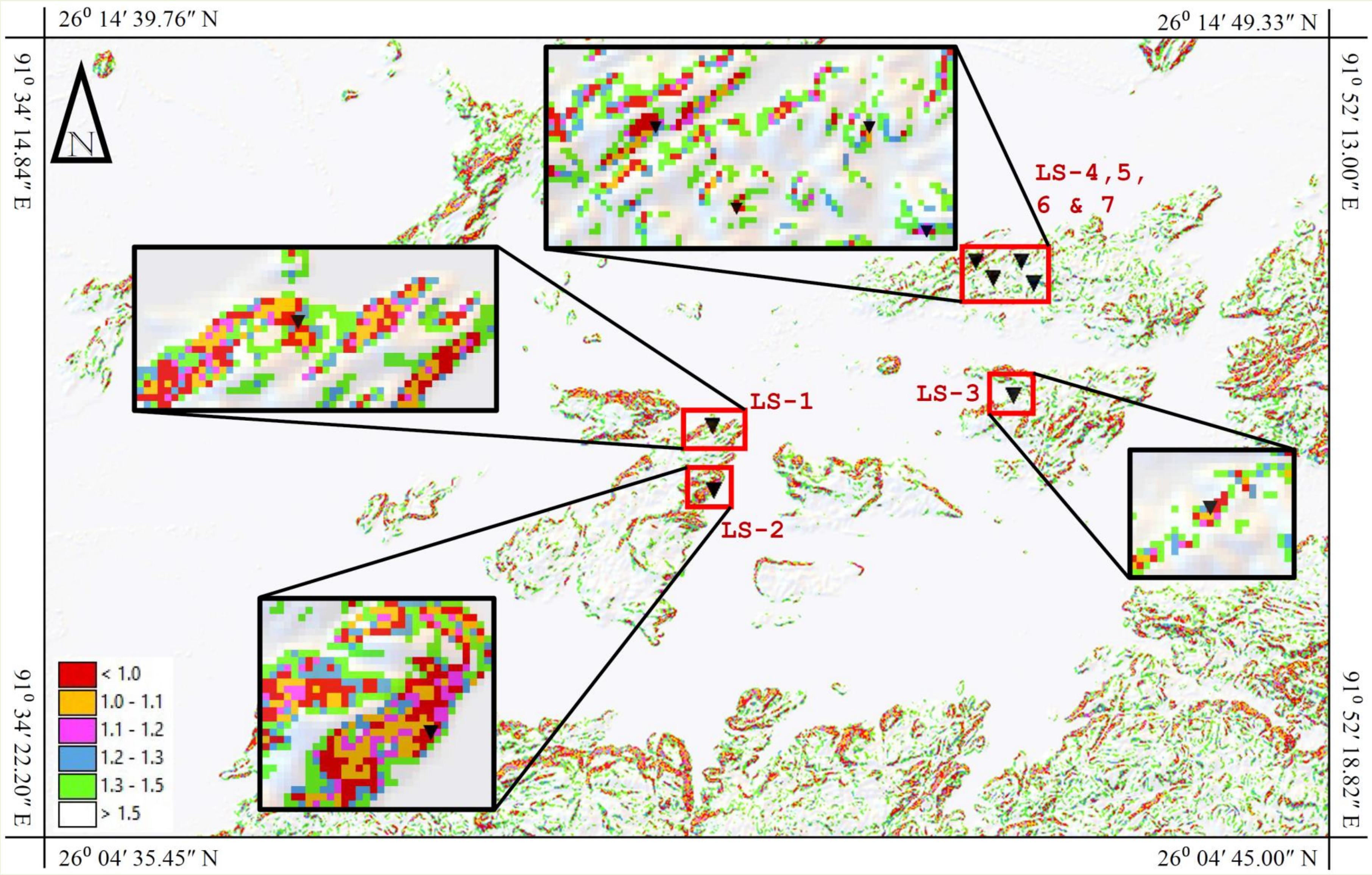
TRIGRS model for Guwahati city (Regional scale)



TRIGRS model for Guwahati city (Regional scale)

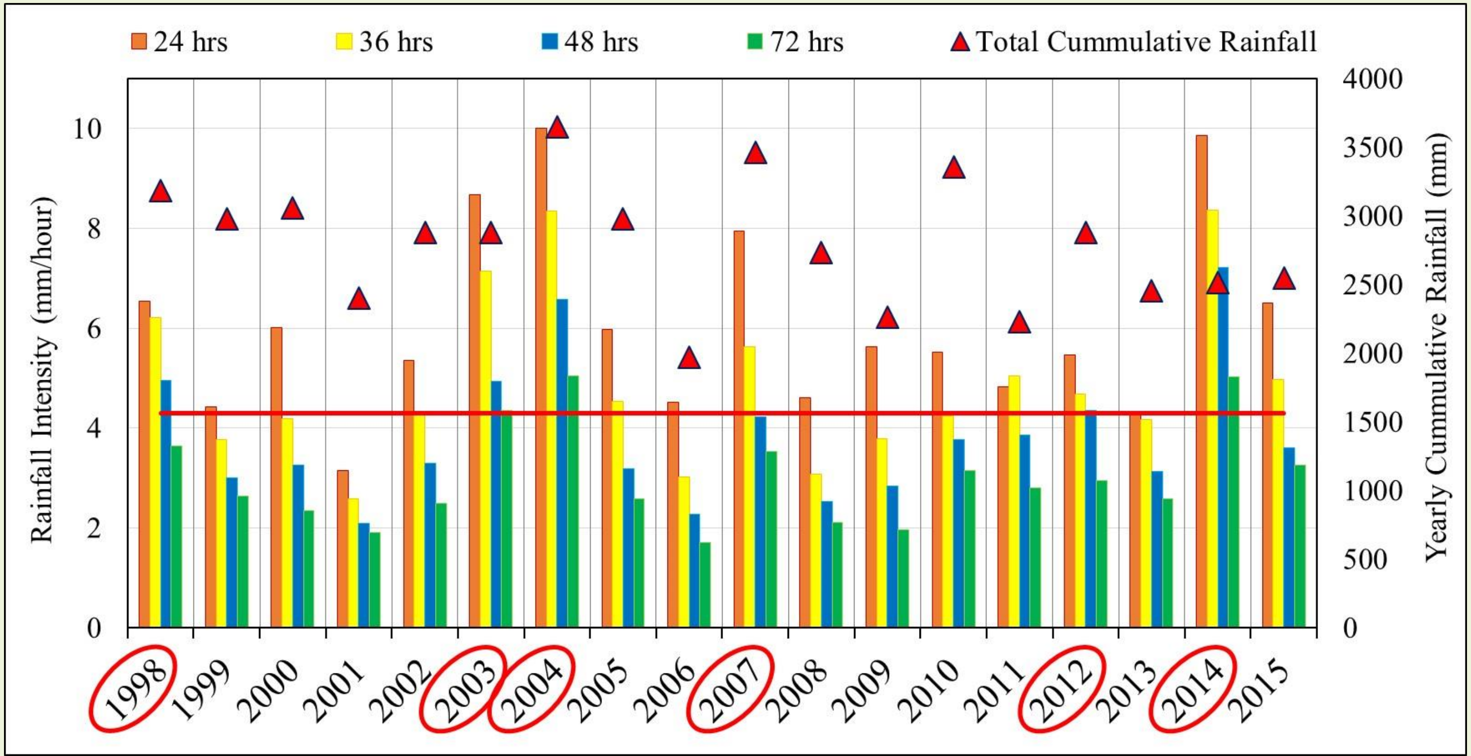


TRIGRS model for Guwahati city (Regional scale)



Rainfall event triggering landslide in Guwahati

- Detailed Rainfall record
  - TRMM Daily (24–hour) rainfall data
    - 1998 – 2015, July
    - The yearly reports of landslide occurrence
    - Relation of rainfall events and landslide

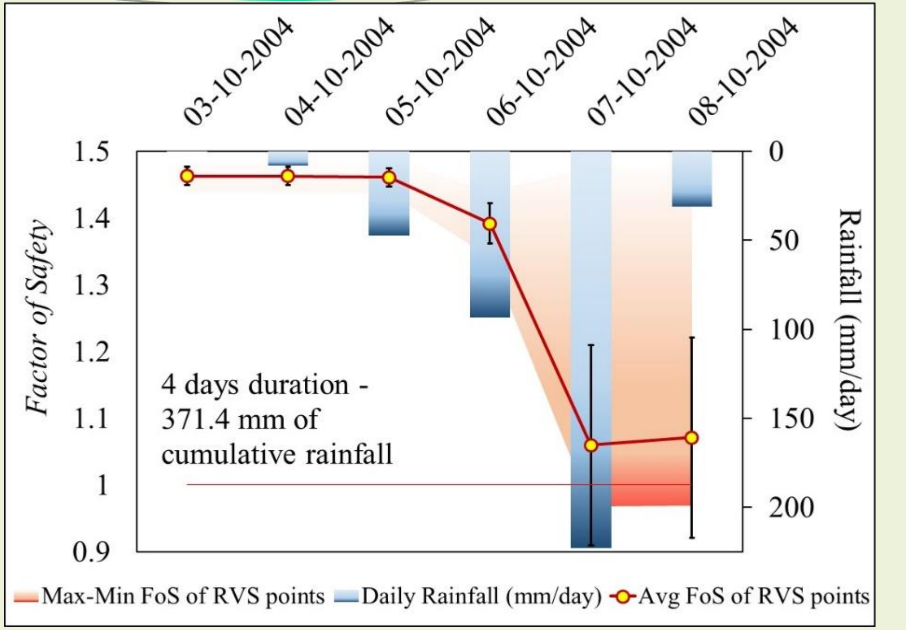


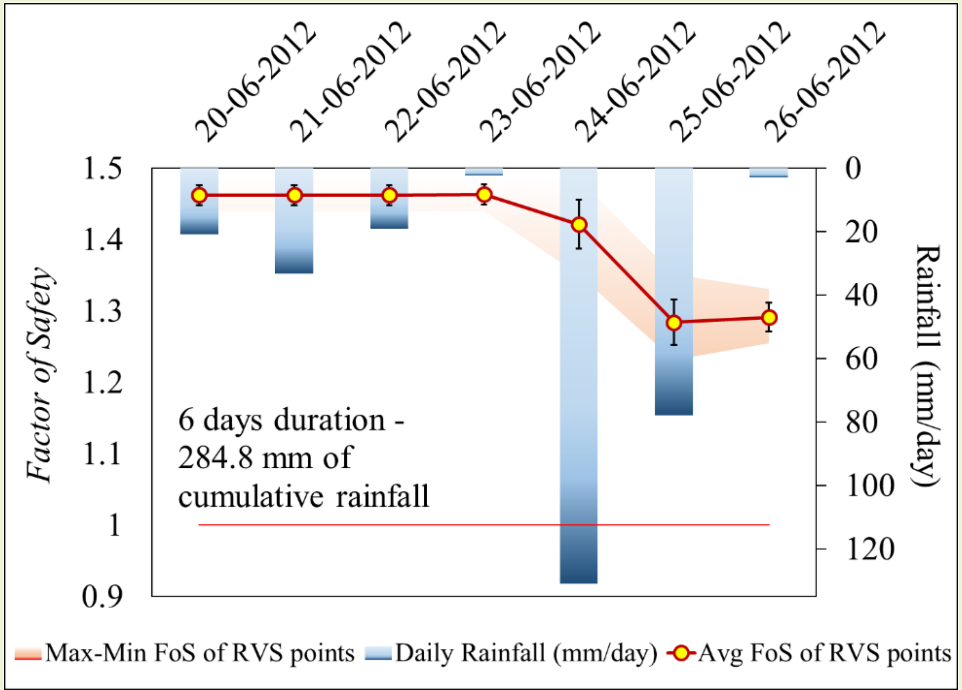
Rainfall event triggering landslide in Guwahati

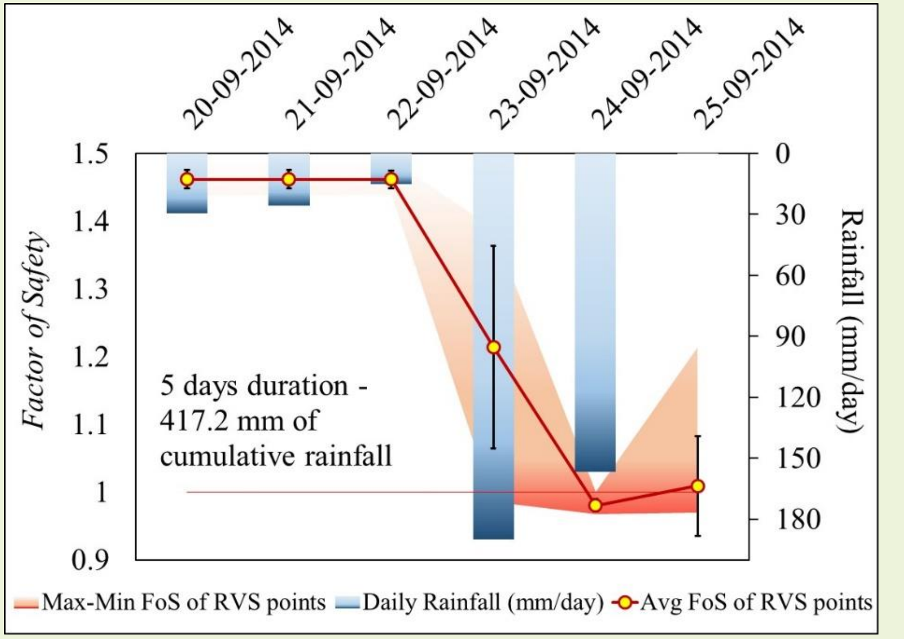
Year	No of days with Rainfall	Cumulative Rainfall (mm)	No of days for Daily Rainfall (10mm - 25 mm)	No of days for Daily Rainfall (25mm-50mm)	No of days for Daily Rainfall (50mm - 80mm)	No of days for Daily Rainfall (80mm - 100mm)	No of days for Daily Rainfall > 100mm	Max Daily Rainfall (mm)	Max Cumulative Rainfall within 48 hours (mm)	Max Cumulative Rainfall within 72 hours (mm)	Landslides Reported
1998	**170**	**3185**	**39**	**20**	**6**	**8**	**4**	**148**	**238**	**263**	**y**
1999	179	2978	47	32	11	0	1	106	144	190	
2000	171	3058	26	26	9	2	5	144	157	169	
2001	178	2404	43	25	8	0	0	70	101	138	
2002	178	2878	44	26	7	2	2	104	158	180	
2003	**179**	**2881**	**51**	**15**	**7**	**3**	**4**	**147**	**237**	**313**	**y**
2004	**167**	**3647**	**38**	**27**	**9**	**7**	**4**	**223**	**316**	**363**	**y**
2005	180	2977	42	22	15	2	1	106	153	186	
2006	159	1973	41	16	6	0	1	108	109	124	
2007	**169**	**3466**	**38**	**24**	**8**	**4**	**6**	**185**	**202**	**254**	**y**
2008	182	2731	47	34	6	1	0	91	122	152	
2009	148	2265	29	14	10	2	2	119	136	141	
2010	171	3356	46	29	11	5	1	105	181	226	
2011	156	2229	51	19	6	1	1	101	185	202	
2012	**152**	**2877**	**34**	**28**	**10**	**1**	**2**	**131**	**209**	**212**	**y**
2013	151	2457	38	25	9	0	1	104	150	185	
2014	**146**	**2513**	**33**	**29**	**3**	**3**	**2**	**190**	**347**	**362**	**y**
2015	143	2547	37	22	8	1	3	111	173	234	
Maximum	182	3647	51	34	15	8	6	223	347	363	
Average	166	2801	40	24	8	2	2	127	184	216	
Minimum	143	1973	26	14	3	0	0	70	101	124	

Rainfall event triggering landslide in Guwahati

- TRIGRS simulation
  - Rainfall events of
    - October, 2004 (3-10-2004 to 8-10-2004)
    - June, 2012 (20-6-2012 to 26-6-2012)
    - September, 2014 (20-9-2014 to 25-9-2014)

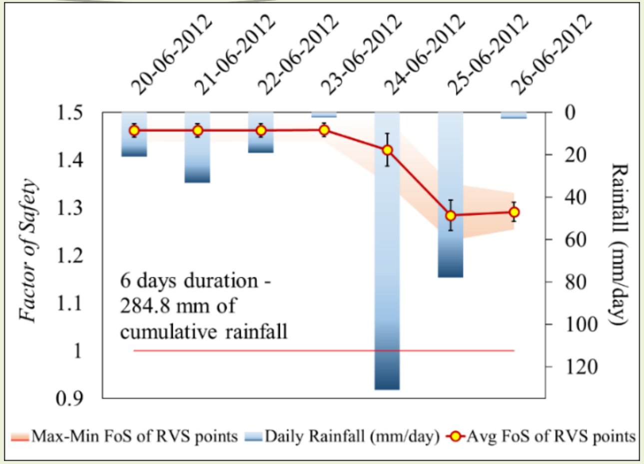


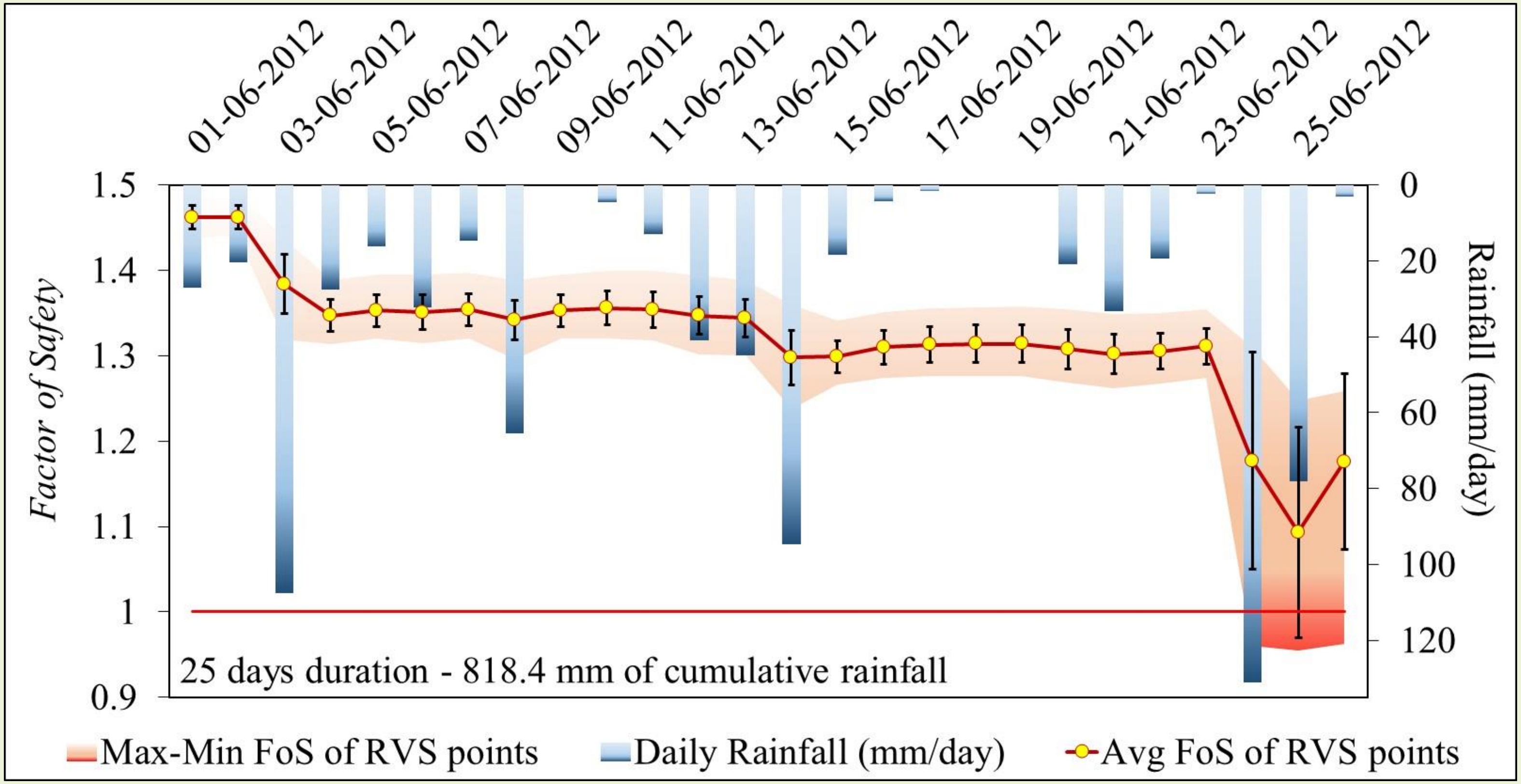




Effect of Antecedent Condition

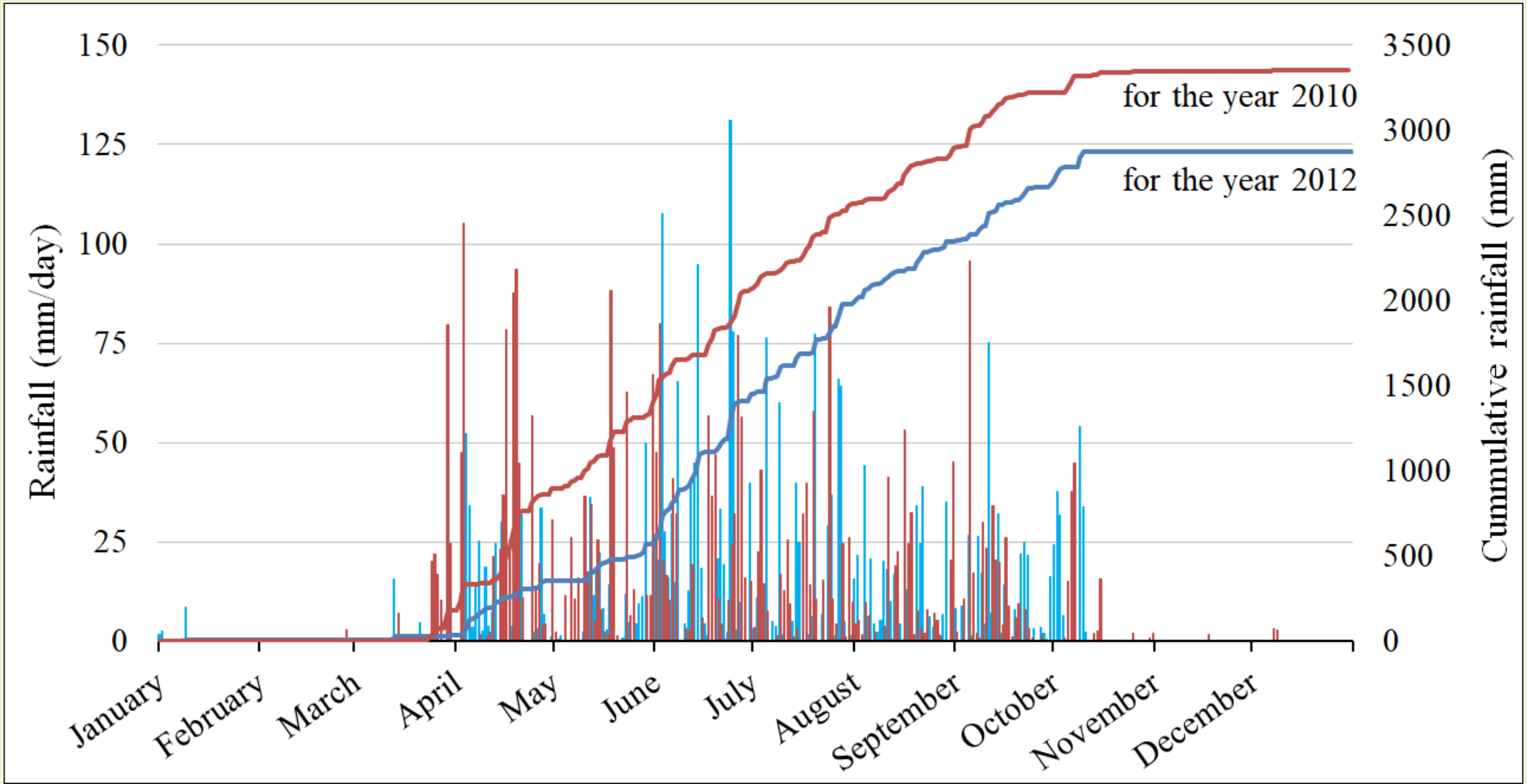
- TRIGRS simulation
  - ❖ Rainfall events of
    - June, 2012 (01-6-2012 to 26-6-2012)





Intricate combination of the Antecedent and Triggering Rainfall

- Rainfall events of
  - June, 2012 (01-6-2012 to 26-6-2012)
  - March-April 2010



Intricate combination of the Antecedent and Triggering Rainfall

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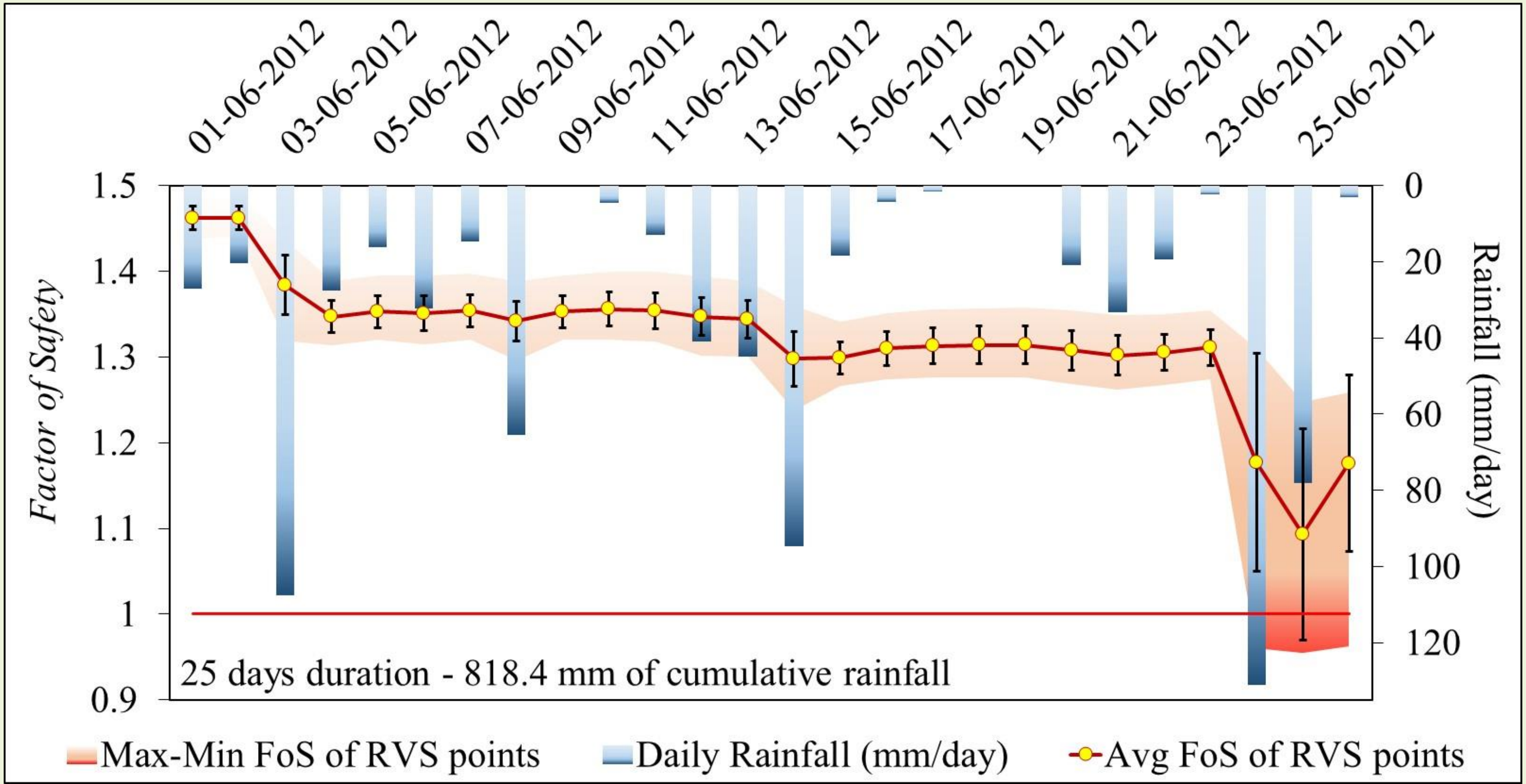

Intricate combination of the Antecedent and Triggering Rainfall

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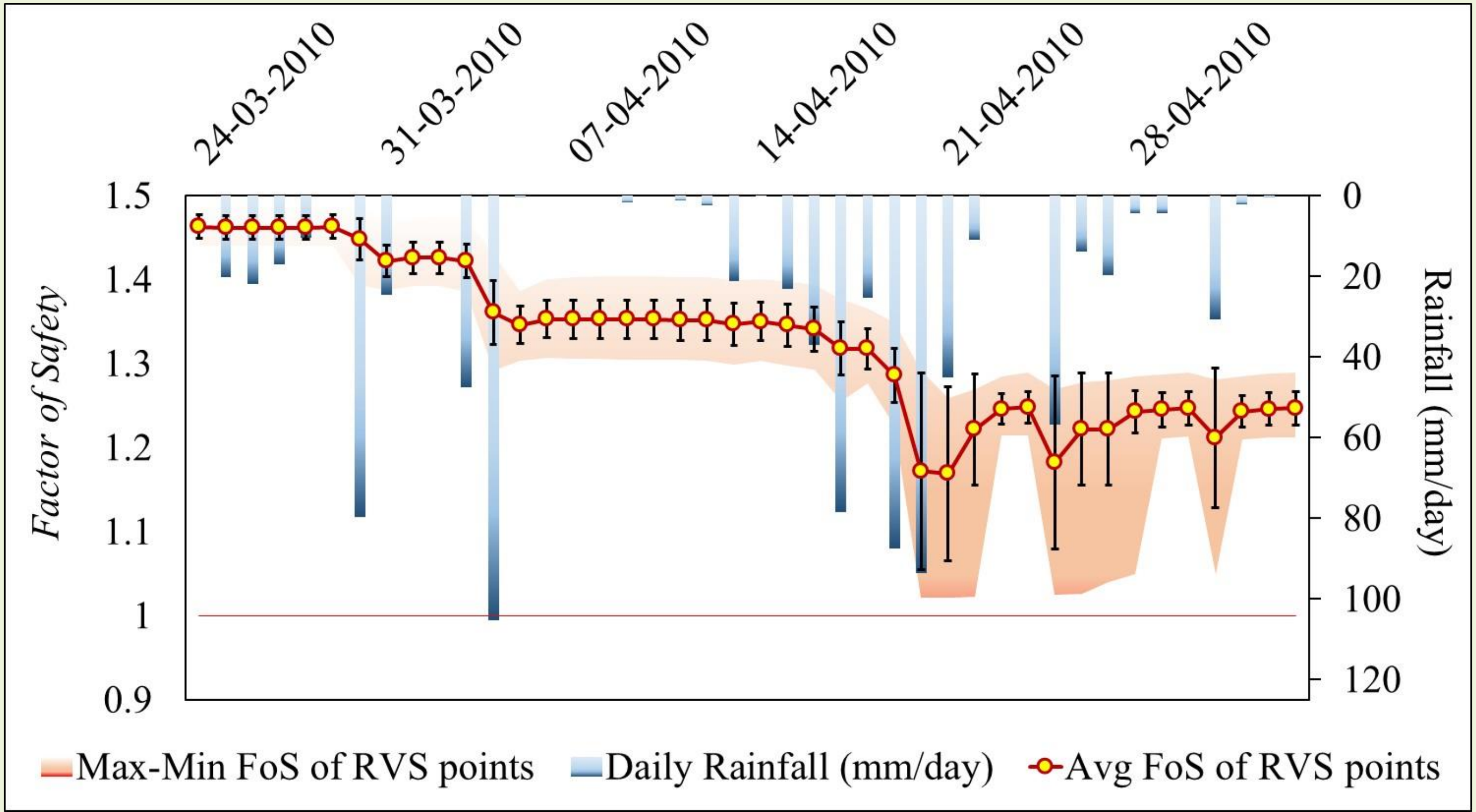

Intricate combination of the Antecedent and Triggering Rainfall

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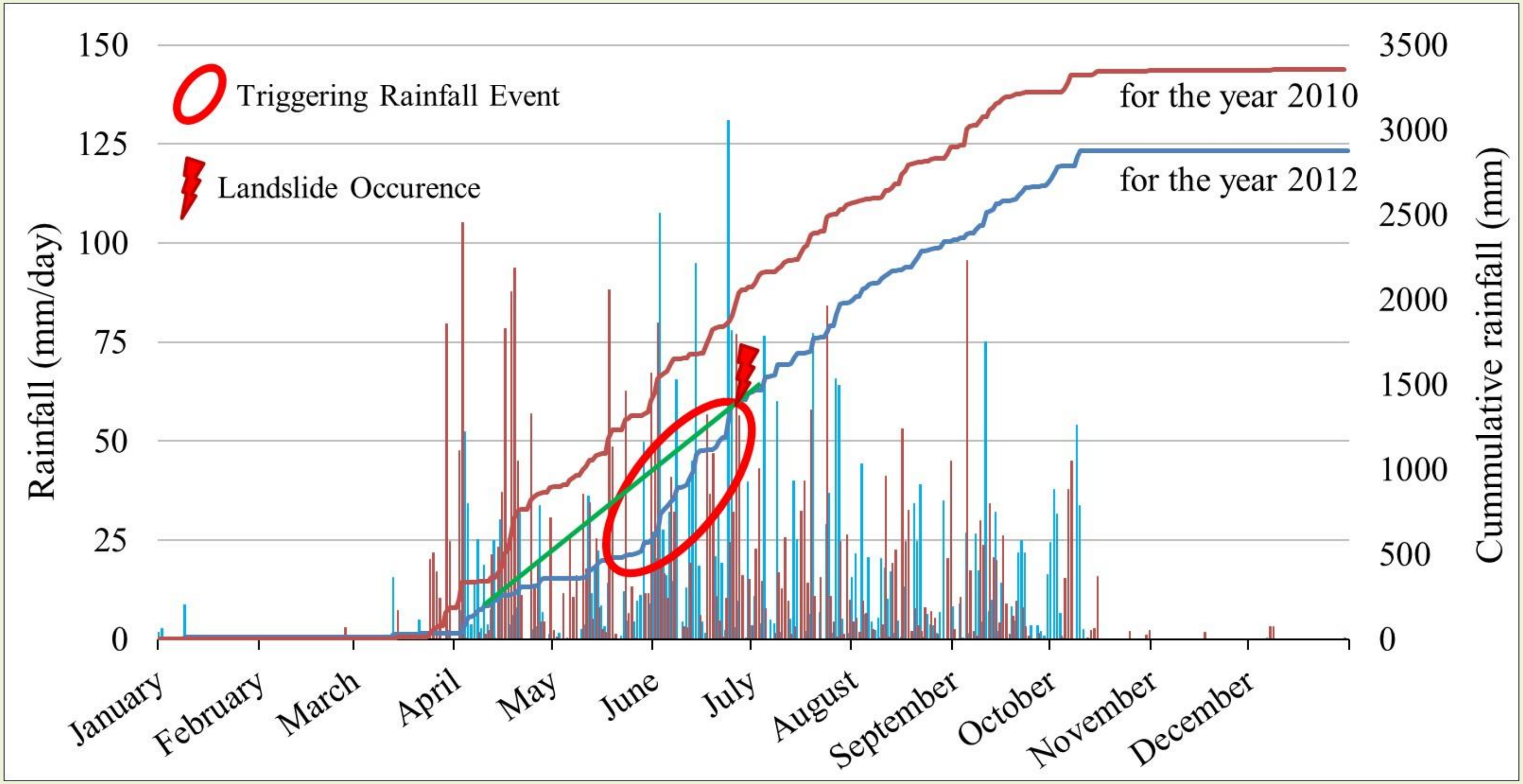
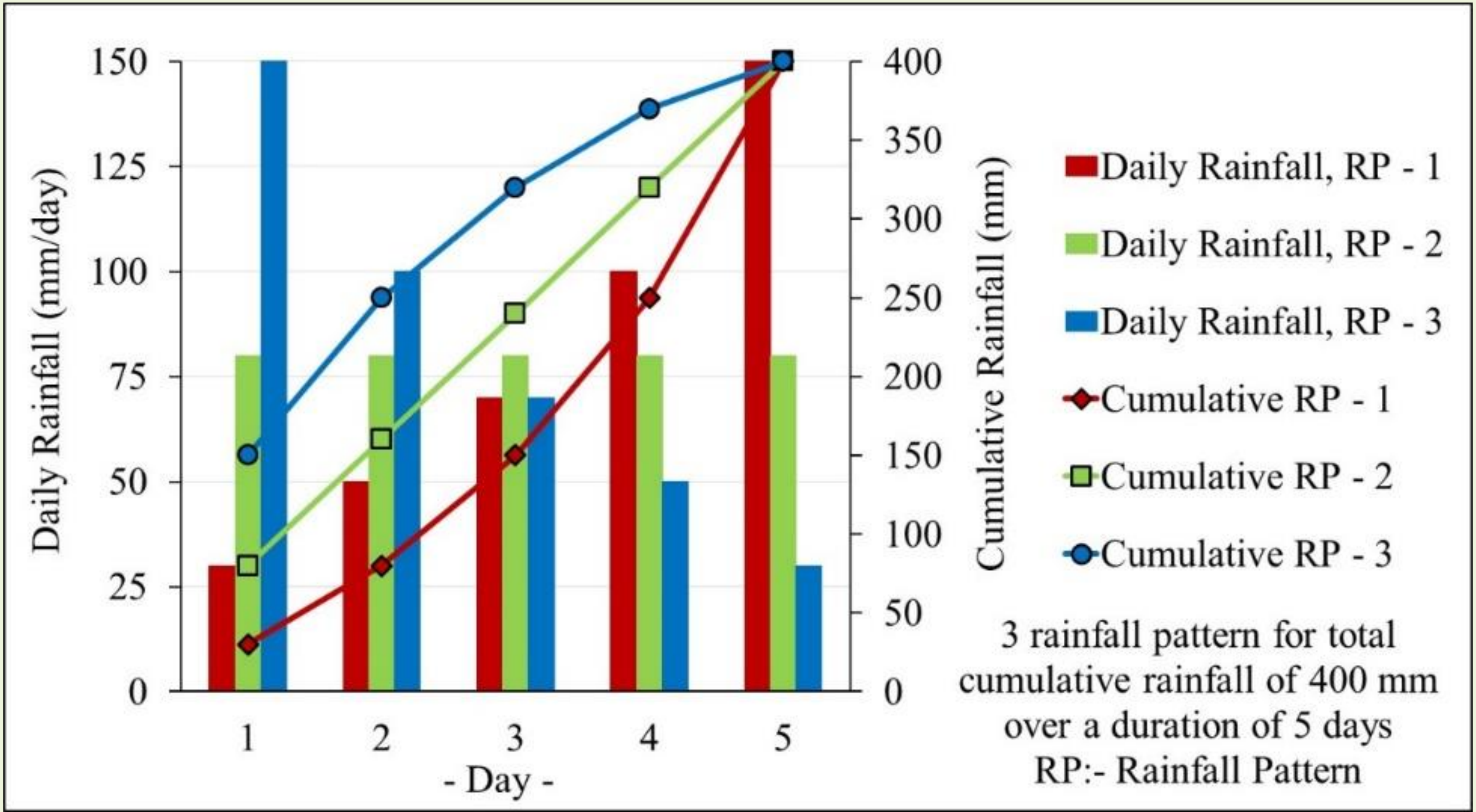


Effect of Rainfall Pattern

- Cumulative rainfall of
  - 400 mm distributed over 5 days



Effect of Rainfall Pattern

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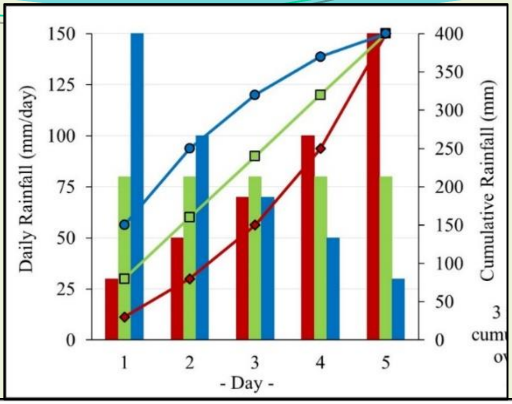

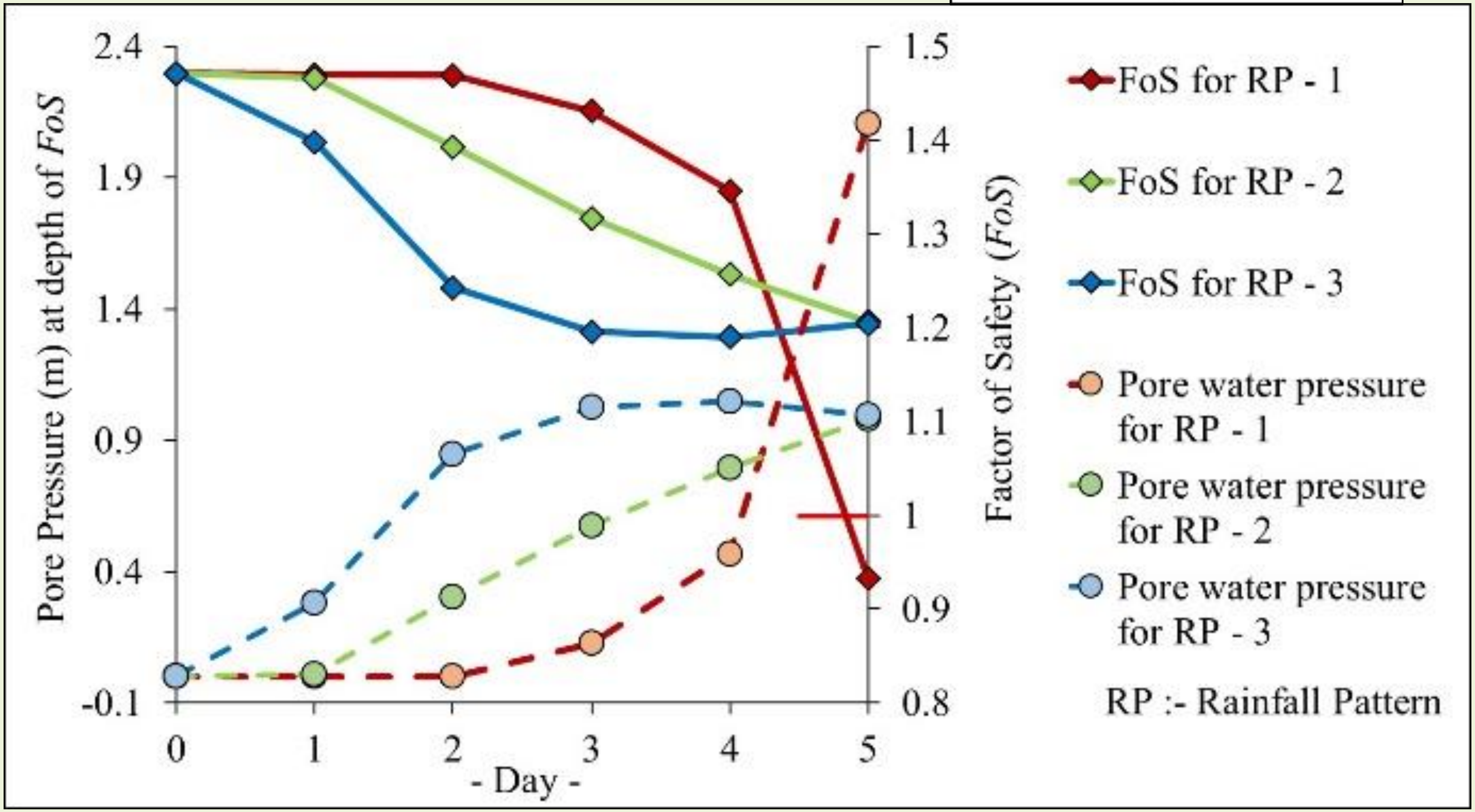

Effect of Rainfall Pattern

- Cumulative rainfall of
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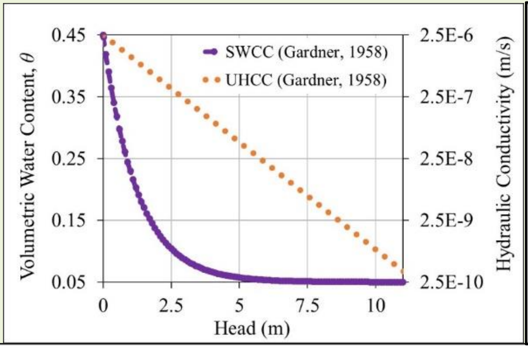

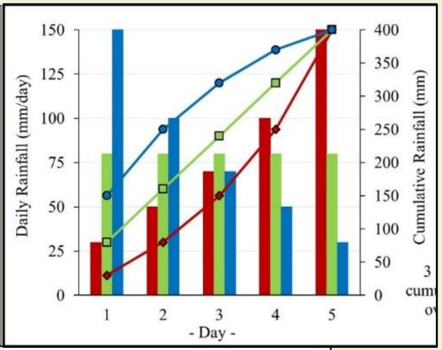

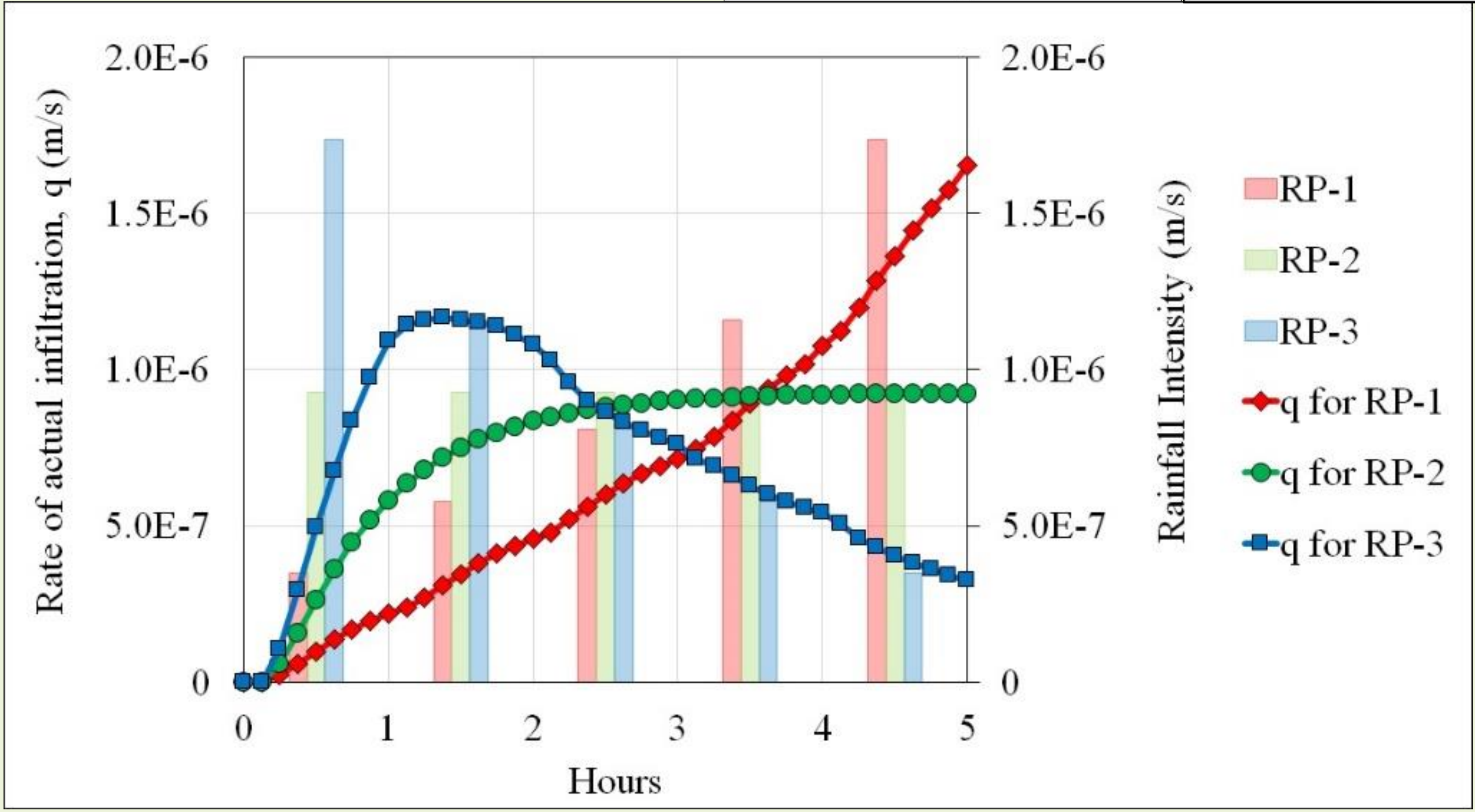

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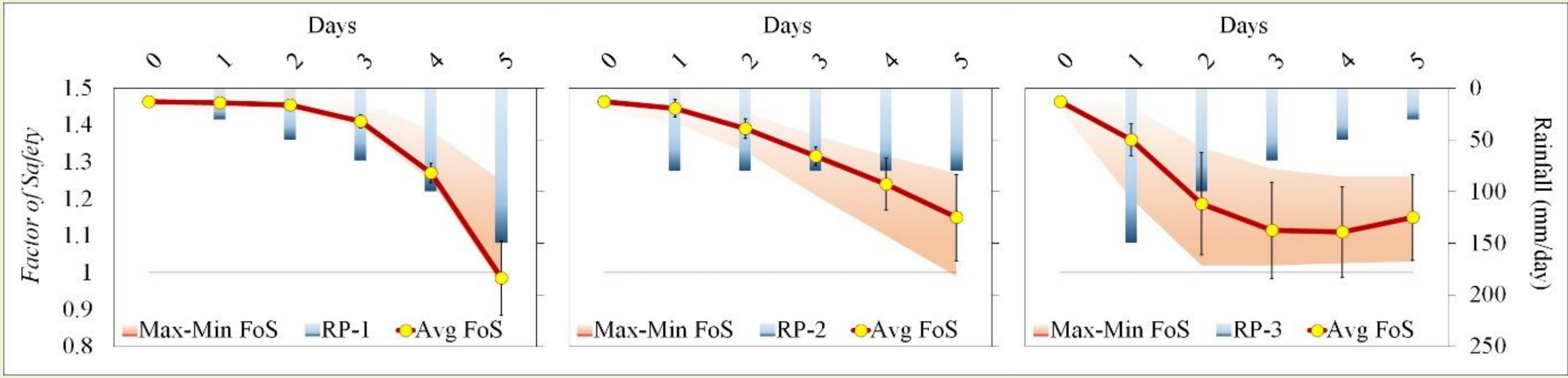

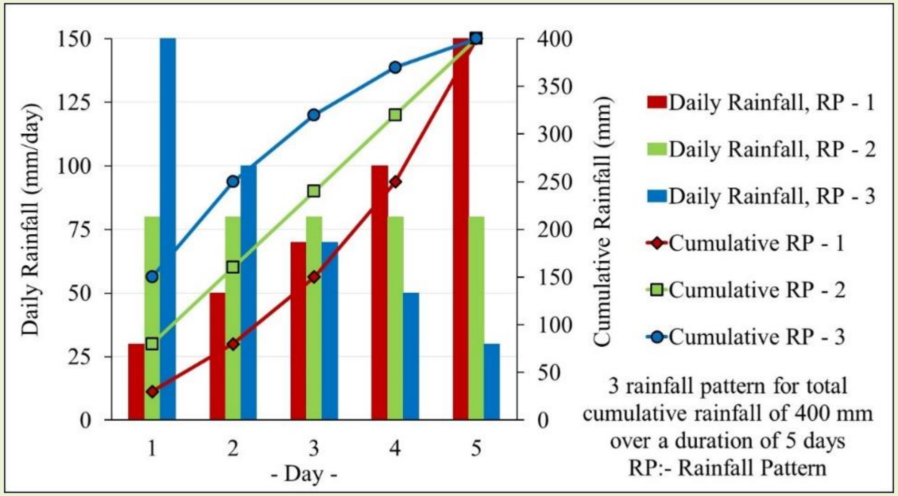

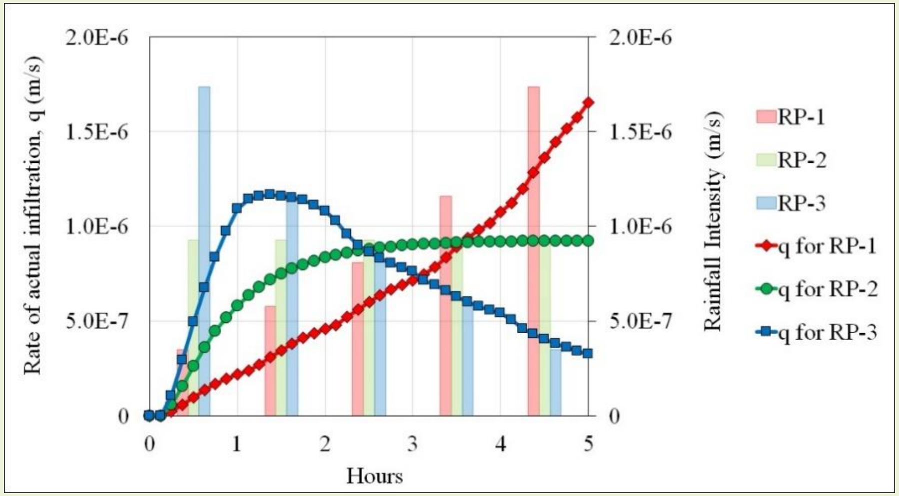

Rainfall Data

- Tropical Rainfall Measuring Mission (TRMM) 3-hourly rainfall data
- TRMM Daily (24–hour) rainfall data
  - ❖ 1998 – 2018, July
  - ❖ Goddard Earth Sciences Data and Information Services Center (GES DISC)
- Monthly Rainfall Data of Kamrup District
  - ❖ 1901 – 2002
  - ❖ www.indiawaterportal.org/met_data
- Indian Meteorological Department Guwahati, Daily (24–hour) Rainfall Data
  - ❖ 1969 – 2012

Rainfall Data

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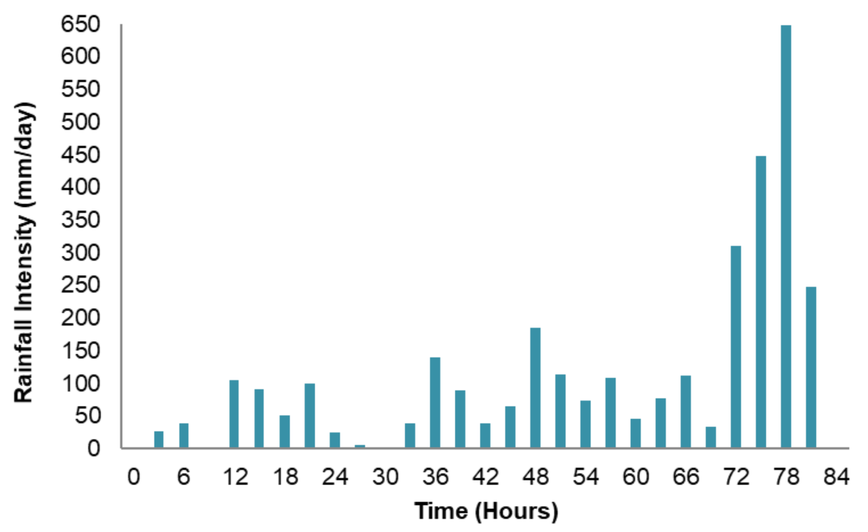
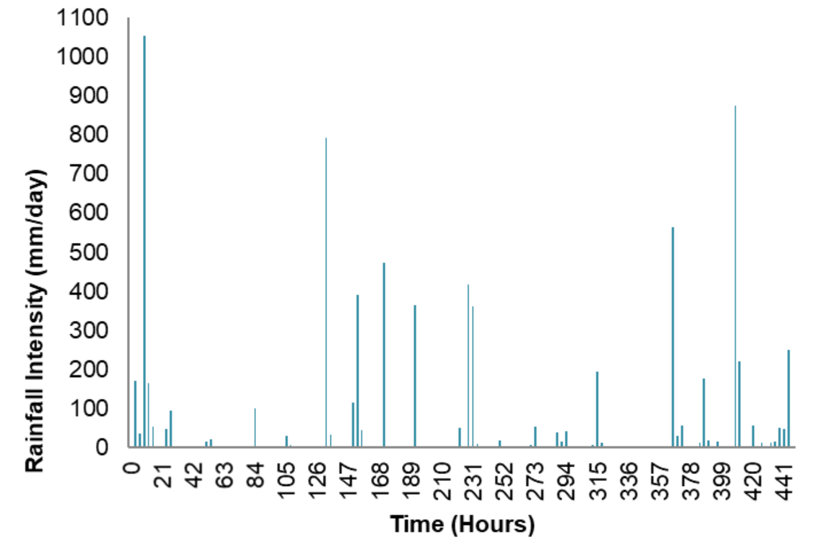


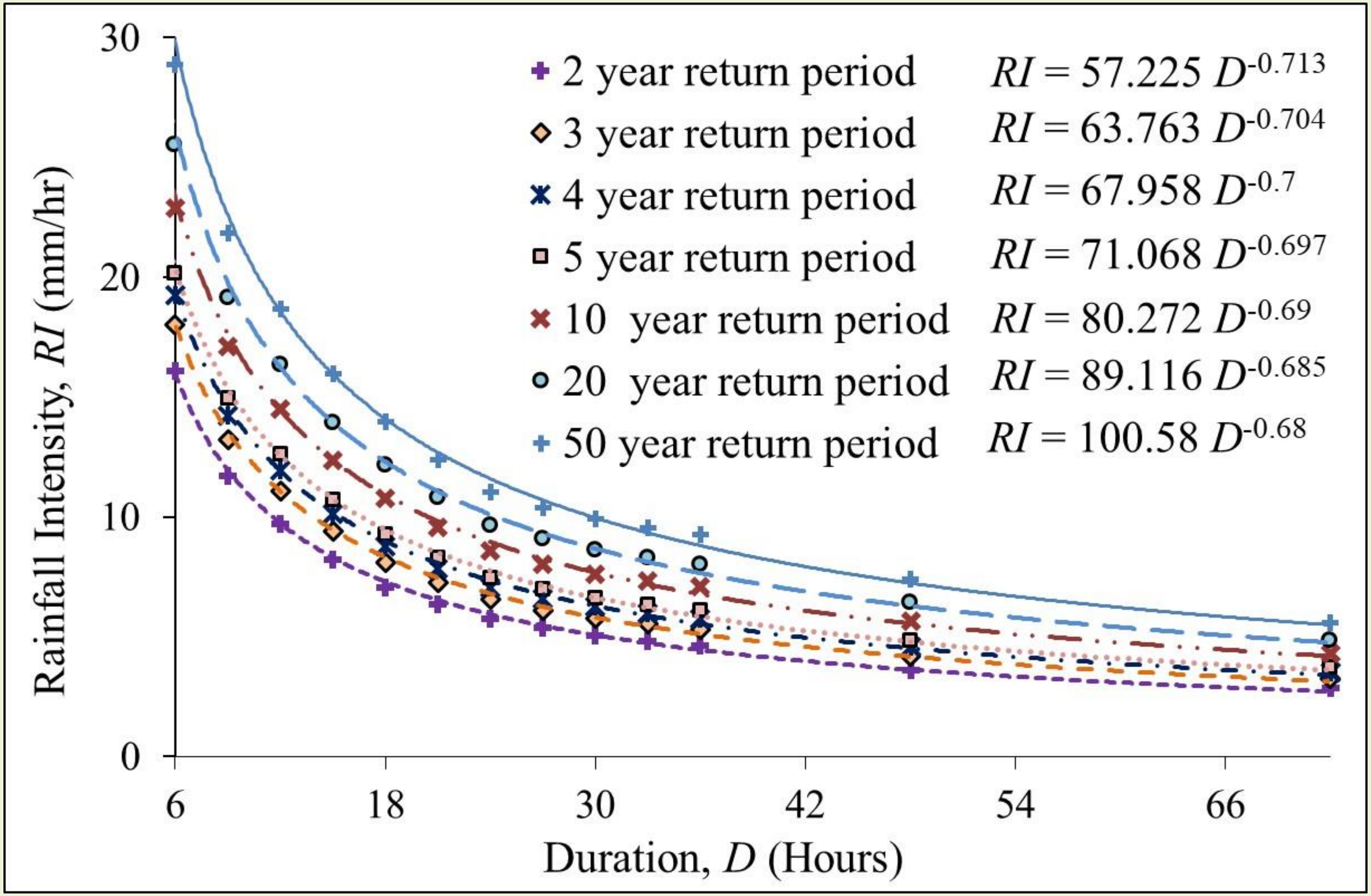
Rainfall Storm Event of October 2004



Rainfall in May - Aug, 2007

Landslide Hazard

- Rainfall Intensity – Duration – Frequency



Landslide Hazard

- Combining the FoS maps for generating the landslide recurrence map

Rainfall Intensity in mm/day		Rainfall Return Period				
		2 year	5 year	10 year	20 year	50 year
Rainfall Duration	24 hour	142	186	215	243	278
	36 hour	107	140	163	184	211
	48 hour	87	115	133	151	174
	60 hour	74	98	114	129	149
	72 hour	65	87	101	114	132

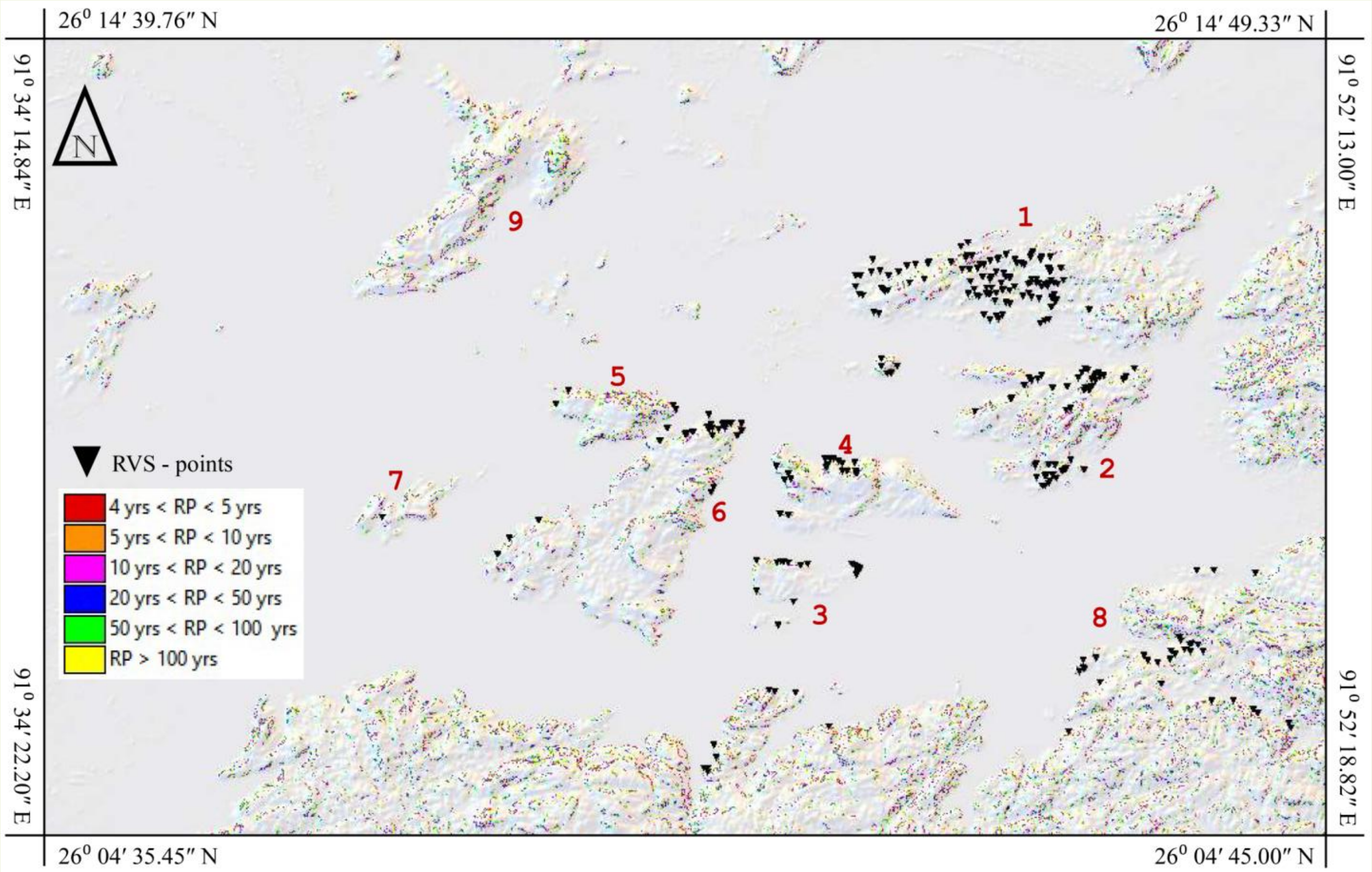
Landslide Hazard

- Combining the FoS maps for generating the landslide recurrence map

Rainfall intensity (mm/hr) corresponding to -		Return period in years						
		3	4	5	10	20	50	100
Duration of a single rainfall event (hours)	6	18.1	19.4	20.4	23.3	26.1	29.7	32.5
	12	11.1	11.9	12.6	14.5	16.2	18.6	20.3
	24	6.8	7.3	7.8	9.0	10.1	11.6	12.7
	36	5.1	5.5	5.8	6.8	7.7	8.8	9.6
	48	4.2	4.5	4.8	5.6	6.3	7.2	7.9
	60	3.6	3.9	4.1	4.8	5.4	6.2	6.8
	72	3.1	3.4	3.6	4.2	4.8	5.5	6.0

Landslide Hazard Map of Guwahati City

- FoS maps are combined to form a landslide hazard map
  - ❖ Location of probable landsliding
  - ❖ Within specified Return Period



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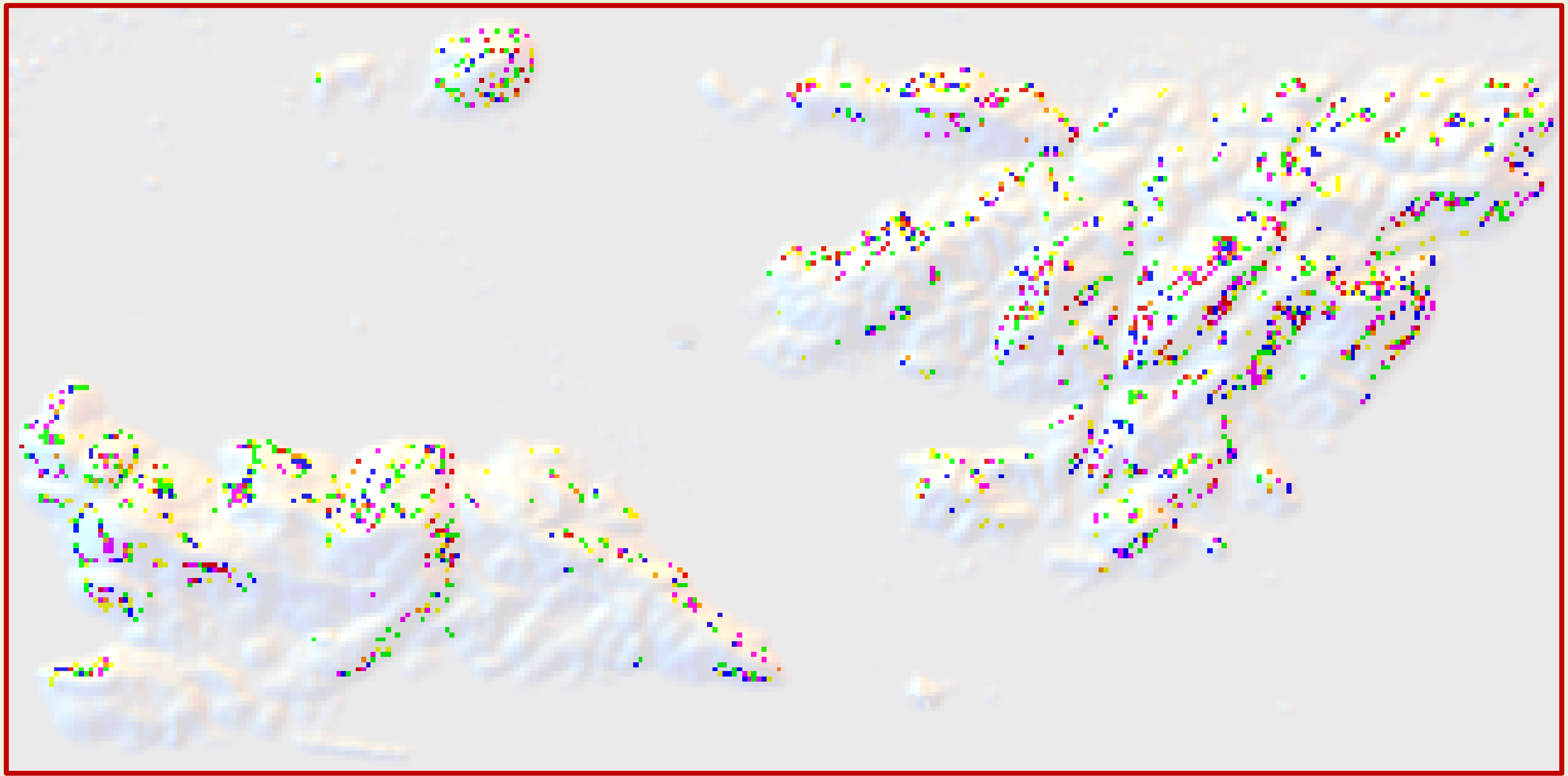

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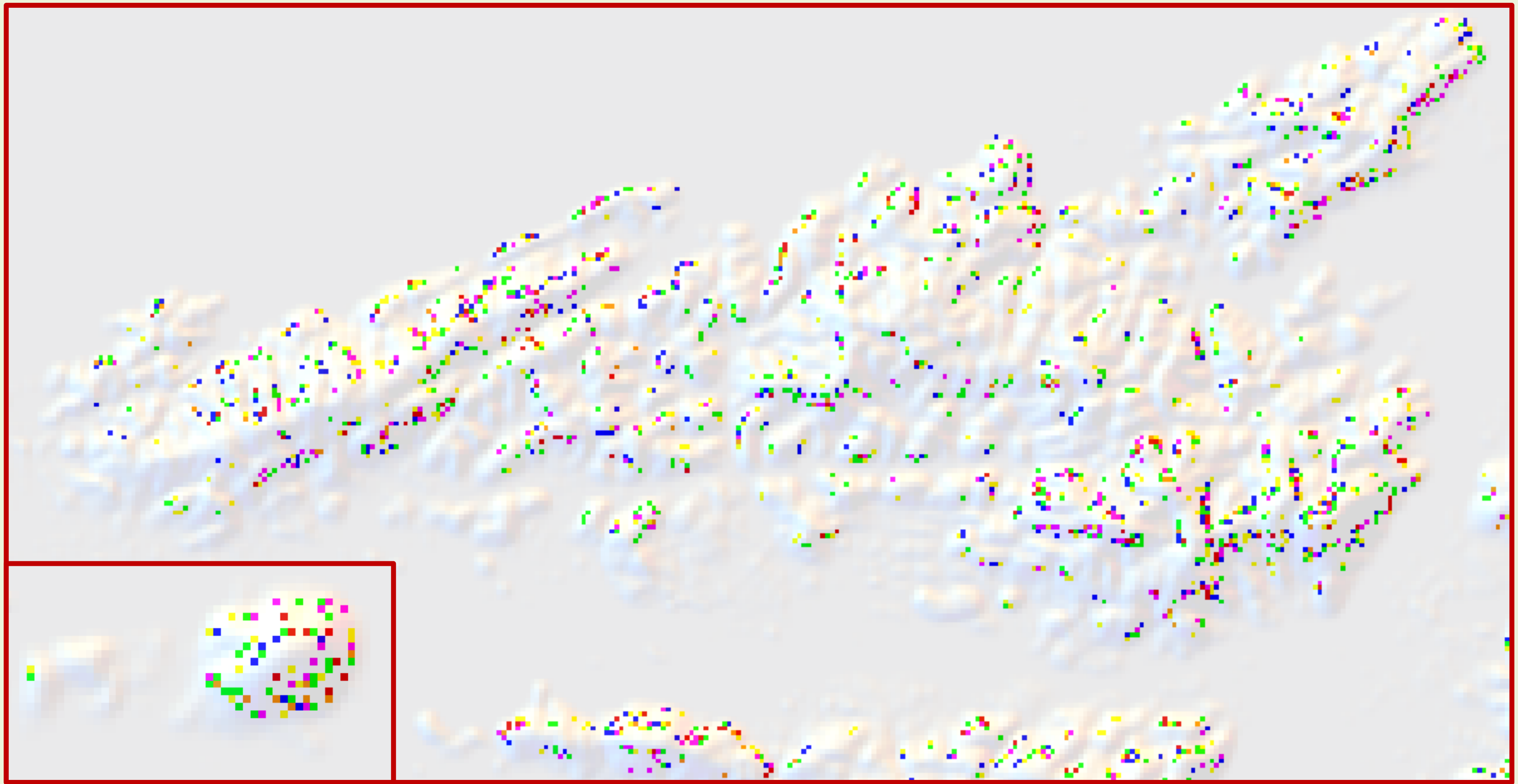


Probabilistic Regional Analysis

- Probabilistic Approach
  - Distributed Soil Property
    - Statistics of the distribution
  - Probability of Failure







Probabilistic Regional Analysis

- Probability Distribution of the soil parameters

Site name	Maximum infiltration rate $\times10^{-6}$(m/s)	Minimum infiltration rate $\times10^{-6}$(m/s)	Average infiltration rate $\times10^{-6}$(m/s)
Chunsali hill	8.68	4.42	**6.55**
Noonmati hill 1	3.51	0.051	**2.01**
Noonmati hill 2	3.06	1.4	**2.23**
Kailash nagar hill 1	3.14	0.21	**1.67**
Kailash nagar hill 2	0.81	0.614	**0.444**
Shree nagar Kailash nagar hill	2.93	0.911	**1.92**
Punnya nagar hill	6.33	0.98	**4.84**
Jyoti ban	8.4	1.12	**2.53**
Indupur kharghuli	12.9	1.9	**7.82**
Kamakhya hill	9.46	1.35	**5.78**
Shantipur hill	17.9	1.9	**9.91**

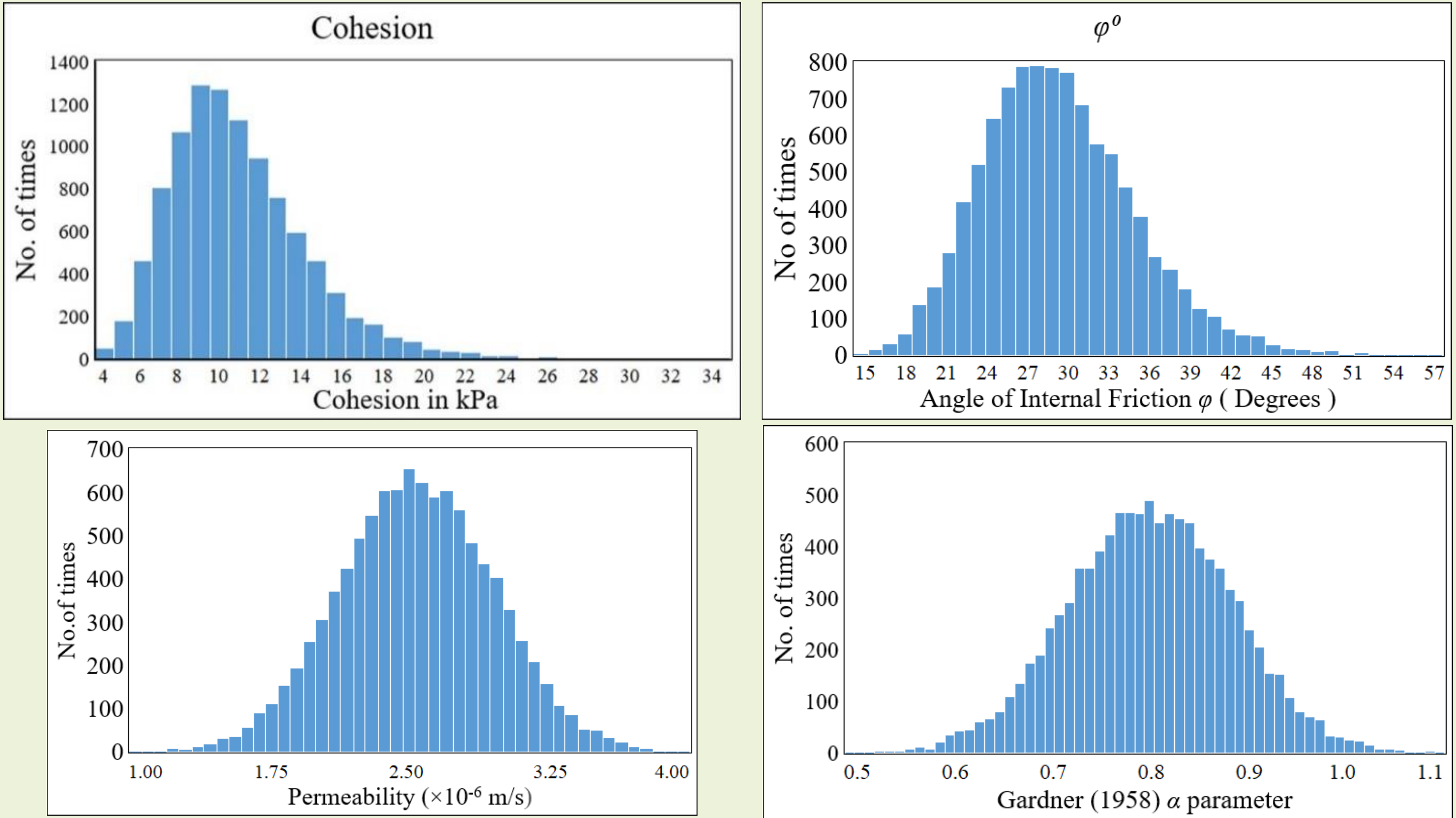
Site name	Maximum infiltration rate $\times10^{-6}$(m/s)	Minimum infiltration rate $\times10^{-6}$(m/s)	Average infiltration rate $\times10^{-6}$(m/s)
Chunsali hill	0.955	0.867	**0.911**
Noonmati hill 1	1.75	0.160	**0.955**
Noonmati hill 2	7.36	6.70	**4.02**
Kailash nagar hill 1	2.12	1.83	**1.97**
Kailash nagar hill 2	0.828	0.614	**0.721**
Shree nagar Kailash nagar hill	0.566	0.462	**0.514**
Punnya nagar hill	4.59	4.48	**4.53**
Jyoti ban	17.5	11.1	**1.43**
Indupur kharghuli	113.0	9.00	**10.1**
Kamakhya hill	0.661	0.58	**0.623**
Shantipur hill	1.59	1.08	**1.33**

Soil Parameter	Maximum	Minimum
Cohesion, c' (kPa)	20	5
Angle of Internal Friction, ϕ' (°)	31°	25°
In-situ unit weight γ_s (kN/m³)	19.0	16.5
Saturated Permeability, k_s (m/s)	10^{-5}	10^{-6}

c' (kPa)	ϕ' (°)	γ_s (kN/m³)	k_s (m/s)	D_o (m/s)	θ_s	θ_r	α
10	**27°**	**18.5**	**2.5×10^{-6}**	**2.5×10^{-5}**	**0.45**	**0.05**	**0.8**

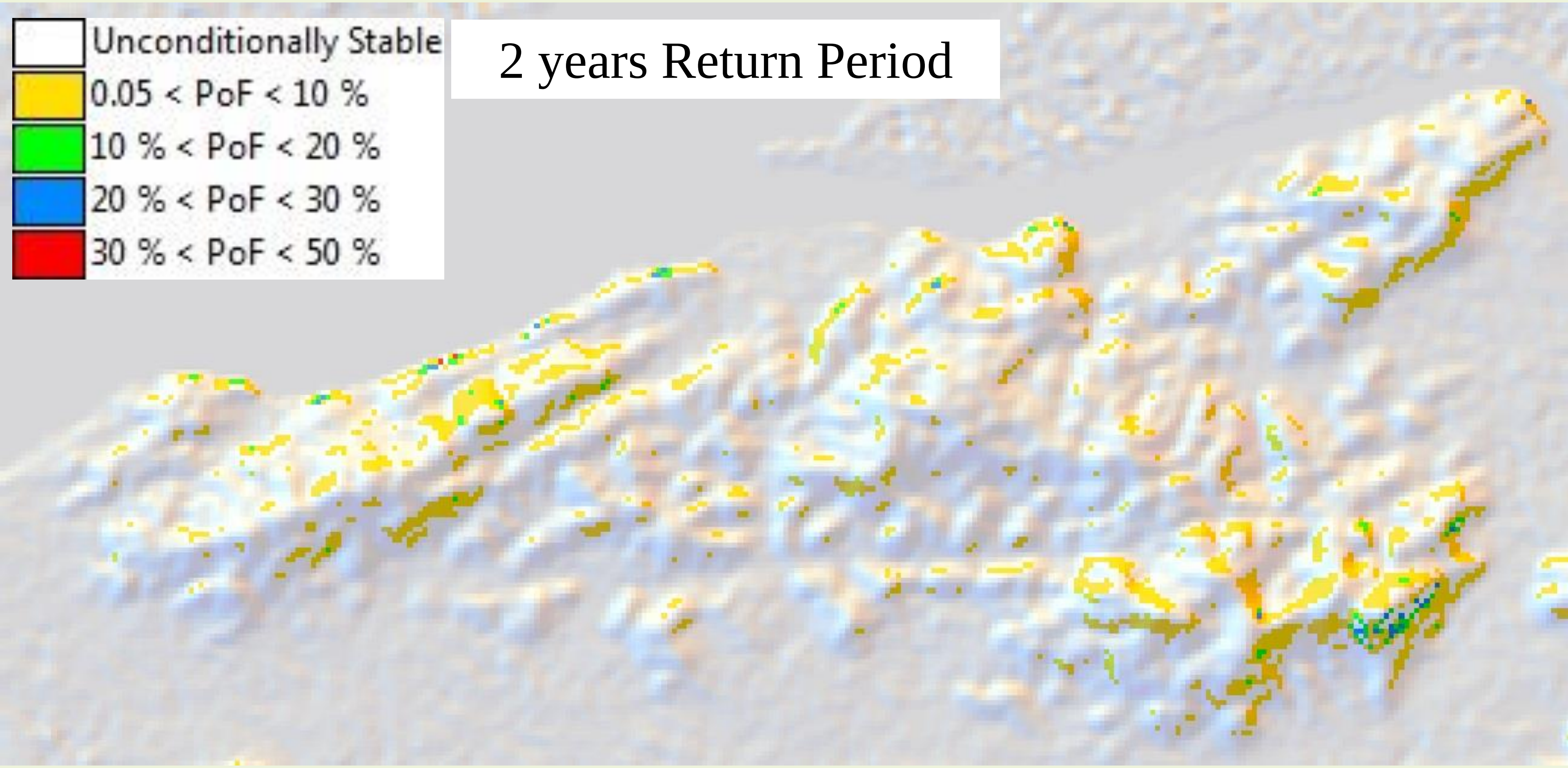
Probabilistic Regional Analysis

- Probability Distribution of the soil parameters



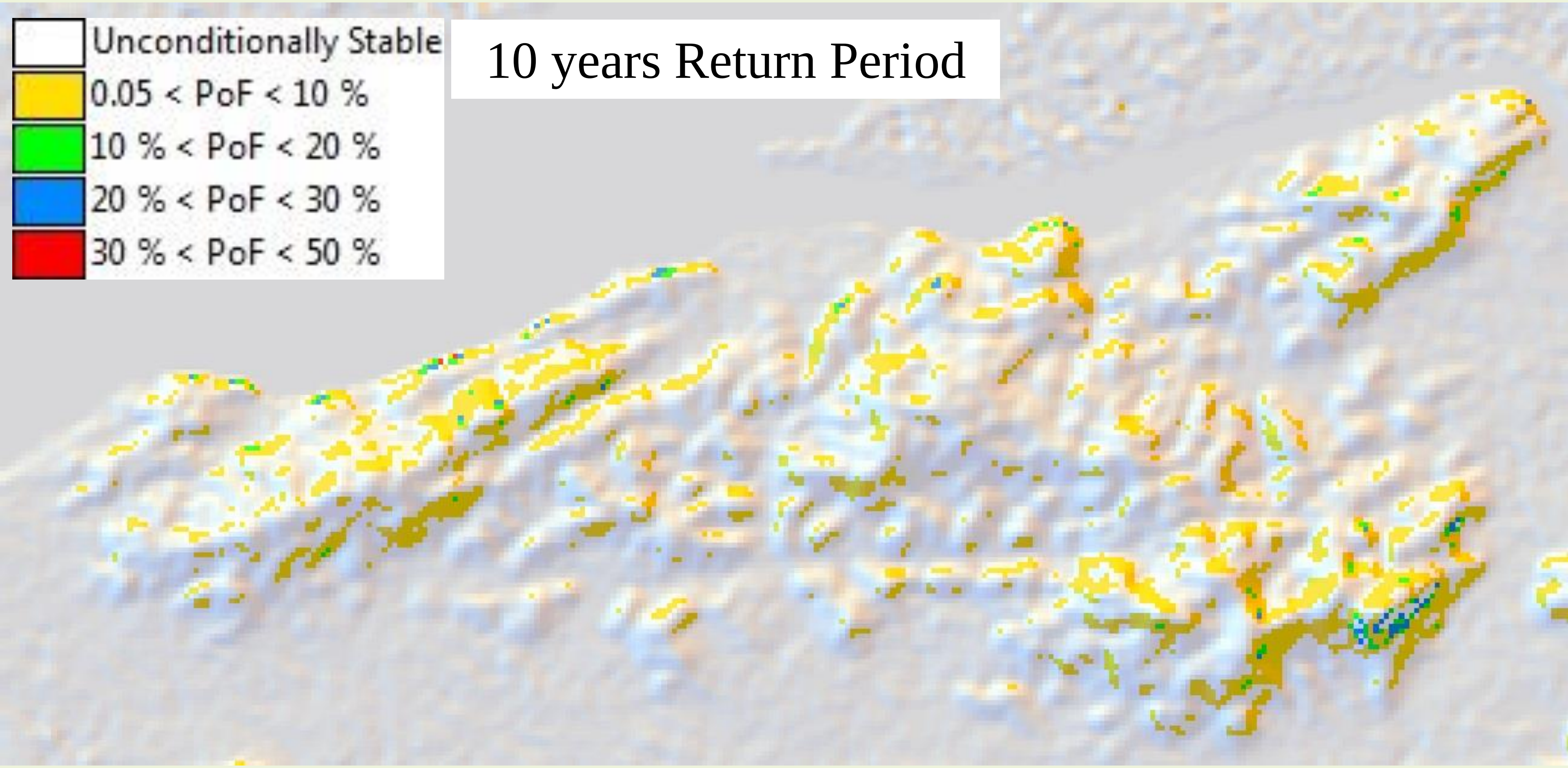
Probabilistic Regional Analysis

- Probability of Failure Maps – Direct Representation of the associated Risk



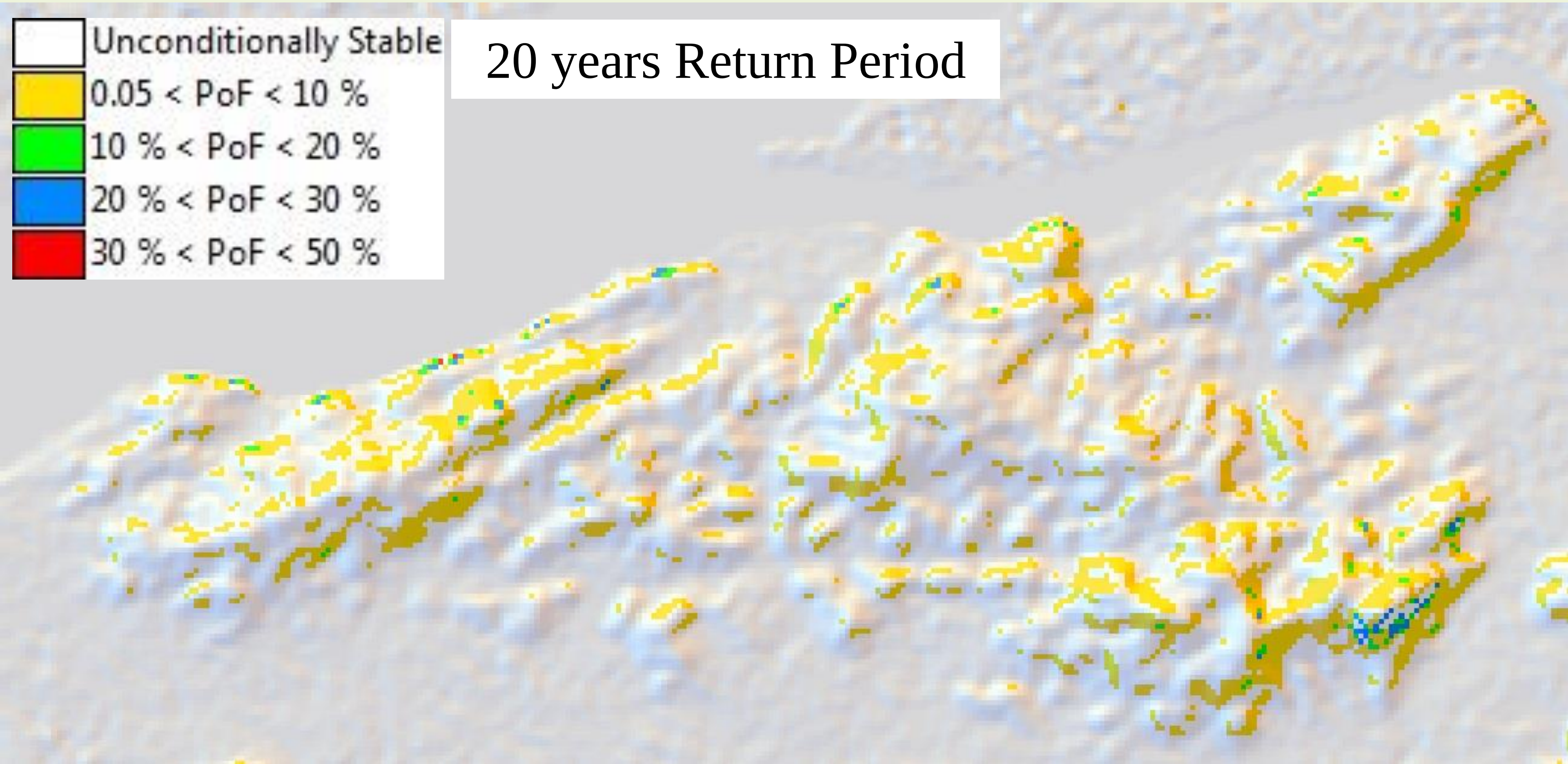
Probabilistic Regional Analysis

- Probability of Failure Maps – Direct Representation of the associated Risk



Probabilistic Regional Analysis

- Probability of Failure Maps – Direct Representation of the associated Risk



Probabilistic Regional Analysis

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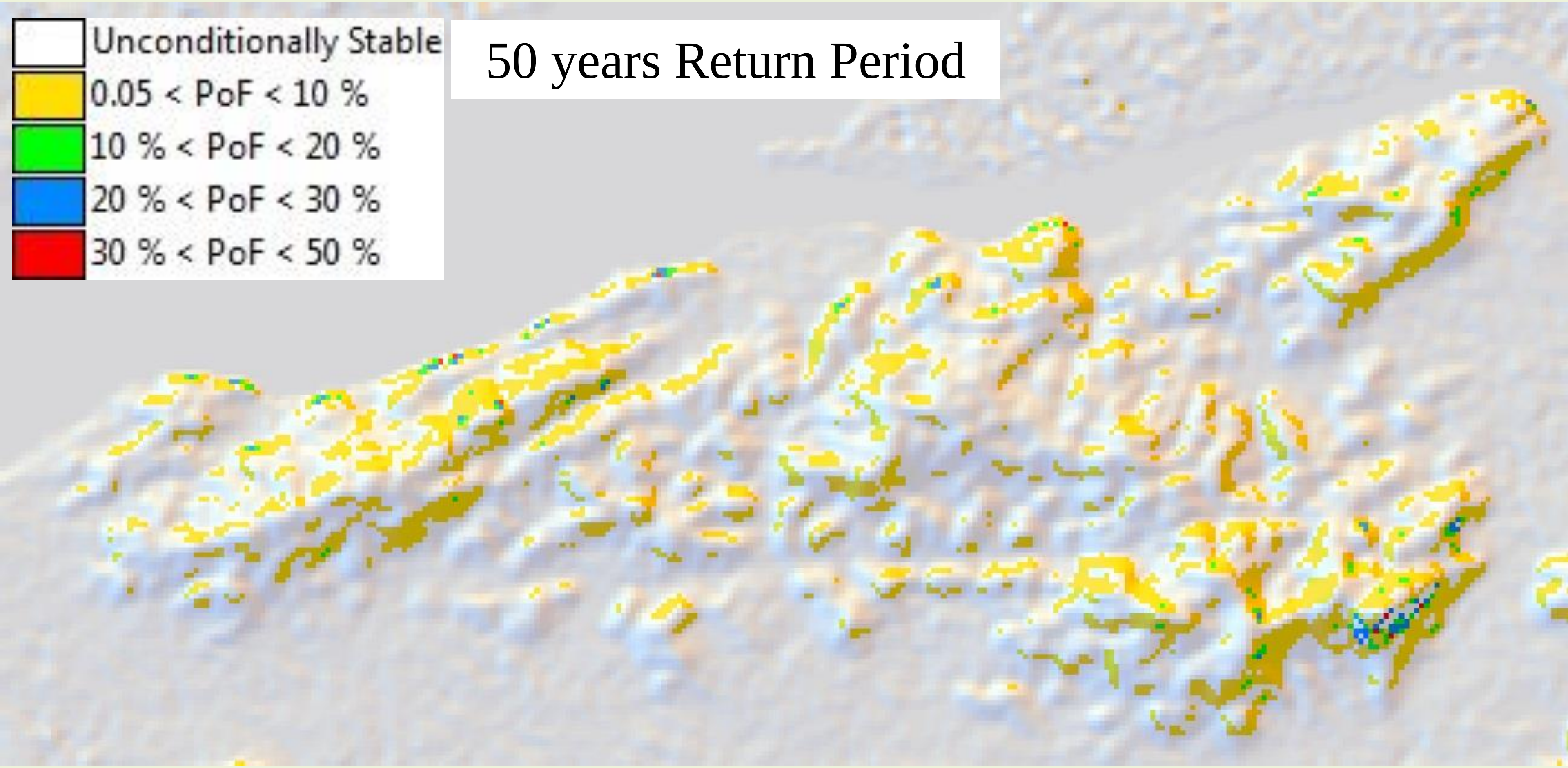
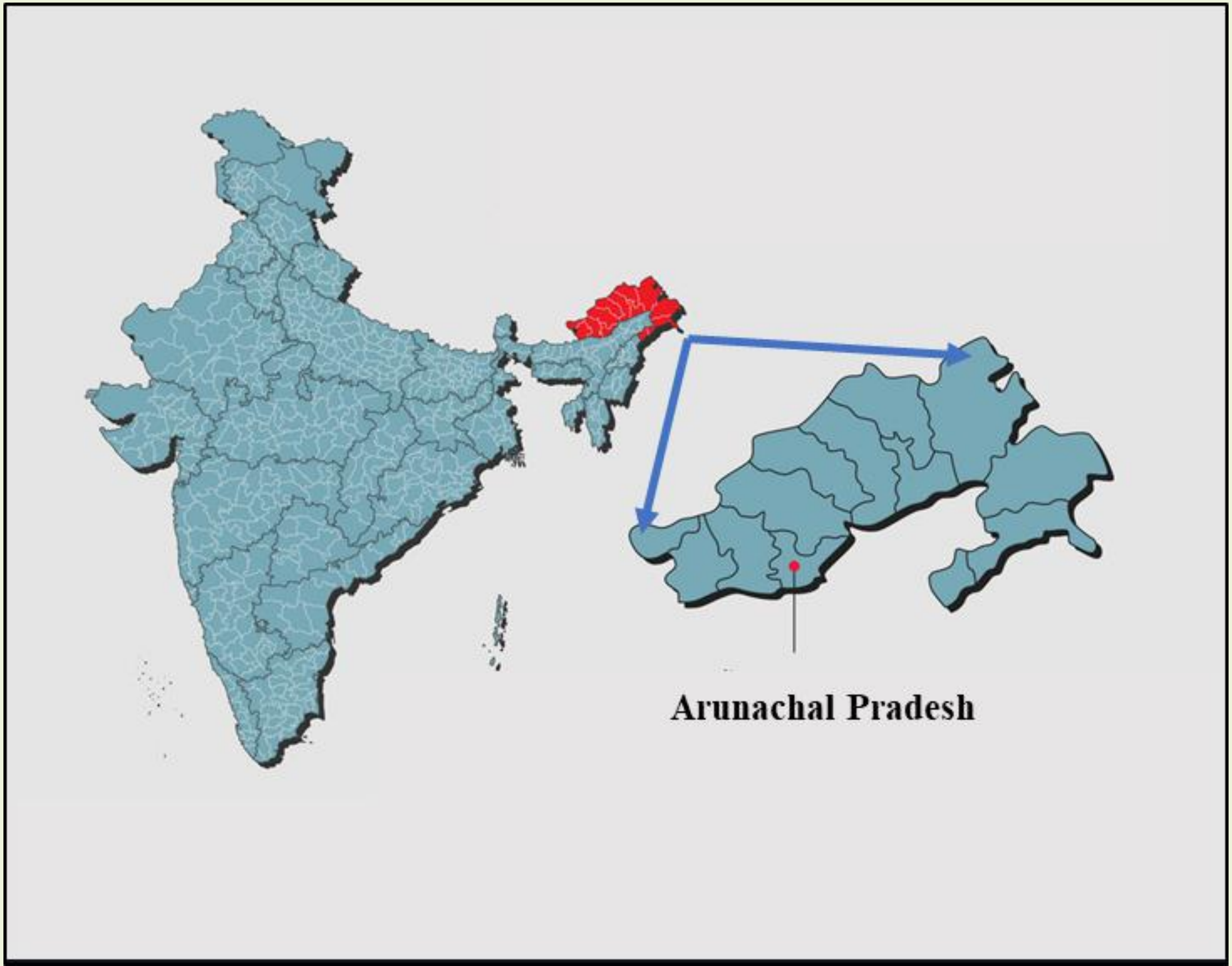


Rainfall Induced Landslide Susceptibility Map of Arunachal Pradesh

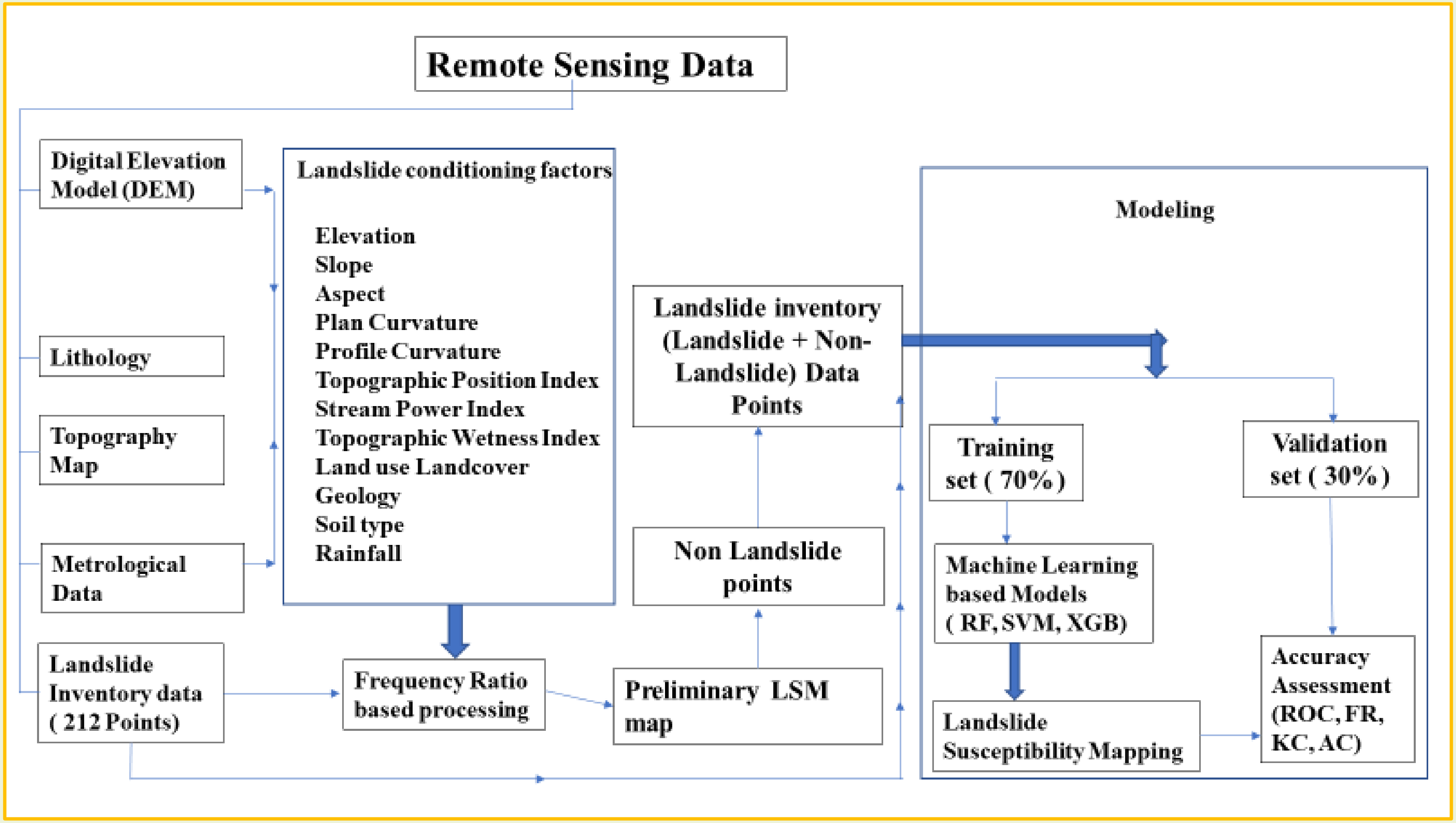
- Study area: Arunachal Pradesh
  - ❖ Northeastern state of India, located in the foothills of the eastern Himalayas with an area of 83,743 sq. km.
  - ❖ Elevation ranges from mountains that are 7,000 meters above the (M.S.L.) to the towns in the plains with an elevation of fewer than 100 meters.
  - ❖ The slope gradient ranges from 0° in flat areas to 84.5° in nearly vertical cliffs, indicating a wide variability across different regions of the state.
  - ❖ The average rainfall received by the state is about 3000 mm with some areas up to 4000 mm.
  - ❖ The region is susceptible to landslides due to its topographic and extreme climate conditions.
  - ❖ July month experiences maximum rainfall, while December being the month of least rainfall
  - ❖ Five tributaries of the River, Brahmaputra that flows through the region named Siang, Subansiri, Lohit, Kameng and Tirap.

Rainfall Induced Landslide Susceptibility Map of Arunachal Pradesh



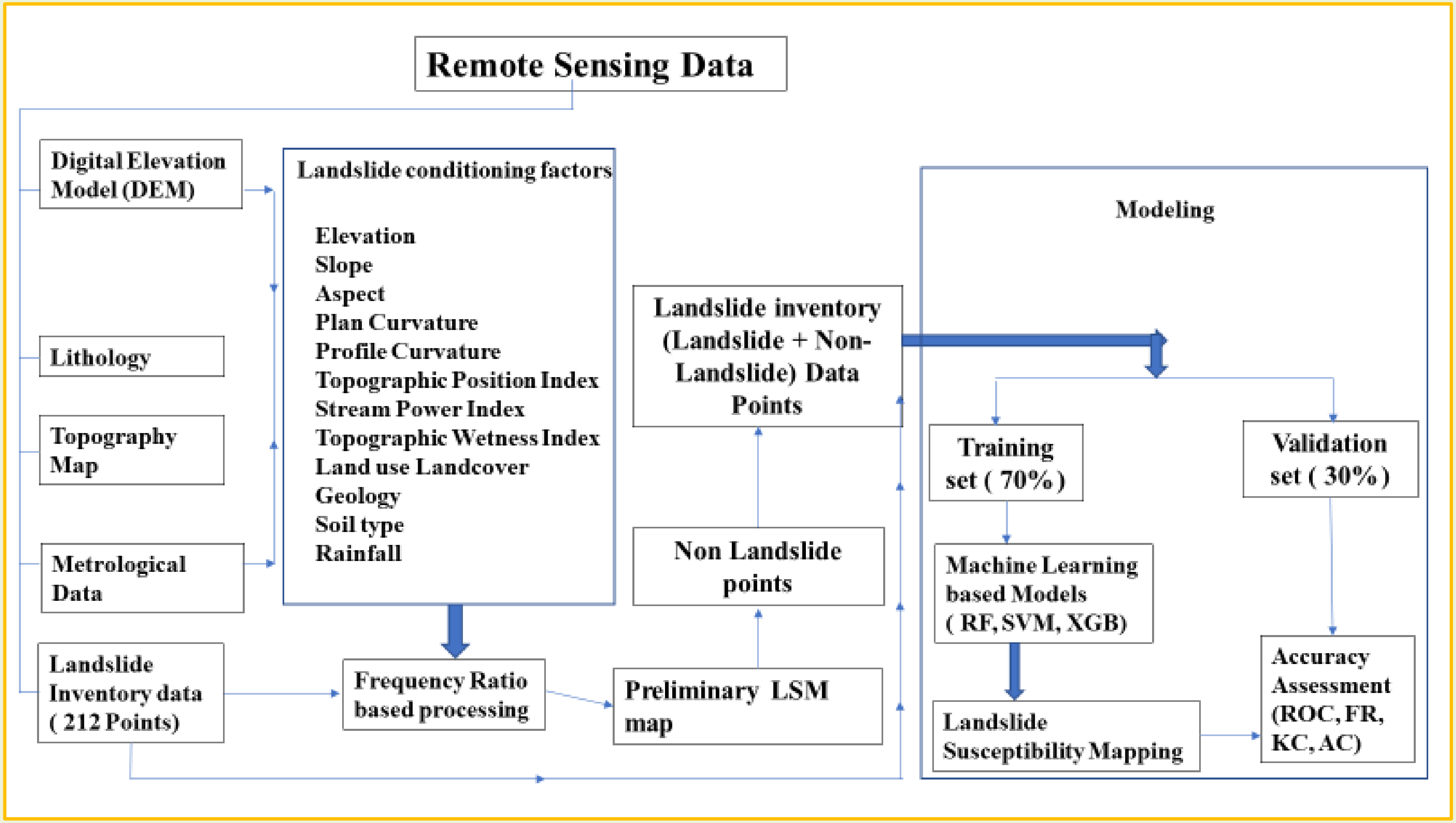
Rainfall Induced Landslide Susceptibility Map of Arunachal Pradesh

- Methodology and work flow



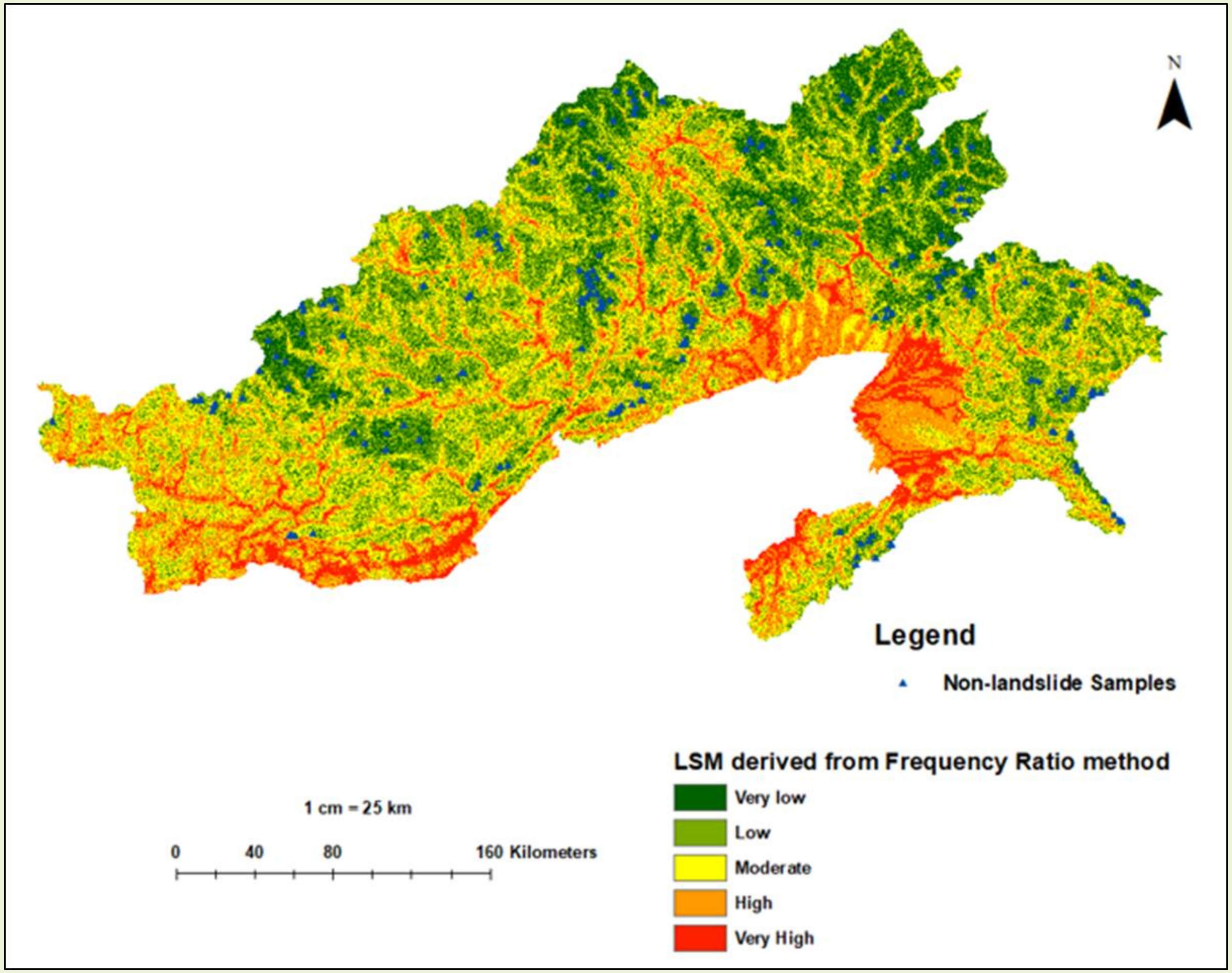
Rainfall Induced Landslide Susceptibility Map of Arunachal Pradesh

- Methodology and work flow



Rainfall Induced Landslide Susceptibility Map of Arunachal Pradesh

- Methodology and work flow

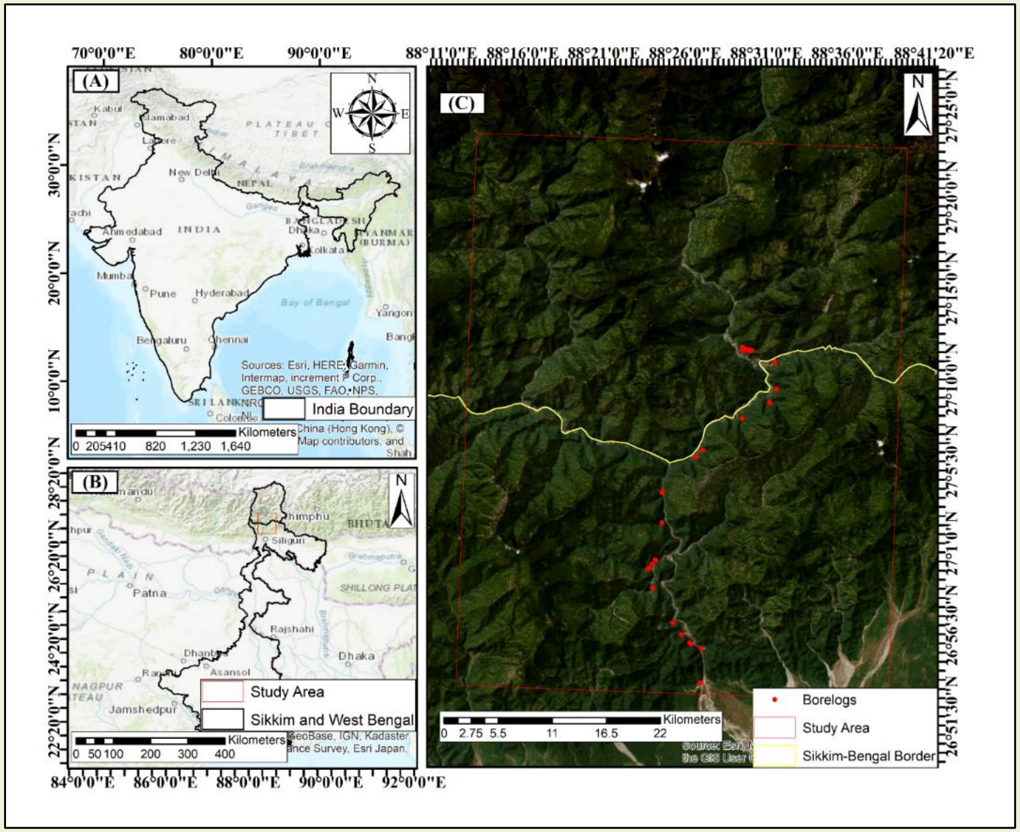


Rainfall Induced Landslide Susceptibility Map of Arunachal Pradesh

- Way forward
  - Consideration of collated multi-hazard scenarios to develop a comprehensive hazard zonation maps of the areas
    - Flood
    - Rainfall
    - Seismicity
    - Rockfall and Debris flows
    - Anthropogenic activities
    - Glaciatic effects and snow avalanches in the northern parts

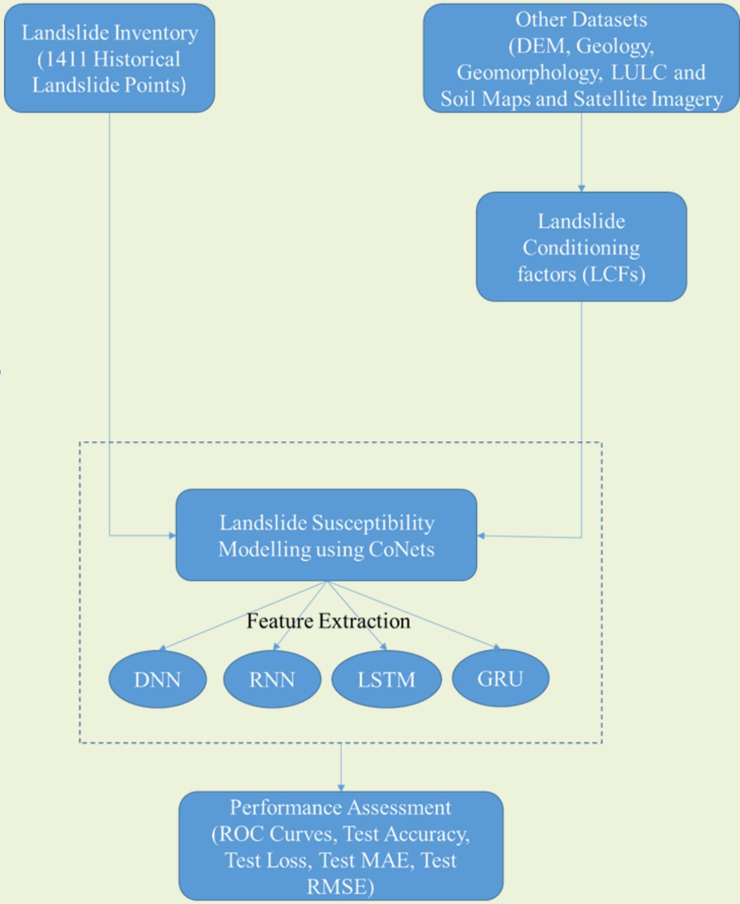
Landslide Susceptibility Mapping (LSM) Using Deep Learning (DL) Techniques

- Study area
  - ❖ Darjeeling – Gangtok
  - ❖ Elevation
    - Min – 82 m above MSL
    - Max – 3206 m above MSL
  - ❖ Slope
    - Min – 0°
    - Max – 81°
  - ❖ Rainfall - > 3000 mm/year

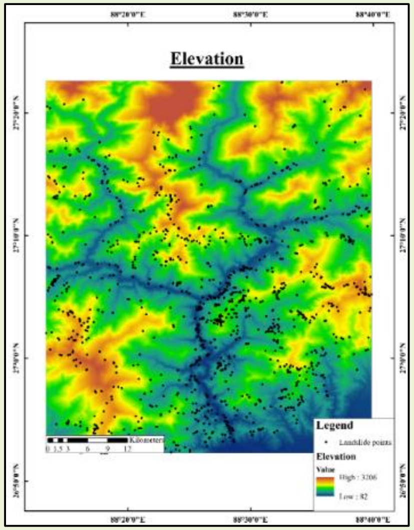


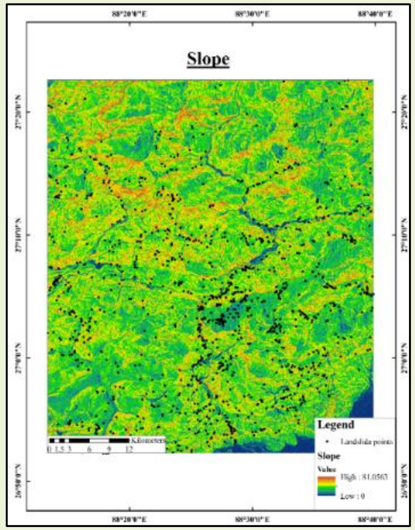
Landslide Susceptibility Mapping (LSM) Using Deep Learning (DL) Techniques

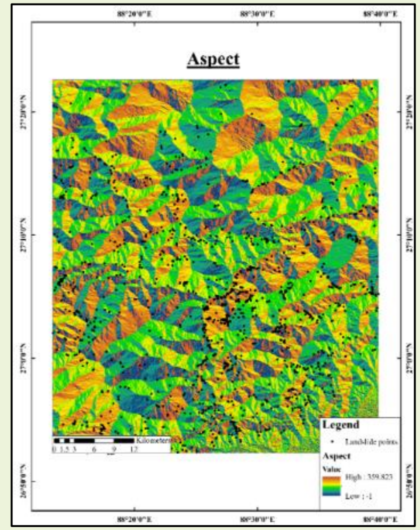
- Methodology
  - ❖ Dense Neural Networks (DNN)
    - Fully connected layers where each neuron is connected to every neuron in the next layer.
  - ❖ Recurrent Neural Networks (RNN)
    - Specialized neural networks for processing sequential data, where the output from previous time steps is fed back into the network, allowing it to learn dependencies over time.
  - ❖ Long Short-Term Memory Networks (LSTM)
    - RNNs with gates to manage long-term dependencies and prevent vanishing gradients.
  - ❖ Gated Recurrent Units (GRU)
    - Simplified LSTMs with fewer parameters, using gates to control information flow.

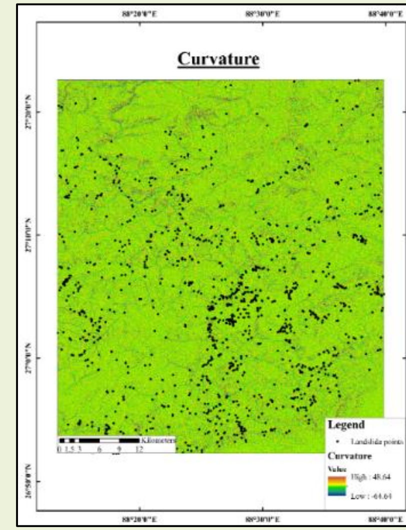


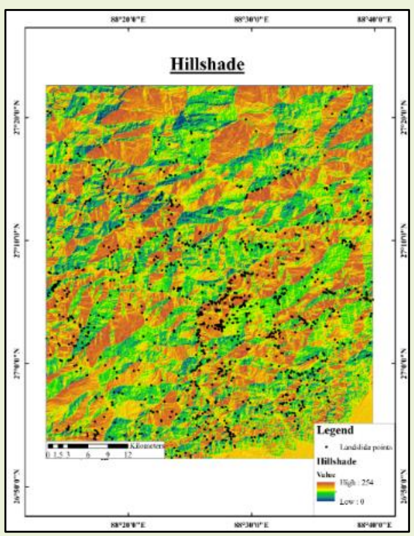
Morphological Features

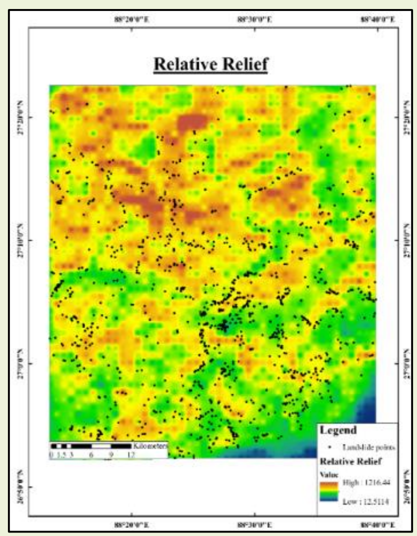


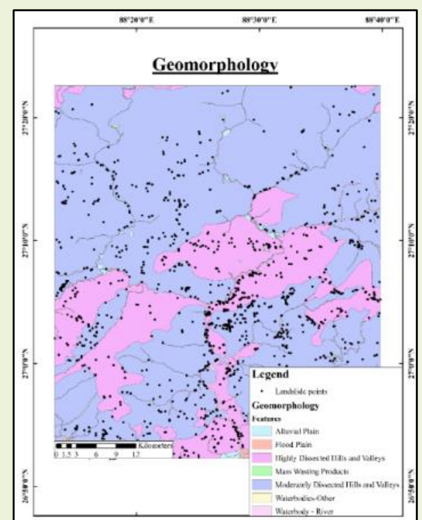




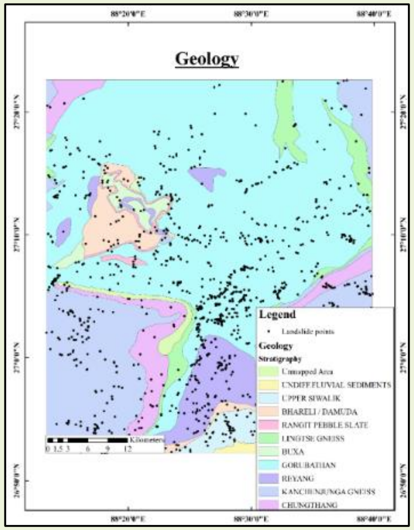


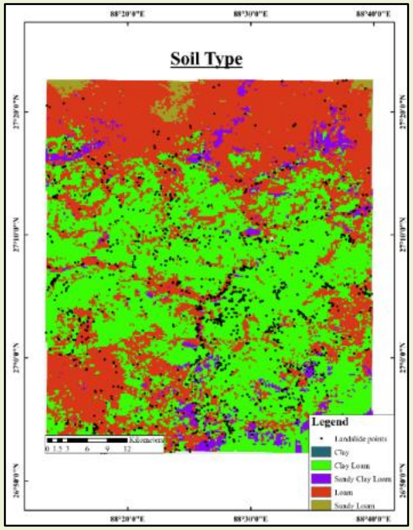


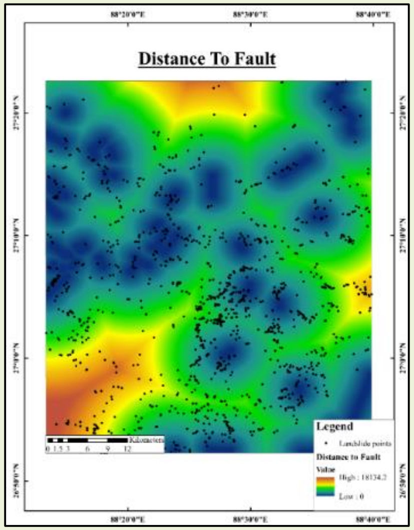


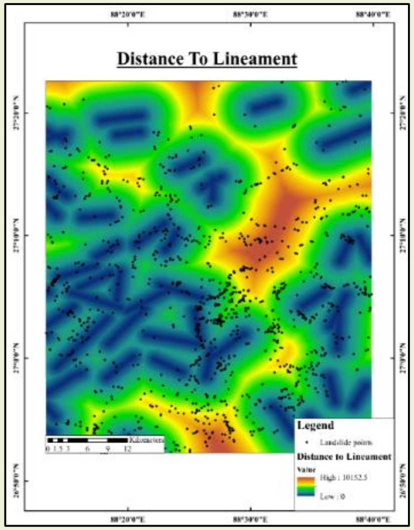


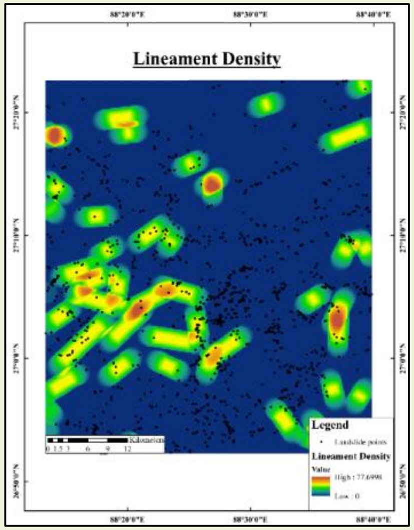
Geological Features



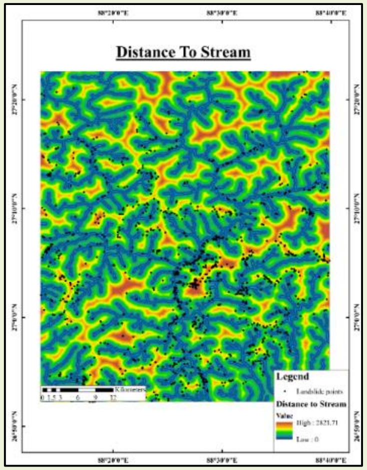


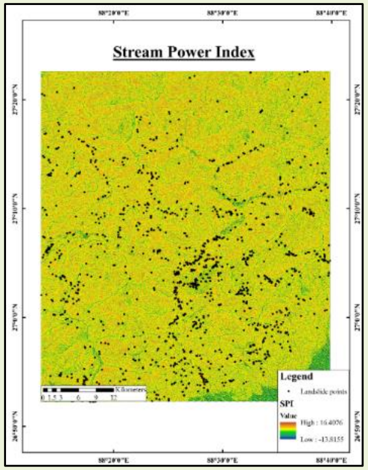


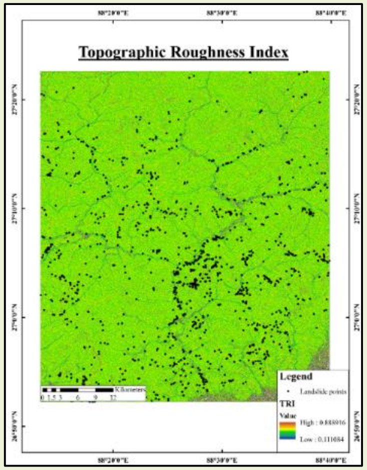


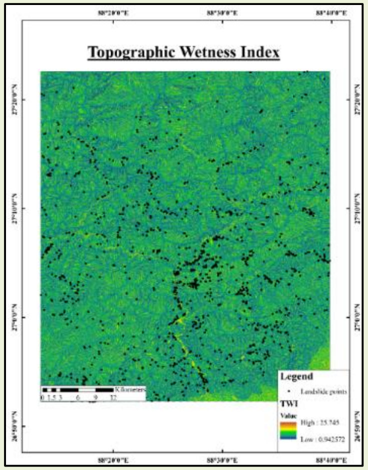


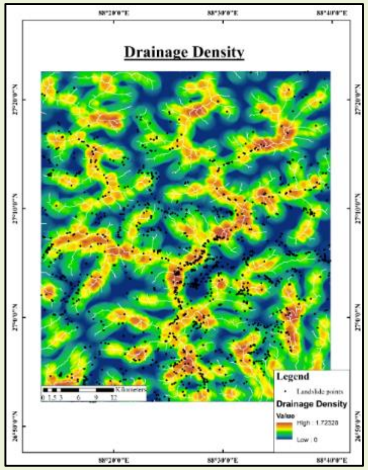
Hydrological Features

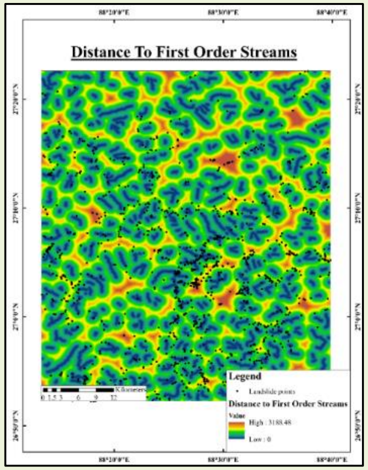


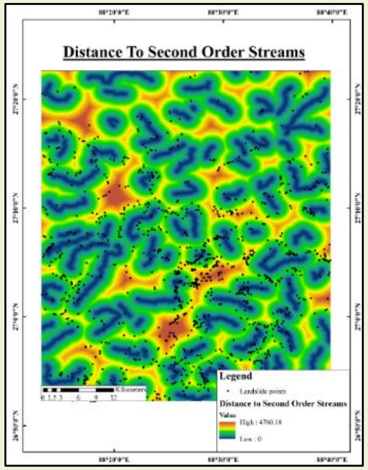


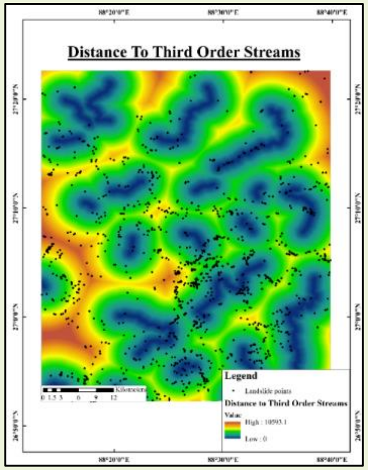


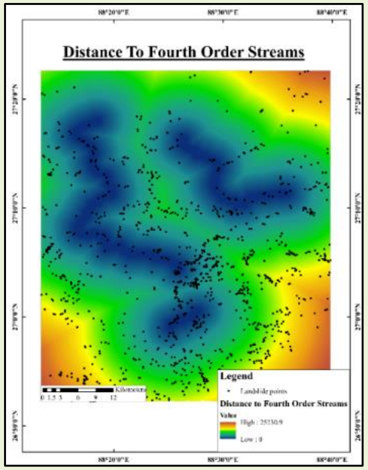


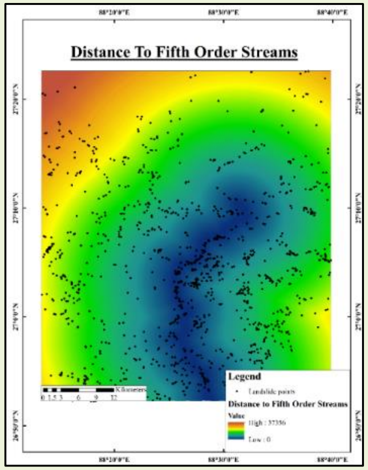




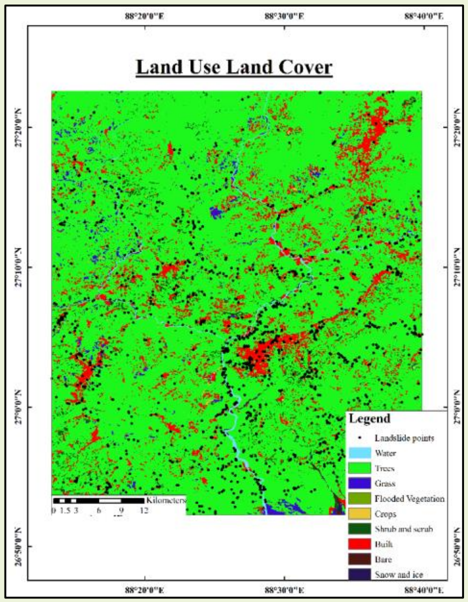


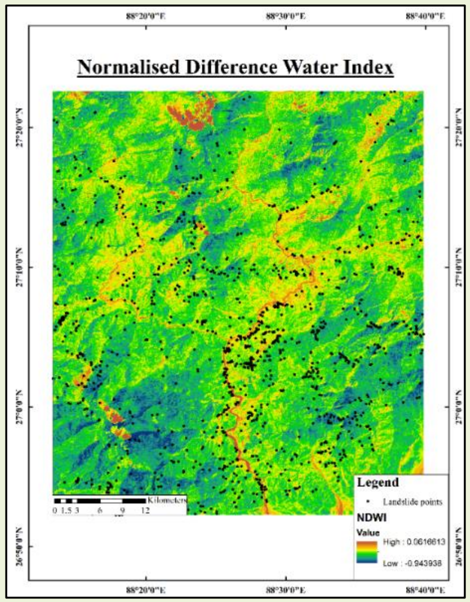


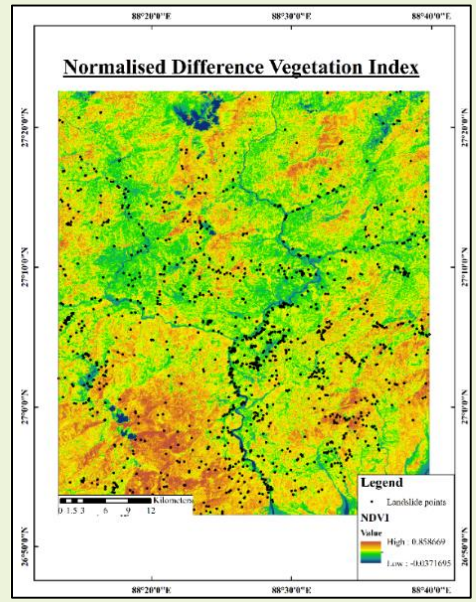


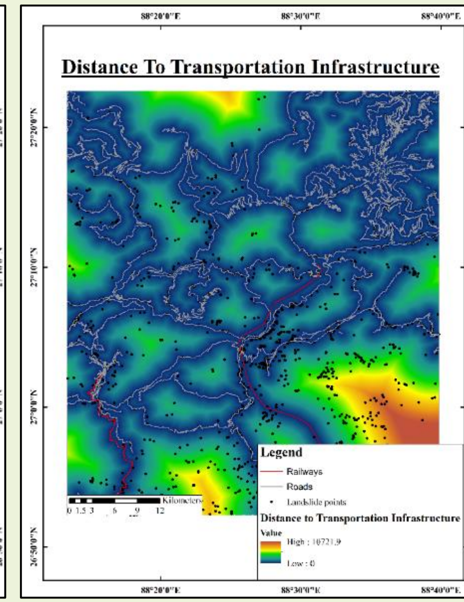


Land Cover Features

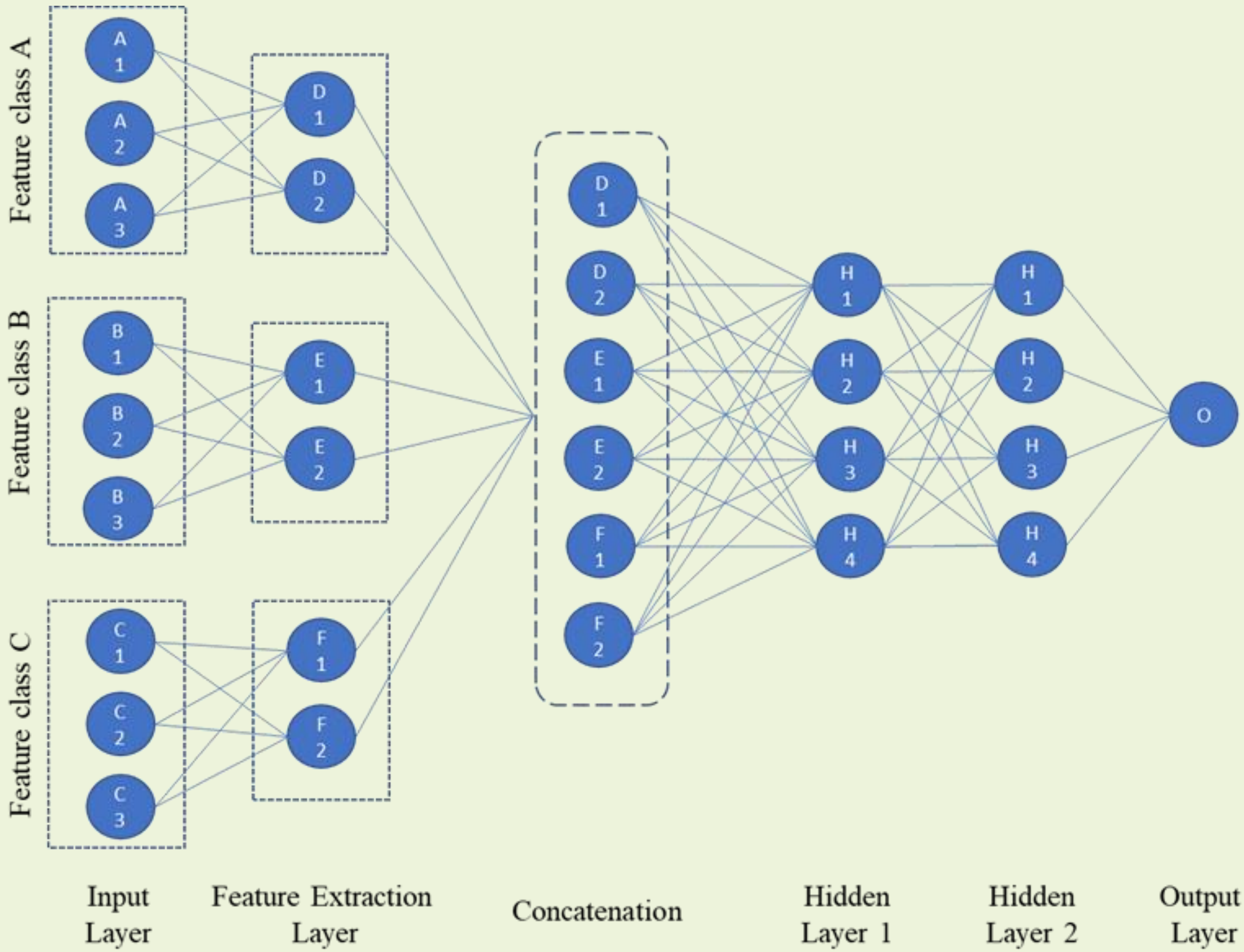






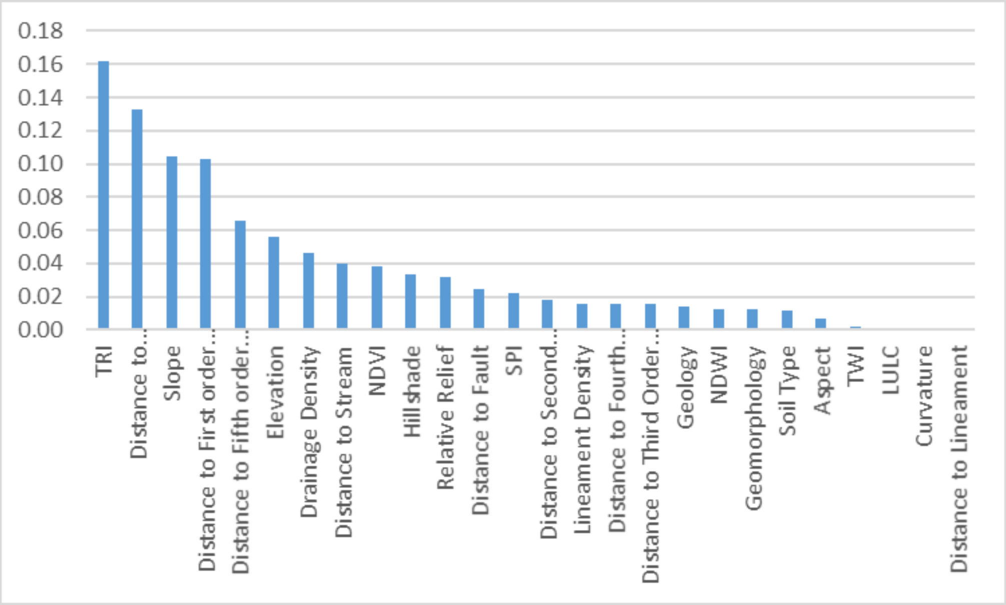


Structure of Co-NET



Feature Importance

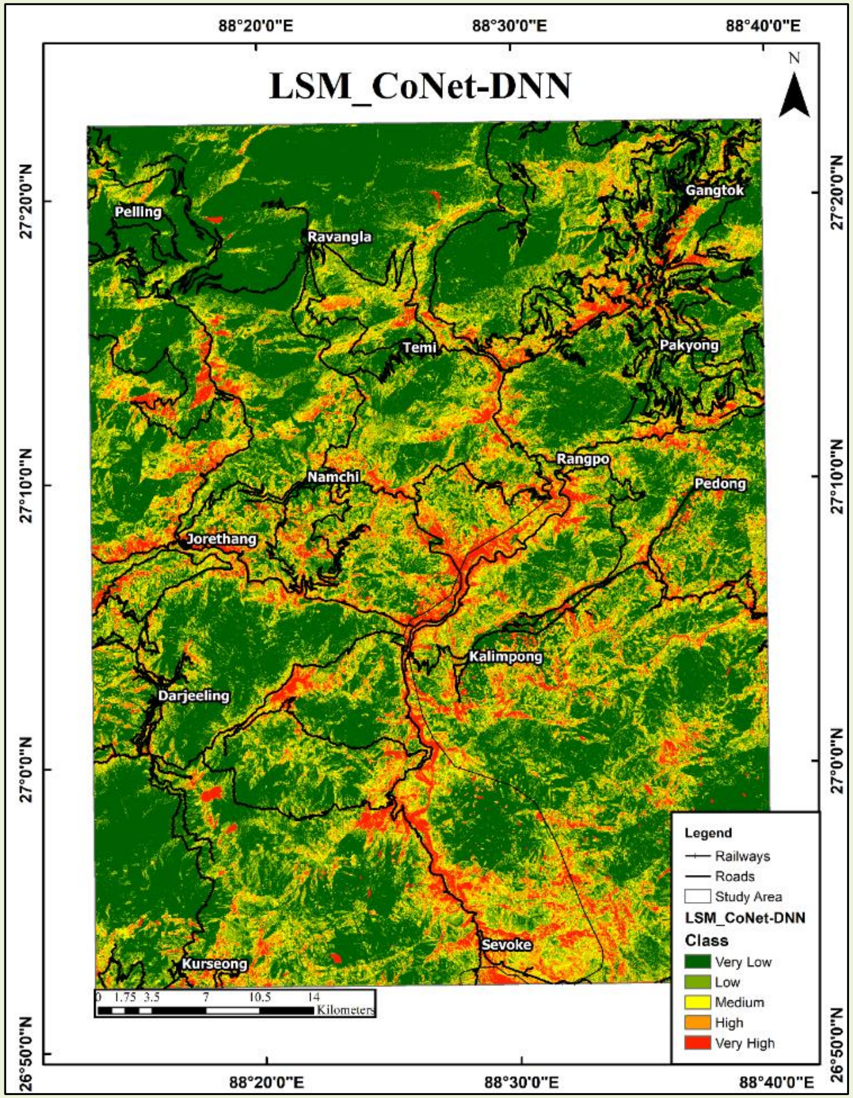
- Method - Mutual Importance
  - ❖ Data Dependent
  - ❖ Model Independent

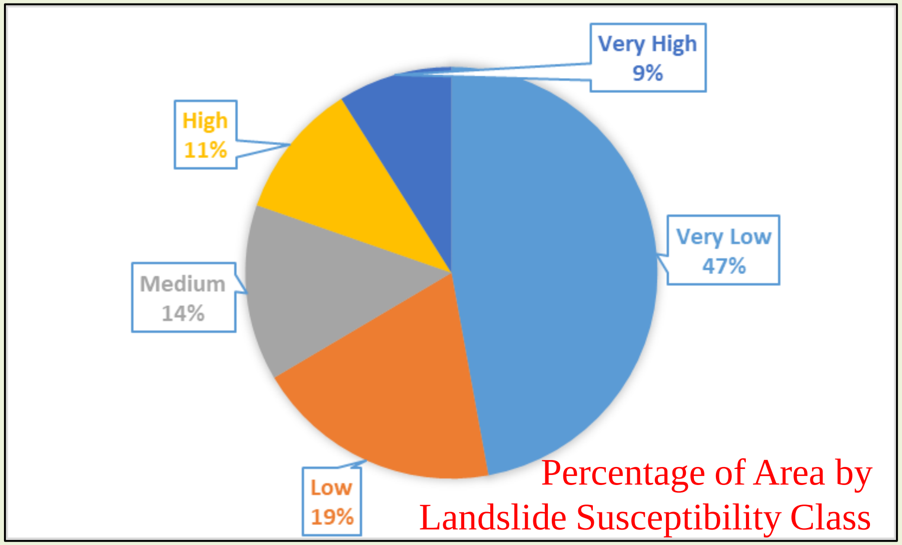


LCFs and their corresponding Importance Indices

Features	Importance Index
TRI	0.162
Distance to Transportation infrastructure	0.133
Slope	0.104
Distance to First order streams	0.103
Distance to Fifth order streams	0.065
Elevation	0.056
Drainage Density	0.046
Distance to Stream	0.040
NDVI	0.038
Hillshade	0.033
Relative Relief	0.032
Distance to Fault	0.025
SPI	0.022
Distance to Second Order Streams	0.018
Lineament Density	0.016
Distance to Fourth Order Streams	0.015
Distance to Third Order Streams	0.015
Geology	0.014
NDWI	0.013
Geomorphology	0.012
Soil Type	0.012
Aspect	0.007
TWI	0.002
LULC	0.000
Curvature	0.000
Distance to Lineament	0.000

Landslide Susceptibility Maps

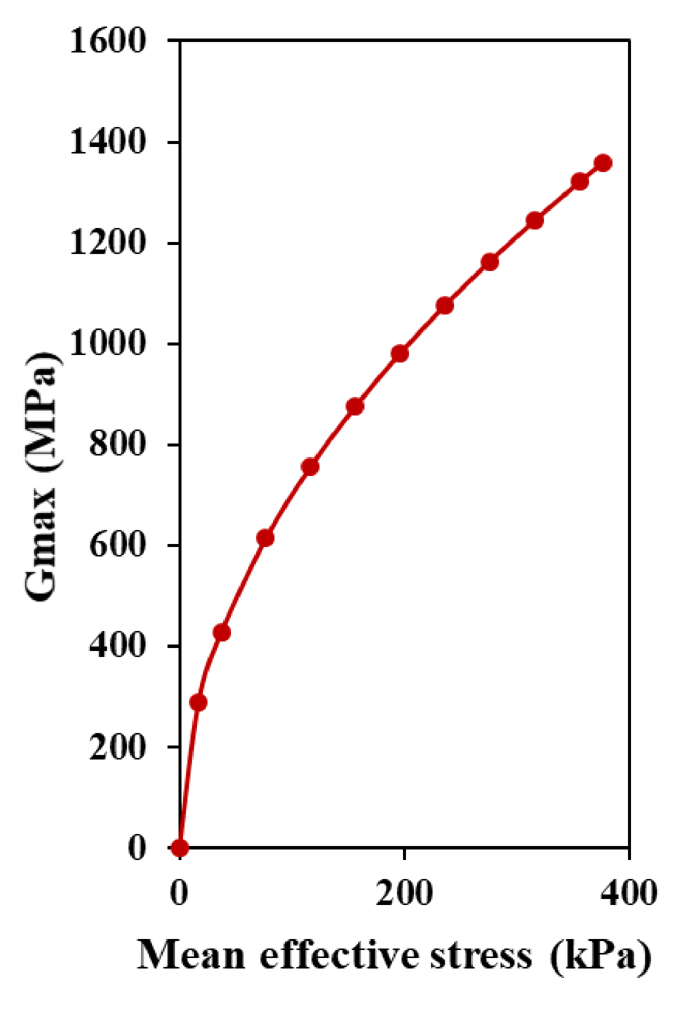




Percentage of Area by Landslide Susceptibility Class

Class-wise Variance of Susceptibility Prediction

Food for Thought: Stress-Dependent Shear Stiffness

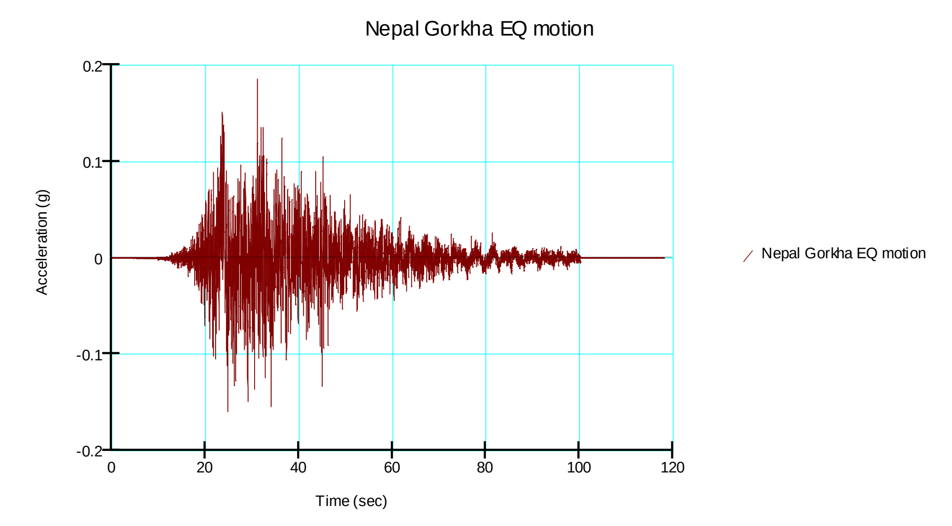


K_{max} = 70 (for 90% RD)

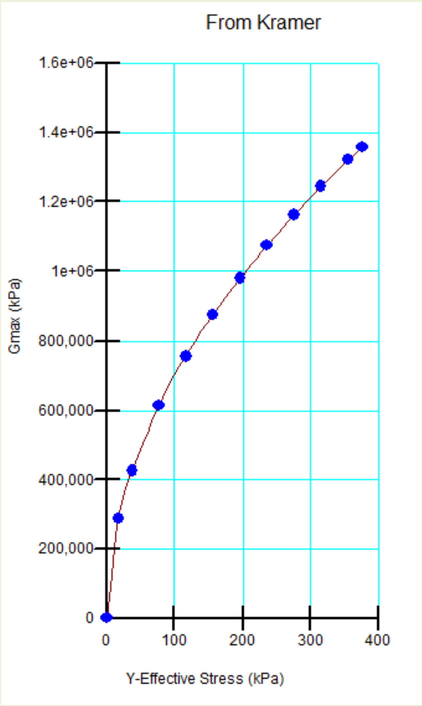
D_r (%)	K_{max}
30	34
40	40
45	43
60	52
75	59
90	70

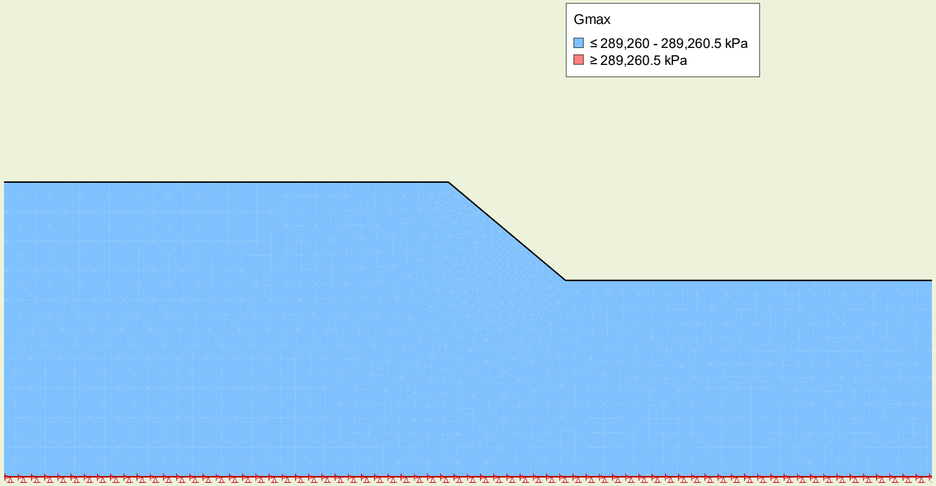
$G_{max} = 1000\ K_{max}\ (\sigma_m')^{0.5}$

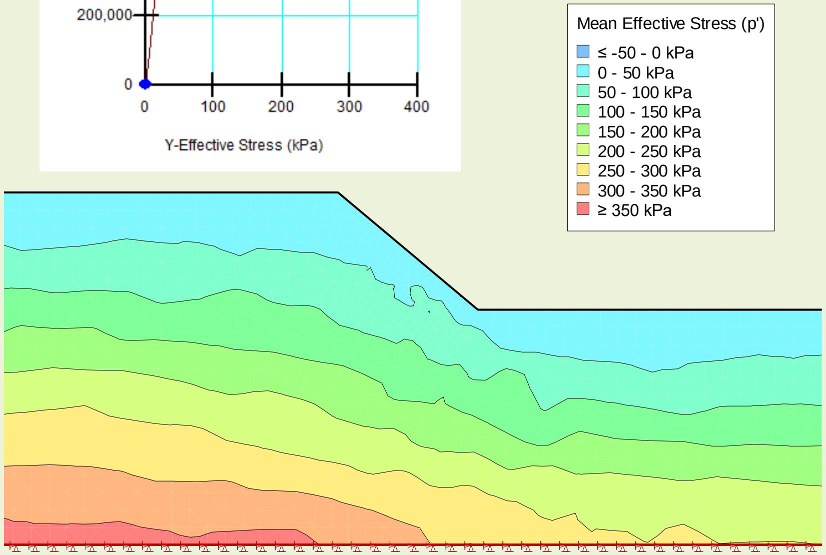
Y (m)	Mean Effective Stress (p') (kPa)	Gmax (kPa)
0	377.07278	1359285
2.994	356.15244	1321040
5.988599	316.13035	1244604
8.983797	276.18214	1163311
11.97959	236.2711	1075978
14.99368	196.25286	980631.9
18.0036	156.32157	875200.4
21.0024	116.58449	755820.1
24.0006	76.869038	613724.9
27	37.125764	426516.4
30	17.075766	289259.8
	0	0

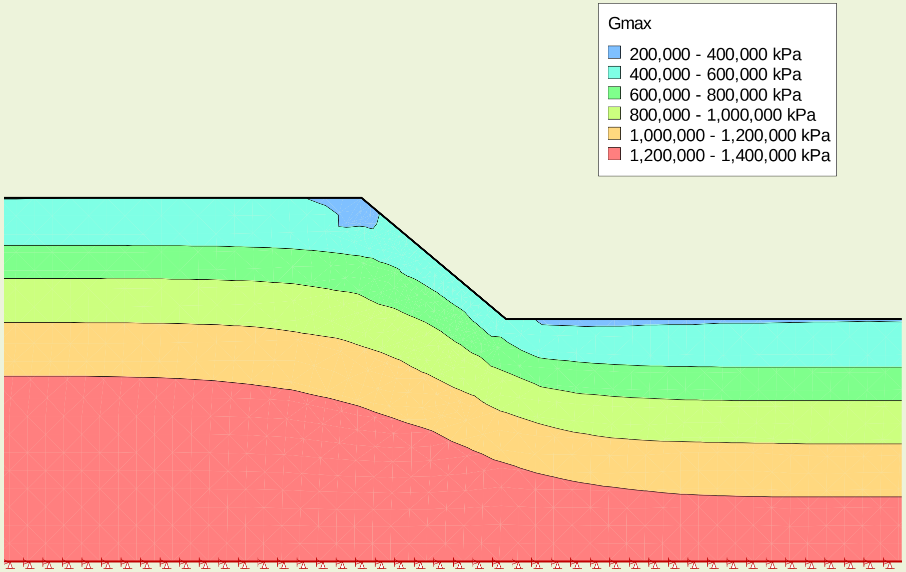


Food for Thought: Stress-Dependent Shear Stiffness

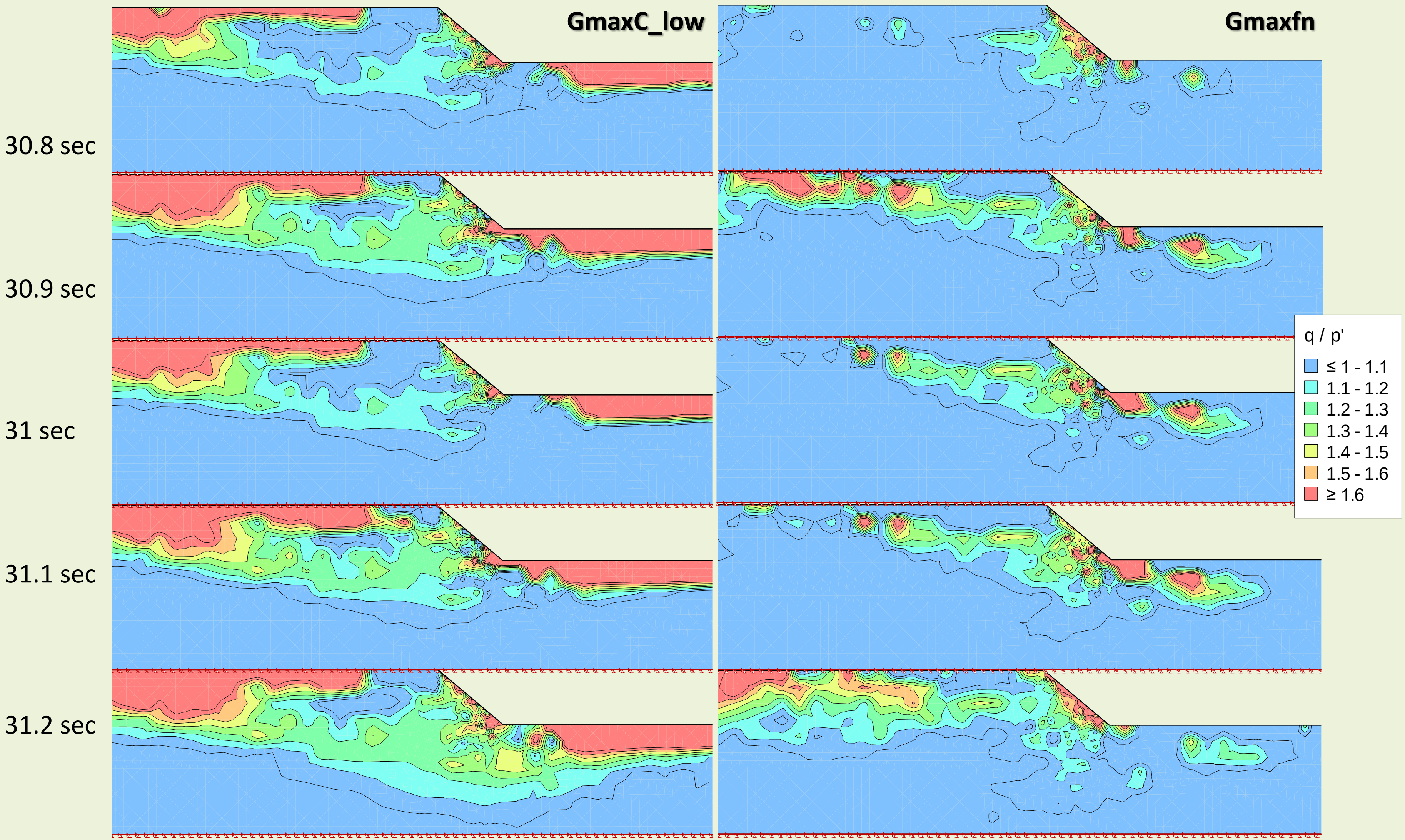




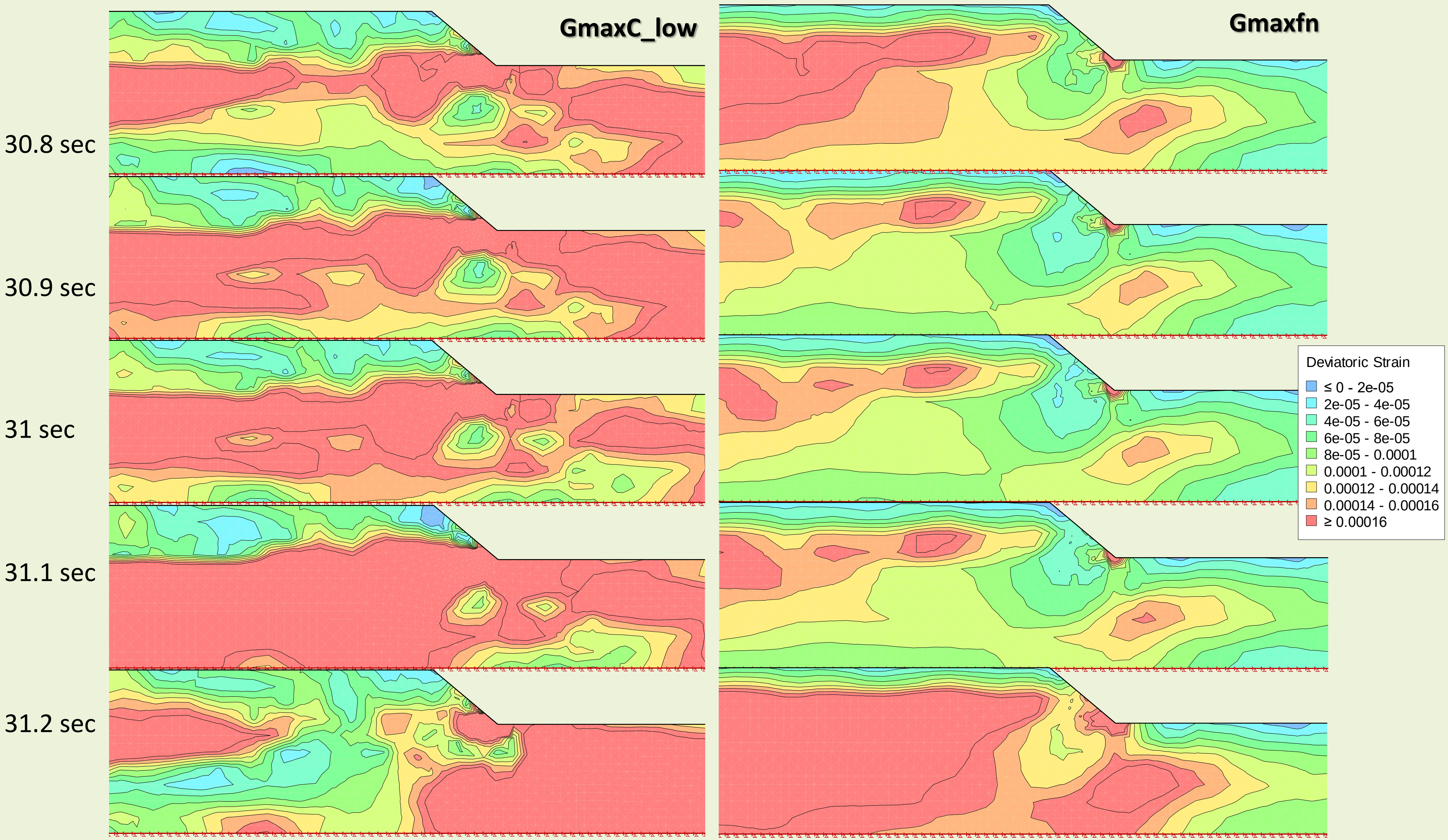




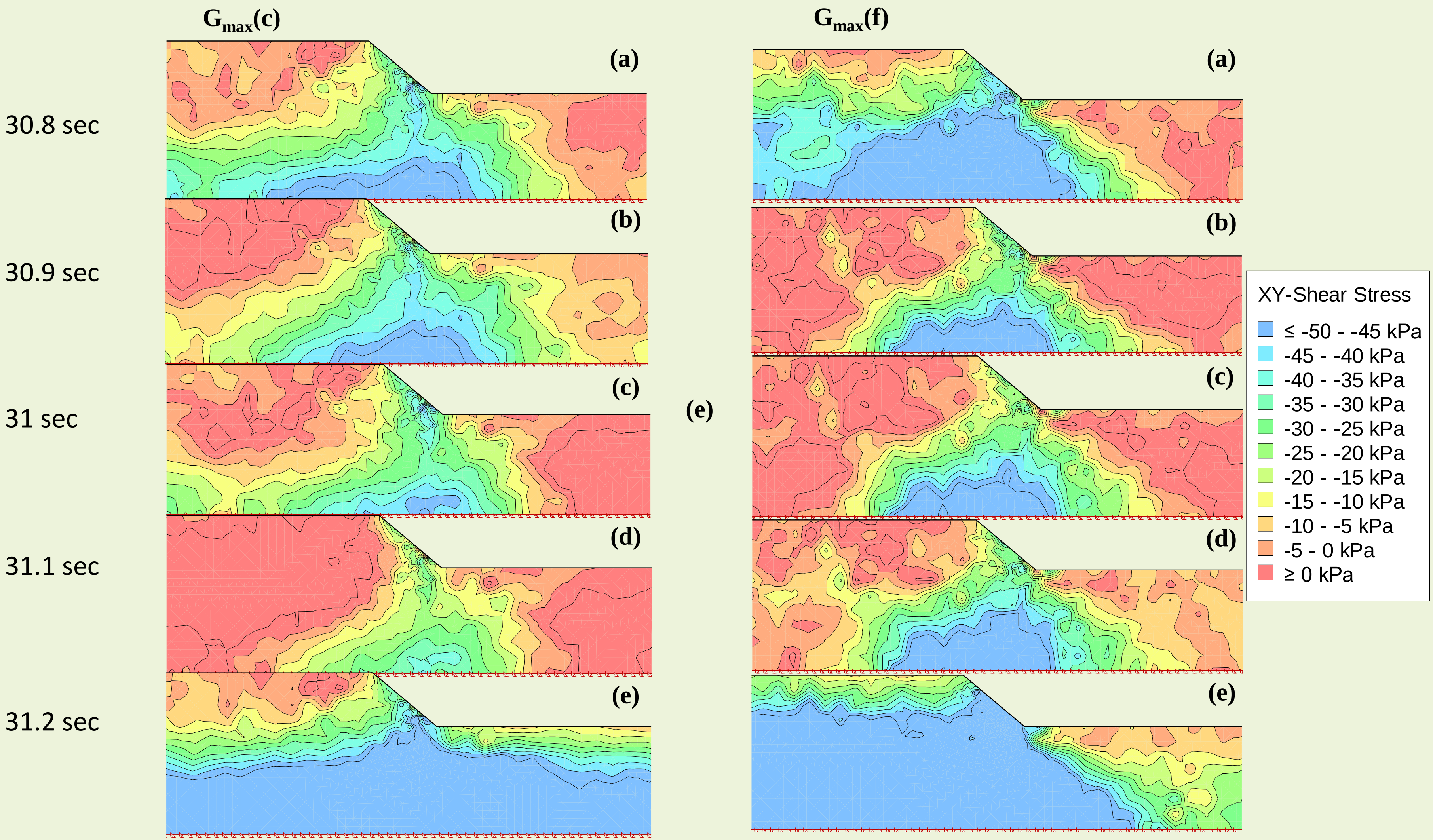
Influence of Stress-Dependent Shear Stiffness



Influence of Stress-Dependent Shear Stiffness

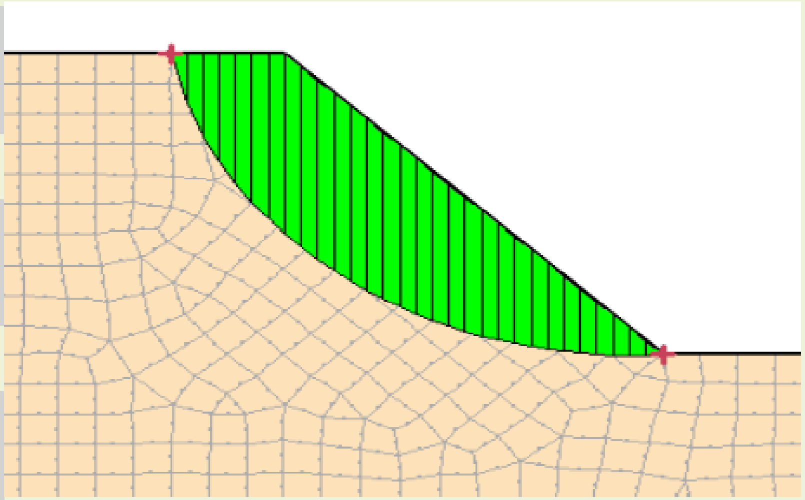


Influence of Stress-Dependent Shear Stiffness

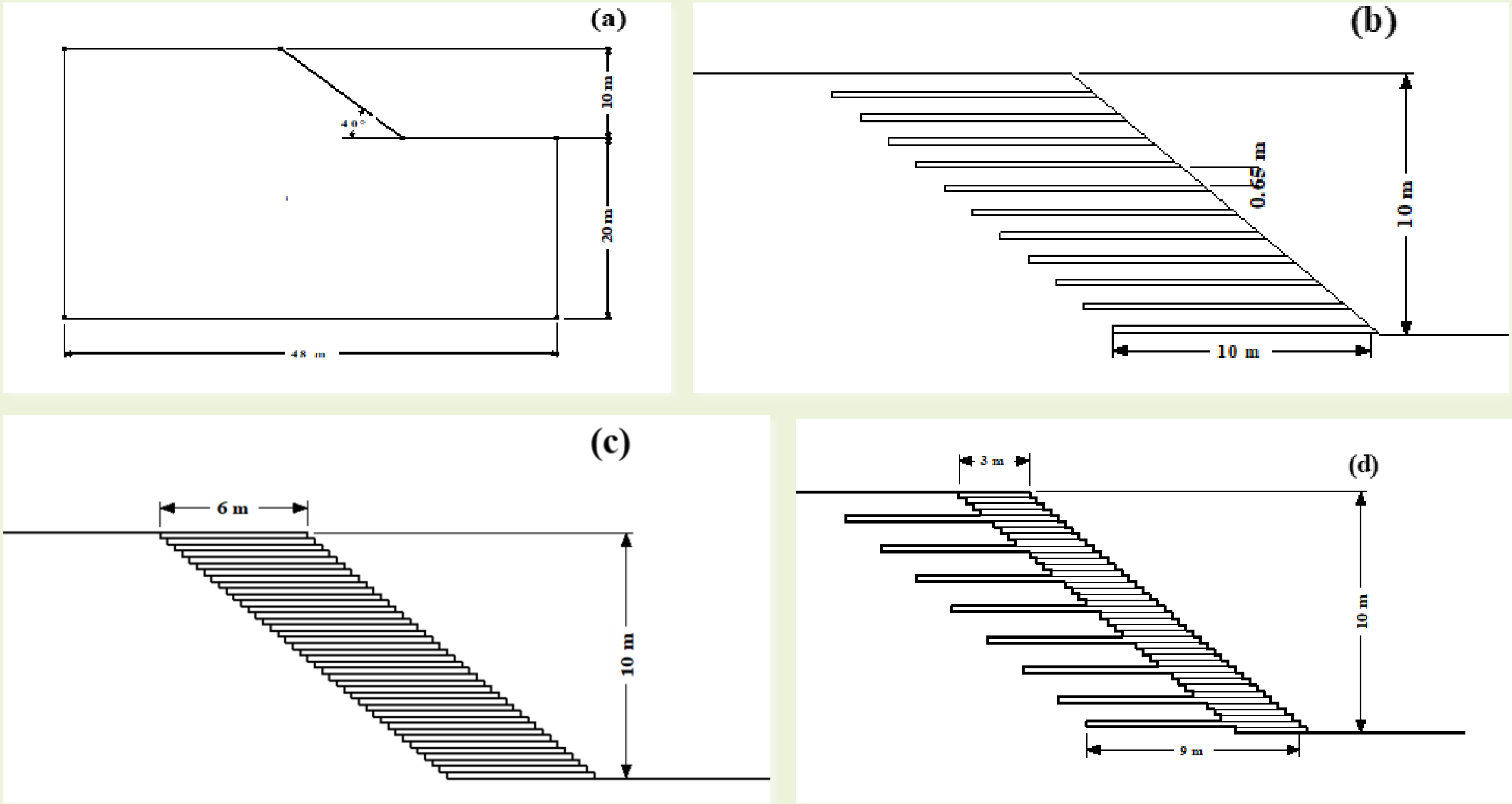


Stress-Based FOS

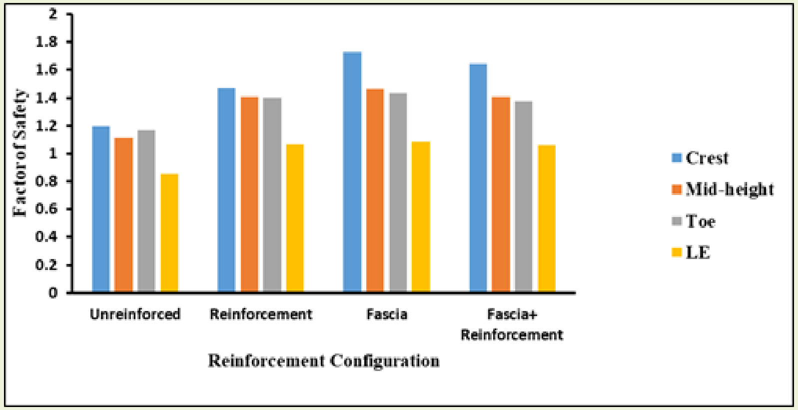
Determine Average Stresses	Calculate the average stresses at nodes.
Superimpose Slip Surface	Overlay the slip surface on the results and divide the enclosed soil mass into slices
Calculate stresses	Use the Mohr circle method to calculate shear and normal stresses at each slice base.
Find Local Safety Factor	Divide shear resistance by mobilized shear for each slice.
Obtain Global Safety Factor	Integrate shear stresses and resistances across all slices.

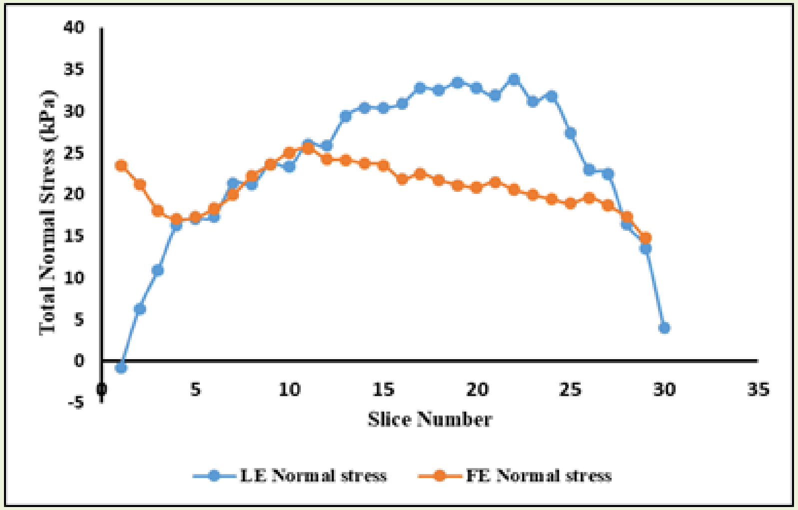


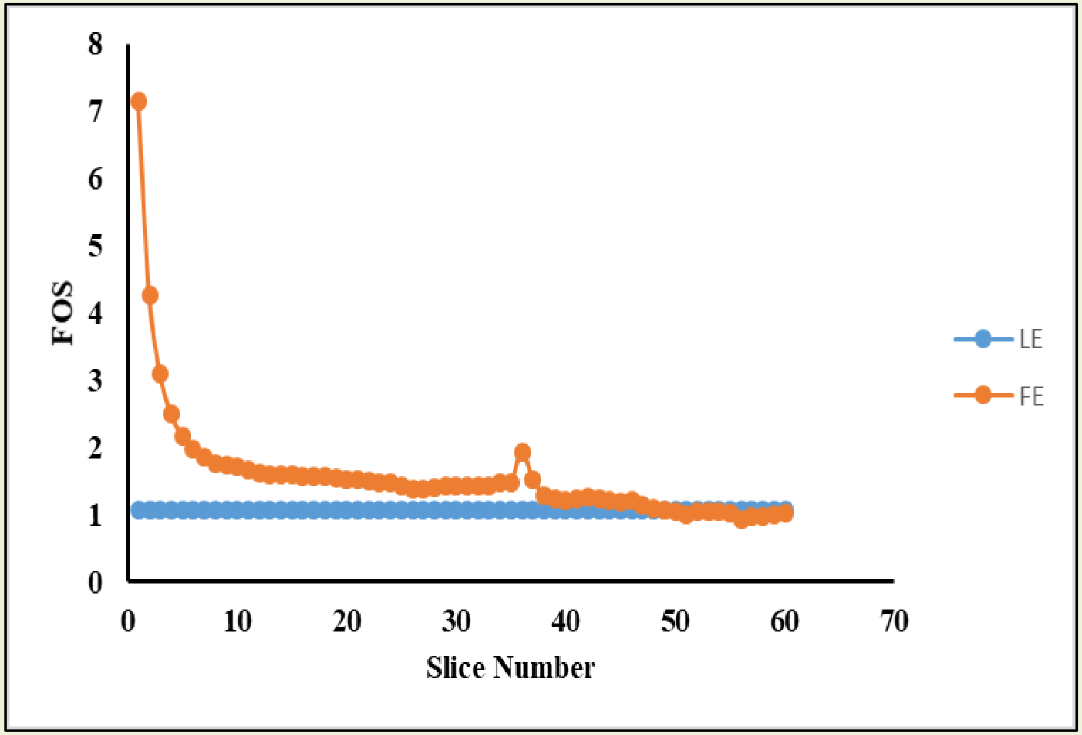
Geocell-Reinforced Slope



Stress-Based FOS







Acknowledgments

- **Students**

- **Collaborators**

- **Dr. Chiranjib, Dr. Arup and full team for this FDP Program**

Thank You for Patient Hearing