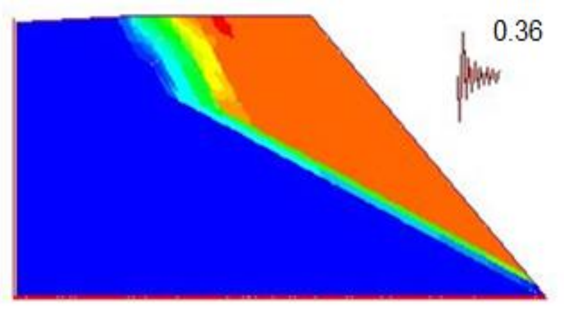
Faculty Development Program

Geotechnical Engineering for Sustainable and Resilient Infrastructure: Foundations for a Greener Future

CV Raman Global University, Odisha

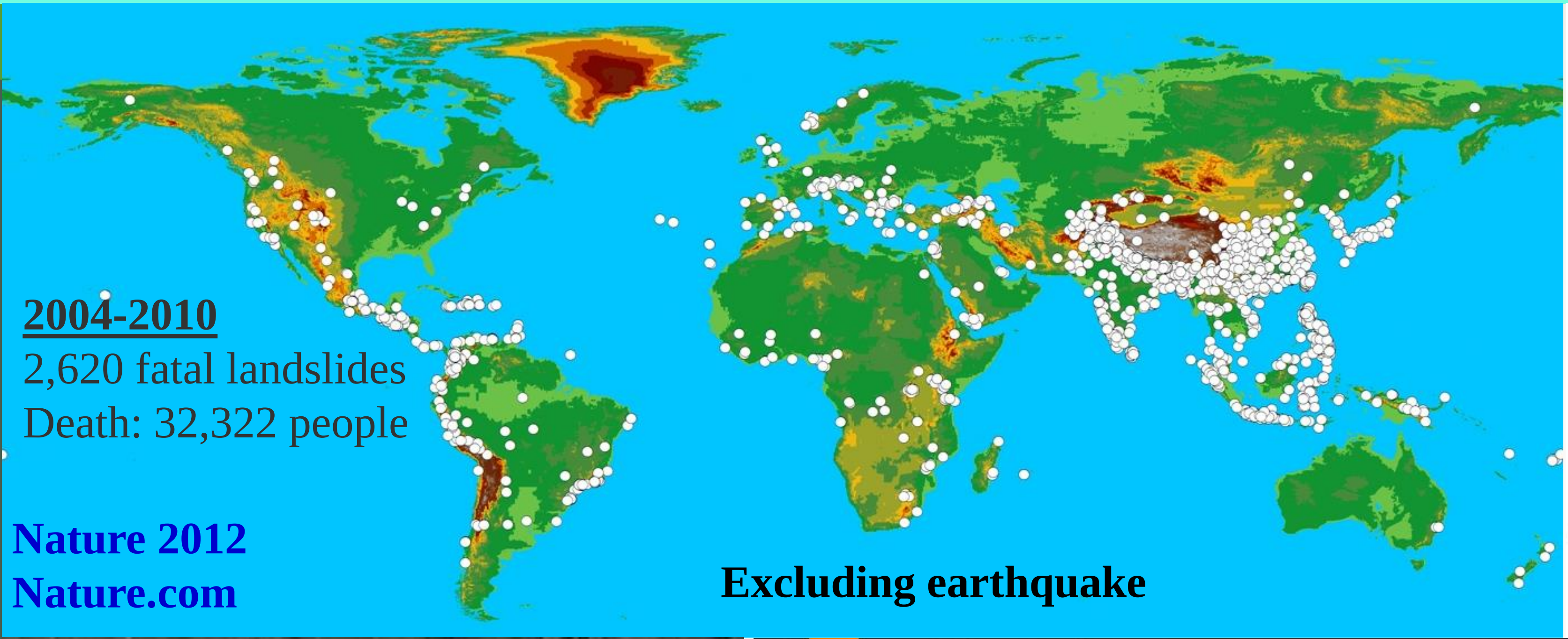


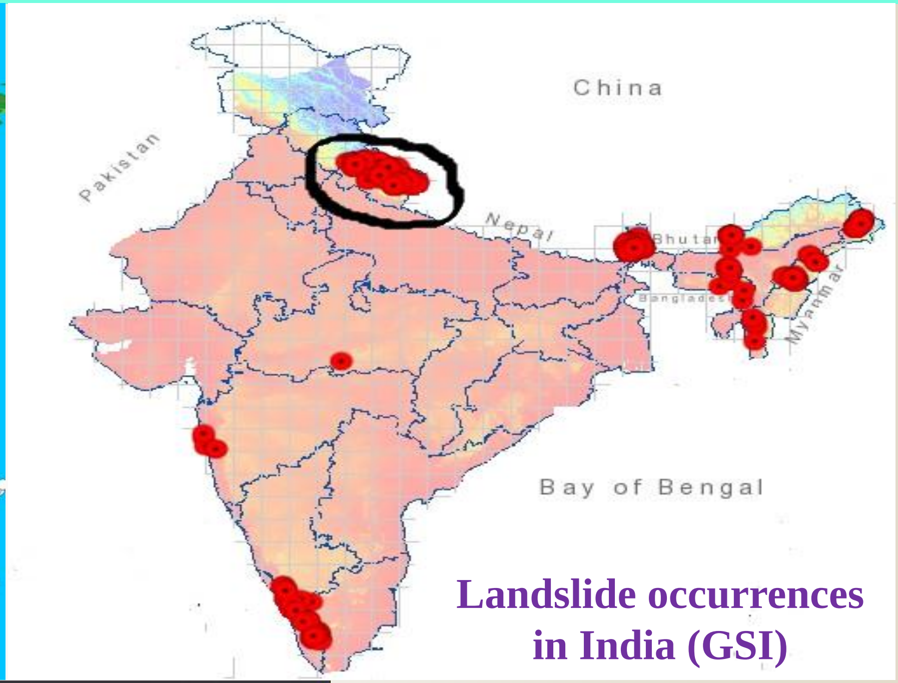
Rock Mechanics and Rock Slope Stability

Stability Analysis of Jointed Rock Slope

Dr. Arindam Dey
Associate Professor
Geotechnical Engineering Division
Department of Civil Engineering
Center for Disaster Management and Research (CDMR)
IIT Guwahati

Landslide: A Serious Natural Calamity

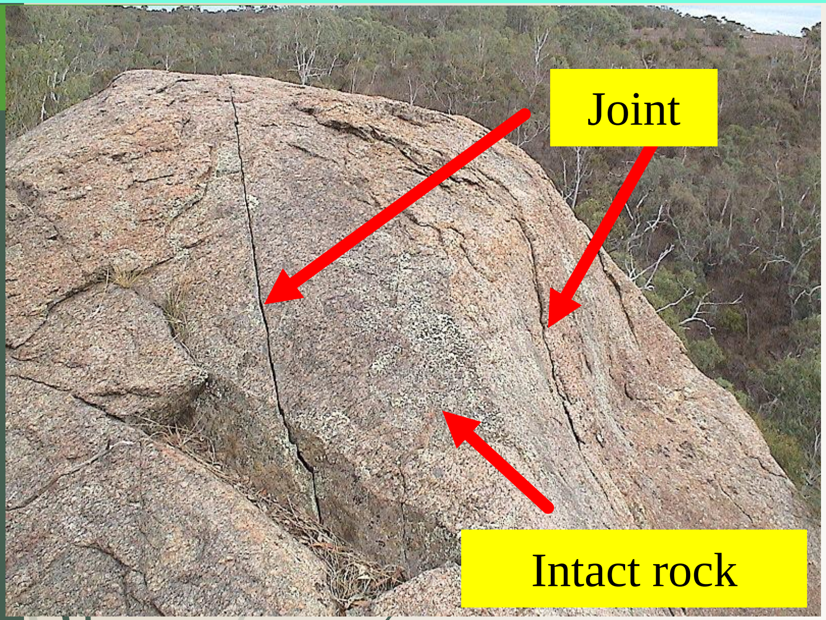


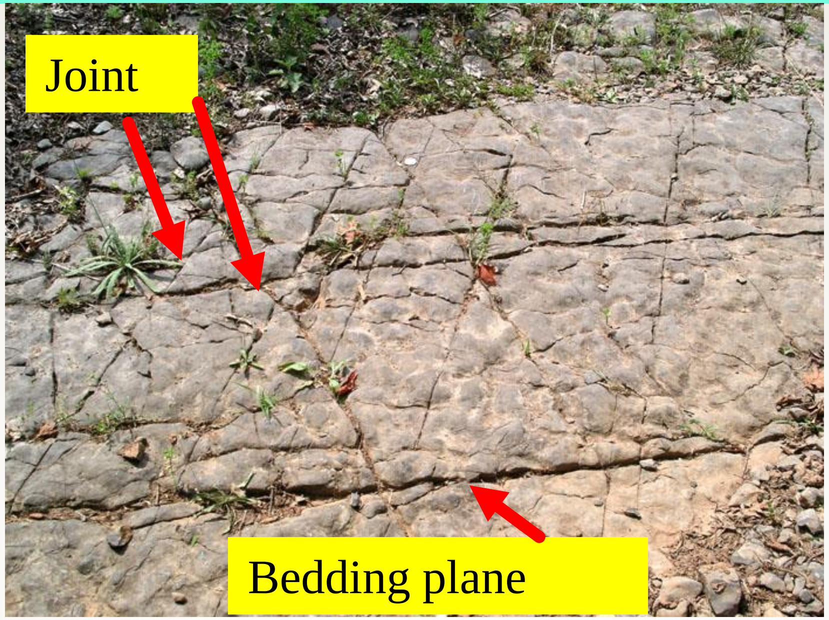


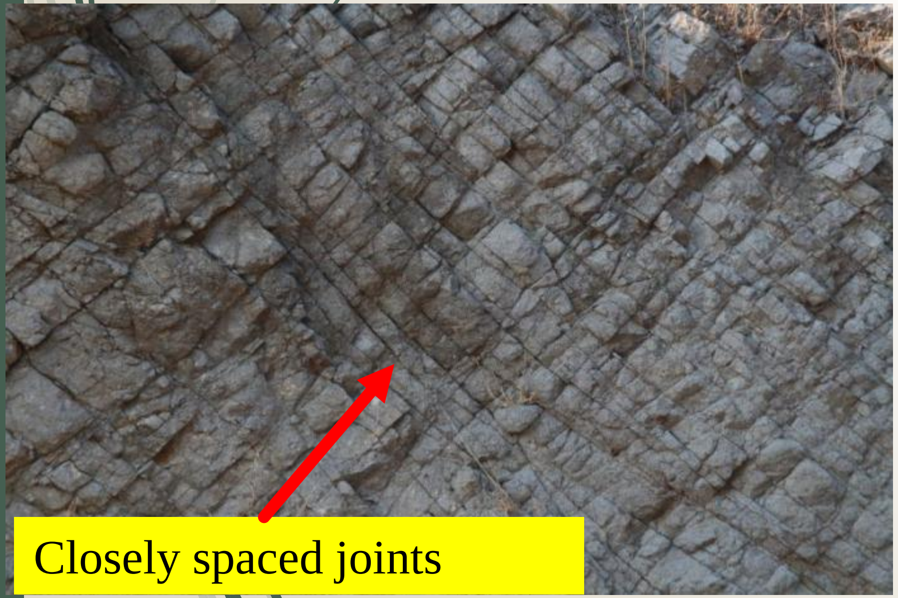
By News Nation Bureau |
Updated On : May 19, 2017
15,000 people stranded

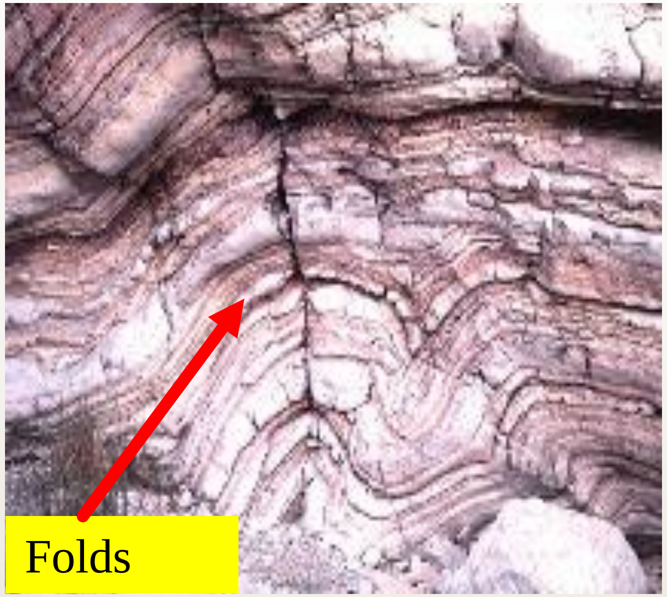
Increase in population
Development in deforested areas
Increase in trend of fatalities

Discontinuity in Rock: Complex Structure

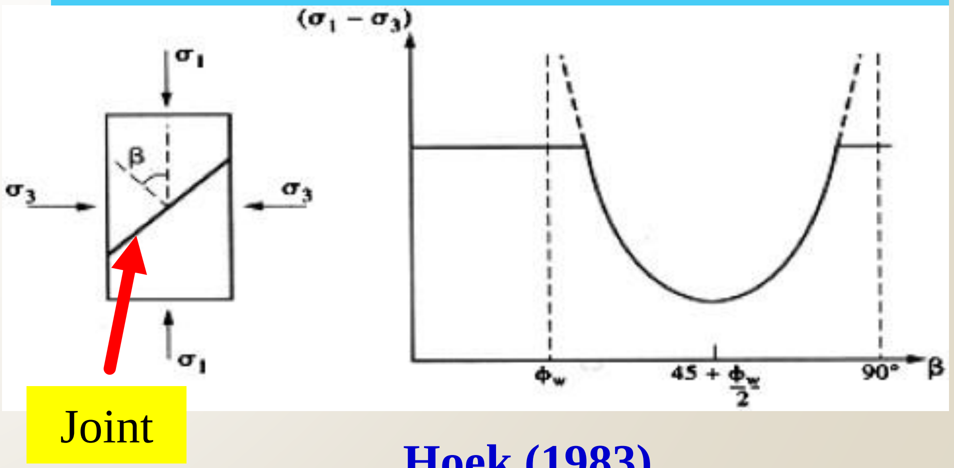






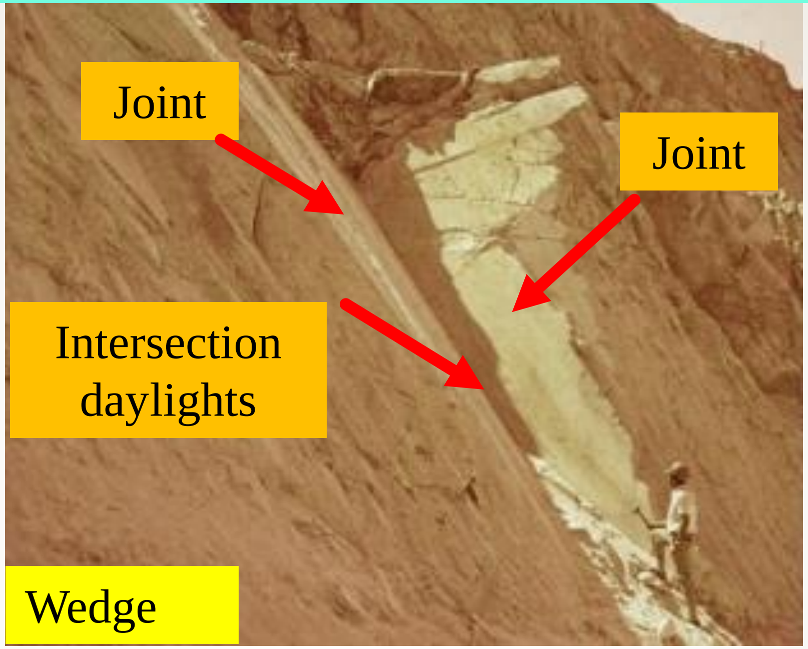


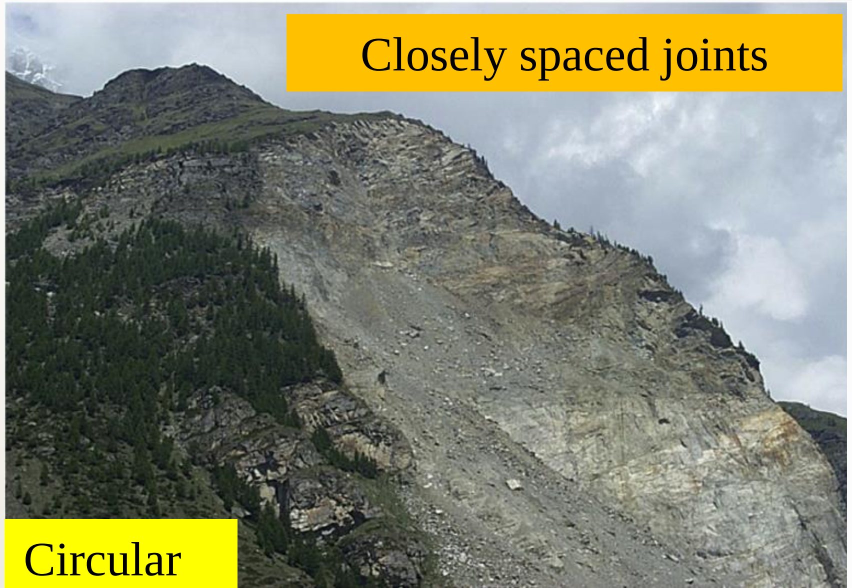
Anisotropic response of joint

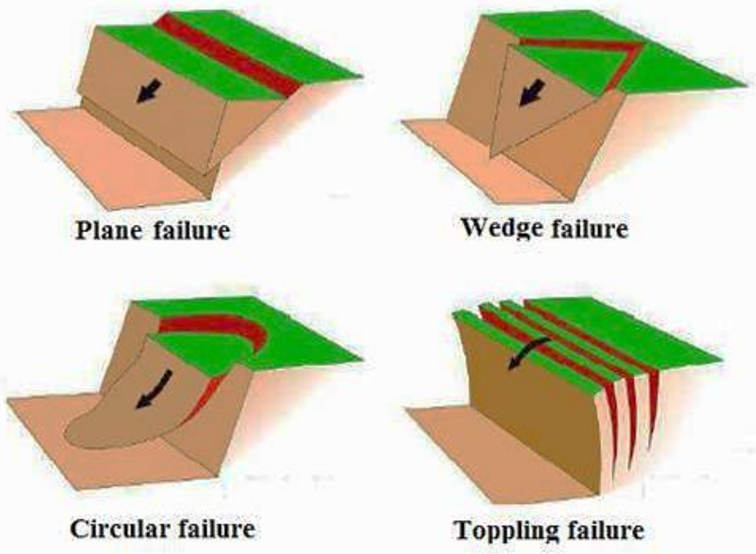


Hoek (1983)

Rock Slope Failure: An Intricate Mechanism







Rock Slope Stability Analysis

Conventional Method

Kinematic Analysis
- Stereonet plot
- Friction cone

Limit Equilibrium Analysis
- Planar sliding
- Wedge analysis
- Slip surface

Numerical method

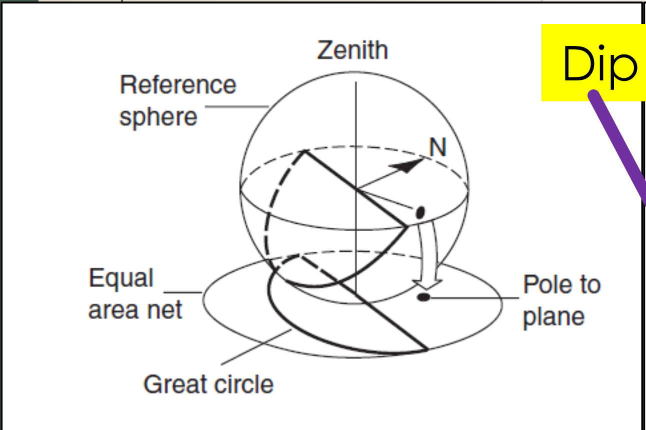
Continuum Modeling
- Finite element
- Finite difference
- Boundary element
- Meshless

Discontinuum Modeling
- Distinct/Discrete element
- Discontinuum deformation
- Hybrid modeling

INCREASING COMPLEXITY → MOVING CLOSER TO REALITY

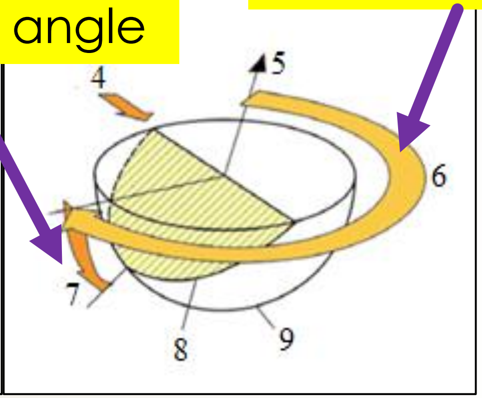
Kinematic Analysis using Dips/Rocscience

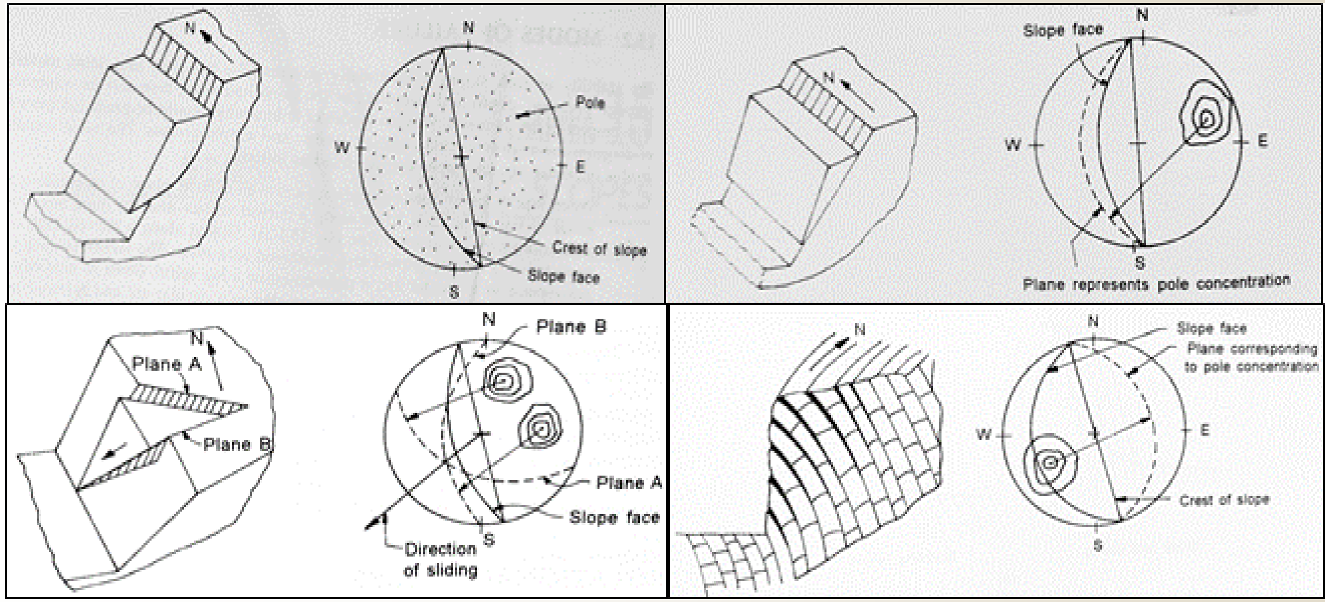
Possibility of translational failures to the formation of daylighting wedges or planes



Dip angle

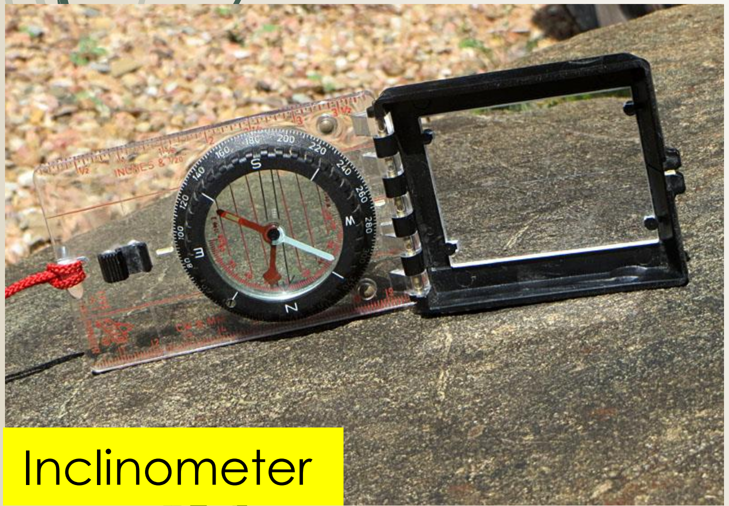
Dip direction



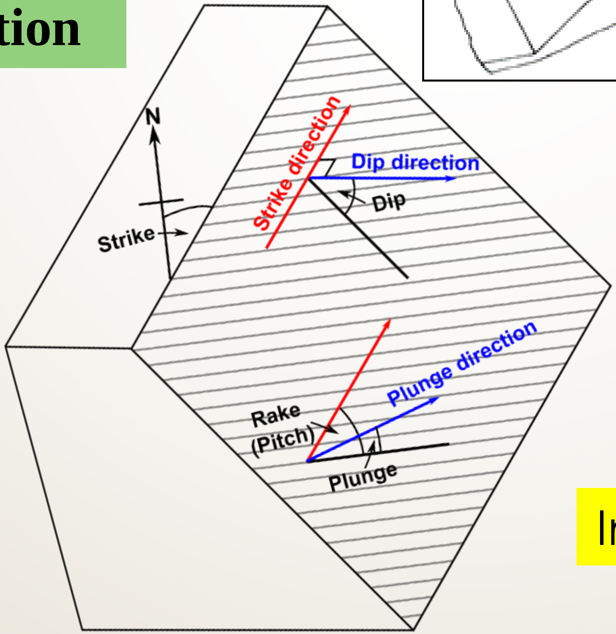


Wyllie and Mah (2004)

Stereographic projection

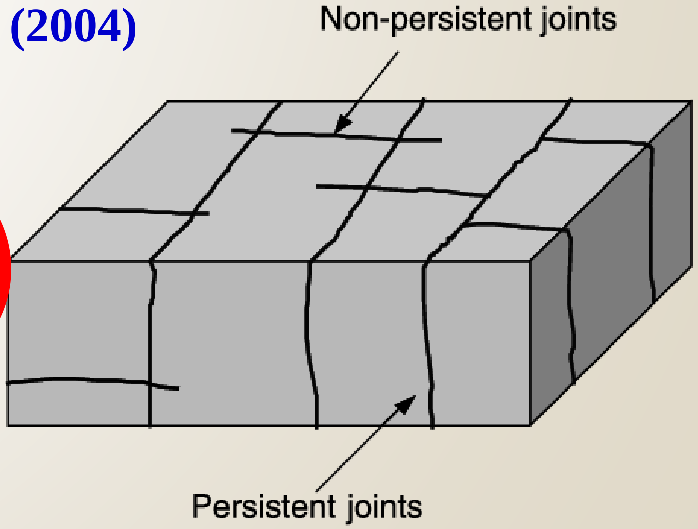


Inclinometer

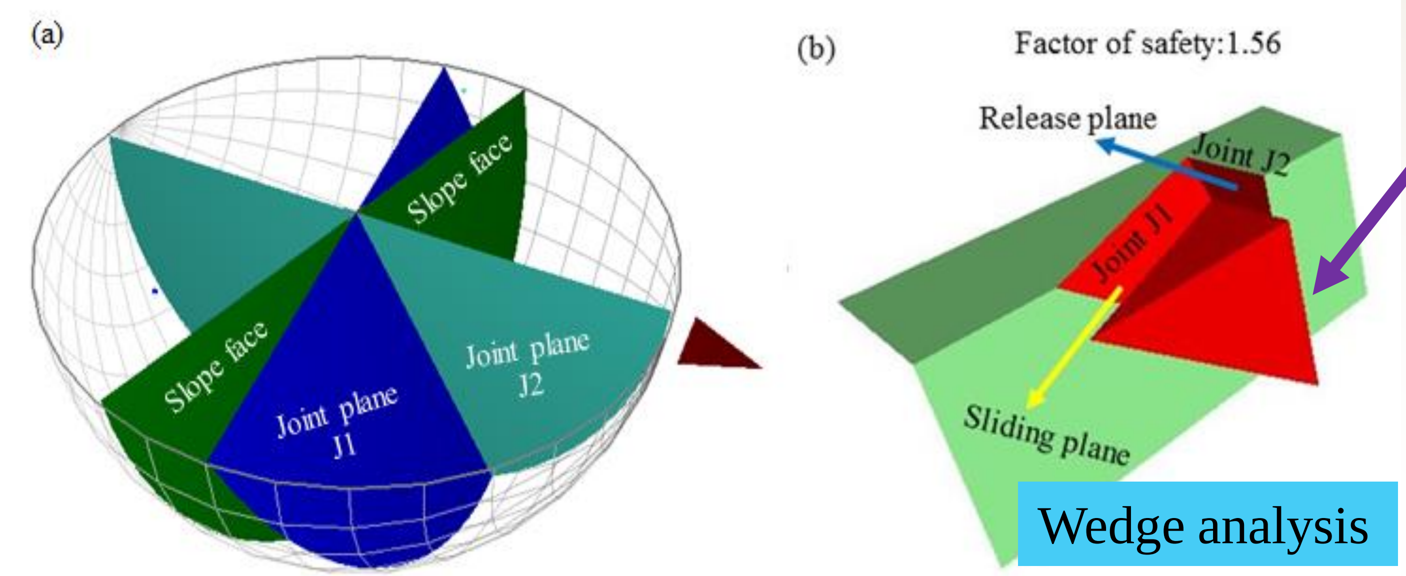


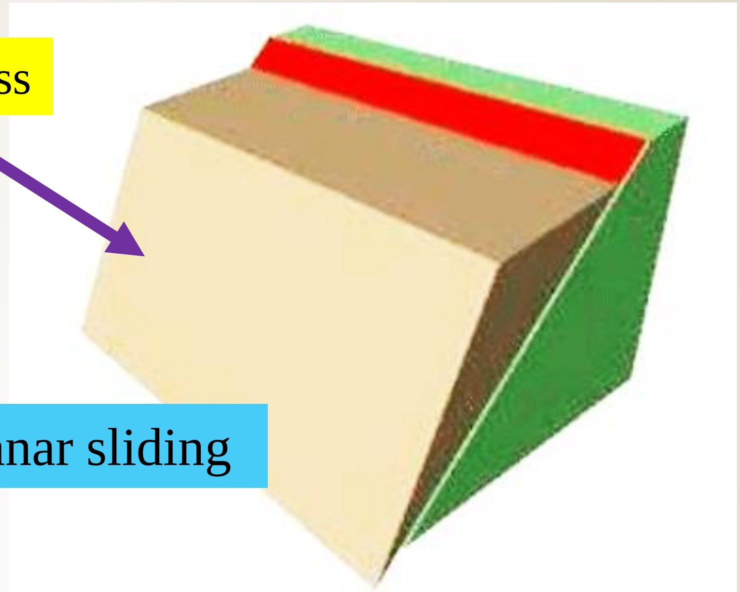
X

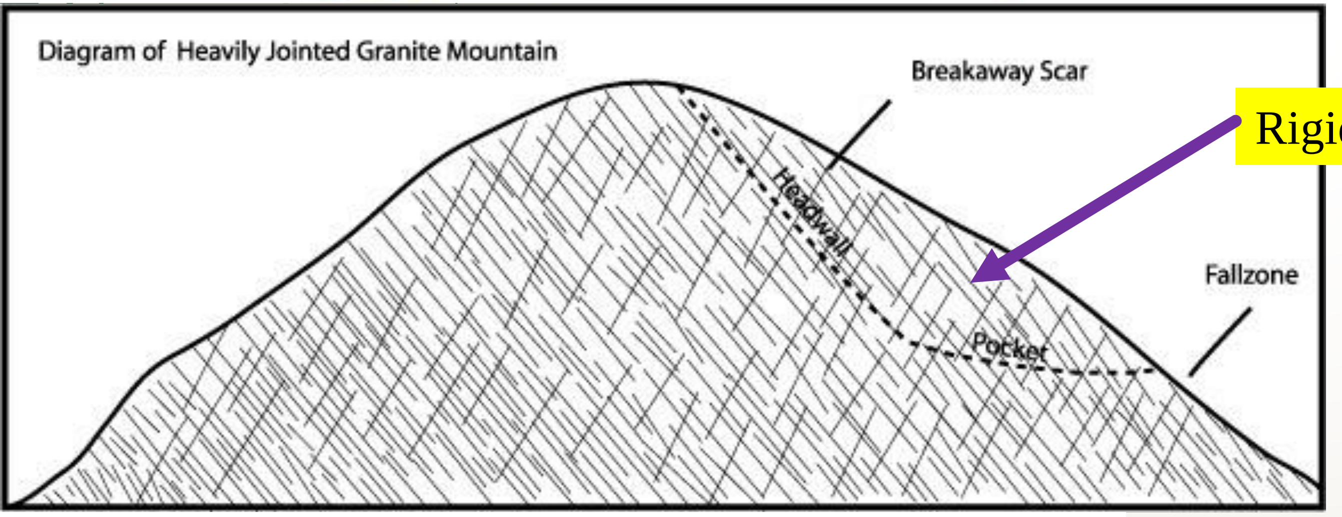
Inadequate

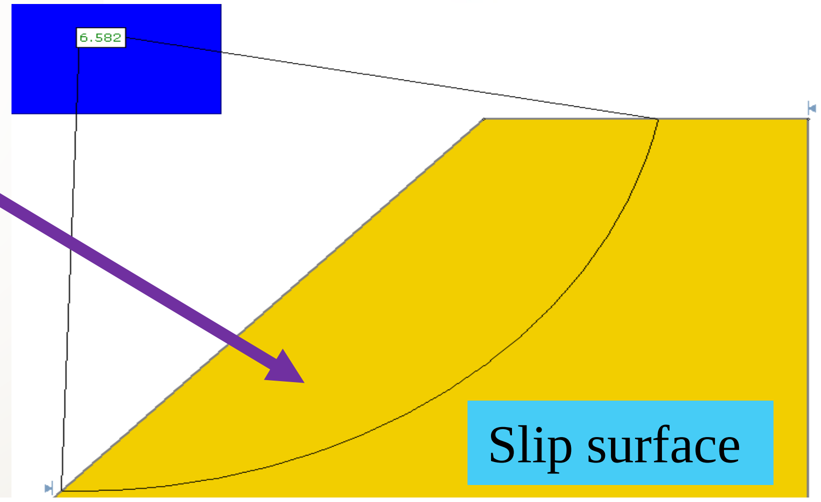


Limit Equilibrium Analysis using Swedge/Rocscience









- **FOS same along the predefined surface**
- **Rigid body above the slip surface**

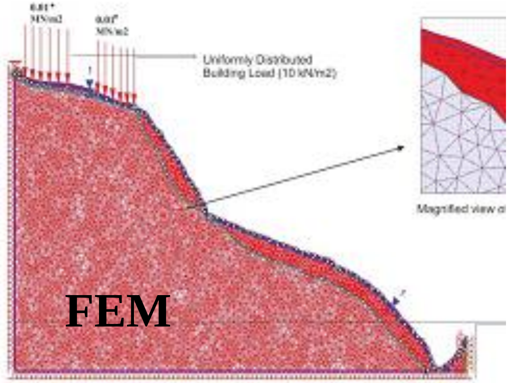
- **Joint persistence and spacing are neglected**
- **Intricate internal deformation and fracturing neglected in 2-D rigid block assumptions**

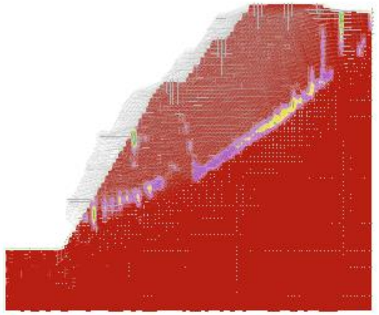
Continuum Modeling using Phase^2(Now RS^2)/Rocscience

- Equivalent continuum method
  - Estimation of equivalent rock mass parameter
  - Homogeneous system (Joints are only geometrical inclusions)
  - Shear strength reduction technique used to assess stability

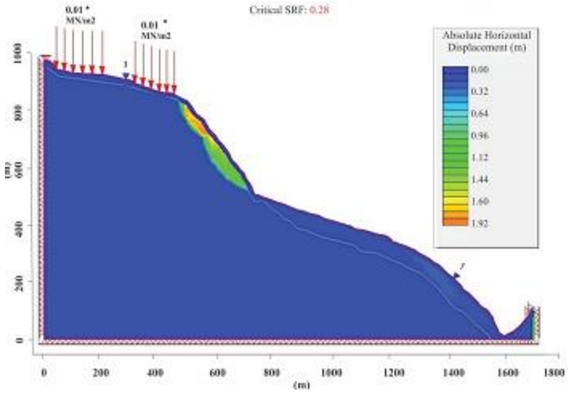
Equivalent Continuum Method

Appropriate for the analysis of rock slopes that are comprised of massive intact rock, weak rocks, or heavily fractured rock masses

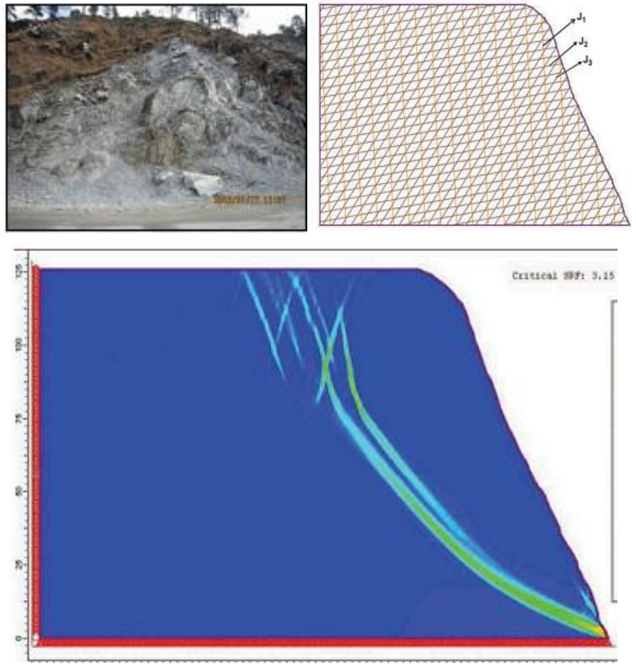




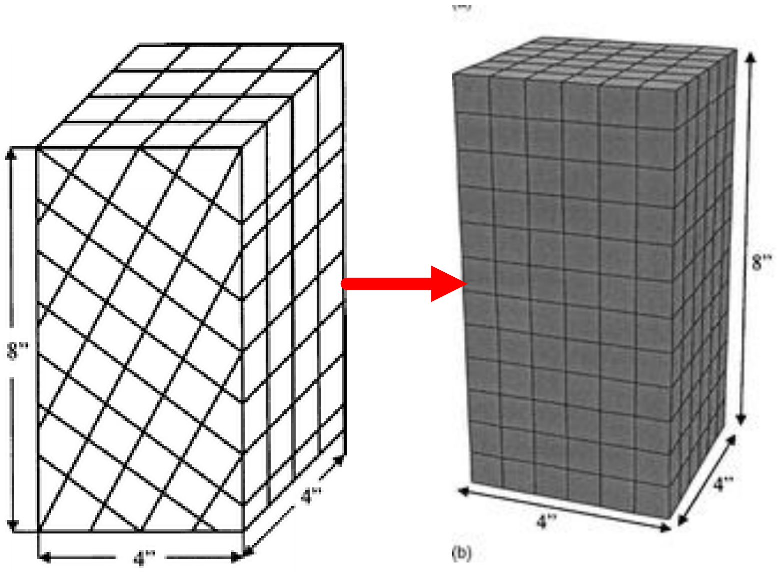
Latha and Garaga, 2010



Gupta and Tandon, 2015



Pain *et al.* 2014



Jointed model to Rock mass

Discontinuum Modeling (Jointed Rock Slopes)

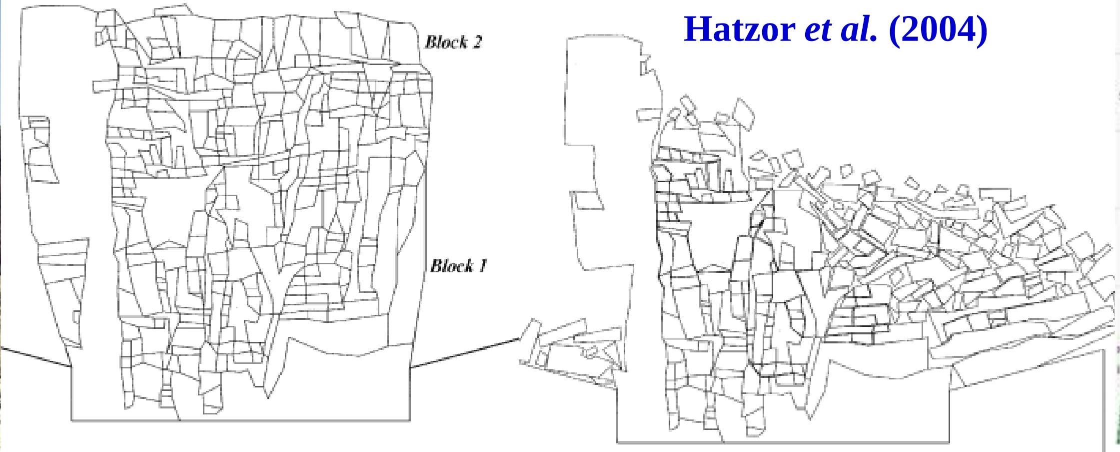
- ❖ Blocky rock slopes
  - ❖ Structural failure occurs due to anisotropy created by the joints
- ❖ Predict the behavior of jointed rock slopes
  - ❖ Discontinuum Deformation Analysis (DDA) and Distinct/Discrete Element Method (DEM)
- ❖ Consideration of stress-strain interactions with the incorporation of explicit joints

DDA (Shi and Goodman 1985, 1989)

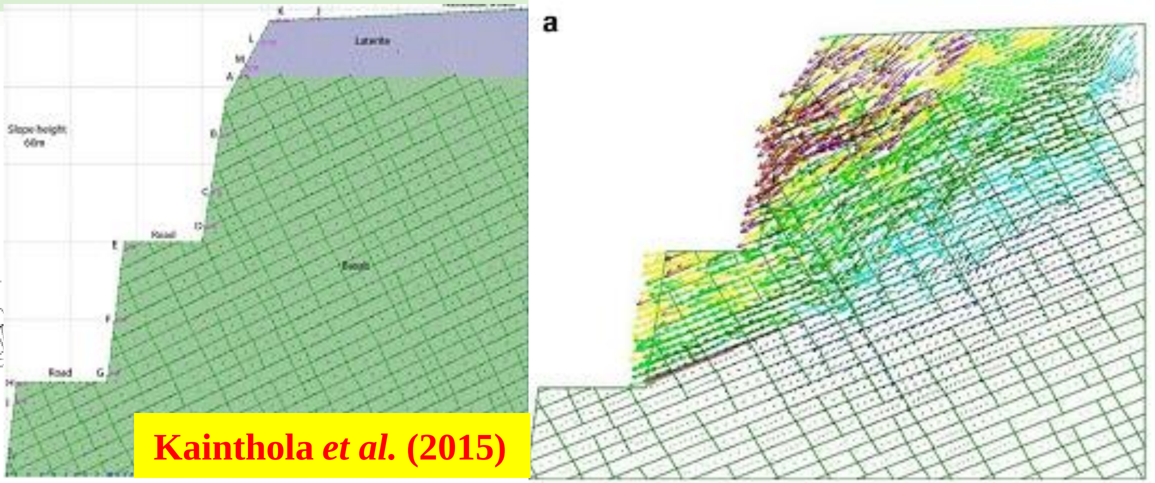
- ❑ Working principle of DDA similar to FEM
- ❑ **Isolated blocks are bounded by discontinuities** to represent the jointed slope
- ❑ Advantage of being able to model **large deformations and rigid body movements**

DEM (Cundall 1971)

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

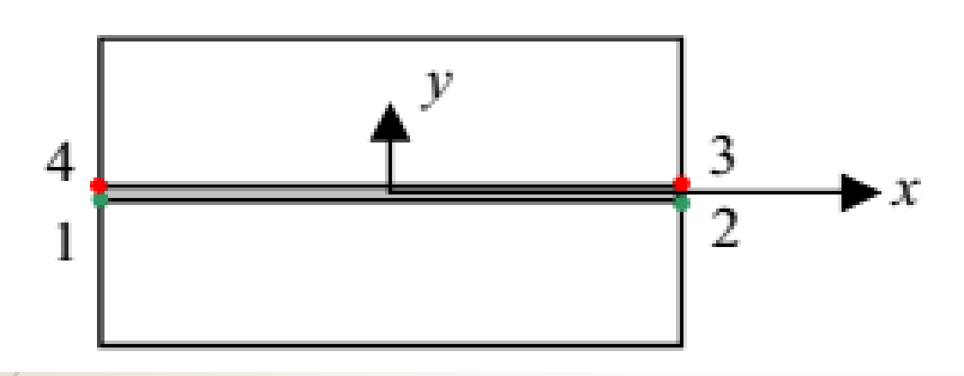


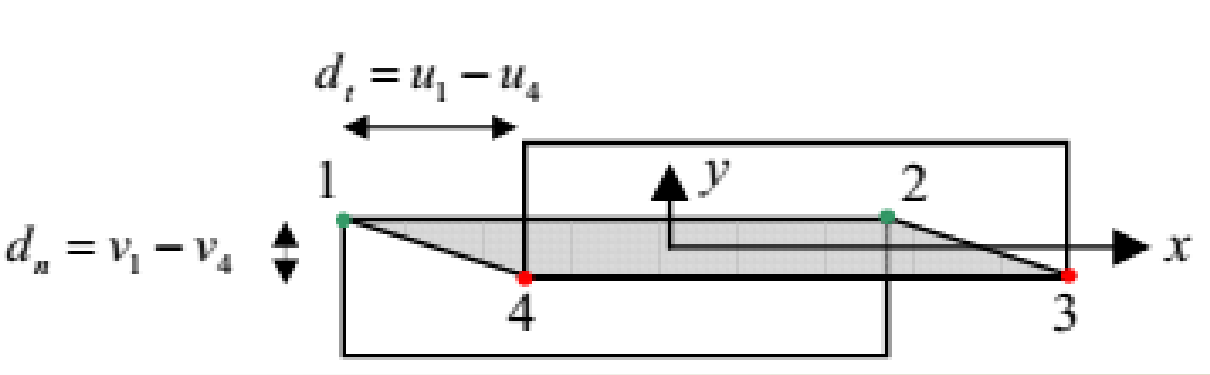
Hatzor *et al.* (2004)



Kainthola *et al.* (2015)

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





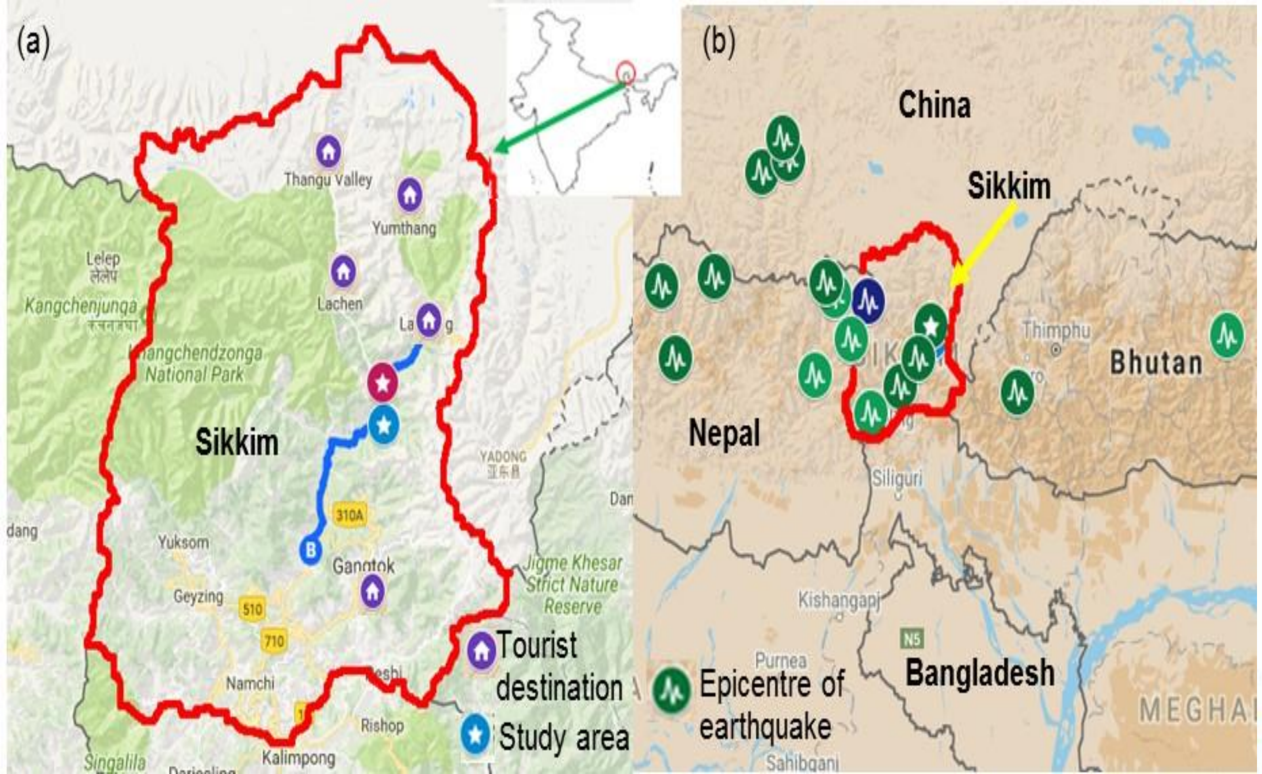
- ❖ **Zero thickness Rectangular element**
- ❖ **Four nodes and Eight degrees of freedom**
- ❖ **Normal displacement and tangential displacement**
  - ❖ **Interface stresses related to relative displacements governed by constitutive relation**
- ❖ **Uncoupled tangential and normal stiffness**
  - ❖ **The 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**
- ❖ **RELATIVE DISPLACEMENT OCCURS when the JOINT SHEAR STRESS EXCEEDS THE SHEAR STRENGTH**

STATIC STABILITY ANALYSIS OF JOINTED ROCK SLOPE

Sikkim Himalaya Case Study: North Sikkim Gangtok-Lachung Highway

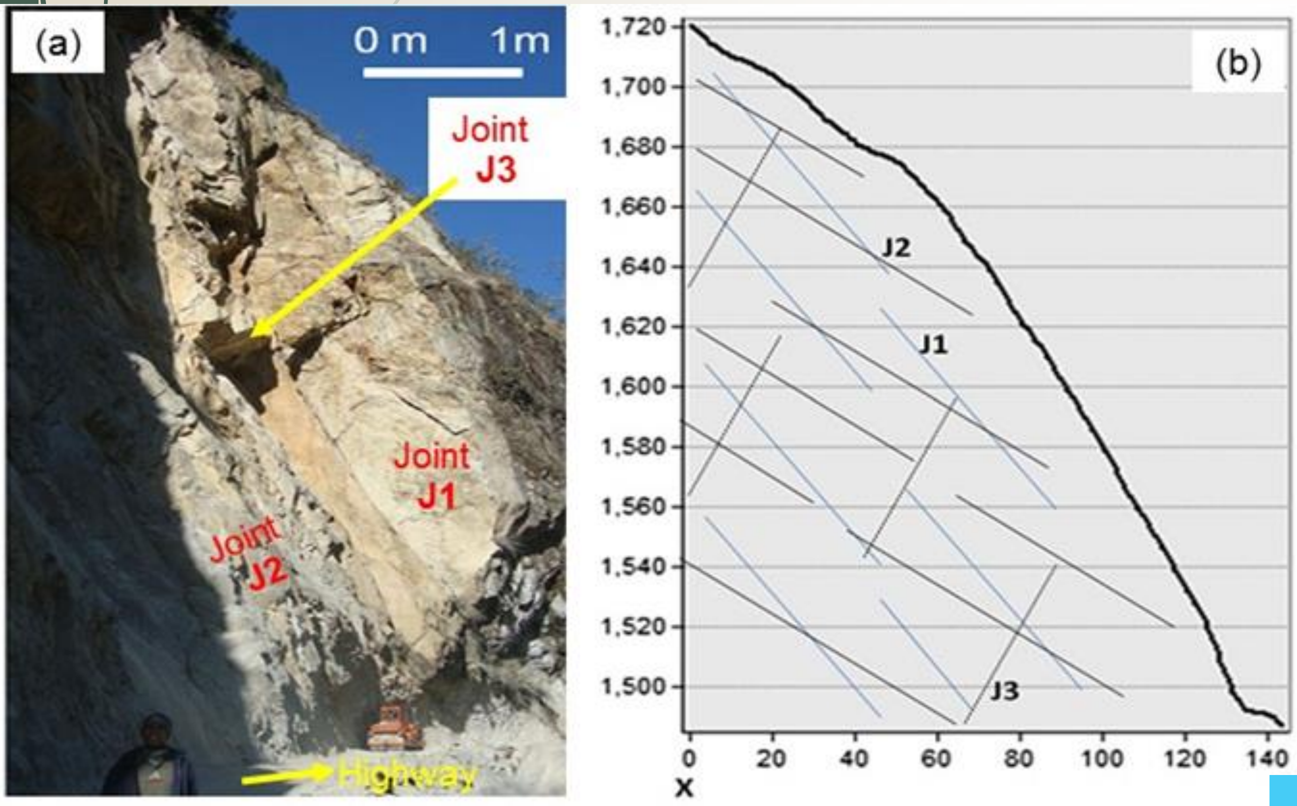
IMPORTANCE OF STUDY AREA

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)

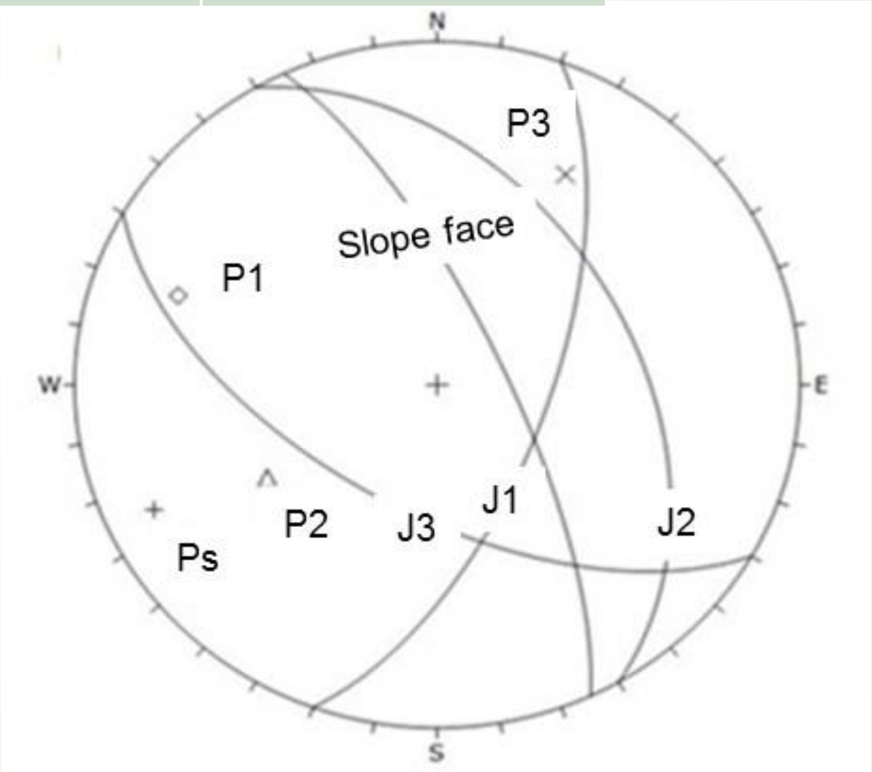


Description of Slope and Joint Geometries

Joint sets	Dip/Dip Direction (°)	Joint spacing (m)	Joint Length (m)
J1 (Foliation)	65/110	0.3	> 5
J2	45/60	0.5	> 2
J3	60/210	0.5	> 2
Slope Face	75/65	-	
Trace plane	90/335	-	



(Modified after Ghosh *et al.*, 2014)

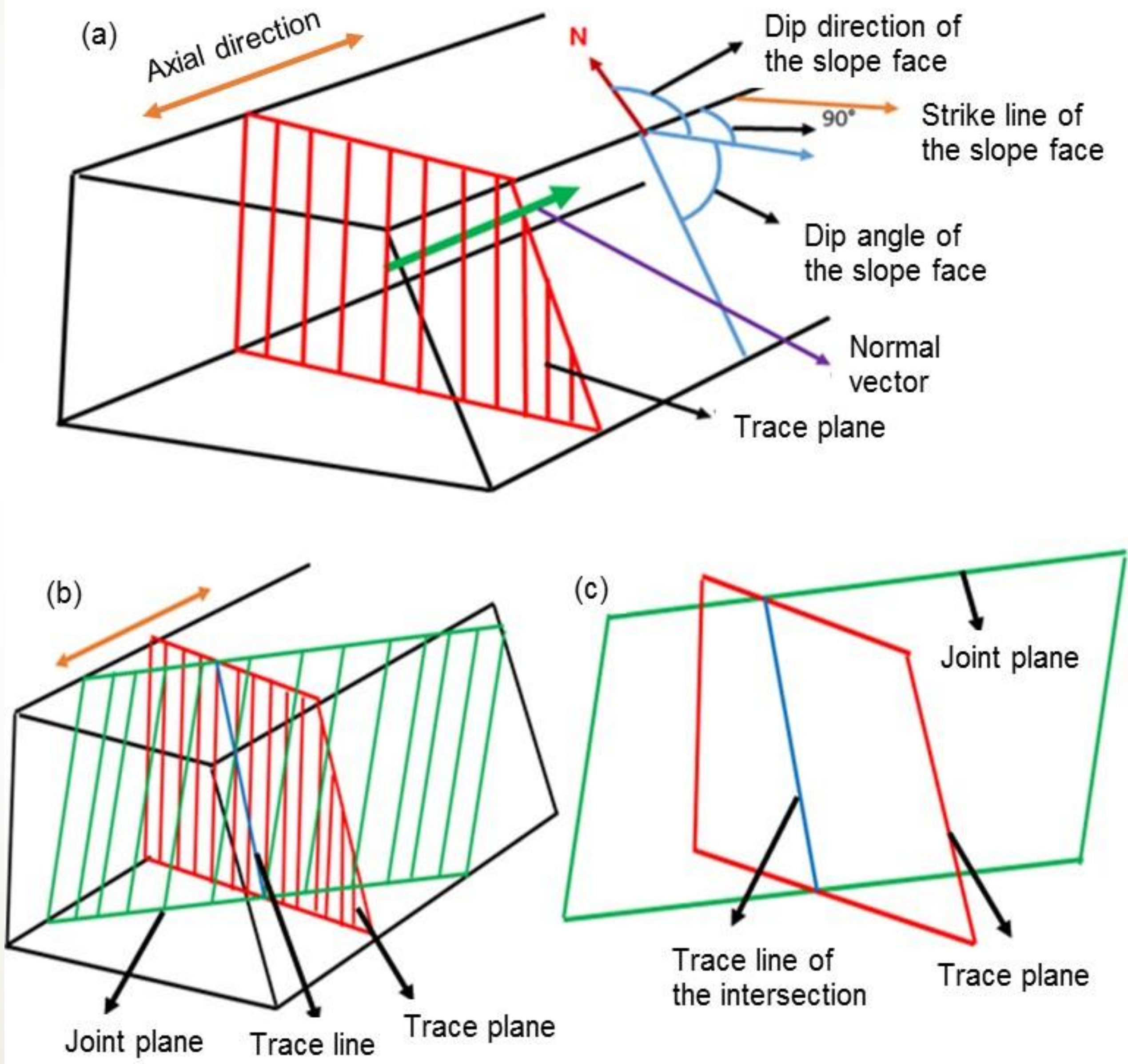


Stereographic plots of the rock slope orientation of three set of joints, orientation of slope face and location of the poles

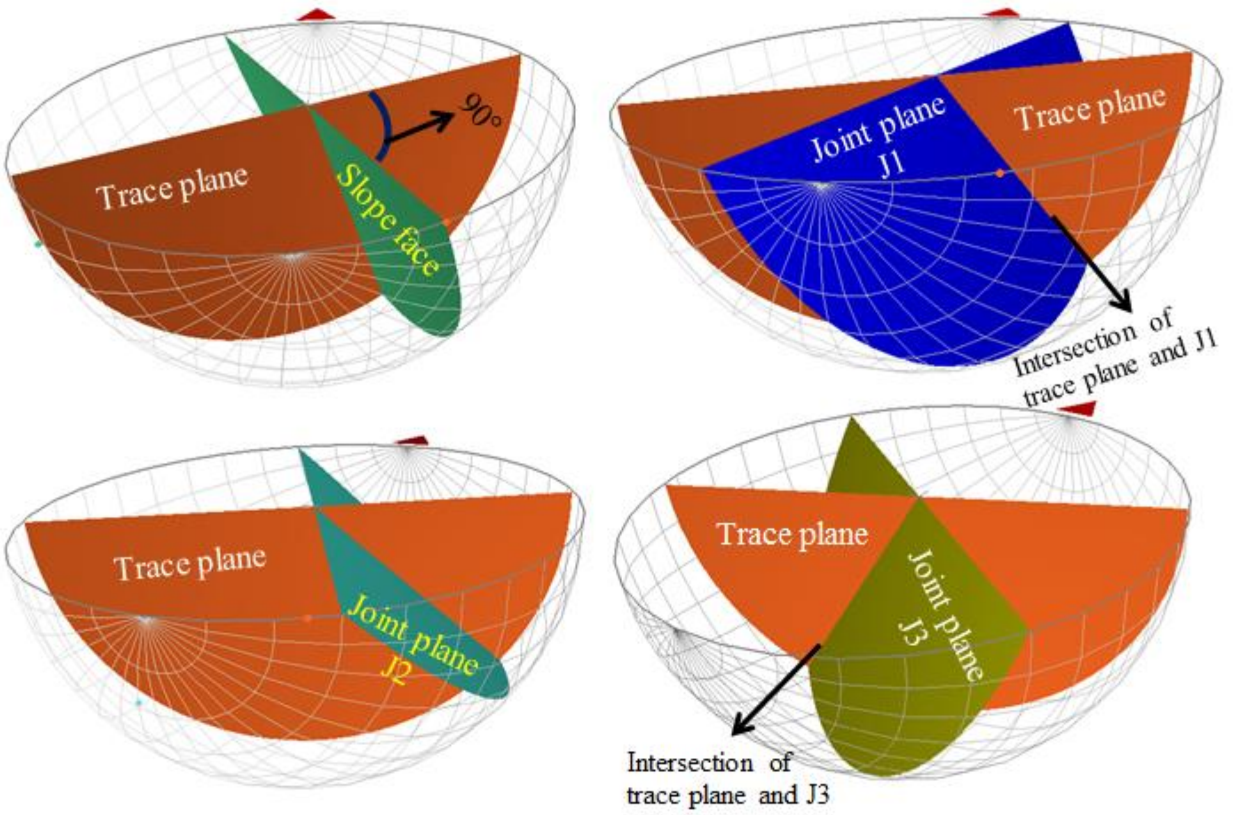
Necessity of 2-D Model of Jointed Rock Slope

- **Three-dimensional model for a jointed rock slope would predict more realistic results**
  - **Requires huge computational efficiency**
- **Joints creates stress anisotropy in rock slope**
  - **Failure mechanism depends on their orientation with respect to loading directions**
    - **Hoek 1983, Ramamurthy and Arora 1994, Singh *et al.* 2002**
- **Development of 2-D Jointed Model from 3-D field information**
  - **Pal *et al.* 2012, Kanungo *et al.* 2013, Pain *et al.* 2014, Singh *et al.* 2015, Kainthola *et al.* 2015, Tiwari and Latha 2016, Kaya *et al.* 2016**

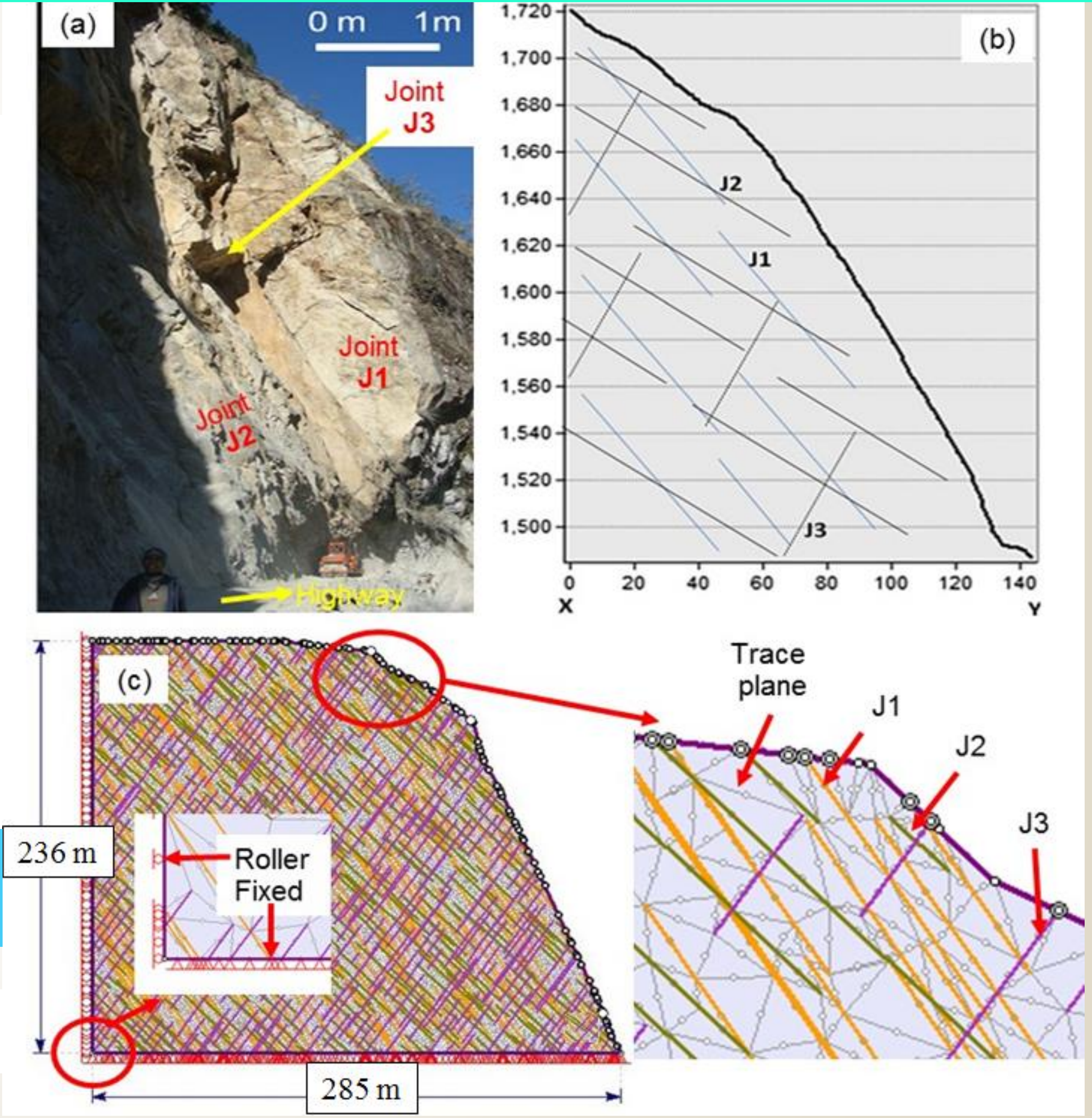
Trace line of the intersection of joint and trace plane



2-D Model of Chosen Jointed Rock Slope



Three dimensional orientation of trace plane for the concerned slope



Model verified with real field observation

Geotechnical Details – Equivalent Strength Parameters

Barton and Bandis (1990) Failure Criterion

$$\tau = \sigma_n \tan\left[\phi_r + JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right)\right]$$

$$\phi_r = (\phi_b - 20) + 20\left(\frac{r}{R}\right)$$

Wet and fractured surface

Dry unweathered sawn surface

Schmidt Rebound Hammer

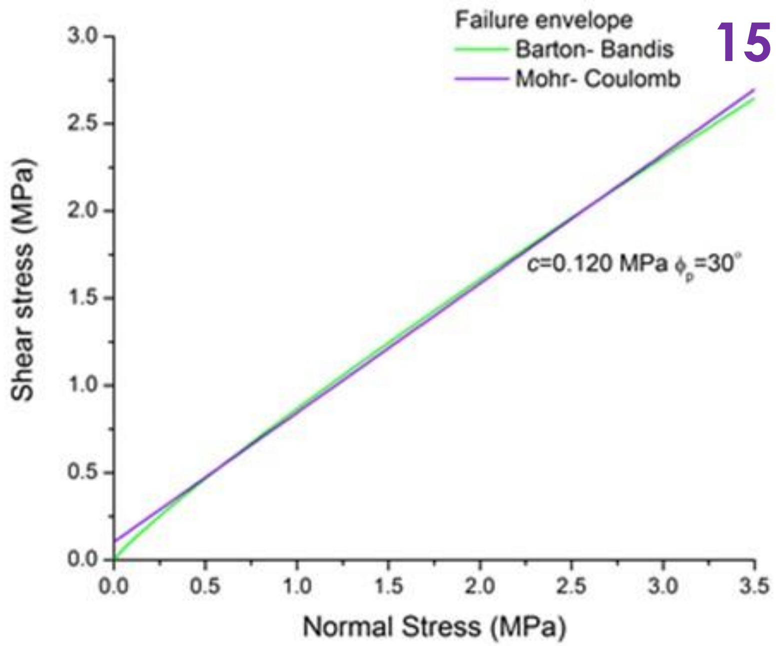


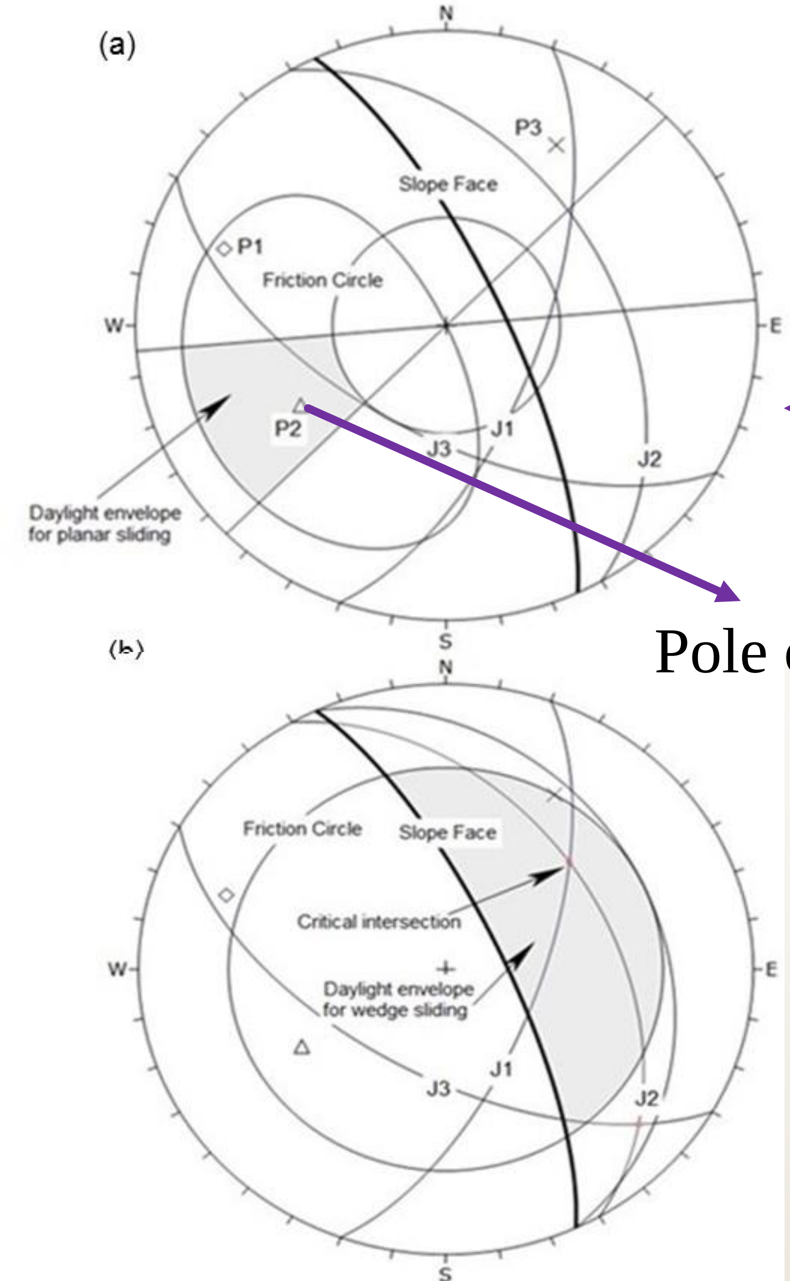
Table 3.2 Mechanical and elastic properties of intact rock and rock mass

Rock mass	
Rock mass parameter, *RMR*	64
Geological strength index, *GSI*	59
Elastic modulus of rock mass, E_m (GPa)	18.92
Intact rock	
Elastic modulus of intact rock, E_i (GPa)	38.06
Unconfined compressive strength (MPa)	70
Poisson's ratio (μ)	0.3
Unit weight (γ, kN/m^3)	27
Damage factor (D)	0
m_i	28
s	0.5
a	1
Equivalent friction angle	60°
Equivalent cohesion, c (MPa)	9
Equivalent tensile strength (MPa)	-2.5

Table 3.3 Joint strength parameters

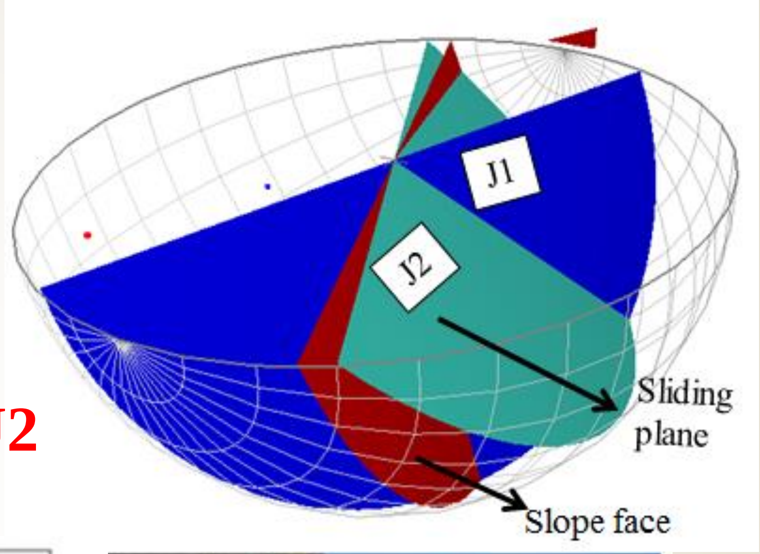
Normal stiffness, k_n (GPa/m)	J1	J2	J3
	125	75	75
Shear stiffness, k_s (GPa/m)	J1	J2	J3
	12.5	7.5	7.5
Joint compressive strength (JCS) (MPa)		17.5	
Joint roughness coefficient (JRC)		5.5	
Residual friction angle, ϕ_r (°)		23°	
Equivalent friction angle, ϕ_p (°)		30°	
Equivalent cohesion, c (kPa)		120	

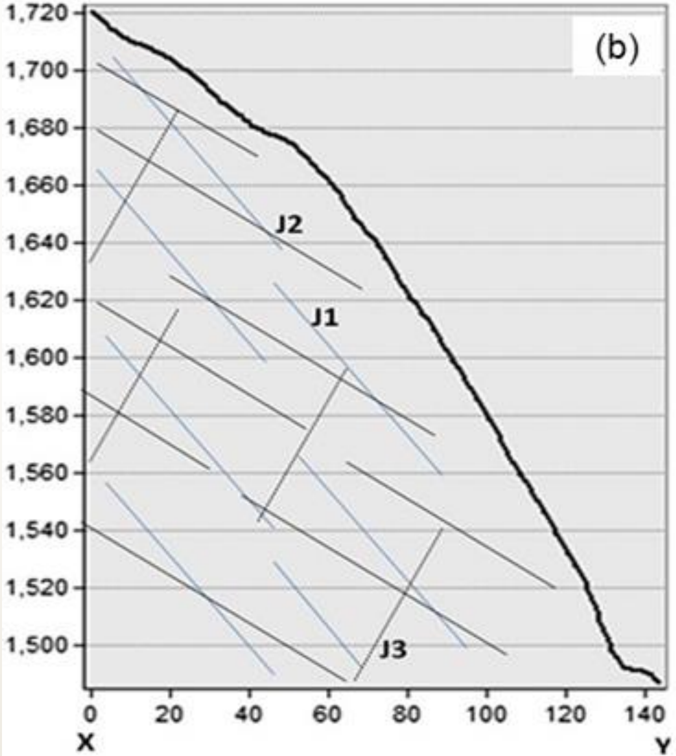
Kinematic Analysis of Rock Slope

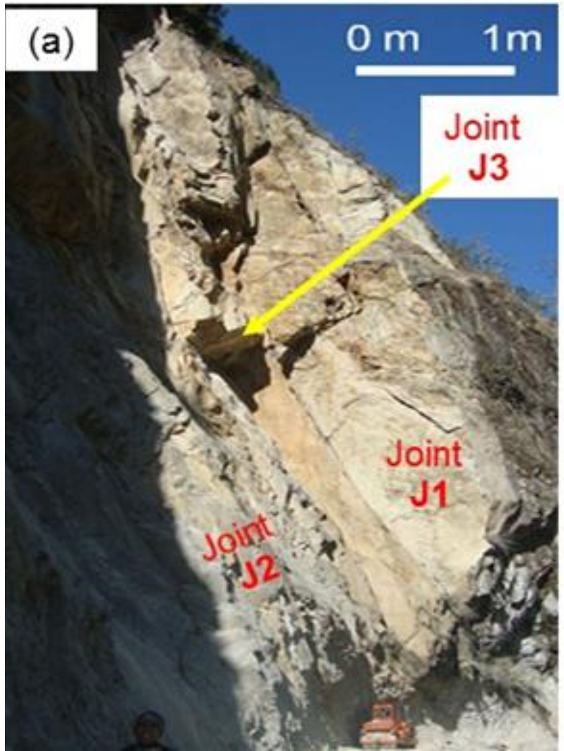


Sliding failure along J2

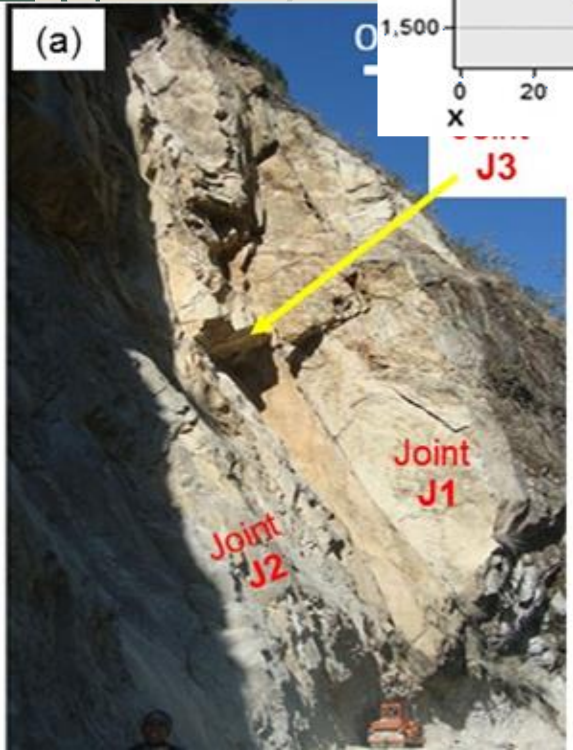
Pole of J2

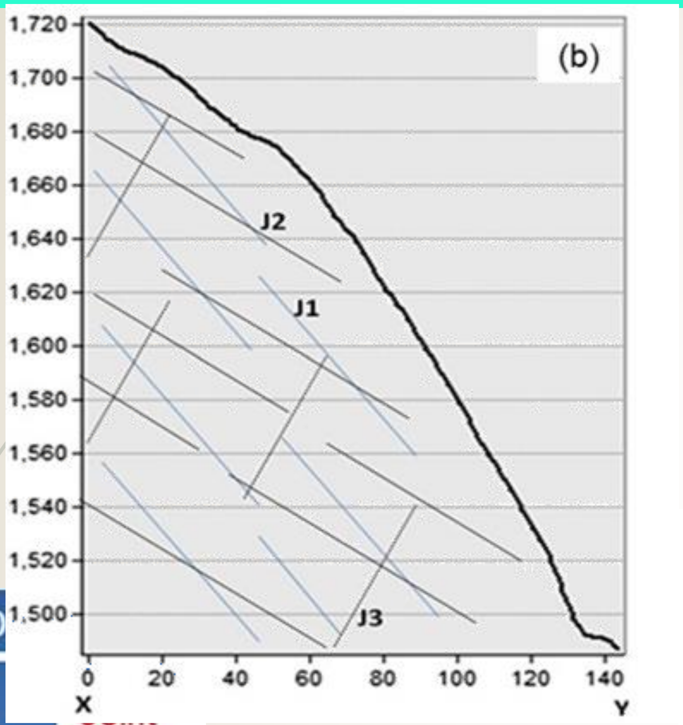






Shear Strength Reduction Technique





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

$$c_f = \frac{c}{SRF}$$

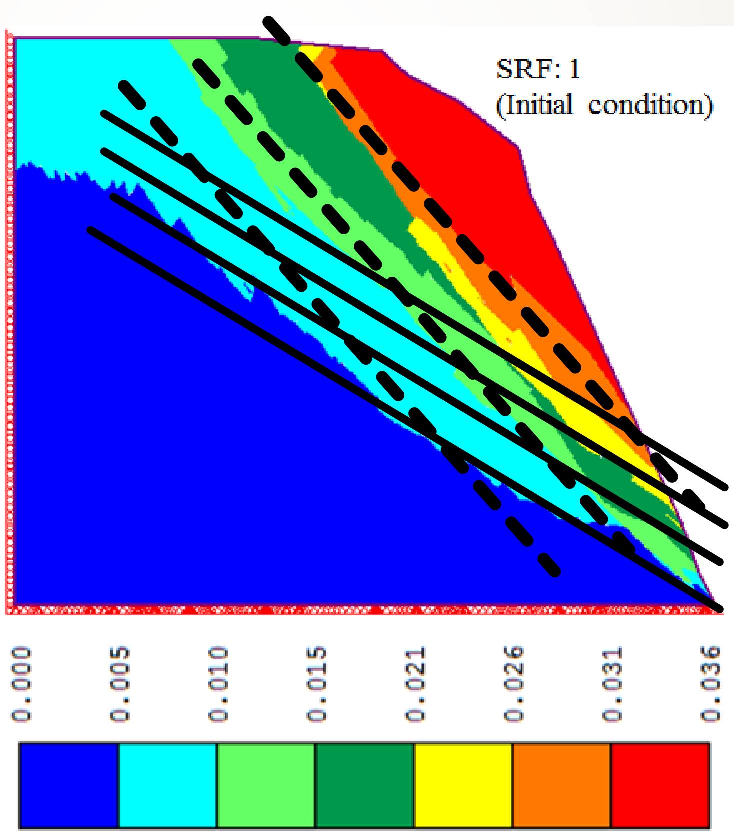
$$\text{FoS} = \frac{\text{Strength}}{\text{Stress}}$$

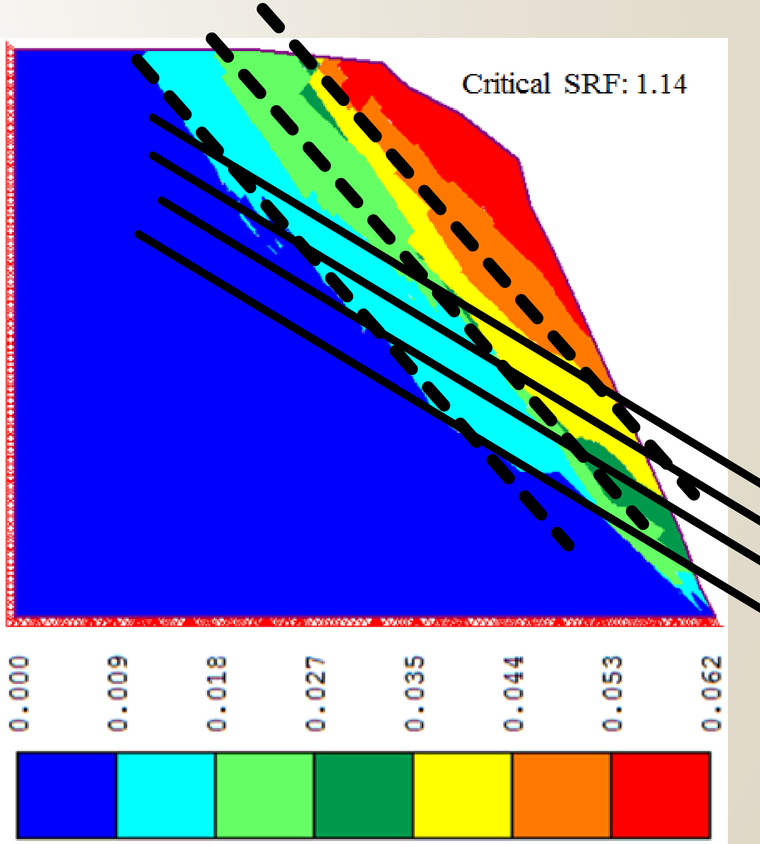
Critical Strength Reduction Factor (SRF) = 1.14 is less than minimum Factor of Safety (FoS) = 1.5

Sliding failure along J1 in upper reaches of slope

MIXED_MODE

Sliding failure along J2 in lower reaches of slope



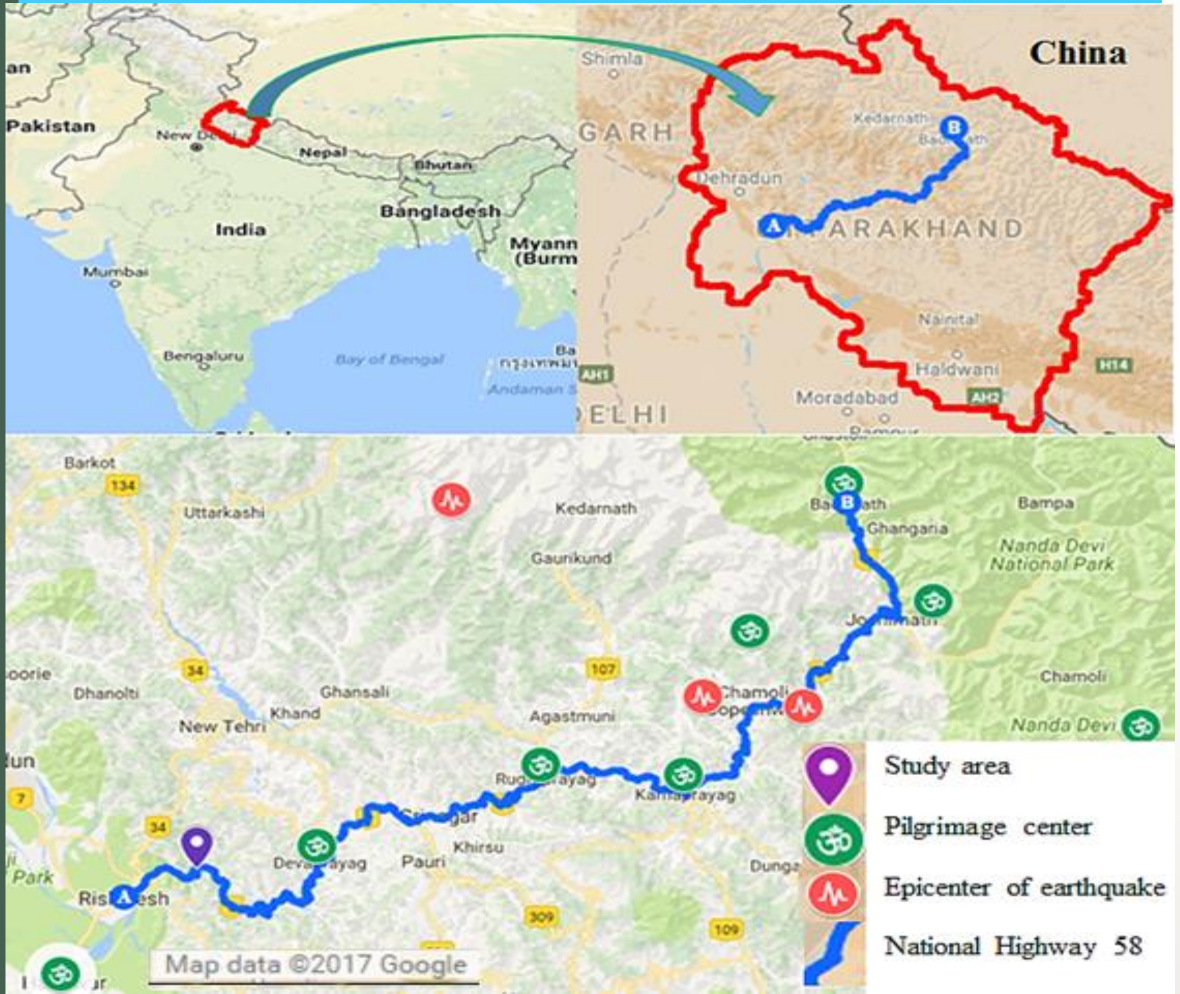


DYNAMIC STABILITY ANALYSIS OF JOINTED ROCK SLOPE

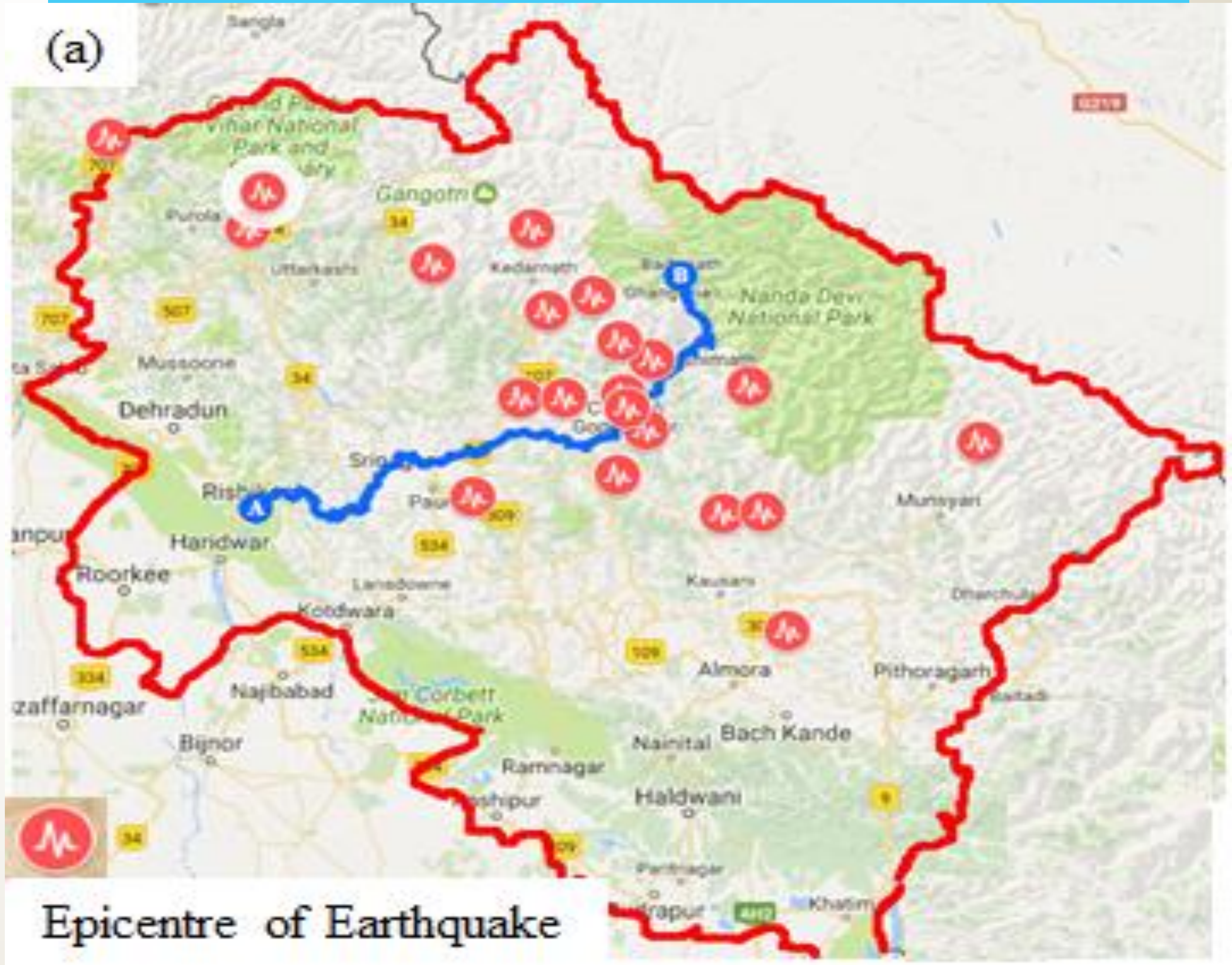
Garhwal Himalayan Case Study: National Highway-58 (Rishikesh-Badrinath)

IMPORTANCE OF STUDY AREA

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



Earthquake history of Uttarakhand showing locations of seismic epicenters

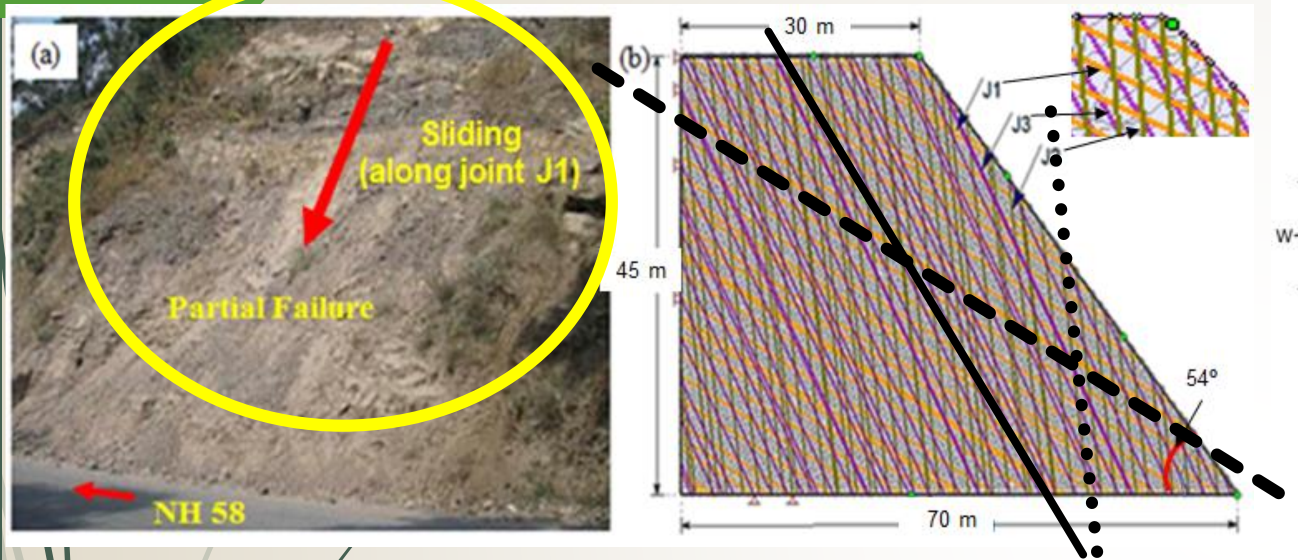


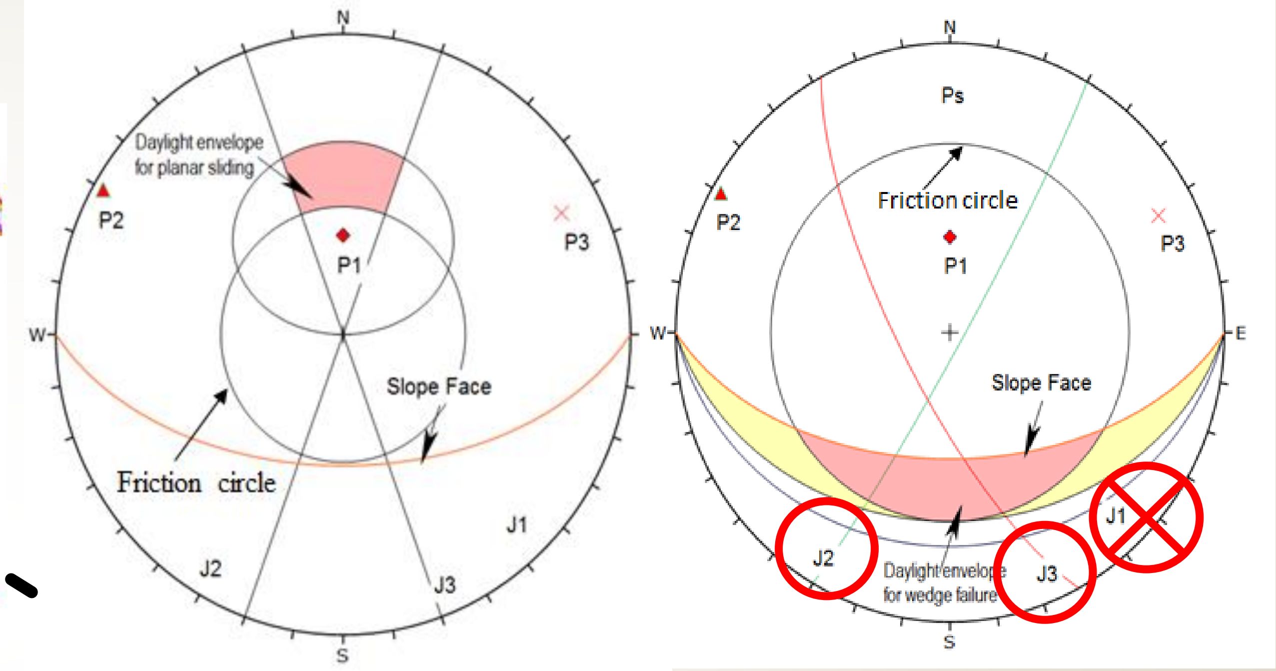
Dynamic Stability Assessment of Jointed Rock using FE-EJM

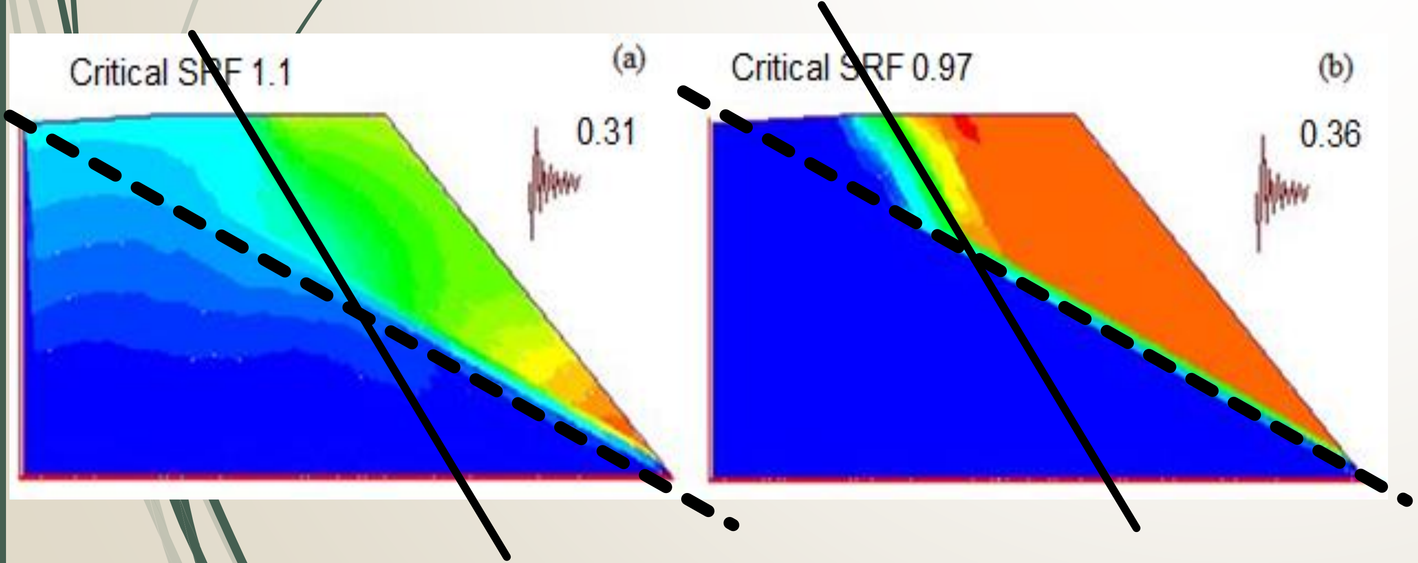
DYNAMIC ANALYSIS OF JOINTED ROCK SLOPE

- Simulate wave transmission through jointed rock (Zhang *et al.* 1997, Pal *et al.* 2012)
- Dynamic stability of rock slope using Finite Element-Explicit Joint Model (FE-EJM)
- Phase^2 (Now RS^2) has the capability of utilizing the FE-EJM
  - Incorporate Cauchy strain definition
  - Provide accurate results up to a strain of 1% (Rocscience 2016d)
  - Reasonably predict deformation of the rock slope under seismic event if the strain developed is less than 1% (mostly within the limits when there is minimal development of non-linearity)
  - Limiting value of post seismic displacement is **50 mm** for rock slope for non-triggering of landslide (Wilson and Keefer 1985, Nichols *et al*. 2004, Jibson and Michael 2009, Jibson and Keefer 1993, Dreyfus *et al.* 2013)
    - WHEN COMPLETE FAILURE OF ROCK SLOPE IS NOT OF INTEREST, then FE-EJM can be used for the prediction of the stability condition of a rock slope (Hoek 2009)

Pseudo-Static Slope Stability Analysis







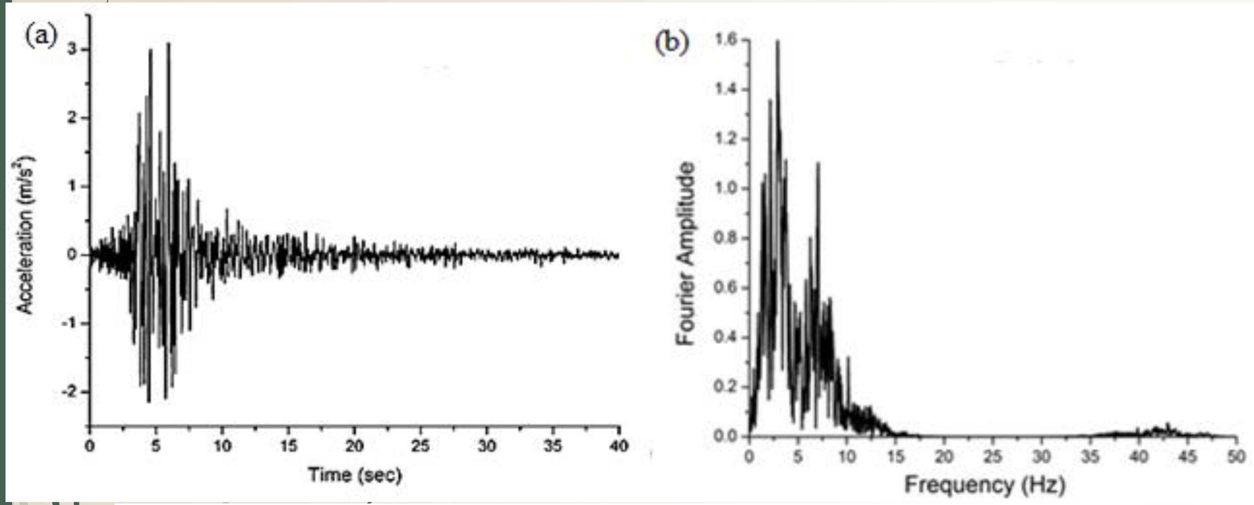
k_h (g)	0 (Static)	0.15	0.2	0.31	0.36
SRF	1.78	1.4	1.27	1.10	0.97

Jointed rock slope is vulnerable to failure when subjected to Maximum Credible Earthquake (MCE) for the region or $k_h \geq 0.3$

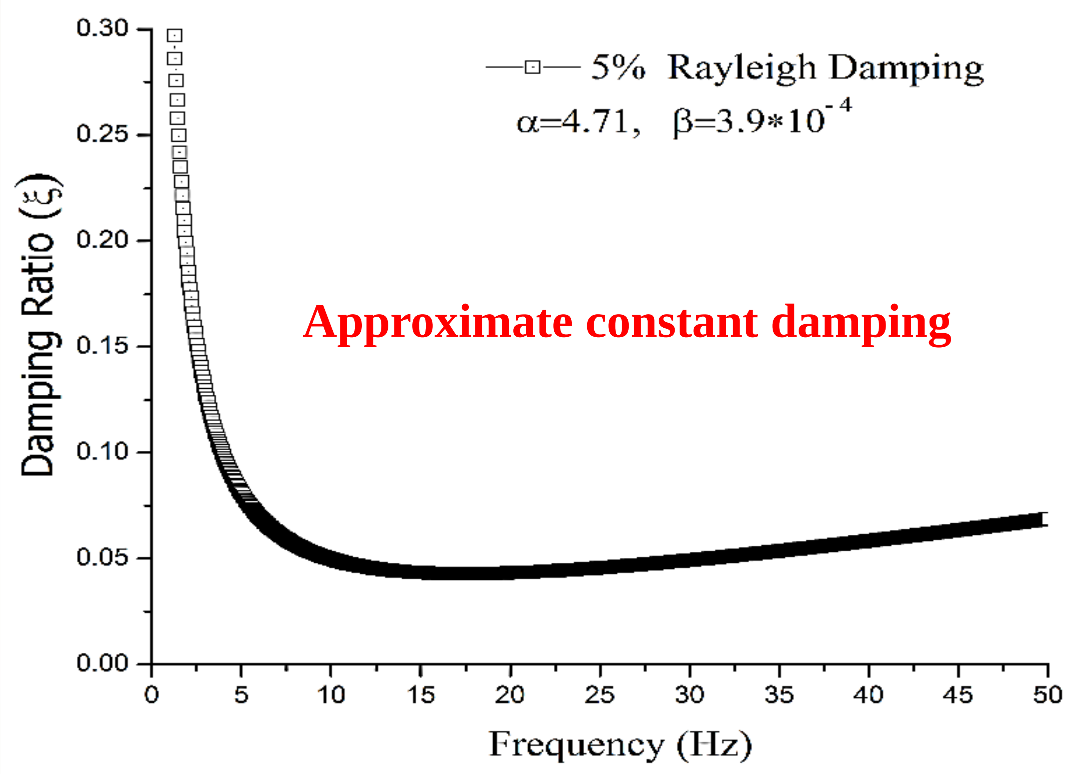
Utilizing Seismic Motion - Time History Analysis

Dynamic loading

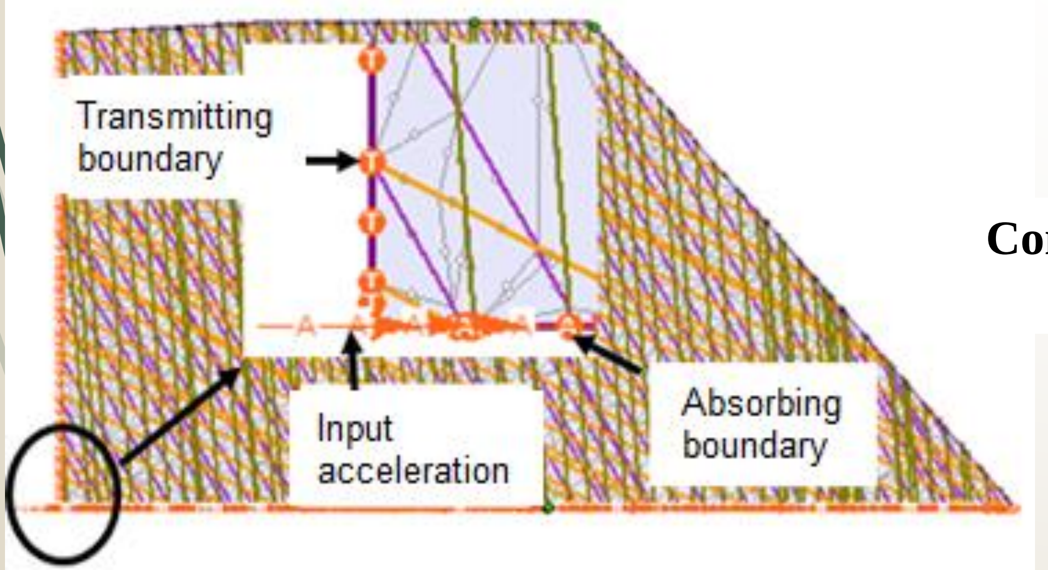
Uttarkashi earthquake (16th October 1991)



5% Rayleigh Damping



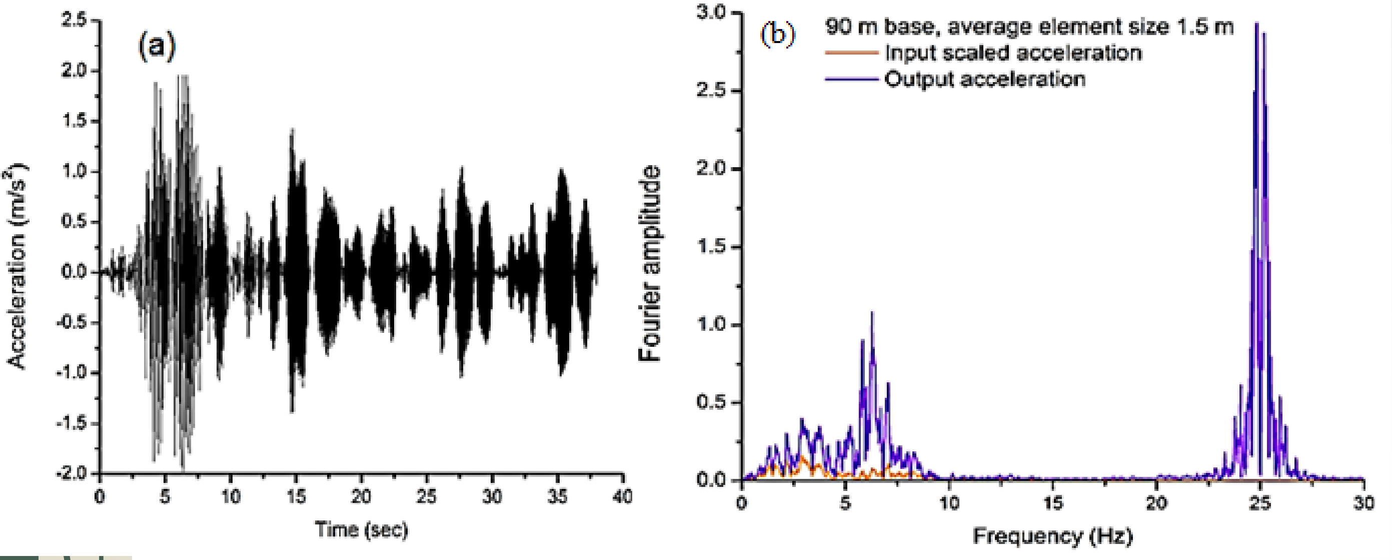
Boundary conditions: Modeling and Application



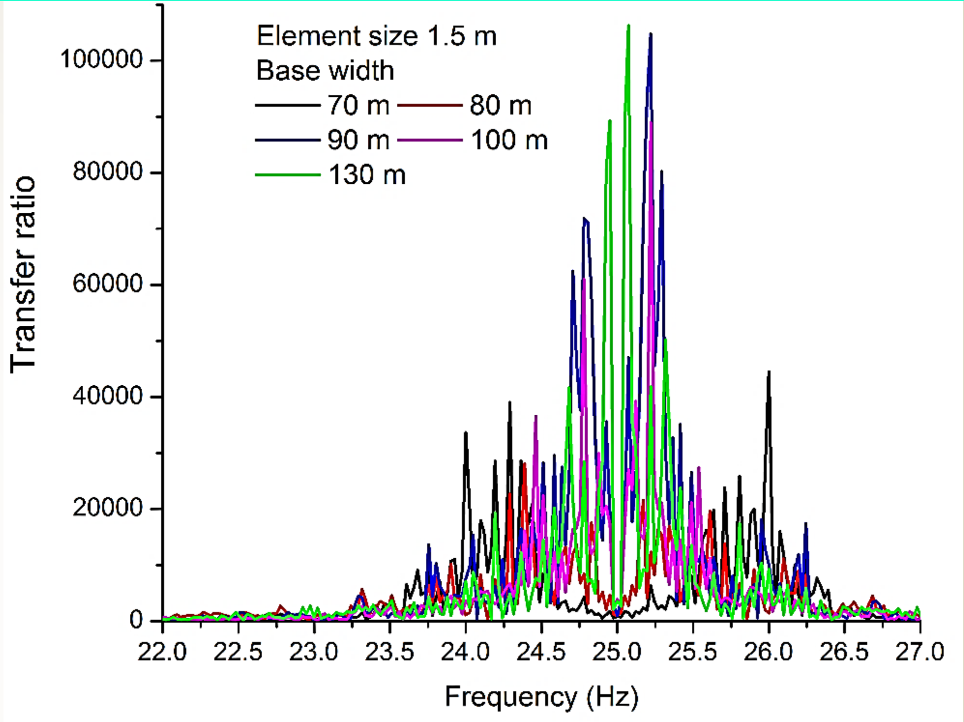
Compliant Base: Convert Velocity to Shear Stress

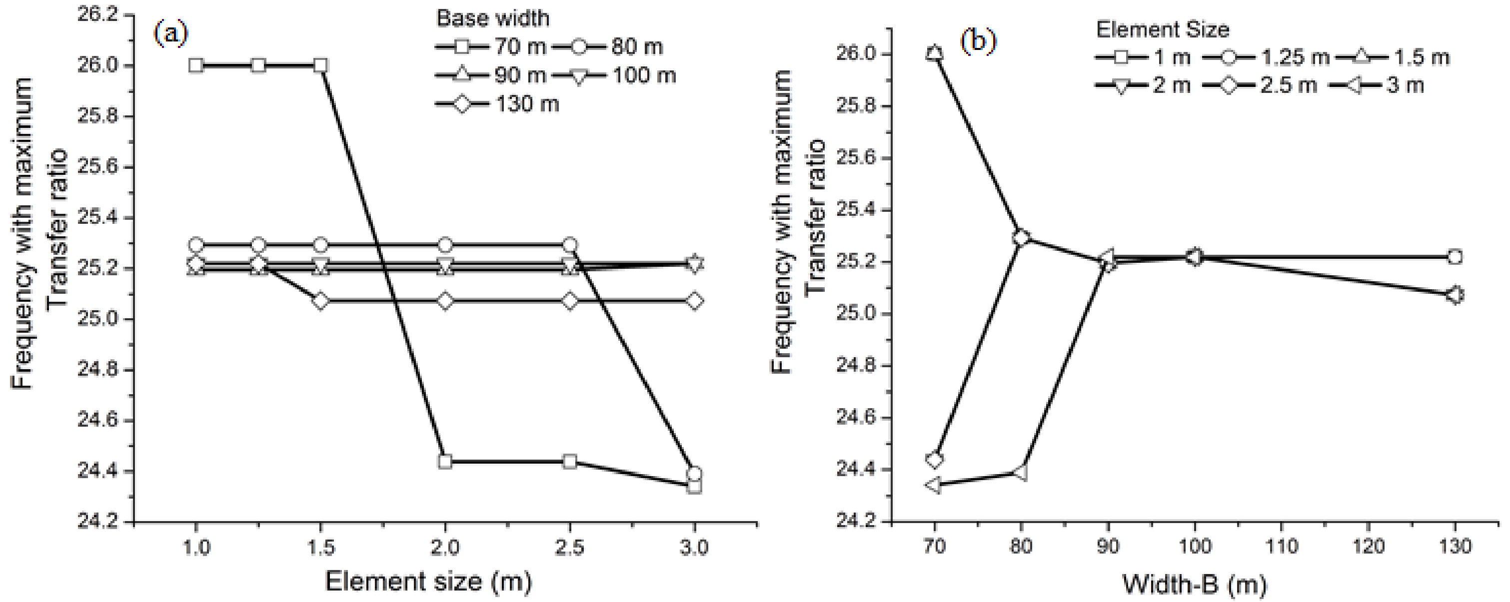
$$\tau_s(t) = V_s \rho v_s(t)$$

Optimum Boundary Domain and Average Mesh Size



Acceleration at the top of the rock slope (undamped)





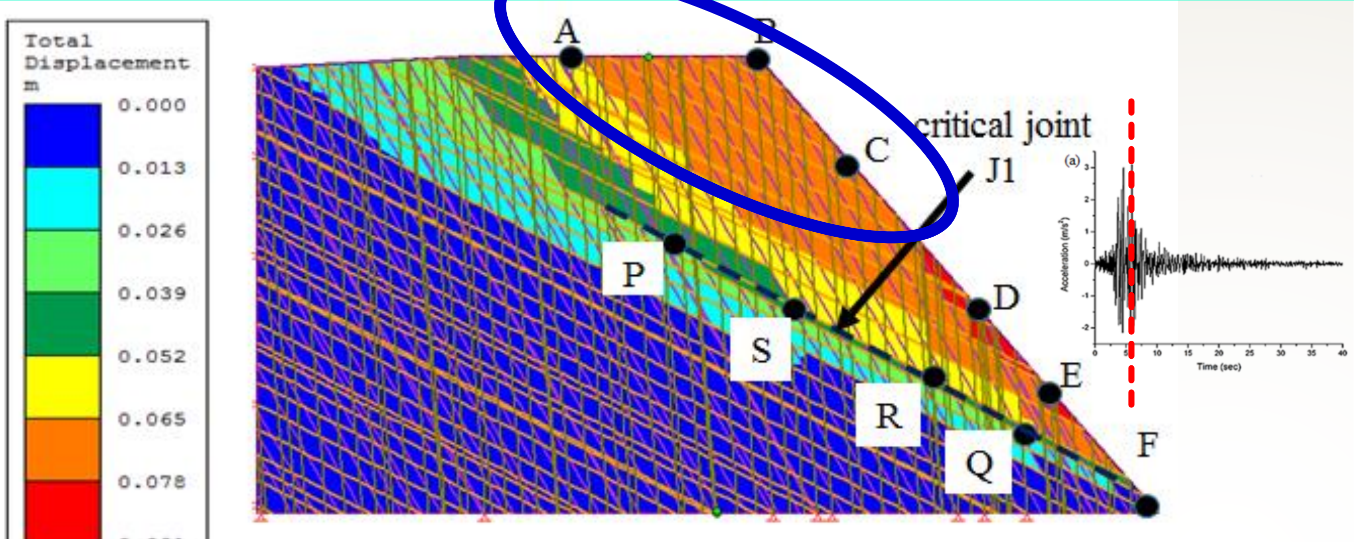
Small boundary domain inadequate to imulate entrapment of energy in jointed rock

Large boundary domain demands unnecessary computational expense

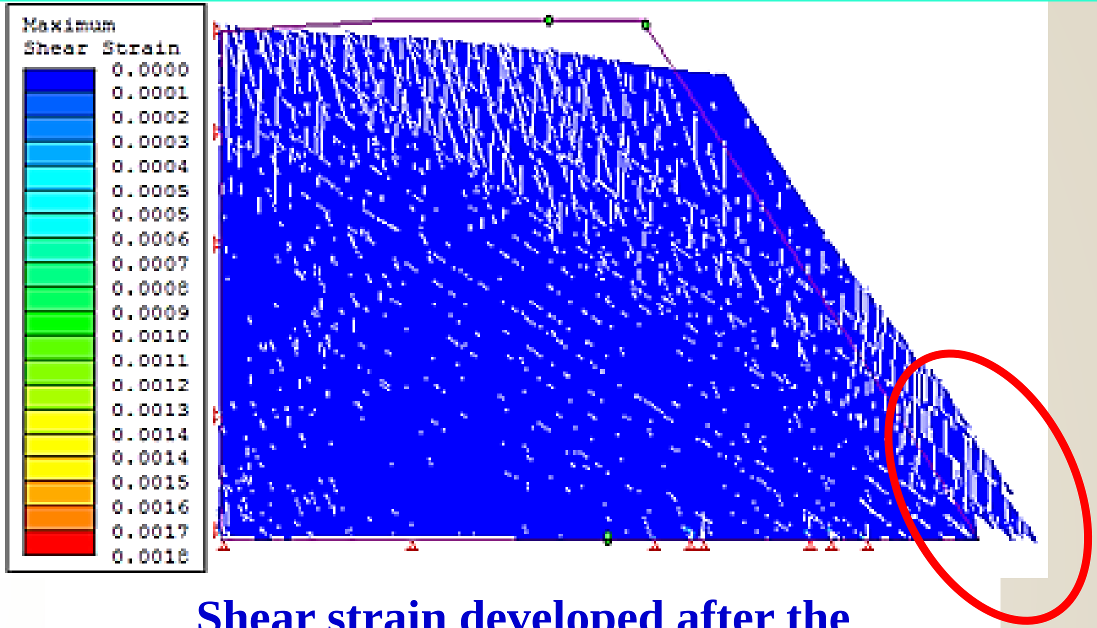
Average mesh size satisfied Lysmer-Kuhlemeyer (L-K) criteria

(Kuhlemeyer and Lysmer 1973)

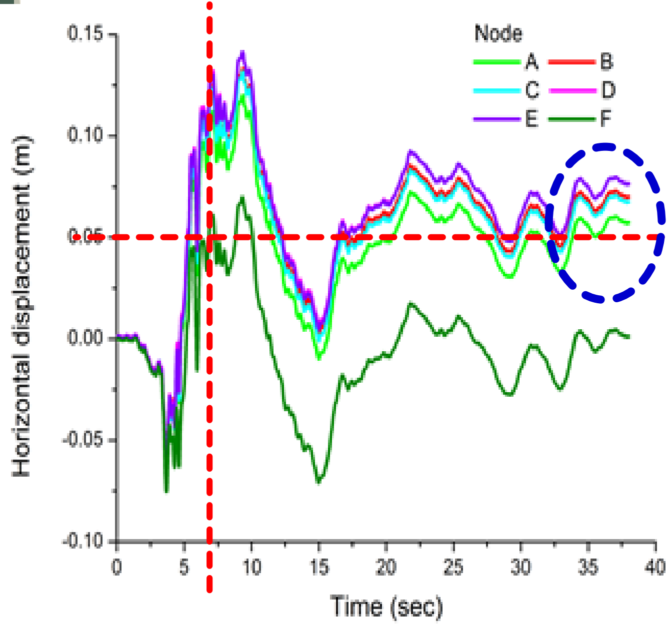
Outcomes from Time History Analysis

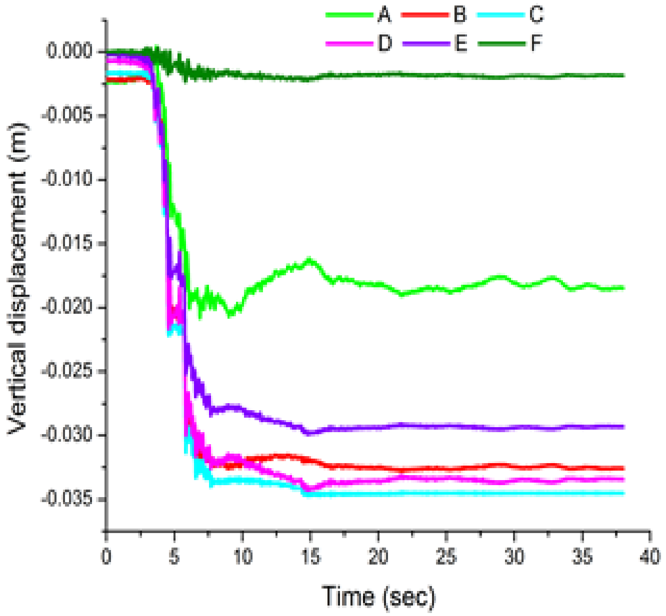


Displacement contour of the slope near the termination of seismic shaking



Shear strain developed after the application of dynamic load



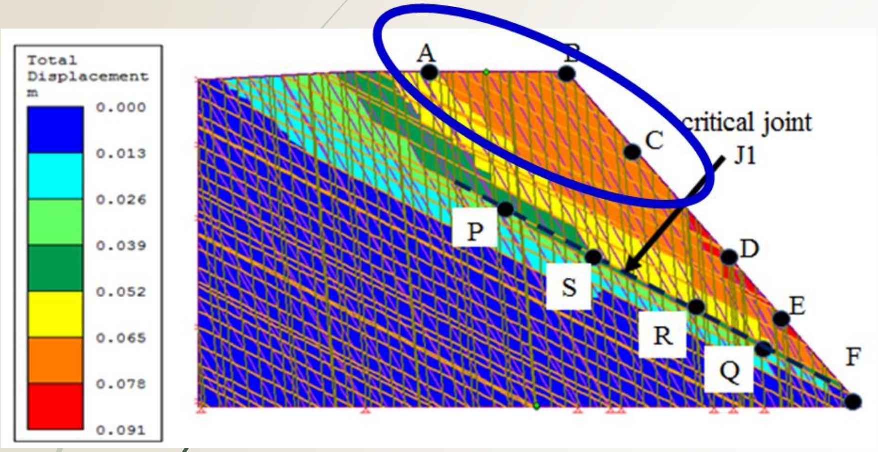


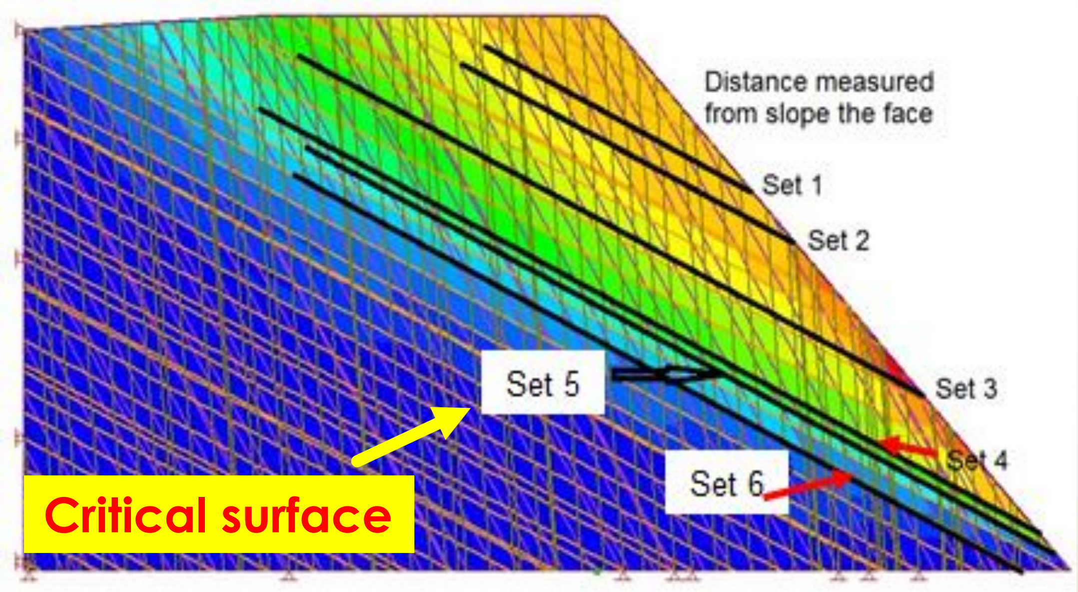
- ❑ Sliding of the slope along the joint set J1 which was predicted by pseudo static analysis
- ❑ Maximum deformation of the slope occurs in the vertical direction after 6.9 s
- ❑ Post seismic displacement more than 50 mm

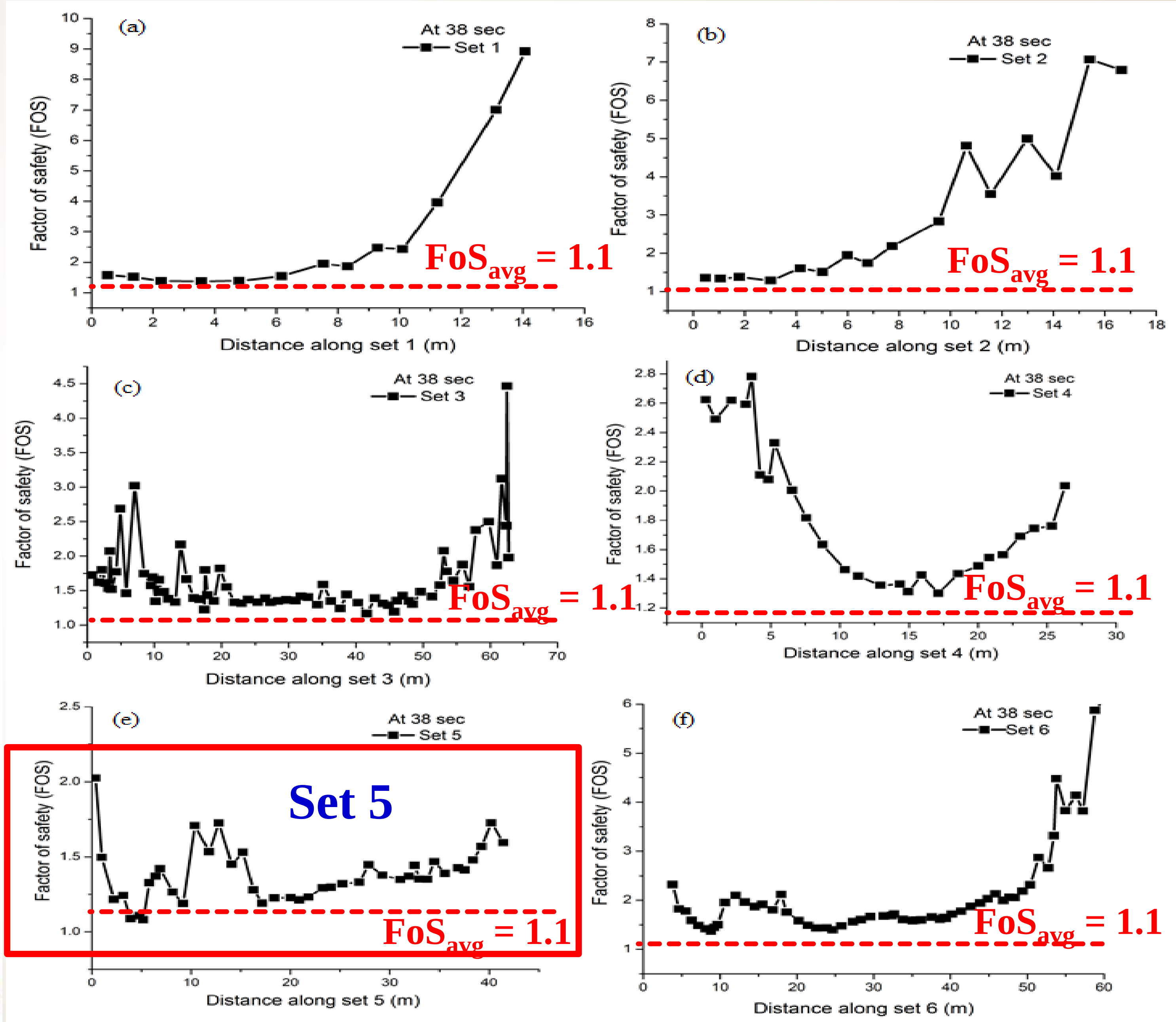
❑ TRIGGERING OF ROCKSLIDE

Outcomes from Time History Analysis

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

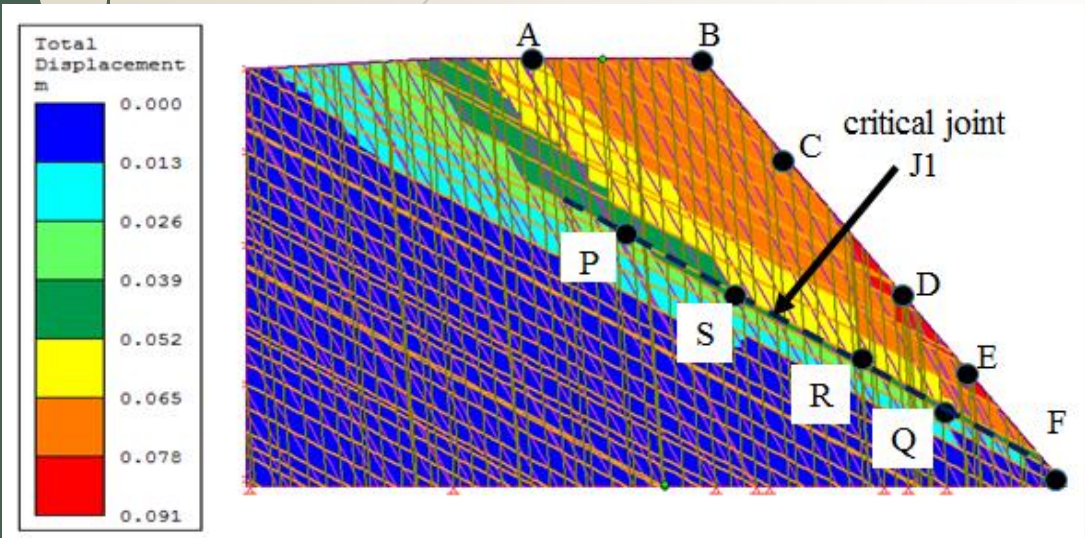


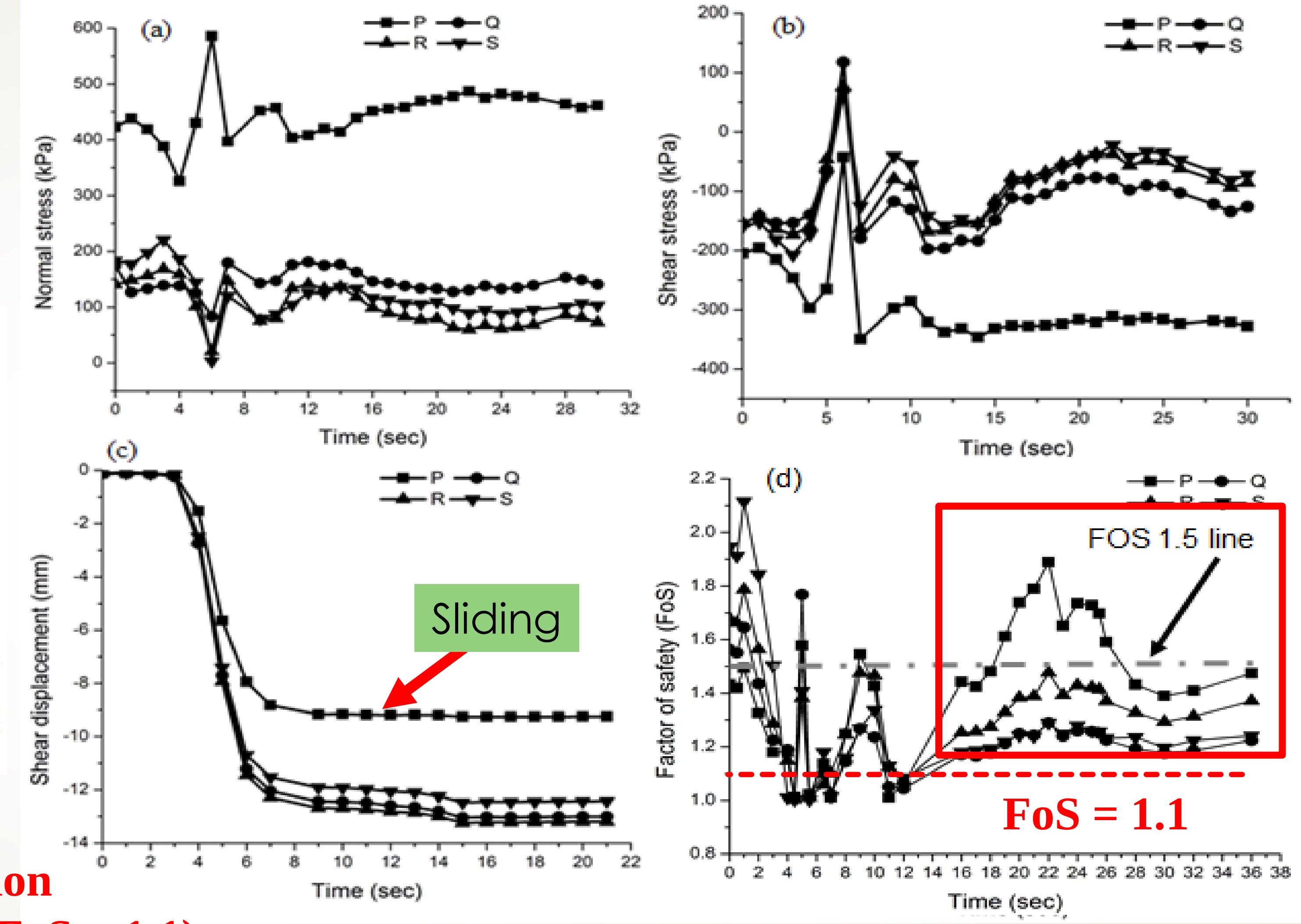




Outcomes from Time History Analysis

Which portion of critical joint Set 5 will fail??





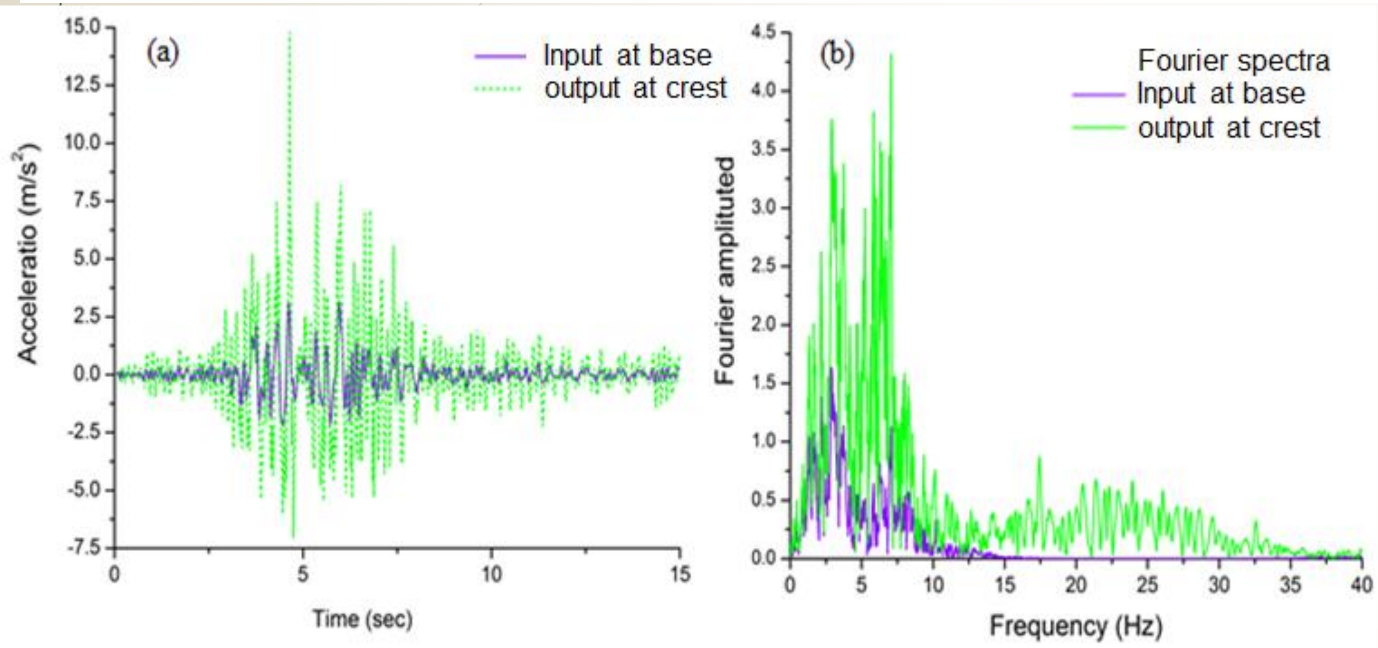
During peak acceleration
Entire joint set starts sliding (FoS < 1.1)

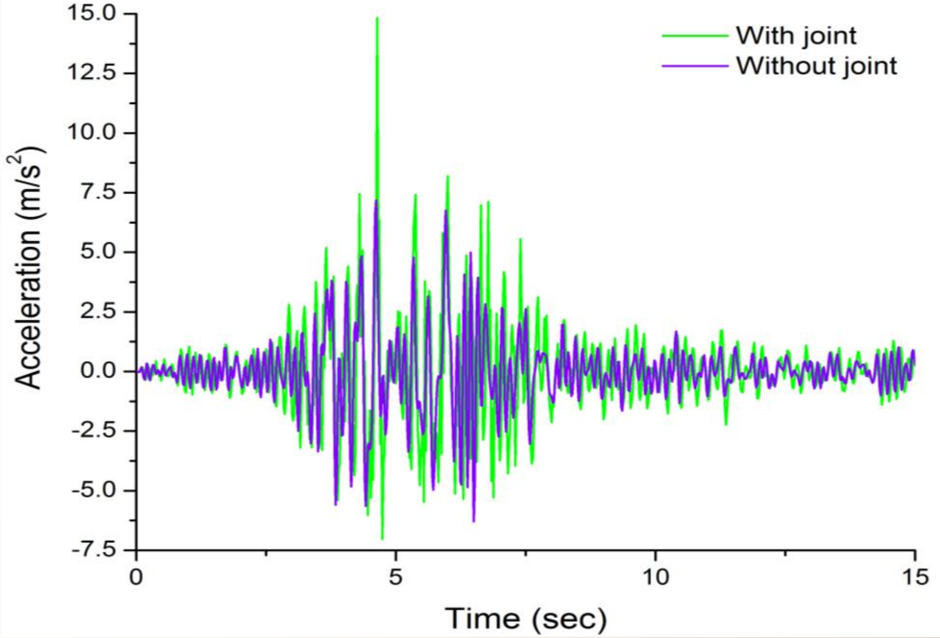
At the end of the motion
A complete sliding takes place (FoS < 1.5)

Temporal variation along the Critical Joint Set 5

Topographic Amplification of Seismic Wave within the Jointed Rock 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 within jointed rock slope

- **Depends on three factors: Geometry of the slope, material contrasts and internal fracture of the slope**
- **Joints can open up due to tensile stress leading to the trapping of energy and causing amplification**

Amplification of seismic wave in intact rock and jointed rock

Presence of joint resulted in higher amplification of the seismic wave

MAJOR CONTRIBUTIONS

- Utilizing the **trace plane concept**, an **efficient mechanism** has been developed that can map the existing joints with prevailing **3-D orientations** (within a jointed rock slope) **onto a 2-D plane**.
- A methodology is proposed to **identify the failure surface of jointed rock based on stress mobilization** at joints due to seismic load.
- **Within the restriction of FEEJM**, the proposed dynamic methodology **proficiently assessed the** vulnerability of a jointed rock slope, subjected to seismic load, **utilizing the post-seismic displacements and FoS obtained** at the cessation of the seismic motion.
- **FEEJM efficiently captured the amplification of input** wave in a steep and jointed rock slope **portraying realistic dynamic** response of the same.

SELECTED PUBLICATIONS

- Aswathi, C. K., Jana, A., **Dey, A.** and Sreedeep, S. (2019) "Stability assessment of reinforced rock slope based on two-dimensional Finite Element approach: A Himalayan case study" *Geotechnics for Transportation Infrastructure Vol 1*, *Lecture Notes in Civil Engineering Vol 28*, Ed. R. Sundaram, J. T. Shahu and V. Havanagi, Springer Nature, Singapore, pp. 639-650: ISBN No. 978-981-13-6701-4. (DOI: https://link.springer.com/chapter/10.1007/978-981-13-6701-4_41)
- Jana, A., Mithresh, P., **Dey, A.**, Sreedeep, S. and Murali Krishna, A. (2018) "Static and dynamic slope stability assessment of a Himalayan rock slope" *Geotechnical Applications*, *Lecture Notes in Civil Engineering Vol. 13*, Ed. I. V. Anirudhan, V. B. Maji, Springer, Singapore, pp. 231-239: ISBN No. 978-981-13-0367-8. (DOI: https://link.springer.com/chapter/10.1007/978-981-13-0368-5_25)
- Aswathi, C. K., Jana, A., **Dey, A.** and Sreedeep, S. (2018) "Stability assessment of reinforced rock slope based on two-dimensional finite element approach: A Himalayan case study" ***The Bridge and Structural Engineer (Indian Association of Bridge and Structural Engineers)***, Vol. 18, No. 2, pp. 56-62.
- Pushpan, M., Jana, A., Murali Krishna, A., **Dey., A.** and Sreedeep, S. (2017) "Stability assessment of a rock slope using finite element modeling" *Geotechniques for Infrastructure Projects*, Thiruvananthapuram, India, pp. 1-4.
- Jana, A., Pushpan, M., K., **Dey**, **A.** and Sreedeep, S. (2025) "Assessing rock slope stability under dynamic loading: A case study of North Sikkim, India" *Geotechnical Frontiers*, Kentucky, USA. (Full Paper Accepted)
- Jana, A., **Dey, A.** and Sreedeep, S. (2017) "Stability analysis of rock slope using combined continuum interface element method" *Geotechnics for Natural and Engineered Sustainable Technologies: Indian Geotechnical Conference (GeoNEst: IGC-2017)*, Guwahati, India, pp. 1-4.
- Aswathi, C. K., Jana, A., **Dey, A.** and Sreedeep, S. (2017) "Stability assessment of a heavily jointed rock slope using limit equilibrium and finite element methods" *Geotechnics for Natural and Engineered Sustainable Technologies: Indian Geotechnical Conference (GeoNEst: IGC-2017)*, Guwahati, India, pp. 1-4.

Acknowledgment

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Thank You for Patient Hearing

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