UNIVERSIDAD NACIONAL DE COLOMBIA

SEDE BOGOTÁ

FACULTAD DE INGENIERÍA

ÁREA CURRICULAR DE INGENIERÍA CIVIL Y AGRÍCOLA

**DOCTORADO EN INGENIERÍA - INGENIERÍA CIVIL**


Doctorado en Ingeniería

# Ingeniería Civil



UNIVERSIDAD NACIONAL DE COLOMBIA

ORGULLO UN

# Reliability Assessment of Rock Slopes by Discontinuous Deformation Analysis

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2. Rock Mass modeling
    1. Discrete models
3. Reliability Assessment
    1. Random set theory
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# Introduction

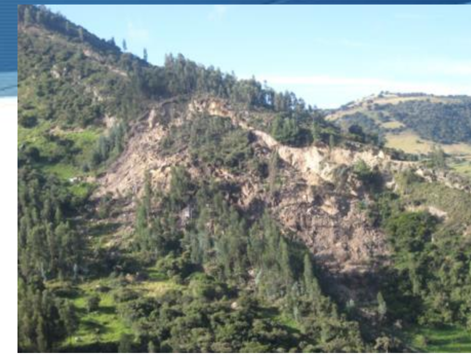
- Rock mass features

(1)

(2)

Rock mass features

Excavation process



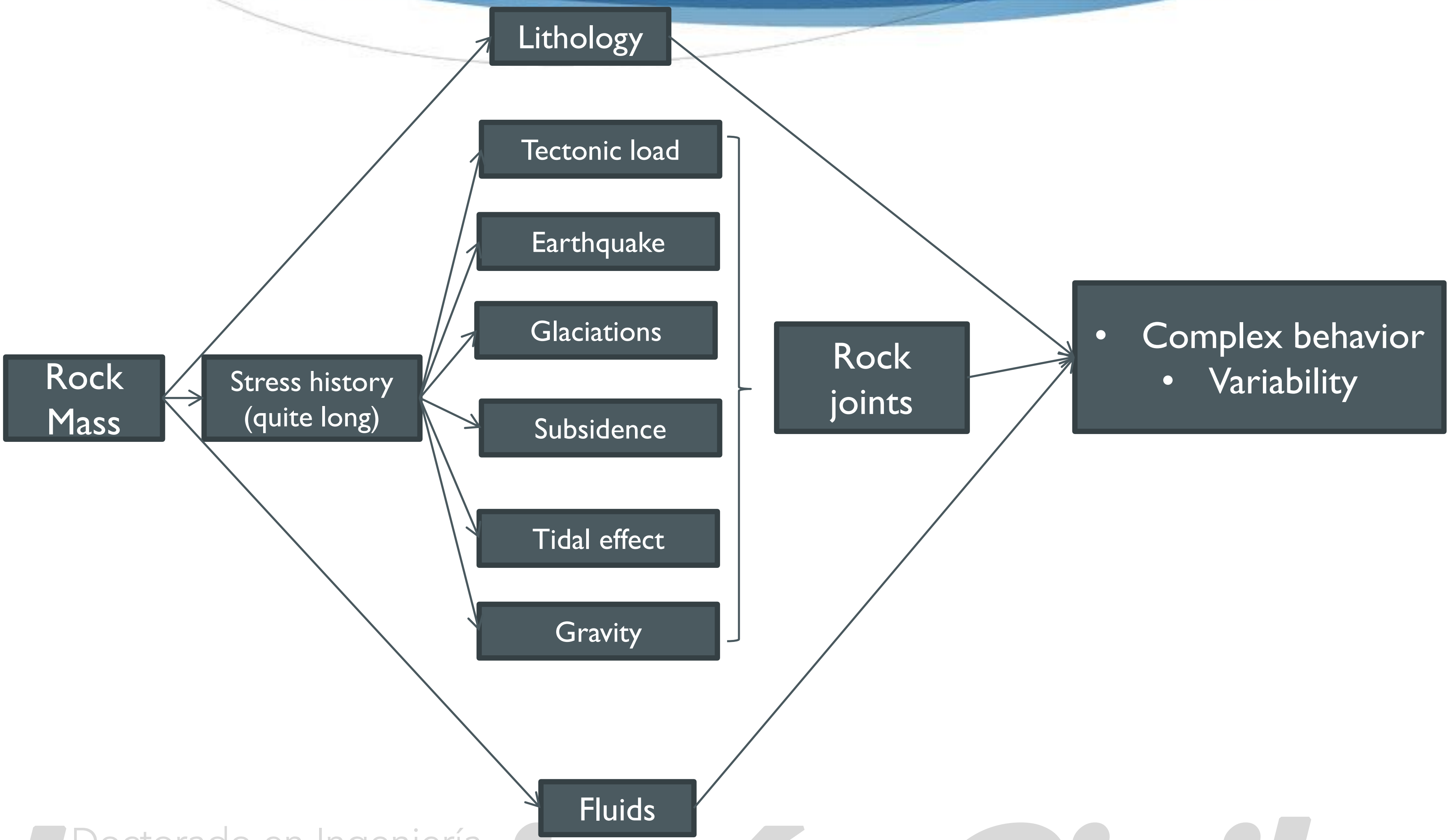
(3)

(4)

Rock slope failure

1. Vertical joint set in a limestone mine. Duitama Boyacá. Dip direction slightly changes from one joint to the next one
2. Rock slope in a limestone mine. Duitama, Boyacá.
3. Phosphate mine. Rock slope failure due to underground tunnel excavation. Firavitova, Boyacá
4. Rock slope failure in a limestone mine, controlled by the vertical joint set. Limestone mine.

# Introduction

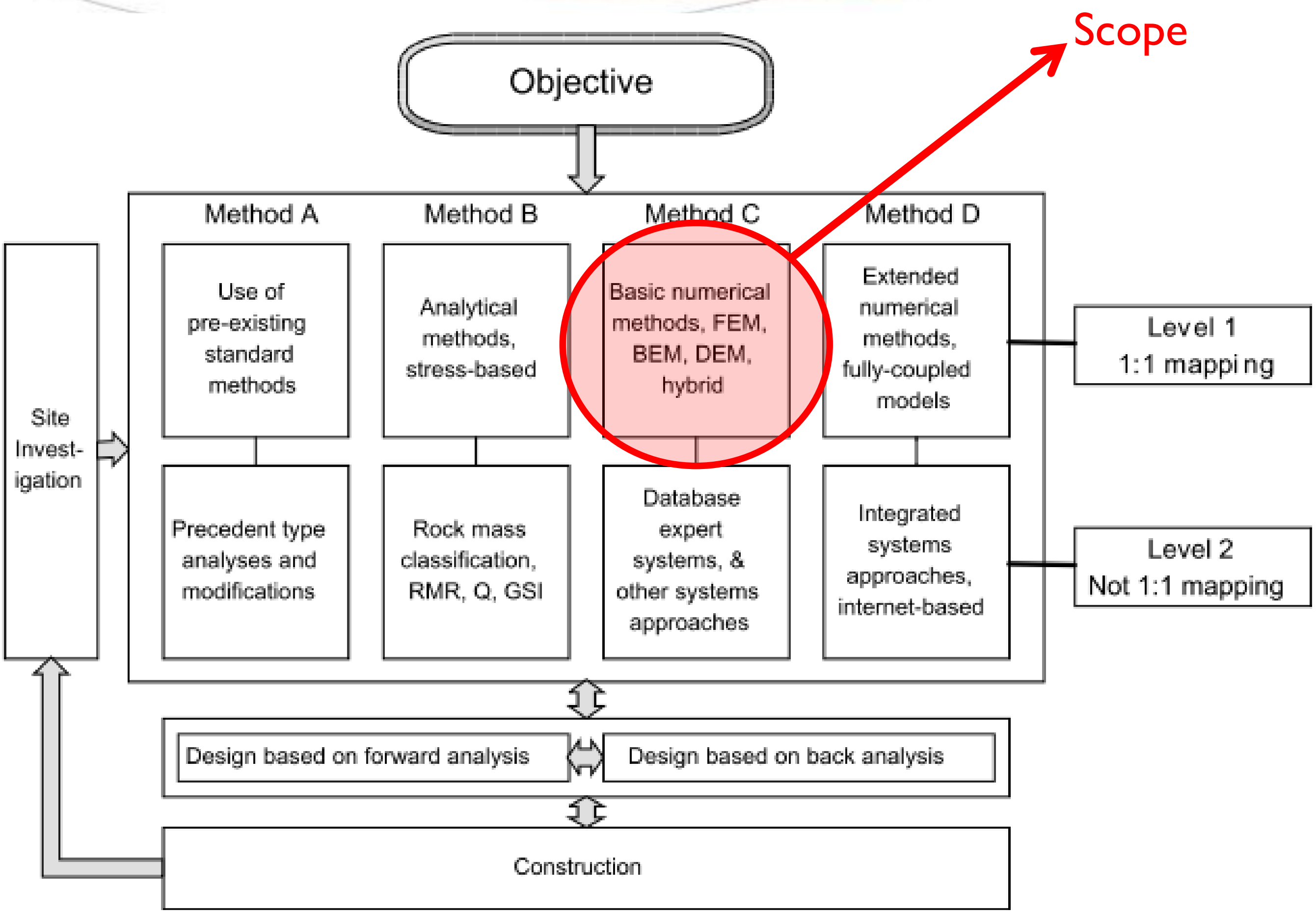


# Rock Mass Modeling

Model should have the following features (Jing, 2007):

- Represent the model rock mass geometry, including fractures and boundaries
- Represent the initial conditions of the problem
- Include the initial state of stresses
- Consider appropriate constitutive laws for both rock block and rock joints
- Include scale and time effects
- When environmental impact is an issue, model should consider a physical and chemical coupling

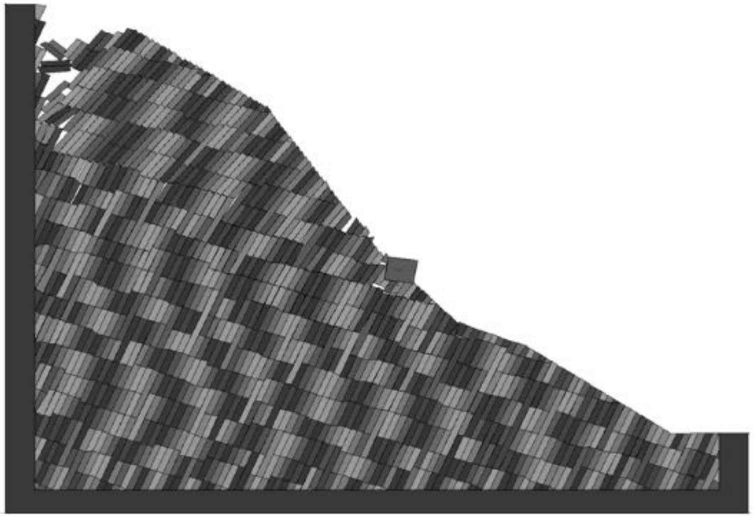
# Rock models




After Hudson 2001

# Numerical methods

- These can be either continuum or discontinuum (Jing and Hudson, 2002; Jing 2003)
- Discrete Elements methods
- Main features (Cundall, 1992)
  - Allow finite displacement and rotation of discrete bodies, including detachment
  - Automatically recognize new contacts between bodies during calculations



# Discontinuum based methods

- Methods
  - Distinct Elements Method (Cundall, 1971)
  - Discontinuos Deformation  Analysis (DDA) (Shi, 1985)
  - Numerical Manifold Method (NMM) (Shi, 1993)

- Three main issues (Jing, 2007):
  1. Representations of contacts
  2. Detection and revision of contacts during execution
  3. Representation of solid materials

# Discontinuous Deformation Analysis

Problems to solve (Jing, 2007)

- Representation of the fracture systems according to field mapping
- Identification of block-fracture system with fracture system regularization
- Formulation of motion equation (equilibrium equation)
- Representation of rock and fracture constitutve laws
- Represention of contact detection and evolution
- Integration of equations of motion and fluid flow
- Proper data structure for efficient computer programs

# Uncertainty

Classified into:

- *Aleatory (inherent) uncertainty*, representing the natural randomness of a variable. Cannot be reduced
- *Epistemic uncertainty*, representing the uncertainty due to lack of knowledge on a variable.
  - Measurement uncertainty
  - Statistical uncertainty (due to limited information)
  - Model uncertainty

  Can be reduced by:
  - Increasing the number of tests
  - Improving measurement methods

Sources of uncertainty in rock slopes:

- Discontinuity geometry (orientation, size, spacing)
- Discontinuity resistance either directly described by friction angle and cohesion or indirectly through roughness/irregularities and infillings
- Resistance of intact rock related to the persistence effect
- Water pressure/Ice pressure
- Vegetation, support
- Slope geometry

# Reliability assessment

Technique to deal with uncertainty

Limit state function g(x):

$$g(x) = \begin{cases} > 0 \; for\ the\ safe\ state\ of\ the\ structure \\ < 0 \; for\ the\ failure\ of\ the\ structure \end{cases}$$

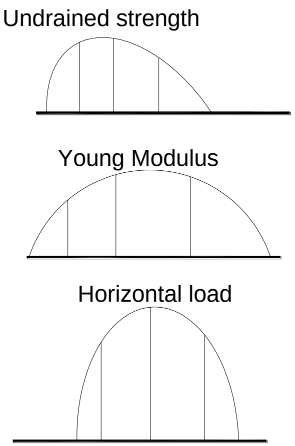
**X**= ($X_1$,$X_2$,...,$X_n$) Random variables

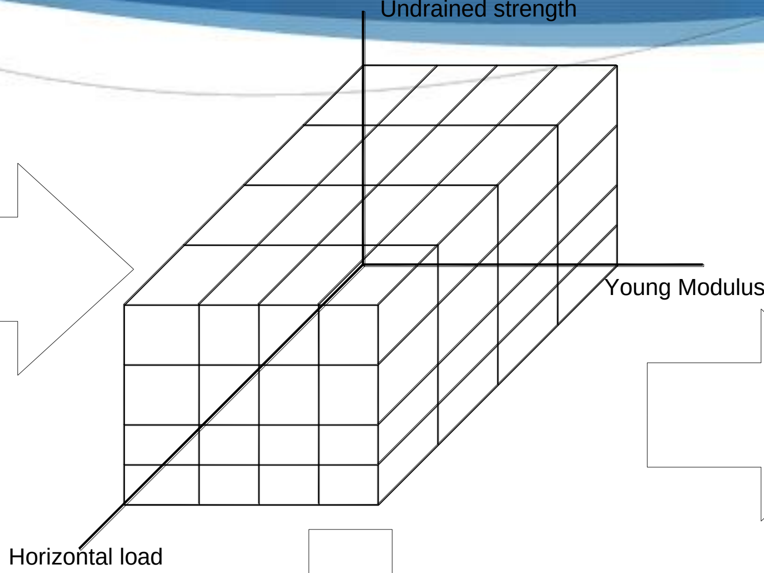
$$\mathrm{g(x)} = \alpha^* - \alpha(X_c, X_E, X_F)$$

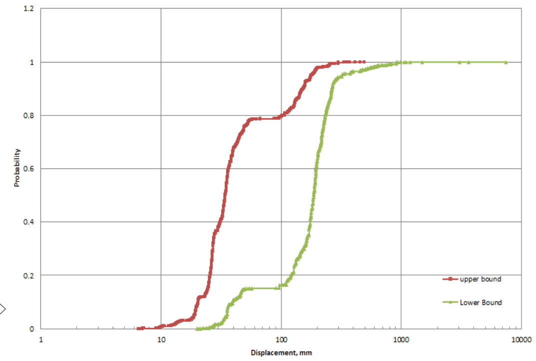
$$\mathrm{g(x)} = \left(\frac{\delta}{L}\right)^* - \left(\frac{\delta}{L}\right)^C$$

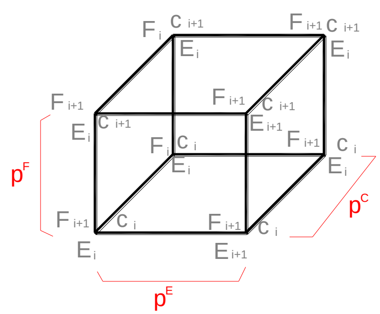
- FOSM Reliability Index. (First-Order, Second-Moment) approach(Ang & Tang 1984)
- *First- and second-order reliability methods(FORM and SORM)* Hasofer & Lind (1974)
- *Monte Carlo Simulation (improved by Latin Hypercube)*
- *RST Random Sets Theory*

PROBABILITY DENSITY FUNCTION




FEM MODEL

$d^{high}=g(c_i\, E_i\, F_{i+1})$

$d^{low}=g(c_{i+1}\, E_{i+1}\, F_i)$

JOINT PROBABILITY

$p^J = p^C * p^E * p^F$

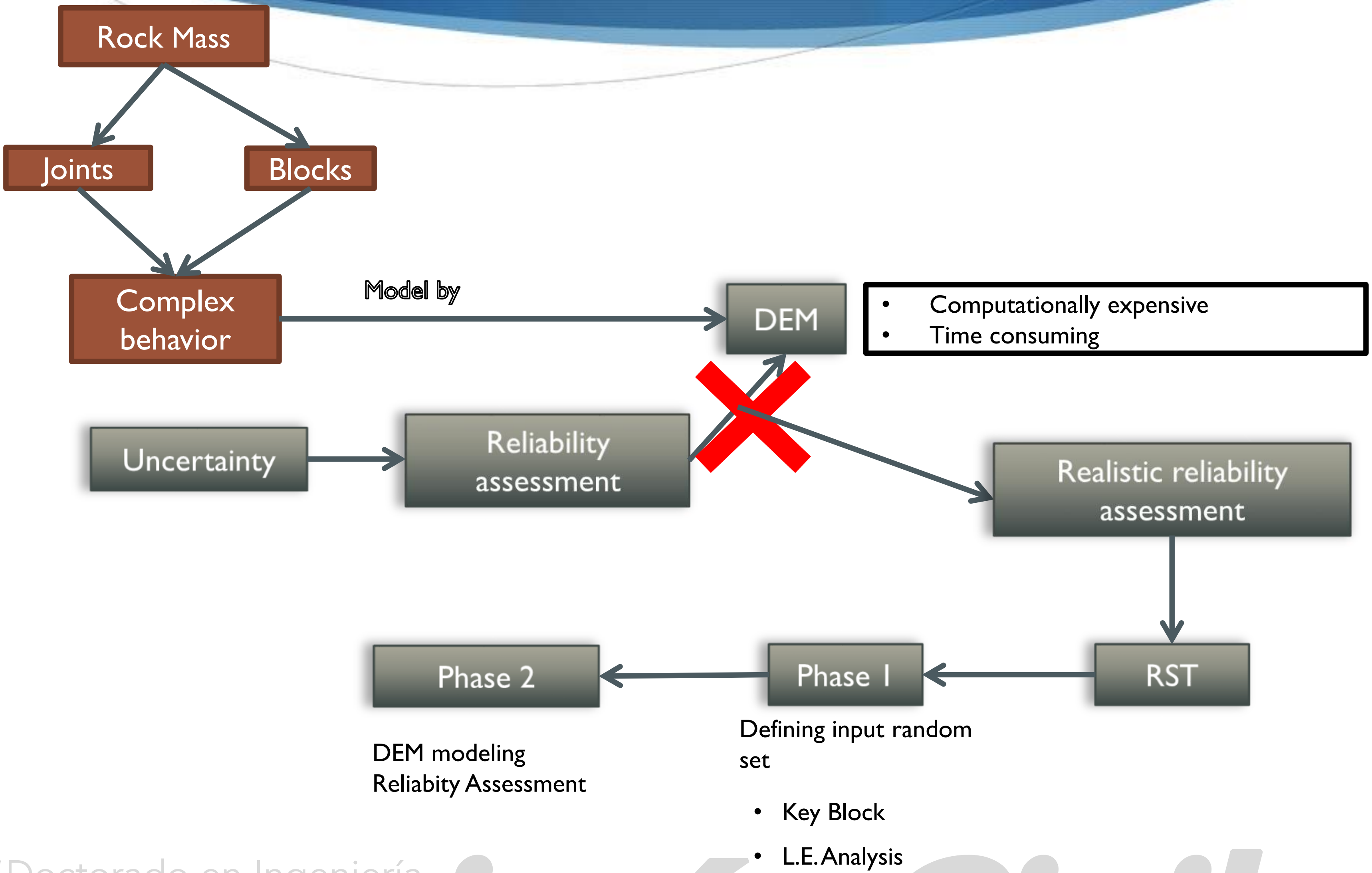
$D_j = (d^{low}\ d^{high})$

With a basic probability assignment $p^J$

# Probability function computation (upper)

- Assume that probability mass of each interval is concentrated at the lower bound of each focal element
- Sort lower bound from the smallest to the greatest
- Define interval from sorted data
- Assign probability concentrated on the low bound of the original focal element to each new interval
- Sum up the probability assigned to each interval

# Problem definition



# Methodology outline

**Field work**
- Rock mass data collection
- Rock block sampling

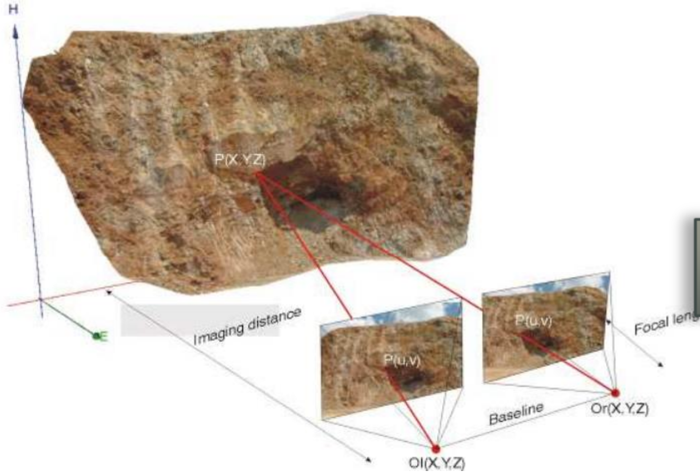
**Model generation**
- Block models generation

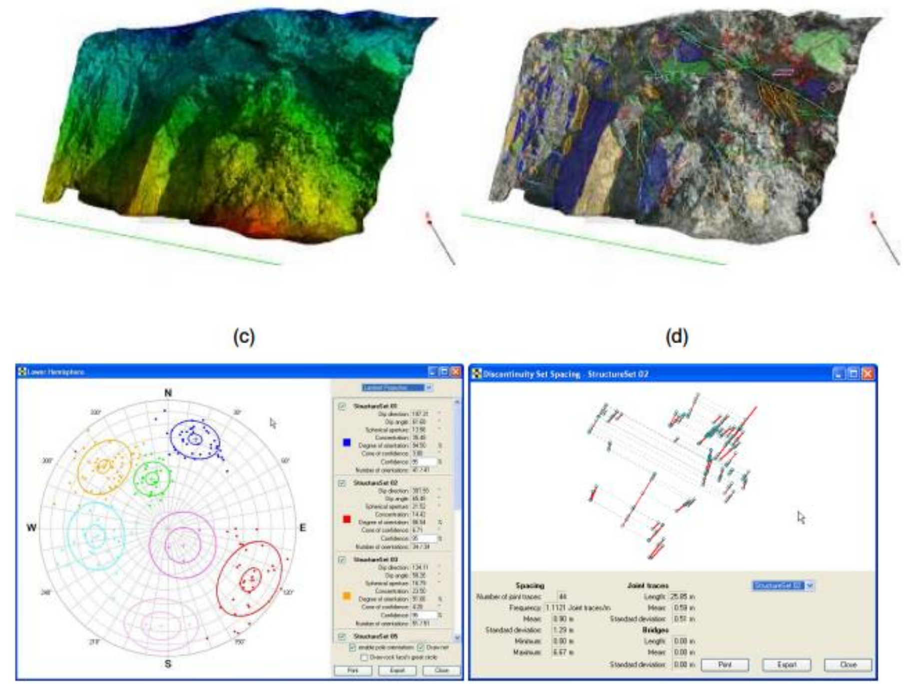
**Input random Sets**
- Key Block Analysis
- LE Analysis

**Discrete modelling**
- Discrete element modeling of all possible random input combinations

**Relability Assessment**
- Performace function definition
- Cumulative probability curves computation (dispolacements on slope face)
- Probability of failure calculation

# Field Work




(c) (d)

(e) (f)

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# THANKS