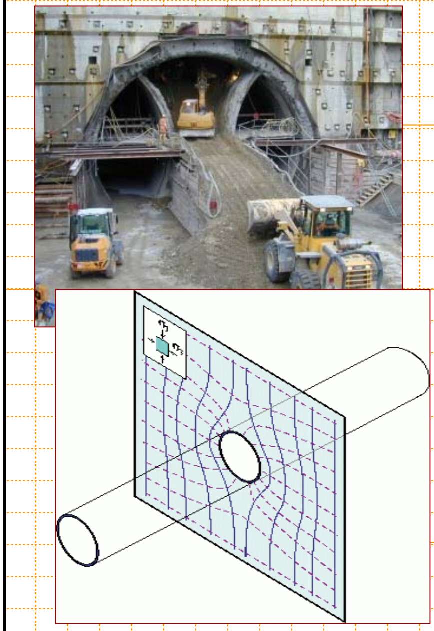


EOSC433/536:

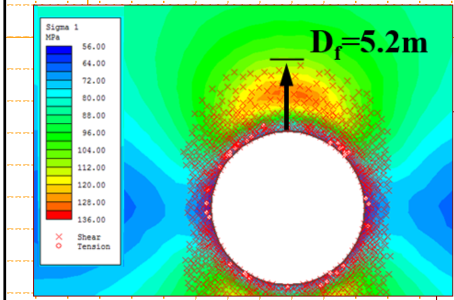
Geological Engineering Practice I – Rock Engineering

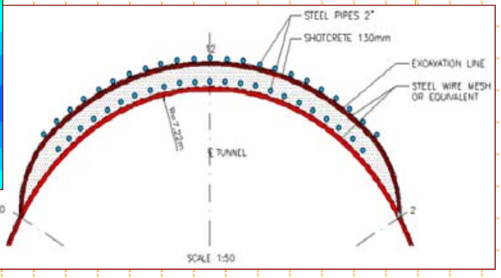
Lecture 1:

Introduction – Uncertainty & Design

Engineering Design

Engineering design is defined as a creative, iterative and open-ended process, subject to constraints imposed through legislative codes, project economics, health, safety, environmental and societal considerations.

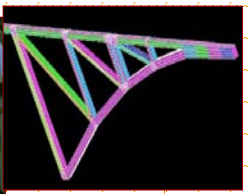




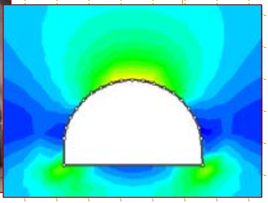
Engineering Design & Problem Uncertainty

Geotechnical engineers routinely deal with natural conditions that are largely unknown and must be inferred from limited and costly observations. Yet, many of the design tools used are borrowed from other engineering disciplines where the accuracy and completeness of the problem conditions are significantly different.

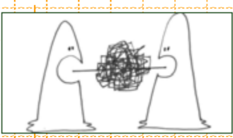
Structural engineering is largely deductive: we start from reasonably well known conditions, where models are employed to deduce the behavior of a reasonably well-specified problem.



In contrast, geological/geotechnical engineering is both deductive and inductive: we start from limited observations, and use judgment, experience, knowledge of geology and statistical reasoning to infer the behavior of a poorly-defined universe.



Complexity & Uncertainty



Discuss: What types of design uncertainty do you think are typically encountered on large engineering projects, for example the design of a large open pit mine?

Complexity & Uncertainty

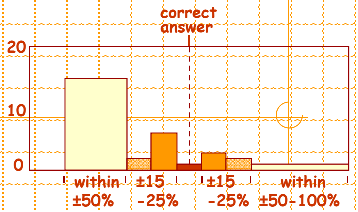
Geological Uncertainty: represents the unpredictability associated with the identification, characterization and interpretation of the site geology and hydrogeology.

Parameter Uncertainty: concerned with spatial variations and the lack of data for key parameters.

Model Uncertainty: arises from gaps in the scientific theory that is required to make predictions on the basis of causal inference.

Human Uncertainty: ranges from subjectivity and measurement error to differing professional opinions.

Prediction competition – collapse height of slope in soft clay. A substantial amount of shear strength data was provided to the 31 participants.



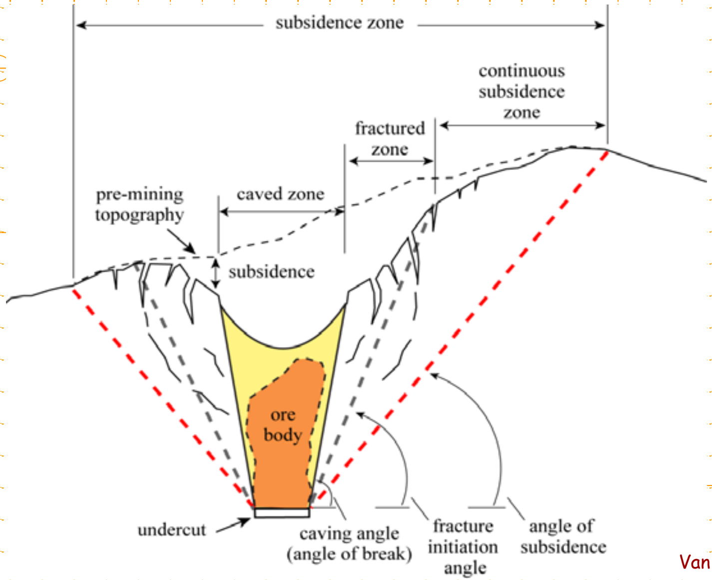
Design & Geological Uncertainty

Palabora (South Africa)

Classification = block cave copper mine
History = transition to underground mining following completion of open pit
Production = 30,000 tons/day
Ore grade = 0.7% Cu

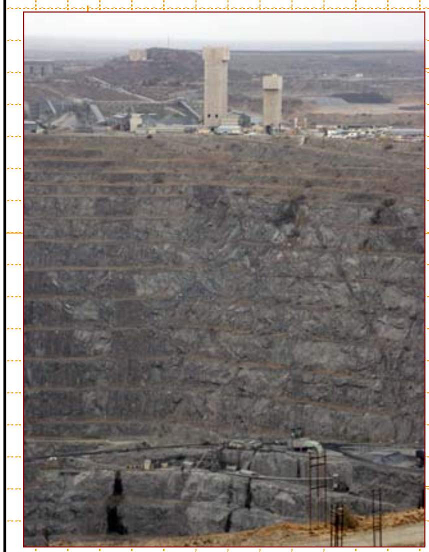
Moss et al. (2006)

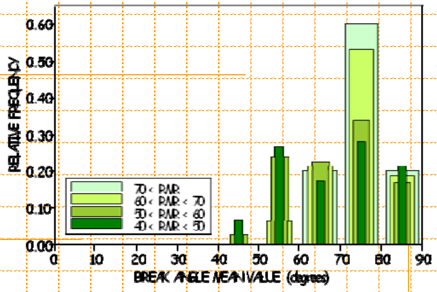
Design & Geological Uncertainty



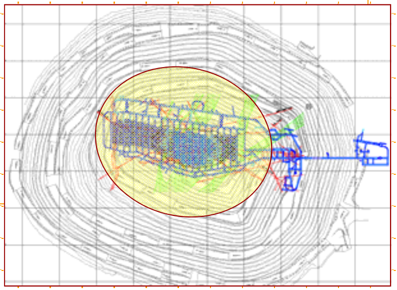
Van As *et al.* (2003)

Underground-Surface Mine Interactions





Flores & Karzulovic (2002)

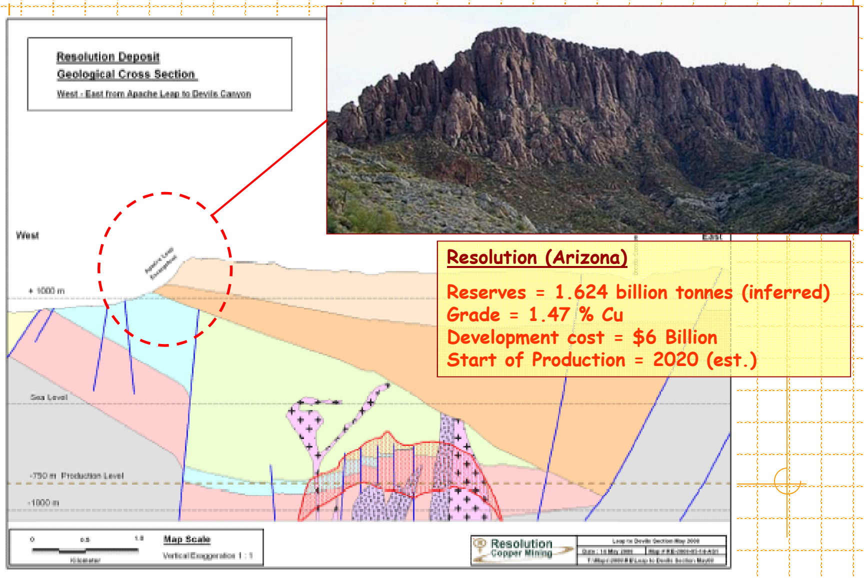


Rio Tinto Technical Services

Design & Geological Uncertainty

Design & Geological Uncertainty

www.resolutioncopper.com



Resolution (Arizona)

Reserves = 1.624 billion tonnes (inferred)
Grade = 1.47 % Cu
Development cost = $6 Billion
Start of Production = 2020 (est.)

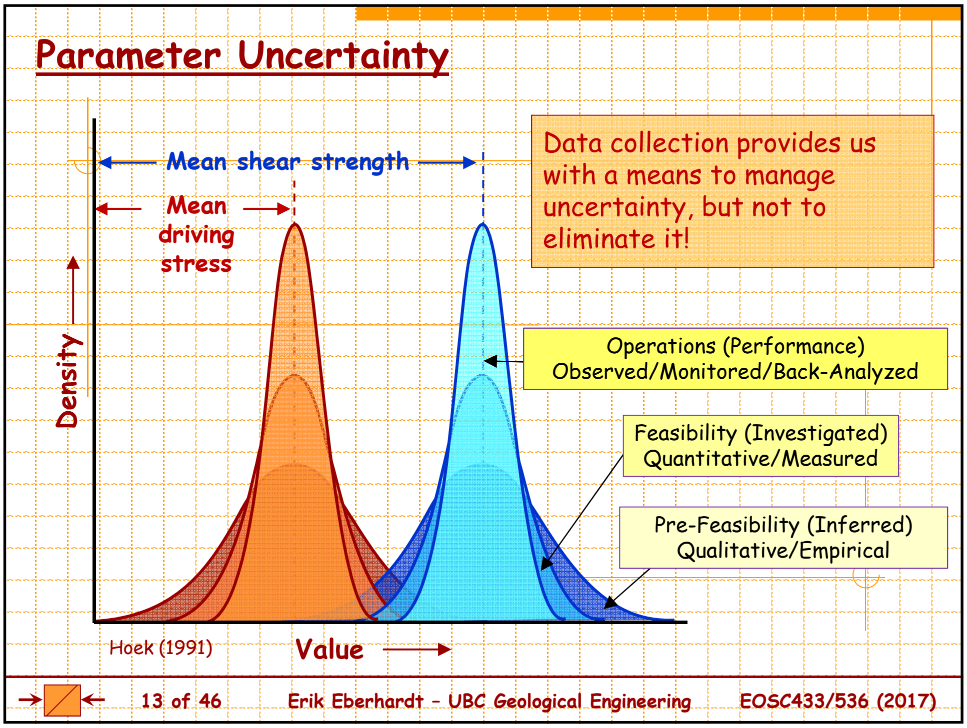
Complexity & Uncertainty

What makes Geological Engineering unique is the complexity and uncertainty involved when interacting with the natural geological environment.

Rock masses are complex systems!

Often, field data (e.g. geology, geological structure, rock mass properties, groundwater, etc.) is limited to surface observations and/or limited by inaccessibility, and can never be known completely.

Complexity & Uncertainty



Parameter Uncertainty

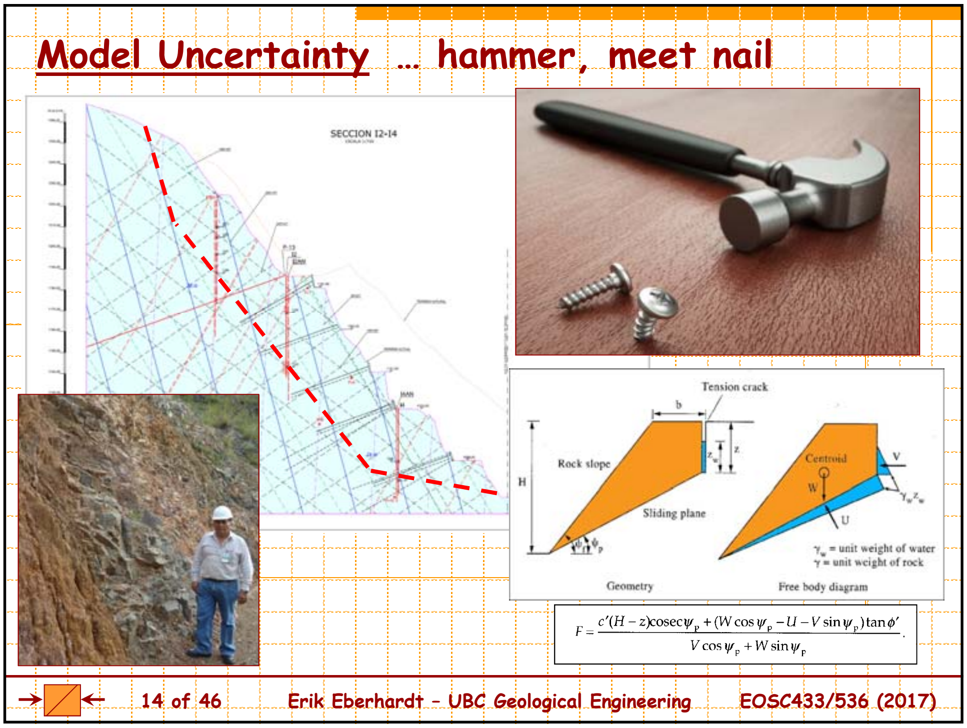
Data collection provides us with a means to manage uncertainty, but not to eliminate it!

Operations (Performance)
Observed/Monitored/Back-Analyzed

Feasibility (Investigated)
Quantitative/Measured

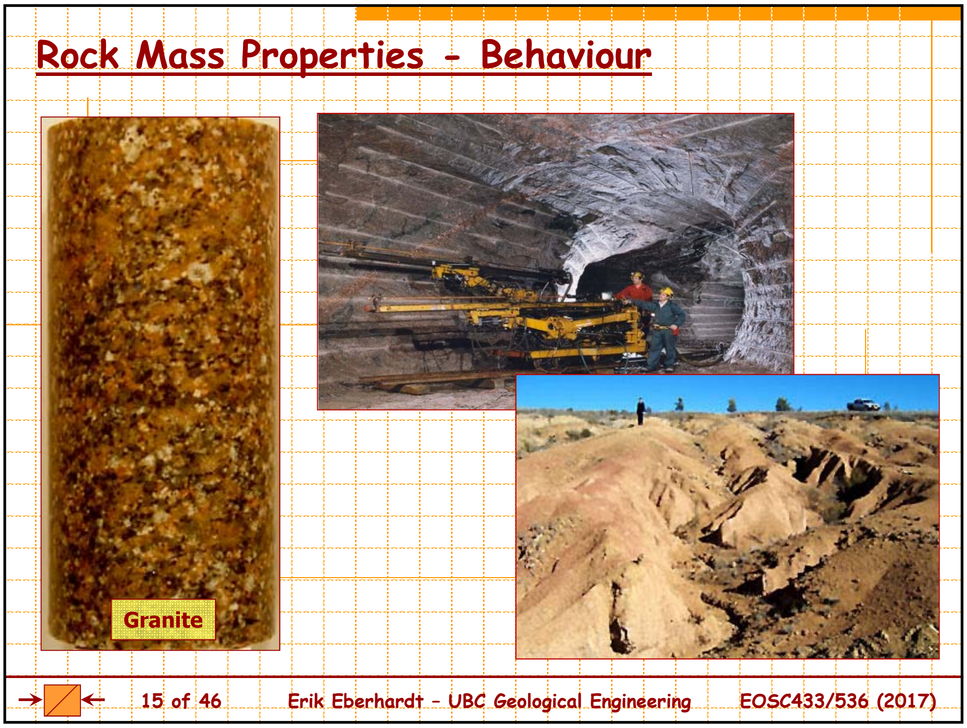
Pre-Feasibility (Inferred)
Qualitative/Empirical

Hoek (1991)



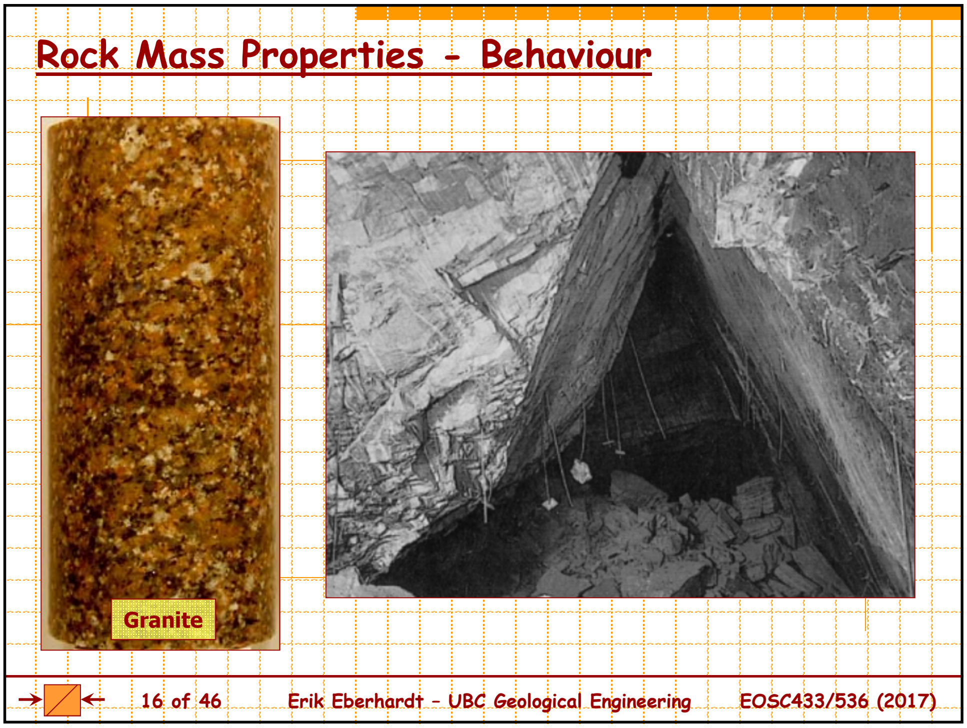
Model Uncertainty … hammer, meet nail

$$F = \frac{c'(H-z)\operatorname{cosec}\psi_p + (W\cos\psi_p - U - V\sin\psi_p)\tan\phi'}{V\cos\psi_p + W\sin\psi_p}.$$



Rock Mass Properties - Behaviour

15 of 46 Erik Eberhardt – UBC Geological Engineering EOSC433/536 (2017)



Rock Mass Properties - Behaviour

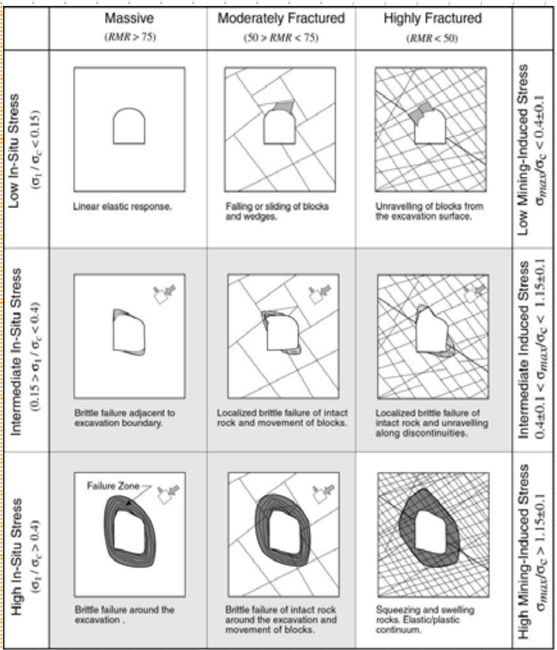
16 of 46 Erik Eberhardt – UBC Geological Engineering EOSC433/536 (2017)

Rock Mass Behaviour – High Stresses

Weak rock under high stresses may lead to **squeezing ground conditions**, which may result in damage/failure to the ground support system, or require the costly re-excavation of the tunnel section.

In strong brittle rock, high stress conditions may lead to **rockbursting** (the sudden release of stored strain energy). Bursts manifest themselves through the sudden ejection of rock into the excavation.

Rock Mass Behaviour



	Massive ($RMR > 75$)	Moderately Fractured ($50 > RMR < 75$)	Highly Fractured ($RMR < 50$)	
Low In-Situ Stress ($\sigma_1 / \sigma_c < 0.15$)	Linear elastic response.	Falling or sliding of blocks and wedges.	Unravelling of blocks from the excavation surface.	Low Mining-Induced Stress $\sigma_{max}/\sigma_c < 0.4\pm0.1$
Intermediate In-Situ Stress ($0.15 > \sigma_1 / \sigma_c < 0.4$)	Brittle failure adjacent to excavation boundary.	Localized brittle failure of intact rock and movement of blocks.	Localized brittle failure of intact rock and unravelling along discontinuities.	Intermediate Induced Stress $0.4\pm0.1 < \sigma_{max}/\sigma_c < 1.15\pm0.1$
High In-Situ Stress ($\sigma_1 / \sigma_c > 0.4$)	Failure Zone Brittle failure around the excavation .	Brittle failure of intact rock around the excavation and movement of blocks.	Squeezing and swelling rocks. Elastic/plastic continuum.	High Mining-Induced Stress $\sigma_{max}/\sigma_c > 1.15\pm0.1$

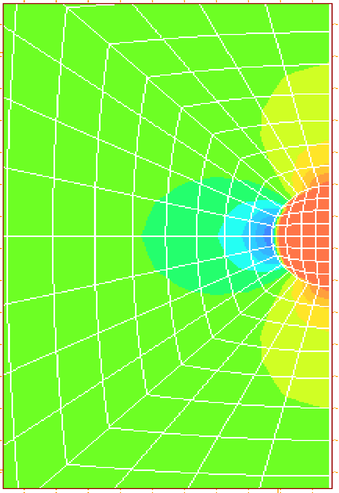
Kaiser *et al.* (2000)

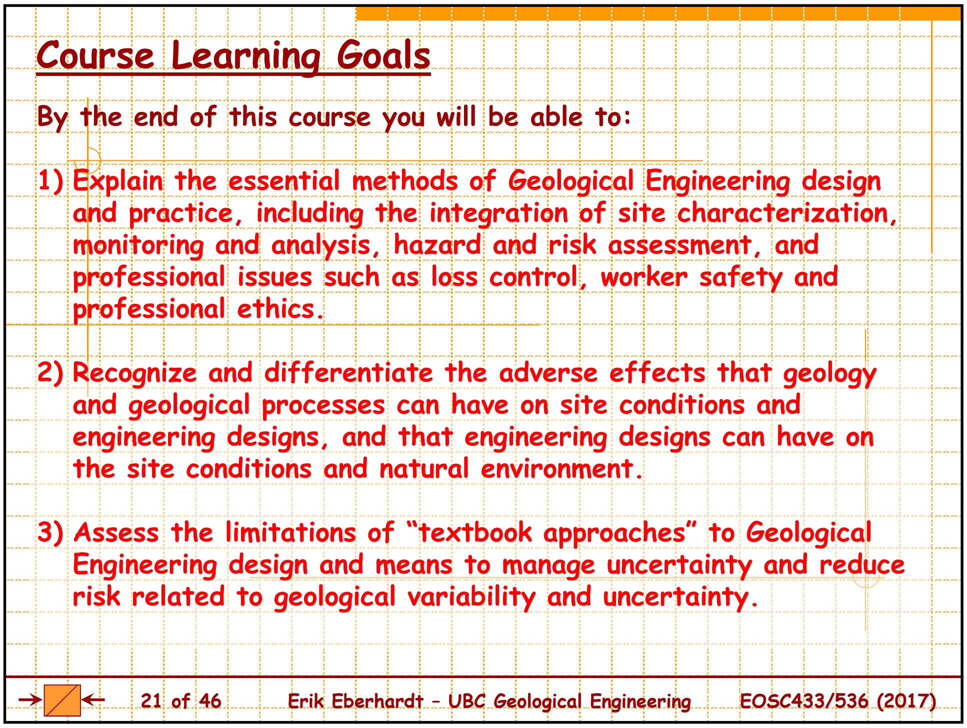
Course Overview & Learning Goals

This course will examine different principles, approaches, and tools used in geotechnical design. The examples and case histories reviewed will focus primarily on rock engineering problems, although many of the analytical, empirical and numerical techniques reviewed are also used in other areas of geological/geotechnical engineering.

Course Overview & Learning Goals

Through this course, you will develop an awareness of the different design methodologies and tools available to practicing geological engineers. More importantly, you will learn how to approach problem solving in the context of geological complexity and uncertainty. Emphasis will be placed on the importance of using design tools to aid in the thought and decision making process, as opposed to relying on them for outright predictions.





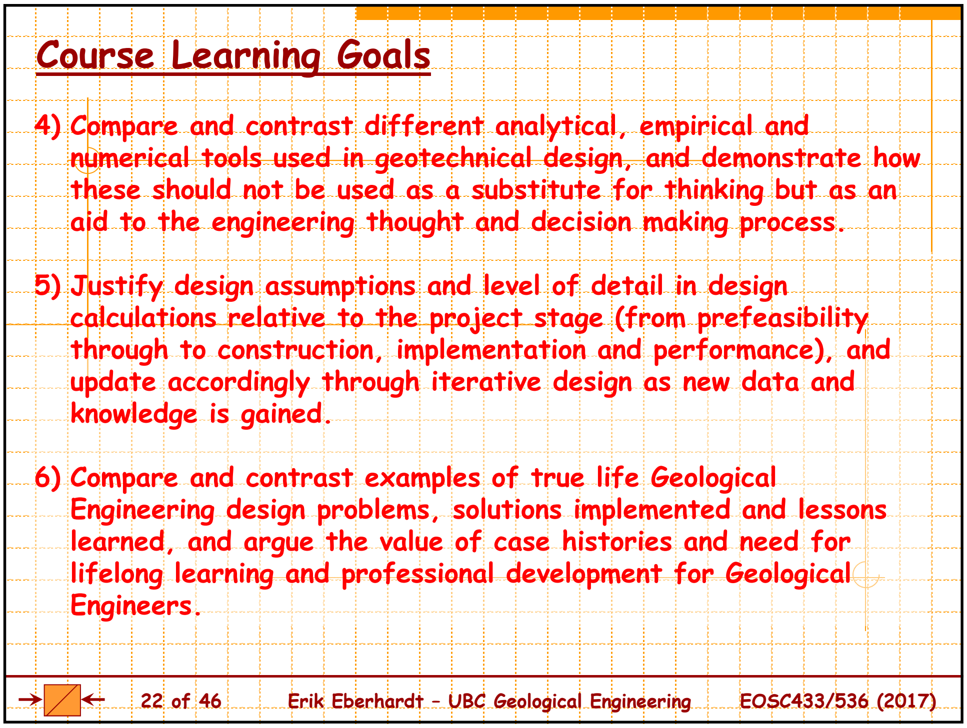
Course Learning Goals

By the end of this course you will be able to:

1) Explain the essential methods of Geological Engineering design and practice, including the integration of site characterization, monitoring and analysis, hazard and risk assessment, and professional issues such as loss control, worker safety and professional ethics.

2) Recognize and differentiate the adverse effects that geology and geological processes can have on site conditions and engineering designs, and that engineering designs can have on the site conditions and natural environment.

3) Assess the limitations of "textbook approaches" to Geological Engineering design and means to manage uncertainty and reduce risk related to geological variability and uncertainty.



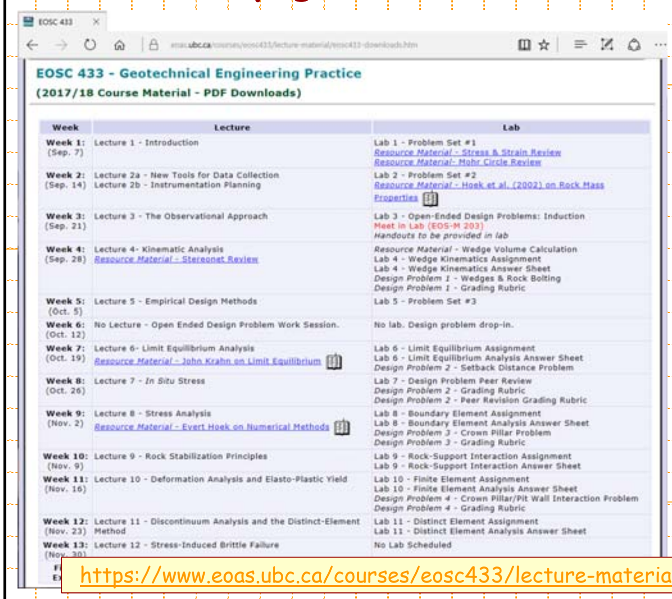
Course Learning Goals

4) Compare and contrast different analytical, empirical and numerical tools used in geotechnical design, and demonstrate how these should not be used as a substitute for thinking but as an aid to the engineering thought and decision making process.

5) Justify design assumptions and level of detail in design calculations relative to the project stage (from prefeasibility through to construction, implementation and performance), and update accordingly through iterative design as new data and knowledge is gained.

6) Compare and contrast examples of true life Geological Engineering design problems, solutions implemented and lessons learned, and argue the value of case histories and need for lifelong learning and professional development for Geological Engineers.

Course Webpage



EOSC 433 - Geotechnical Engineering Practice

(2017/18 Course Material - PDF Downloads)

Week	Lecture	Lab
Week 1: (Sep. 7)	Lecture 1 - Introduction	Lab 1 - Problem Set #1 *Resource Material - Stress & Strain Review* *Resource Material- Mohr Circle Review*
Week 2: (Sep. 14)	Lecture 2a - New Tools for Data Collection Lecture 2b - Instrumentation Planning	Lab 2 - Problem Set #2 *Resource Material - Hoek et al. (2002) on Rock Mass Properties*
Week 3: (Sep. 21)	Lecture 3 - The Observational Approach	Lab 3 - Open-Ended Design Problems: Induction Meet in Lab (EOS-M 203) *Handouts to be provided in lab*
Week 4: (Sep. 28)	Lecture 4- Kinematic Analysis *Resource Material - Stereonet Review*	*Resource Material* - Wedge Volume Calculation Lab 4 - Wedge Kinematics Assignment Lab 4 - Wedge Kinematics Answer Sheet *Design Problem 1* - Wedges & Rock Bolting *Design Problem 1* - Grading Rubric
Week 5: (Oct. 5)	Lecture 5 - Empirical Design Methods	Lab 5 - Problem Set #3
Week 6: (Oct. 12)	No Lecture - Open Ended Design Problem Work Session.	No lab. Design problem drop-in.
Week 7: (Oct. 19)	Lecture 6- Limit Equilibrium Analysis *Resource Material - John Krahn on Limit Equilibrium*	Lab 6 - Limit Equilibrium Assignment Lab 6 - Limit Equilibrium Analysis Answer Sheet *Design Problem 2* - Setback Distance Problem
Week 8: (Oct. 26)	Lecture 7 - *In Situ* Stress	Lab 7 - Design Problem Peer Review *Design Problem 2* - Grading Rubric *Design Problem 2* - Peer Revision Grading Rubric
Week 9: (Nov. 2)	Lecture 8 - Stress Analysis *Resource Material - Evert Hoek on Numerical Methods*	Lab 8 - Boundary Element Assignment Lab 8 - Boundary Element Analysis Answer Sheet *Design Problem 3* - Crown Pillar Problem *Design Problem 3* - Grading Rubric
Week 10: (Nov. 9)	Lecture 9 - Rock Stabilization Principles	Lab 9 - Rock-Support Interaction Assignment Lab 9 - Rock-Support Interaction Answer Sheet
Week 11: (Nov. 16)	Lecture 10 - Deformation Analysis and Elasto-Plastic Yield	Lab 10 - Finite Element Assignment Lab 10 - Finite Element Analysis Answer Sheet *Design Problem 4* - Crown Pillar/Pit Wall Interaction Problem *Design Problem 4* - Grading Rubric
Week 12: (Nov. 23)	Lecture 11 - Discontinuum Analysis and the Distinct-Element Method	Lab 11 - Distinct Element Assignment Lab 11 - Distinct Element Analysis Answer Sheet
Week 13: (Nov. 30)	Lecture 12 - Stress-Induced Brittle Failure	No Lab Scheduled

https://www.eoas.ubc.ca/courses/eosc433/lecture-material/eosc433-downloads.htm

Course Outline

Week 1: Introduction

- coarse overview; rock as an engineering material; design methodologies.

Lab 1 – *Problem set #1.*

Week 2: New Tools for Data Collection

- data quality and confidence; remote sensing tools for discontinuity mapping.

Lab 2 – *Problem set #2.*

Week 3: Observational Approach

- phenomenological vs mechanistic approaches; Terzaghi's observation method; use of monitoring data in design.

Lab 3 – *Lab Introduction to Design Process.*

Week 4: Kinematic Analysis

- structurally controlled failure; wedge volume calculations; key block theory.

Lab 4 – *UNWEDGE exercise & Design Problem #1.*

Course Outline

Week 5: Empirical Design *- derivation and application; rock mass classification vs. characterization; GSI.*	Lab 5 – *Problem Set #3*
Week 6: No Lecture *- Design problem work session.*	Lab – *No lab. Design problem drop-in.*
Week 7: Limit Equilibrium Analysis *- factor of safety; back & forward analysis; probabilistic analysis.*	Lab 6 – *SLIDE/LEM exercise & Design Problem #2*
Week 8: In Situ Stress *- stress as a boundary condition; direct vs. indirect measurement methods.*	Lab 7 – *Design Problem Peer Review.*
Week 9: Stress Analysis *- Kirsch equations; boundary-element method.*	Lab 8 – *EXAM^{2D}/BEM exercise & Design Problem #3*

Course Outline

Week 10: Rock Stabilization Principles *- support vs. reinforcement strategies; ground response curves; support interaction curves.*	Lab 9 – *RocSupport exercise.*
Week 11: Analysis of Yielding Rock *- constitutive behaviour; failure criterion; elasto-plastic yield; finite-element analysis.*	Lab 10 – *RS2/FEM exercise and Design Problem #4.*
Week 12: Analysis of Jointed Rock *- joint stiffness & strength; scale-effects; distinct-element analysis.*	Lab 11 – *UDEC/DEM exercise.*
Week 13: Stress-Controlled Failure *- brittle fracture processes; spalling; rock bursting.*	Lab – *No lab.*

General Information

Lectures: *Thursdays from 13:00 to 15:00 (ESB 2012)*

Labs: *L2A-Fridays from 14:00 to 16:00 (EOS-M 203)*
L2B-Thursdays from 16:00 to 18:00 (EOS-M 203)

TA's: *Afshin Amini (aamini@eoas.ubc.ca)*

Grades:

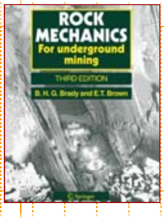
problem sets (2)	*10%*
lab assignments (best 5 of 6)	*10%*
open-ended design problems (4)	*30%*
final exam	*50%*

Contact Info – *Office: 251 EOS South*
E-mail: erik@eoas.ubc.ca

Course Web Page – */eoas.ubc.ca/courses/eosc433/eosc433.htm*

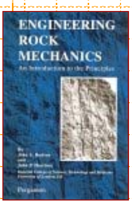
General Information

Text Book – *The textbook (optional) to be used for this course is:*



"Rock Mechanics for Underground Mining " *by B.H.G. Brady and E.T. Brown, Springer: Dordrecht, 2006.*

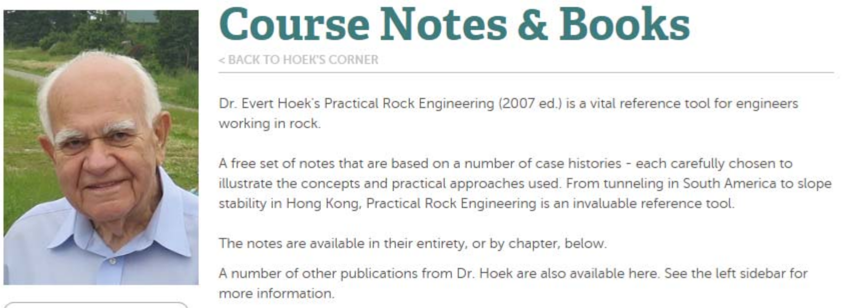
… or another option that isn't as mining-oriented:



"Engineering Rock Mechanics - An Introduction to the Principles " *by J.A. Hudson and J.P. Harrison, Elsevier Science: Oxford, 1997.*

Lecture Notes – *PDF's of these Powerpoint slides will be made available for download via the course web page.*

Free(!!) Resource



Course Notes & Books

< BACK TO HOEK'S CORNER

Dr. Evert Hoek's Practical Rock Engineering (2007 ed.) is a vital reference tool for engineers working in rock.

A free set of notes that are based on a number of case histories - each carefully chosen to illustrate the concepts and practical approaches used. From tunneling in South America to slope stability in Hong Kong, Practical Rock Engineering is an invaluable reference tool.

The notes are available in their entirety, or by chapter, below.

A number of other publications from Dr. Hoek are also available here. See the left sidebar for more information.

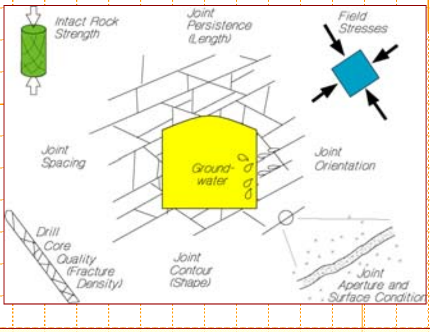
Practical Rock Engineering

www.rocscience.com/learning/hoek-s-corner/books

Influence of Geological Factors

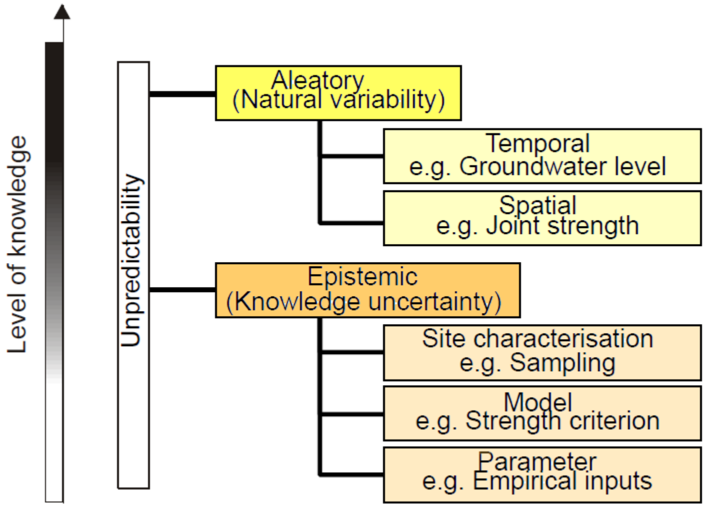
In the context of the mechanics problem, we should consider the material and the forces involved. As such, five primary geological factors can be viewed as influencing a rock mass.

- We have the intact rock which is itself divided by discontinuities to form the rock mass structure.
- We find then the rock is already subjected to an *in situ* stress.
- Superimposed on this are the influence of pore fluid/water flow and time.



With all these factors, the geological history has played its part, altering the rock and the applied forces.

Uncertainty & Variability



Level of knowledge

Unpredictability

Aleatory
(Natural variability)

- Temporal
  e.g. Groundwater level
- Spatial
  e.g. Joint strength

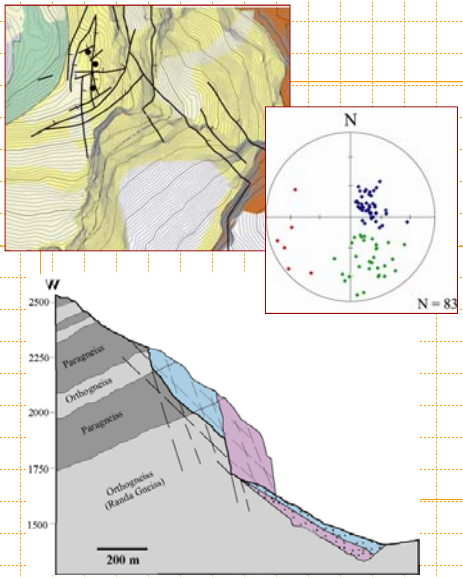
Epistemic
(Knowledge uncertainty)

- Site characterisation
  e.g. Sampling
- Model
  e.g. Strength criterion
- Parameter
  e.g. Empirical inputs

Baecher & Christian (2003)

Site Investigation & Data Collection

Willenberg *et al.* (2008)



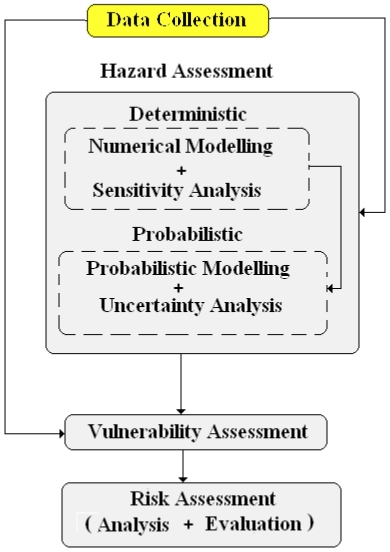
Geological investigations ↔ Geophysical investigations

geological model

↓

Rockmass processes

Integrated Risk Assessment

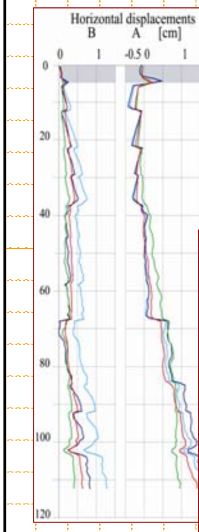


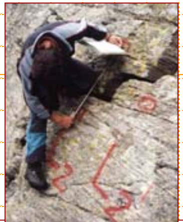
Düzgün & Lacasse (2005)

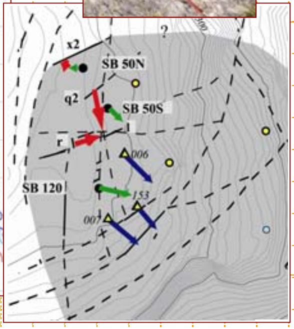
Data Collection

- Geology
- Geometry
- Strength
- Groundwater
- Dynamic loads
- Elements at Risk

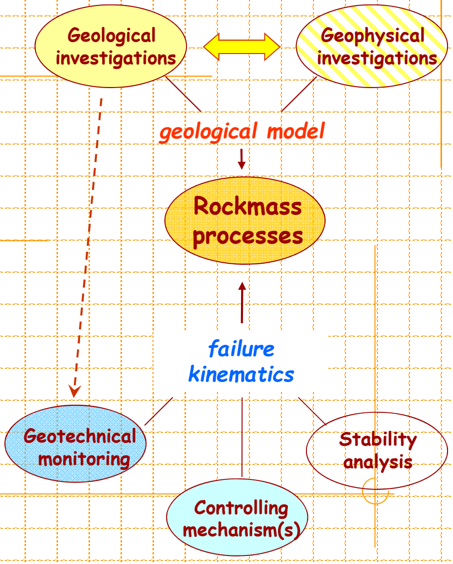
Site Investigation & Data Collection





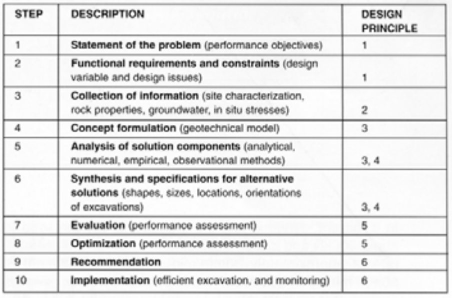


Willenberg *et al.* (2008)

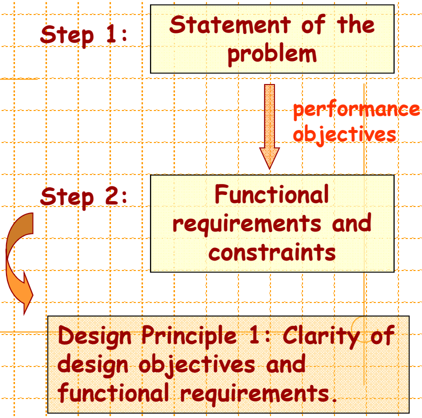


Design Methodology

Successful engineering design involves a design process, which is a sequence of events within which design develops logically. Bieniawski (1993) summarized a 10 step methodology for rock engineering design problems, incorporating 6 design principles:



STEP	DESCRIPTION	DESIGN PRINCIPLE
1	**Statement of the problem** (performance objectives)	1
2	**Functional requirements and constraints** (design variable and design issues)	1
3	**Collection of information** (site characterization, rock properties, groundwater, in situ stresses)	2
4	**Concept formulation** (geotechnical model)	3
5	**Analysis of solution components** (analytical, numerical, empirical, observational methods)	3, 4
6	**Synthesis and specifications for alternative solutions** (shapes, sizes, locations, orientations of excavations)	3, 4
7	**Evaluation** (performance assessment)	5
8	**Optimization** (performance assessment)	5
9	**Recommendation**	6
10	**Implementation** (efficient excavation, and monitoring)	6



Step 1: Statement of the problem

performance objectives

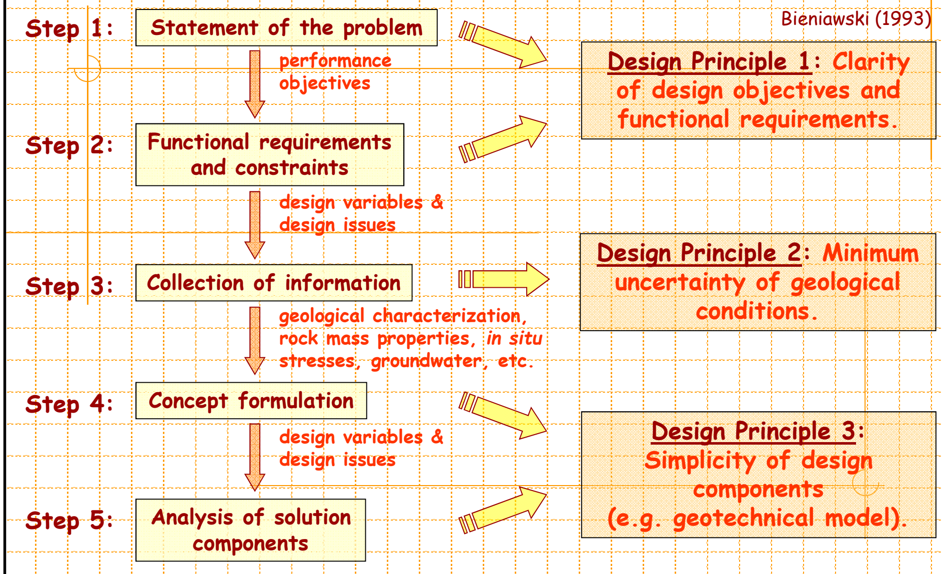
Step 2: Functional requirements and constraints

Design Principle 1: Clarity of design objectives and functional requirements.

Bieniawski (1993)

Design Methodology

Bieniawski (1993)



Step 1: Statement of the problem

performance objectives

Step 2: Functional requirements and constraints

design variables & design issues

Step 3: Collection of information

geological characterization, rock mass properties, *in situ* stresses, groundwater, etc.

Step 4: Concept formulation

design variables & design issues

Step 5: Analysis of solution components

Design Principle 1: Clarity of design objectives and functional requirements.

Design Principle 2: Minimum uncertainty of geological conditions.

Design Principle 3: Simplicity of design components (e.g. geotechnical model).

Step 5: Analysis of solution components

observational, analytical, empirical, numerical methods

Step 6: Synthesis and specification for alternative solutions

shapes & sizes of excavations, rock reinforcement options and associated safety factors

Step 7: Evaluation

performance assessment

Step 8: Optimization

consideration of non-rock engineering aspects (ventilation, power supply, etc.)

Step 9: Recommendation

- feasibility study
- preliminary & final designs

Step 10: Implementation

efficient excavation & monitoring

lessons learned

Design Principle 3: Simplicity of design components.

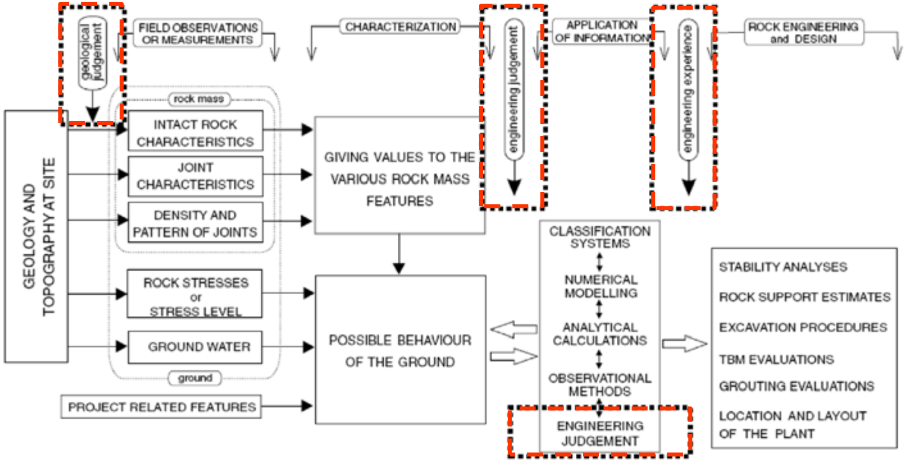
Design Principle 4: State of the art practice.

Design Principle 5: Optimization of design (through evaluation of analysis results, monitoring, etc.).

Design Principle 6: Constructability (can the design be implemented safely and efficiently).

Bieniawski (1993)

Engineering Judgement



Palmström & Stille (2007)

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