DESIGN AND CONSTRUCTION OF LARGE CAVERNS

- Background
  - Requirements
  - Given Conditions
  - Resulting Problems
- Objectives
- Approach
- S-4 Project - Cavern Design for DUSEL
  - Development
  - Structure
  - Project Details
- Comments about Risk
- Conclusions

BACKGROUND

REQUIREMENTS
- Caverns and access tunnels/shafts at various sizes.
  At least one cavern 50 m × 20 (plus) m, 1500 m overburden
- Stable during construction and operation (long term!)
- Minimize deformation (creep) during operation
- Reliable construction cost/time estimates

GIVEN CONDITIONS (WHAT IS THERE, WILL BE THERE)
- Lithology
- Fractures
- Stress State
- Water pressure/flow
- Modification of given conditions through construction - short/long term

RESULTING PROBLEMS
- Exploration what, when
- Exploration cannot be complete - uncertainties remain
- Applicability of existing analysis and design approaches?
- Performance - and cost/time prediction subject to uncertainties

Sources of Uncertainty

Type 1	Innate spatial (and temporal) variability of geological factors of nature in general.
Type 2	Errors introduced by measuring and estimating engineering properties, including statistical fluctuation
Type 3	Model uncertainties
Type 4	Load uncertainty
Type 5	Omissions

OBJECTIVES

- Reduce uncertainties about in-situ conditions and about performance through research

- Use this research to advance knowledge in geomechanics and geotechnical engineering

- Help designers to come up with best design and to consider inevitable remaining uncertainties in design

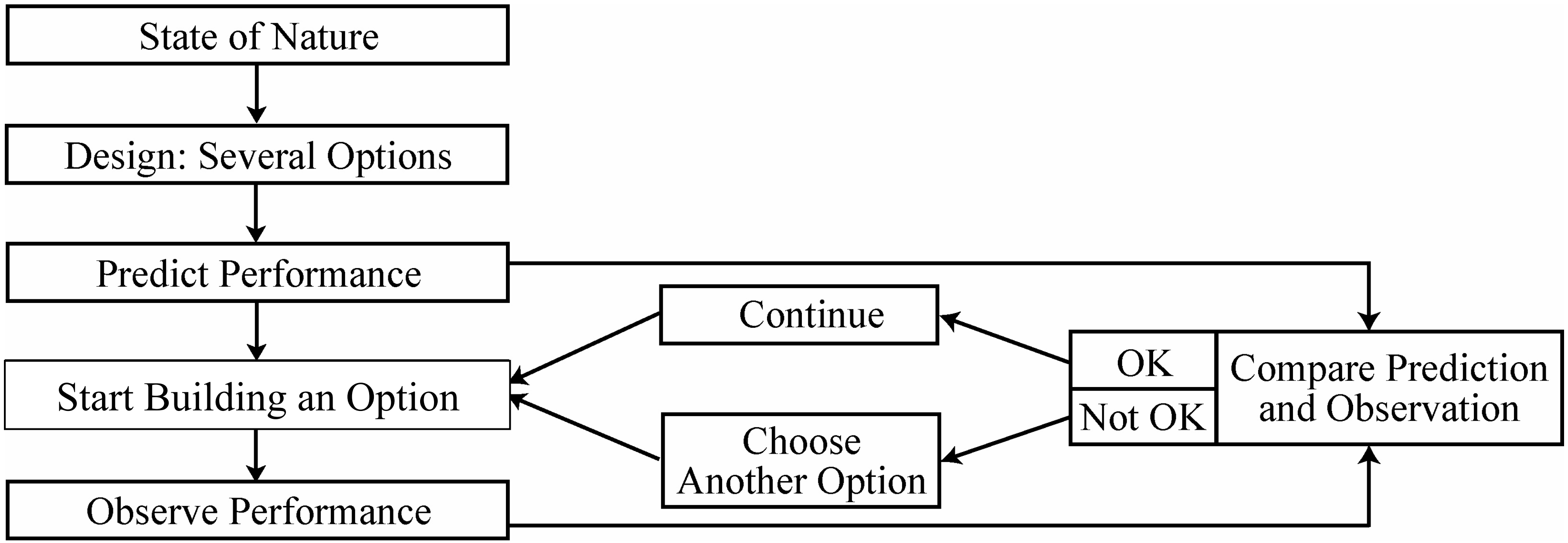
APPROACH

- Extended Observational Method

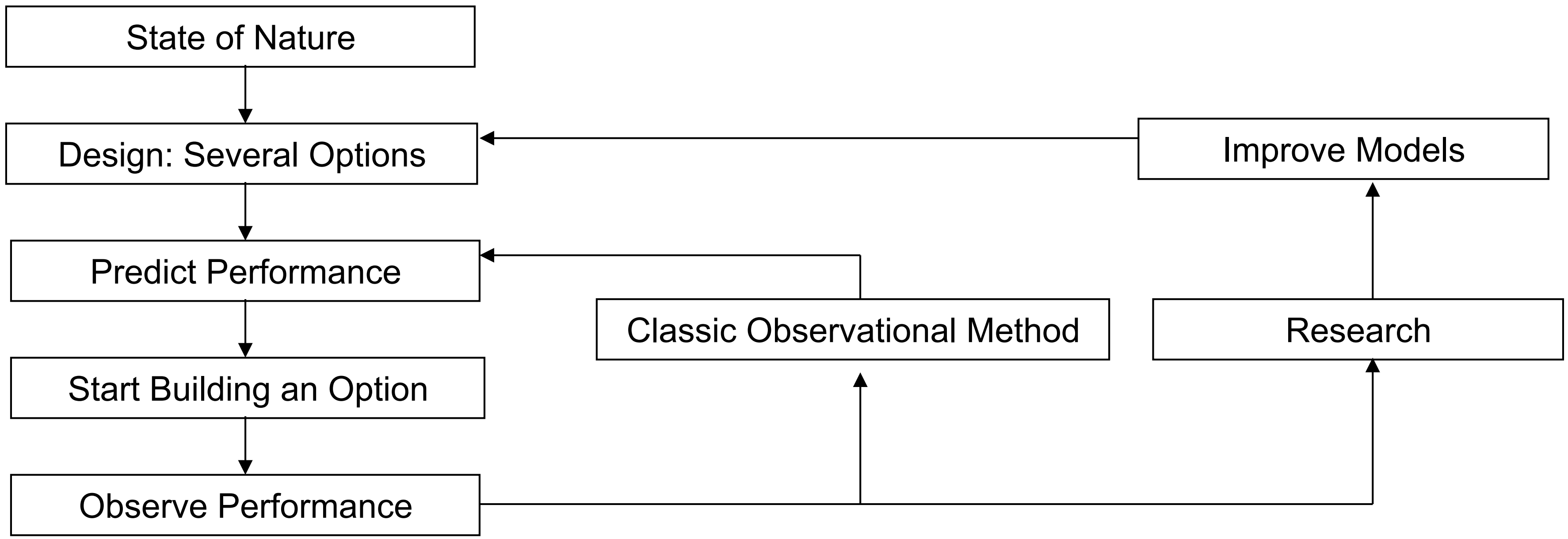
- Risk Analysis

Observational Method

(Terzaghi 1961, Peck 1969)



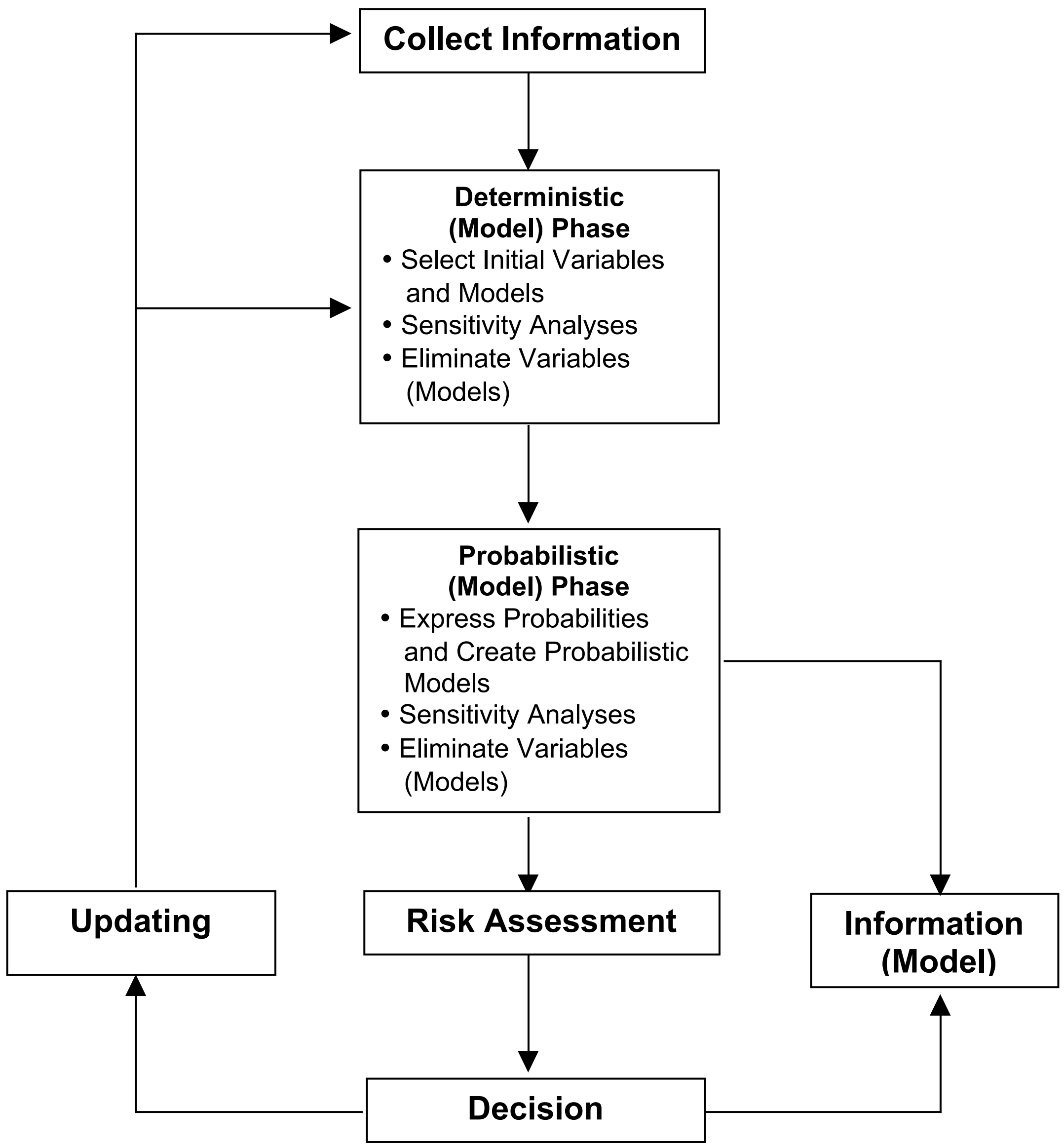
Extended Observational Method



RISK ANALYSIS

The uncertainty in performance i.e. the risk needs to be formally considered through decision analysis using the process of

"Decision Making under Uncertainty"



S-4 Proposal - Cavern Design for DUSEL

Development through several meetings

Lisbon ISRM Congress Workshop	July 2007
Washington D.C NSF Workshop	December 2007
Lead ISE Meeting	April 2008
NSF Meeting San Francisco	June 2008

Intent: Develop and integrate detailed S-5 proposals

Research Areas:

- Predesign
- Design and Construction
- Long Term Performance

All in context of “Observational Approach”!!

RESEARCH AREAS AND (DETAILED) SUB PROPOSALS

Predesign

- Fracture Network (1)
- Lidar on Tunnel Wall (2)
- New Models for Characterization (3)
- Stochastic Characterization (4)

Design/Construction

- Stability Contours (5)
- Damage Mechanisms (6)
- Cavern Design/Monitoring (7)
- Novel Excavation Techniques (8)
- Scale Effects (9)
- Risk Analysis (10)
- Also: 1, 2, 3, 4

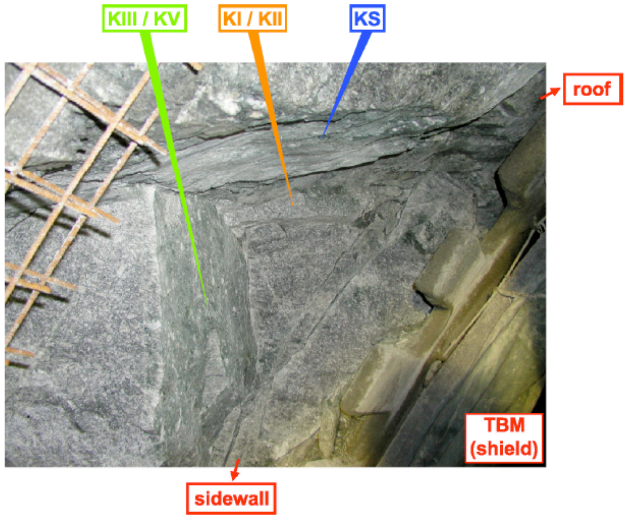
Long Term: 3, 6, 7, 10

INDIVIDUAL RESEARCH PROPOSALS

Project No. 1
Fracture Network Characterization - M. Mauldon, H. Einstein

Problem:

Gotthard Tunnel

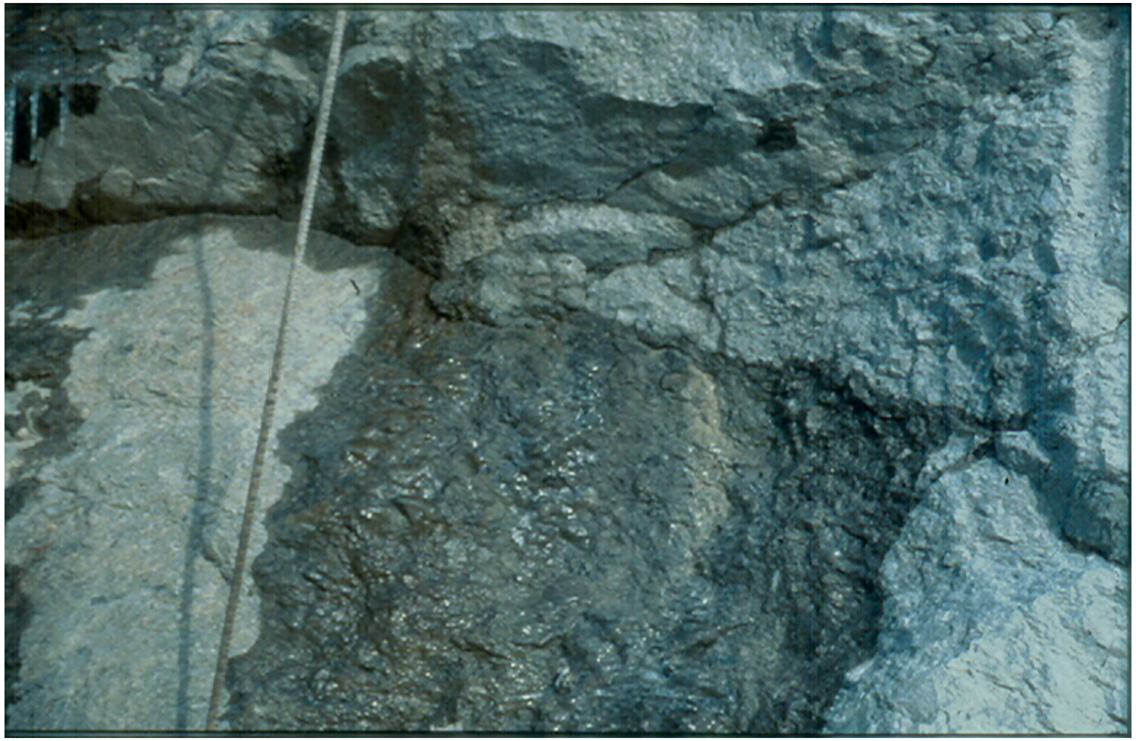


Lötschberg Tunnel

Unknown Tunnel

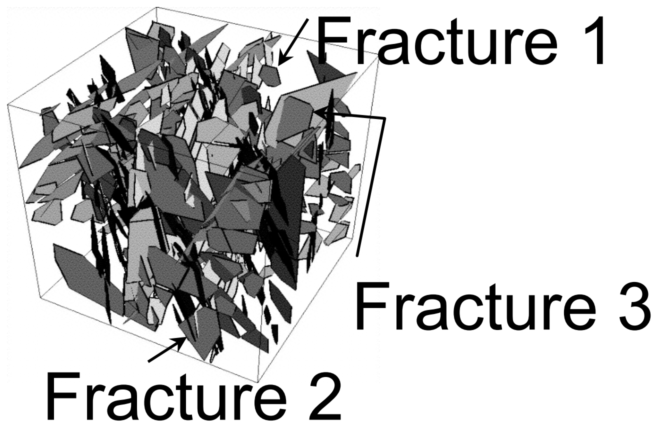

90 10 5

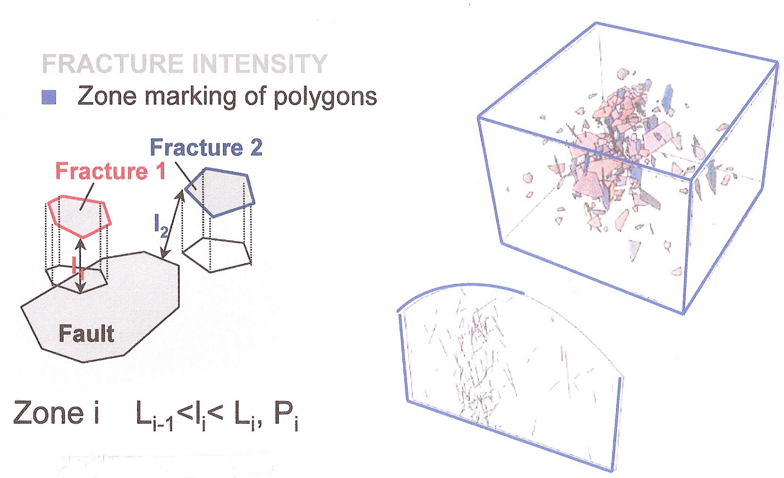

90 10 5



Approach:

Create stochastic fracture pattern model based on information from borings and tunnel surfaces. The interpretation is biased.





- Compare prediction using stochastic model with encountered conditions - 3-dimensional exposure!

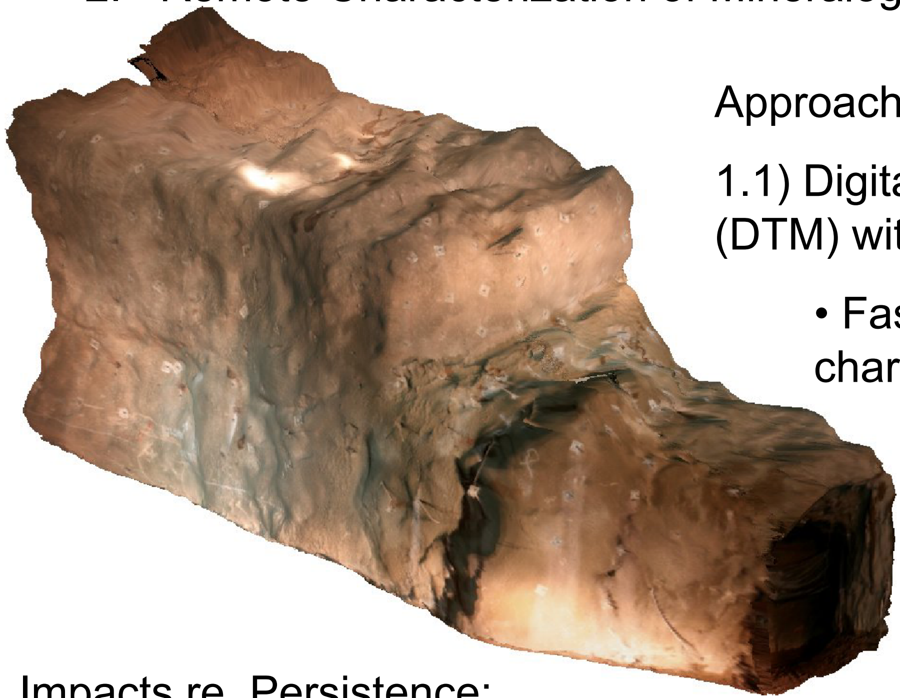
- Improve models
  - bias correction models
  - stochastic fracture pattern model

INDIVIDUAL RESEARCH PROPOSALS

Project No. 2
Use of Lidar and Digital Terrain Photogrammetry - F. Tonon

Problems:

1. 3-D Characterization of Fracture Persistence
2. Remote Characterization of Mineralogy, Petrography



Approach re. persistence:

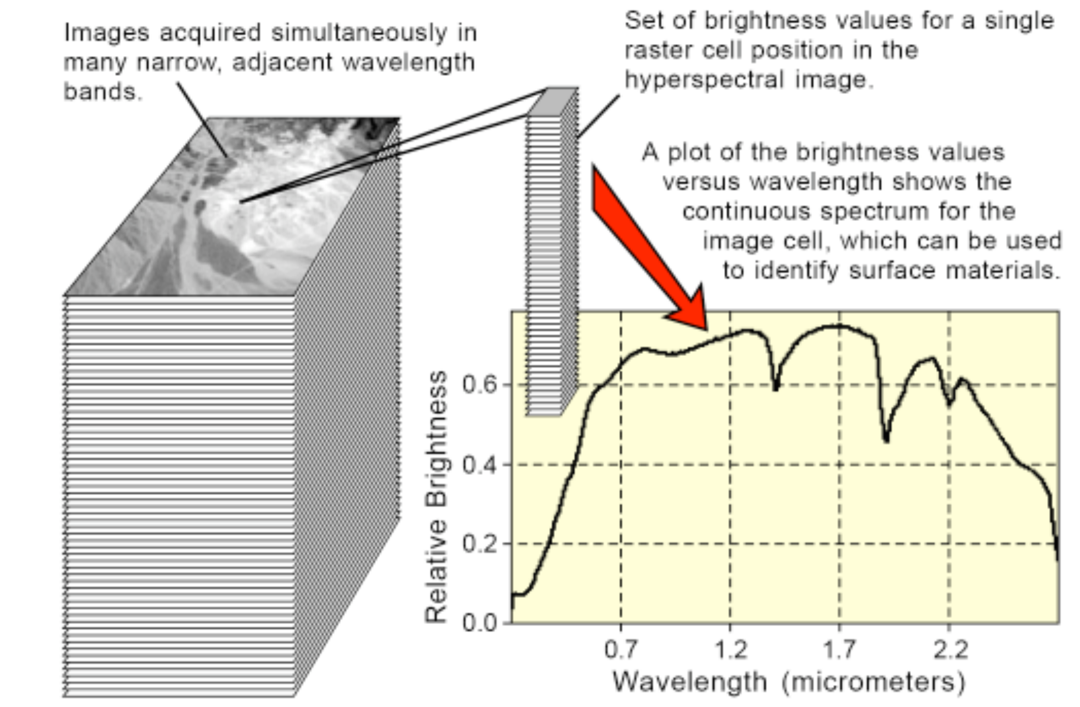
1.1) Digital photogrammetry gives Digital Terrain Model (DTM) with draped photos:

- Fast, safe, reproducible remote fracture characterization: orientation, trace length and shape

1.2) Proposal: follow each fracture from one excavation surface to the next => develop 3-D characterization of fracture trace length/shape => persistence of fractures

Impacts re. Persistence:

- Fracture persistence => distribution of fracture size => risk and risk update for block type/size around:
  - DUSEL cavern => risk minimization
  - Any civil/mining rock mechanics system: slopes, underground excavations, foundations



Approach re. remote characterization:

2.1) Hyperspectral imaging gives mineral/rock type for each pixel

2.2) Proposal: drape hyperspectral imaging over DTM to remotely identity minerals and rocks

Impacts re. remote characterization:

Reduction of cavern construction risk by optimization of blast rounds, minimization of excavation stoppage for mapping, permanent and objective documentation of ground encountered.
In mines: automatic calculation of excavated mineral volumes, and automatic identification of ore grades to optimize excavation sequence

INDIVIDUAL RESEARCH PROPOSALS

Project No. 3
New Models for Geomechanical Characterization of Rock Masses - L. Sousa, et al.

Facts/Problems:

Geologic uncertainties have a major effect on design and construction of underground openings.

DUSEL Opportunity:

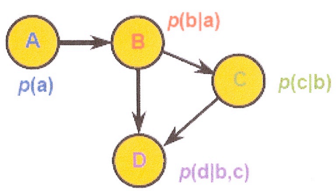
Treasure of data on relevant geologic parameters.

Approach:

1. Use data mining to improve existing and develop new geotechnical models
2. Develop Bayesian Networks to consider uncertainty in decision making:

Bayesian Network – Chain Rule

Compact and graphical representation of a joint distribution (based on simplifying assumptions)



Chain Rule:

$p(a,b,c,d) = p(a)\,p(b|a)\,p(c|a,b)\,p(d|a,b,c)$

independency assumptions

$\Rightarrow p(a,b,c,d) = p(a)\,p(b|a)\,p(c|b)\,p(d|b,c)$

INDIVIDUAL RESEARCH PROPOSALS

Project No. 4
Stochastic Characterization of Rock Mass Properties - E. Asa

Problem:

- Importance of accuracy in characterization and quantification of engineering properties of rocks
- Rock mass response must be understood to predict the performance of large caverns in DUSEL at an acceptable level of uncertainty

Approach:

- Uncertainty (lack of knowledge and randomness) in rock properties must be considered
- Use stochastic research methods to characterize, simulate and analyze rock properties to estimate engineering properties under conditions of uncertainty.
- Optimization of engineering properties through the use of decision making under uncertainty.

INDIVIDUAL RESEARCH PROPOSALS

Project No. 5
Stability Contour Mapping - U. Ozbay

Problem:

- Locating DUSEL caverns will have to be based on safety, serviceability, logistics, specific science experiment requirements and interaction between the experiments
- A pivotal parameter in optimizing the spatial arrangement of DUSEL caverns will be the ground conditions

Approach:

- This research aims at developing a “Stability Contour Map” for the DUSEL cavern designs, based on ground characterization and physics experiments requirements.

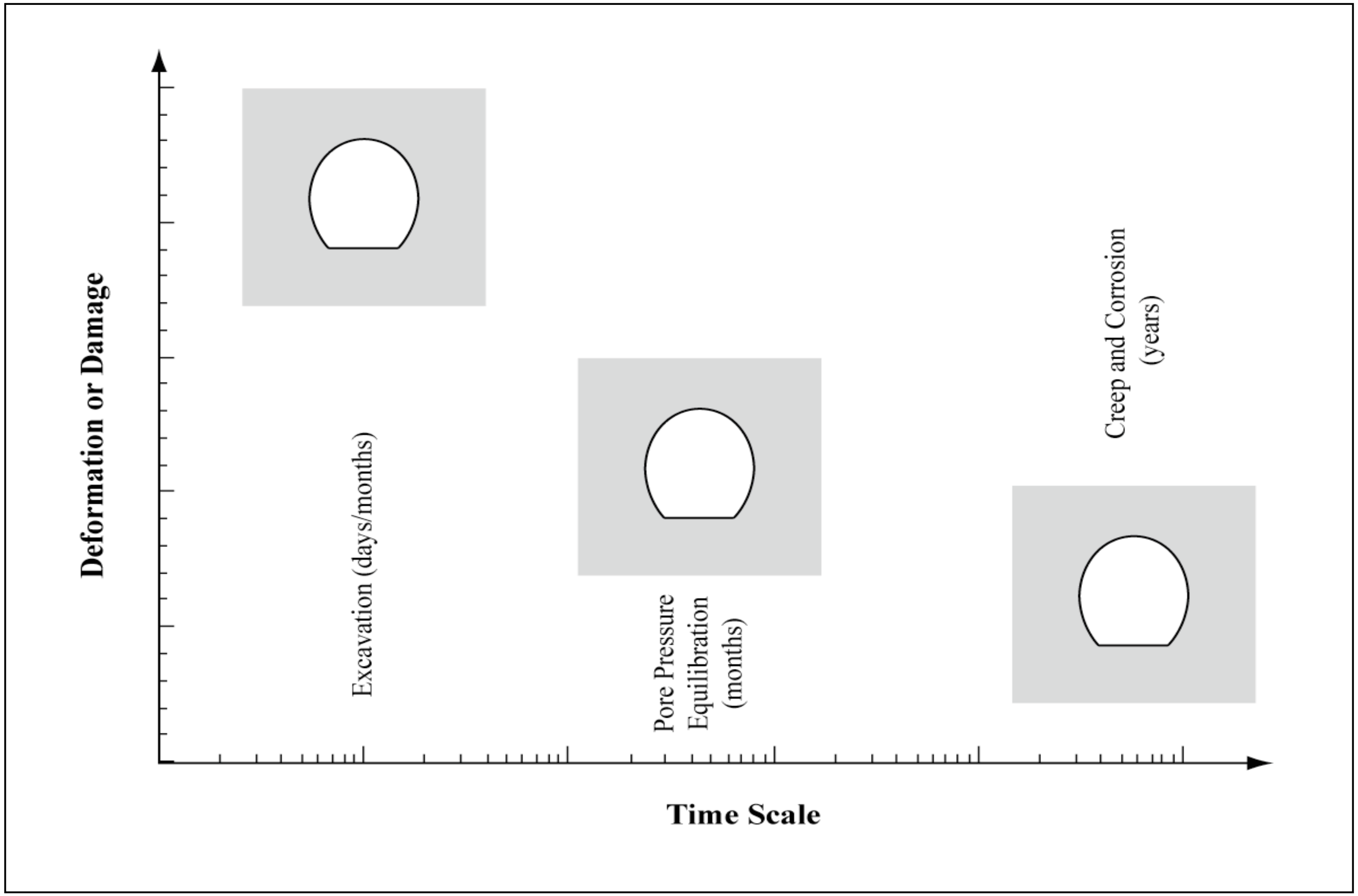
Specifically:

- The methodology will account for the field stresses due to old mine workings, rockmass characteristics, and groundwater conditions.
- The research will make use of the unprecedented level of geotechnical data resulting from the research projects on instrumentation and monitoring.
- Continuous updating of the data and use of numerical modeling as DUSEL caverns develop will provide improved understanding of the interaction between ground conditions and cavern performance.

INDIVIDUAL RESEARCH PROPOSALS

Project No. 6
Multi-time Scale Evaluation of The Mechanical Response of Large Cavities - A. Bobet and L. Pyrak-Nolte

Problem:



Approach - Objectives:

- Investigate rock mass response over large time-scale

- Investigate a single-discontinuity response over large time-scale

- Determine the damage mechanisms associated with each time scale

- Couple mechanical response with geophysical observations

- Upscale theoretical framework from laboratory (current approach) to large spatial- and time-scale

Approach - Experiments:

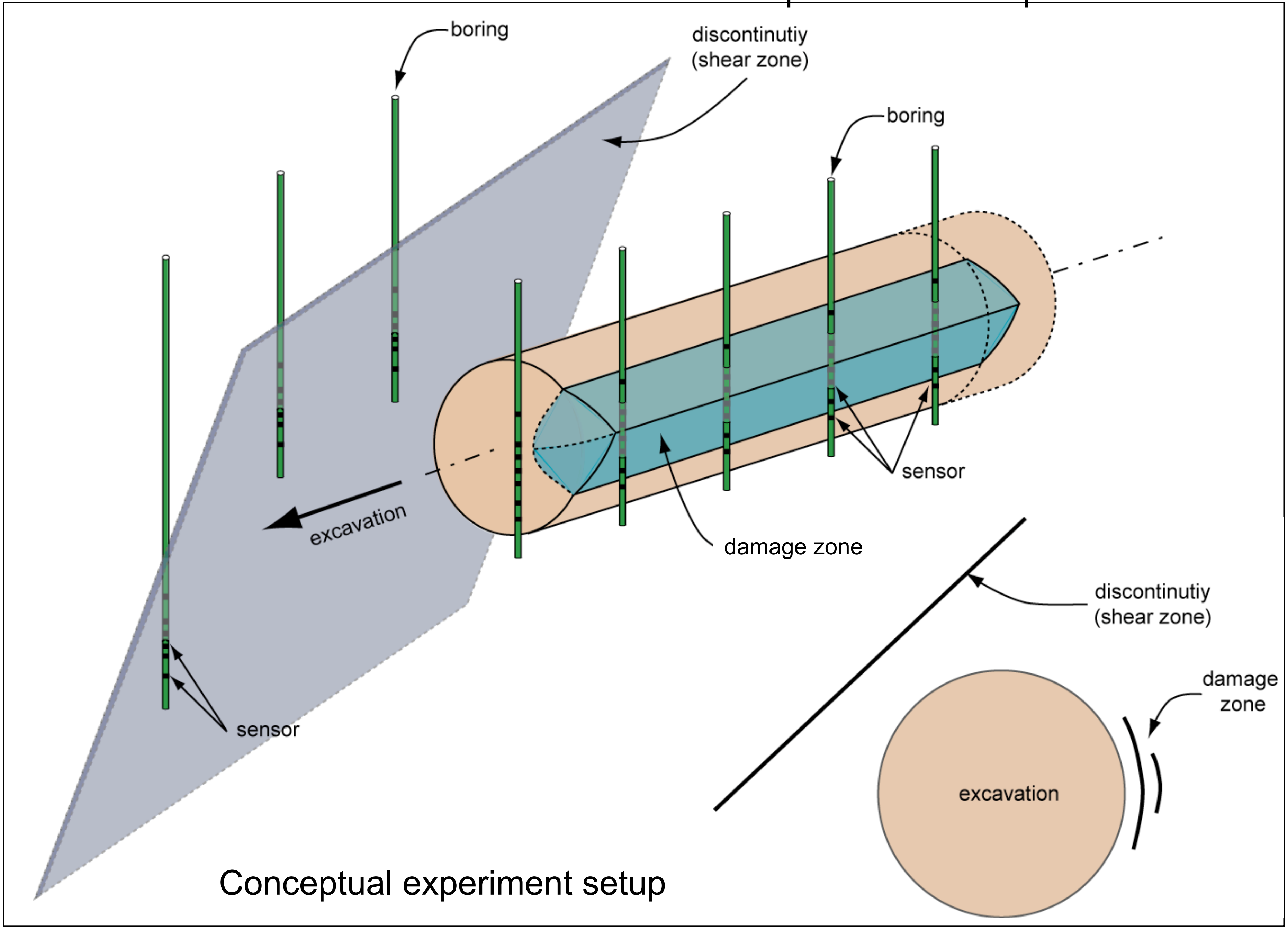
- Induce damage:
  - Changing stress field through excavation
    - additional drifts may be needed
    - upscale results from laboratory
  - Unload/load pre-existing discontinuities - shear zones

- Continuous monitoring:
  - Mechanical sensors - extensometers, pressure transducers
  - Geophysical sensors - seismic methods
  - Other methods - AE

- Couple mechanics of damage and wave transmission

- Link measurements with “transparent earth” project

Experiments Proposed



Conceptual experiment setup

INDIVIDUAL RESEARCH PROPOSALS

Project No. 7
Cavern Design and Monitoring - M. Kuchta

Problem:
- Optimal Design of DUSEL Cavern

Approach - Objective
- Learn from existing design/construction of large caverns at great depth
- Feedback from DUSEL construction to DUSEL design, revise models

Approach - Details:
- Literature study, workshop of experts
- Determine specific DUSEL design requirements (particularly rock mass characterization, applicable design/analysis approaches)
- Develop design/construction strategies
- Use monitoring to check/update design

INDIVIDUAL RESEARCH PROPOSALS

Project No. 8
Use of Novel Rock Cutting Techniques for Stress Relief in the Large Caverns
- J. Rostami

Problem

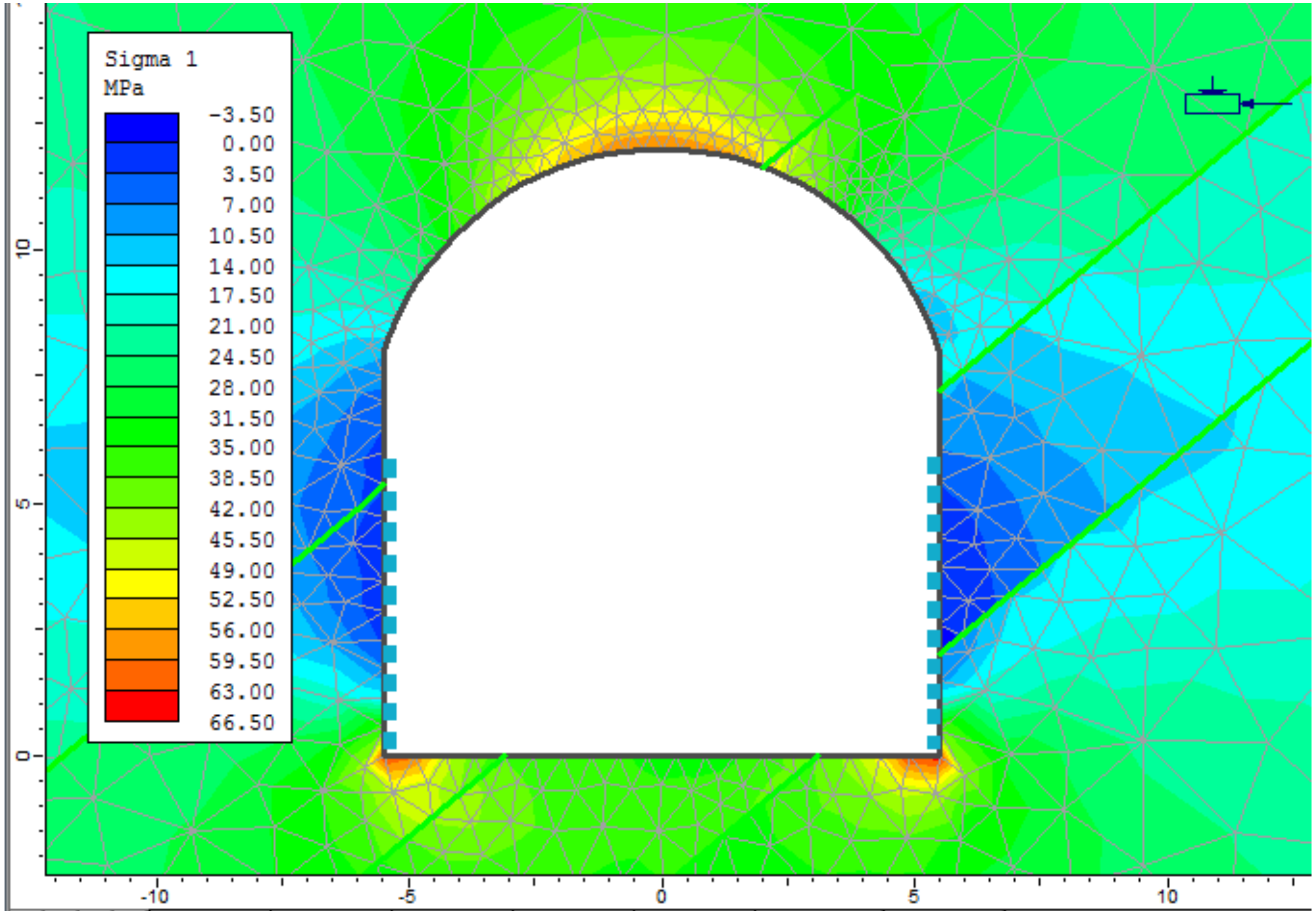
- Stress concentration around the opening can exceed the strength of the rock mass, leading to overbreaks, massive failure, or rock burst

Approach

- A carefully designed cut in the walls can produce stress relief at the high concentration points,
- The shape of cut can be designed to utilize the available rock strength, while shifting the main stress concentrations away from the wall surface, where due to confinement, higher strength could carry the load
- The proposed research will look into this possibility and develop a guideline for designing location, shape and size of the cut
- Since such high precision cuts cannot be made with conventional rock cutting, novel techniques have to be used (flame jet, water jet, others?)

USE OF NOVEL ROCK CUTTING TECHNIQUES FOR STRESS RELIEF IN LARGE CAVERNS

- Stress concentration has been moved inside the body of the rock, where the rock strength is higher due to confinement



Example of A 10 m wide, 12 m high horseshoe tunnel

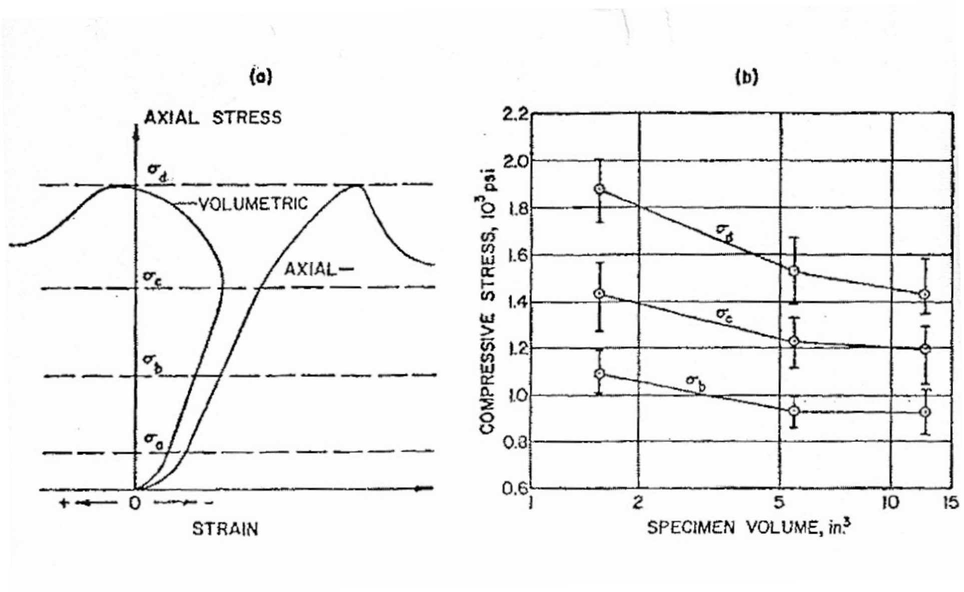
INDIVIDUAL RESEARCH PROPOSALS

Project No. 9
Scale Effect and Mine-By Research - H. Einstein

Scale Effect Problems:

- Time effect - Deformation, Stability with Extended Time
- Size effect - Intact Material (extreme value, strain energy)
  - Jointed (Fractured) Material - Effect of Number of Fractures

SIZE EFFECT - INTACT MATERIAL



Strength

Specimen Size

Individual Research Proposals
Project No. 9

Scale Effect and Mine-By Research - H. Einstein

Scale Effect Problems:

- Time effect - Deformation, Stability with Extended Time
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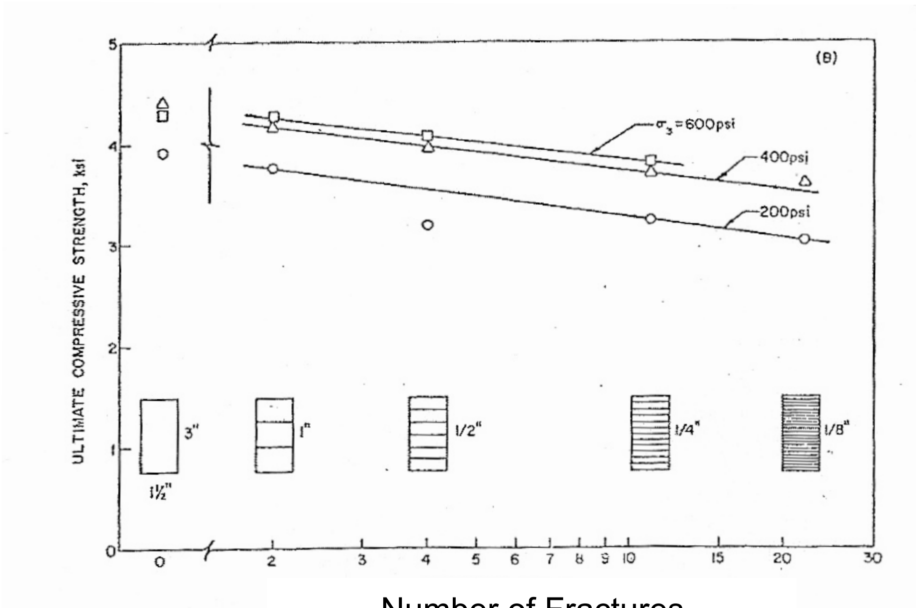
SIZE EFFECT - JOINTED MATERIAL

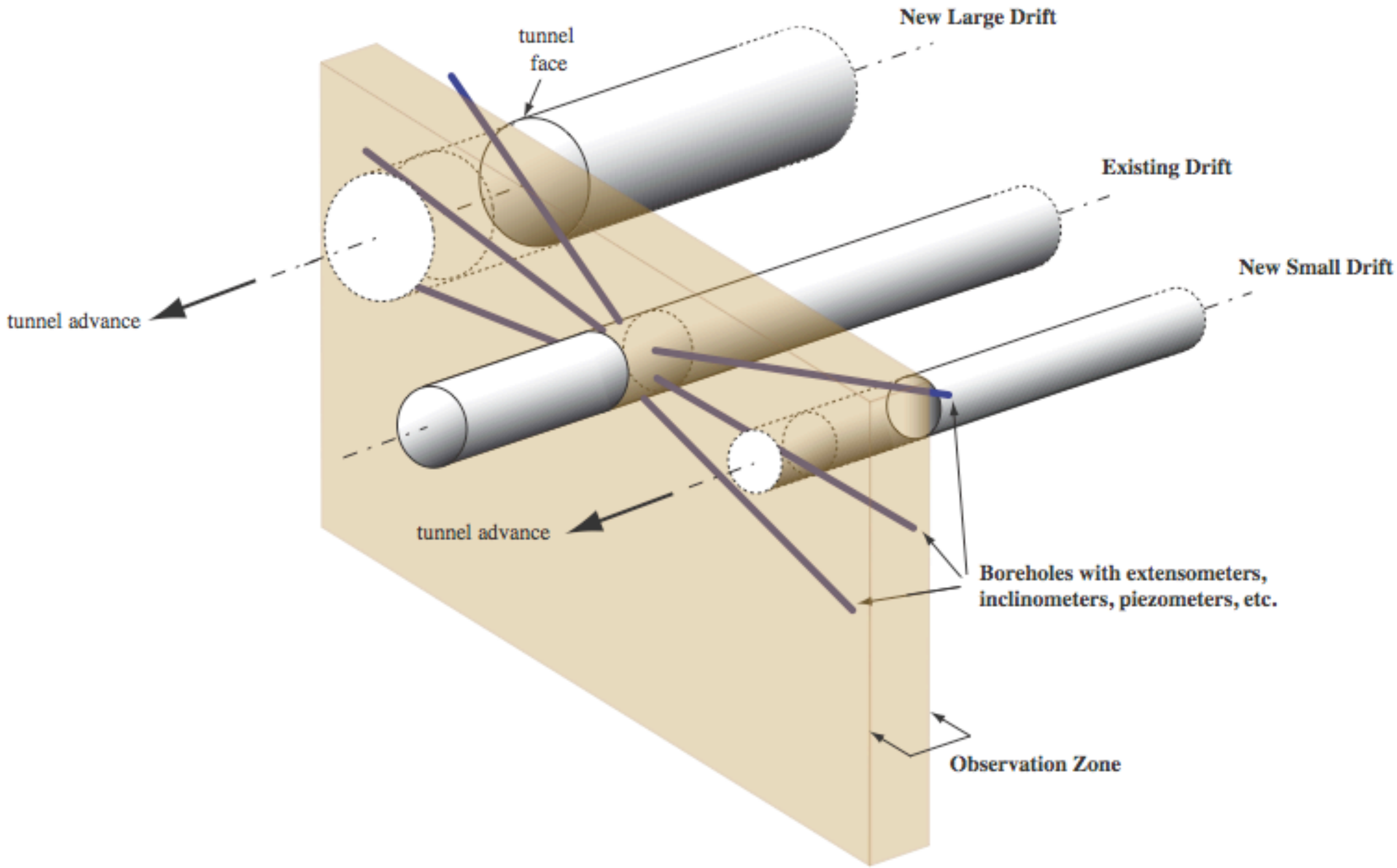
Strength



Number of Fractures

Approach:

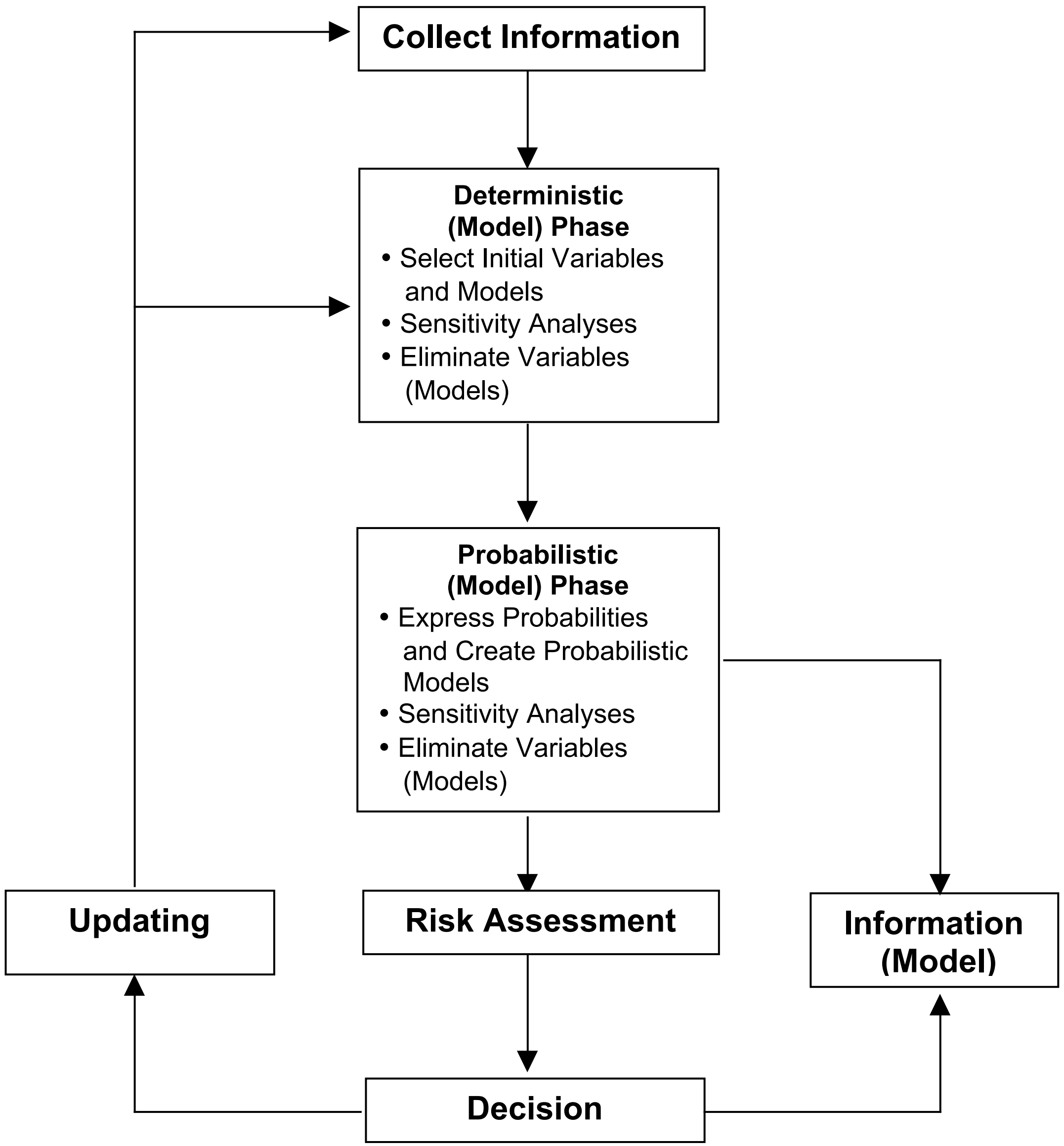
Mine-by experiment with different sized tunnels



INDIVIDUAL RESEARCH PROPOSALS

Project No. 10
Risk Assessment or Underground Space Development - H. Einstein

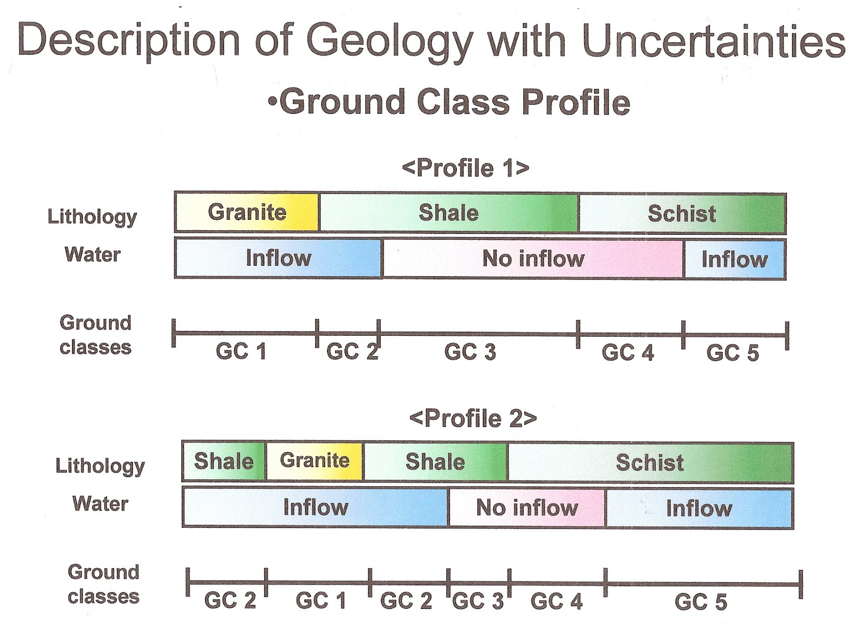
Problem:

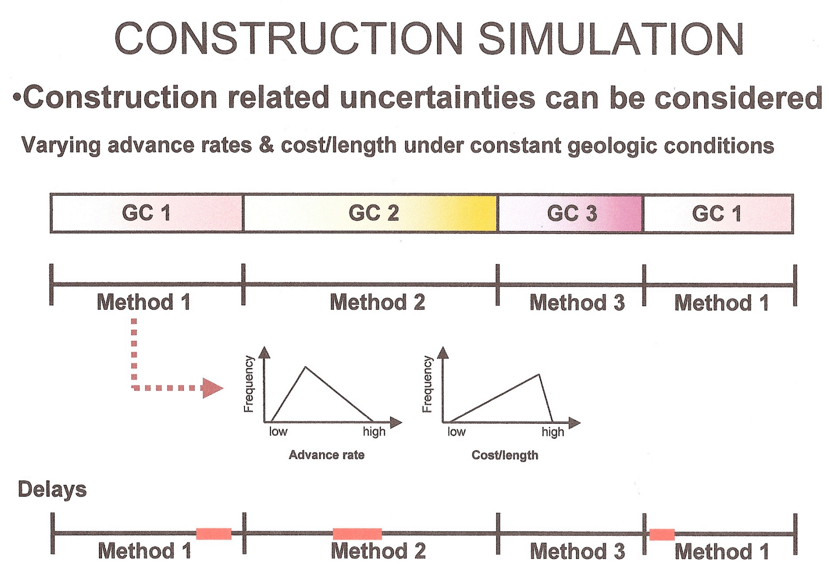


Approach:

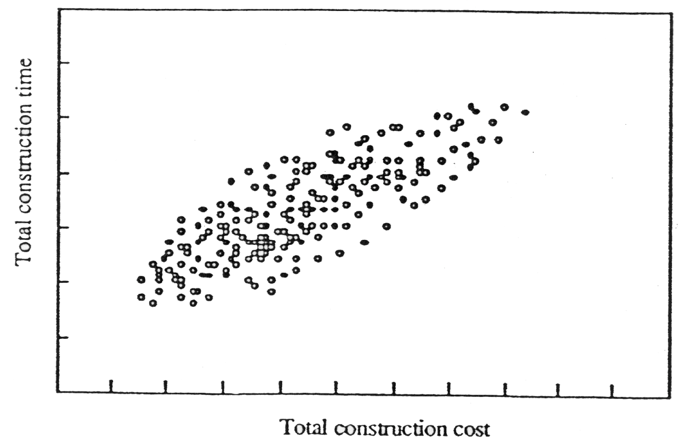
Use the Decision Aids for Tunneling (DAT)

The DAT simulate geologic and construction processes with their uncertainties to produce e.g. cost/ time scattergrams.

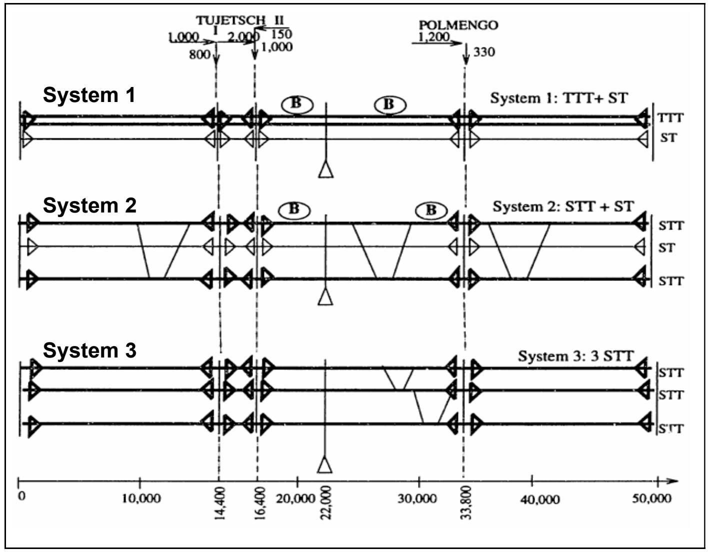




Result
Time-Cost Scattergram

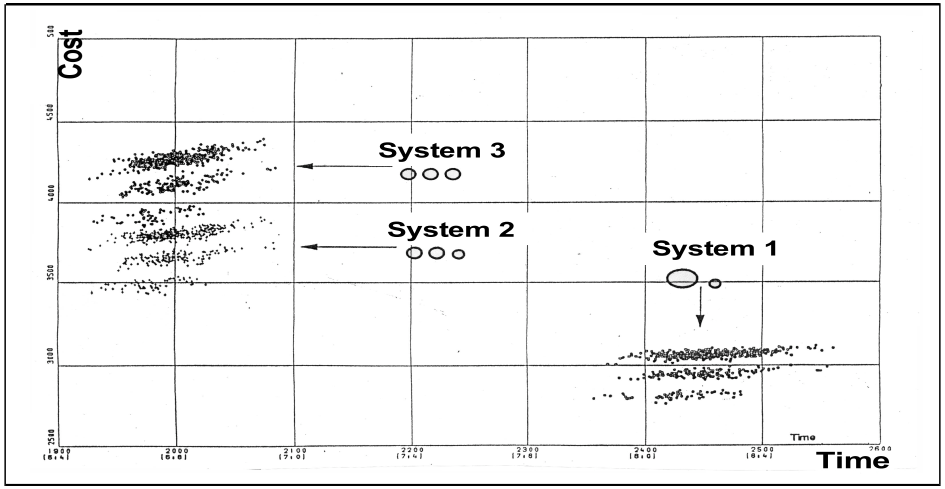


Gotthard Base Tunnel Studies - 1990's



Comparison of the different tunnel systems and alignments

Cost Time Distribution



DAT for DUSEL

- Adapt the DAT for new excavations at Homestake
- Expand the DAT for modification of existing underground openings at Homestake
- Discuss with other science investigators if application of the DAT structure to estimate effect of uncertainties on experiments is desirable

COMMENTS ABOUT RISK

- Safety and Adequate Performance (Serviceability) are essential

- Natural conditions and imposed conditions (excavation, experiments) are uncertain (variable) at this point and may be uncertain during operation (life) of facility

- Uncertainty produces risks

CONCLUSIONS

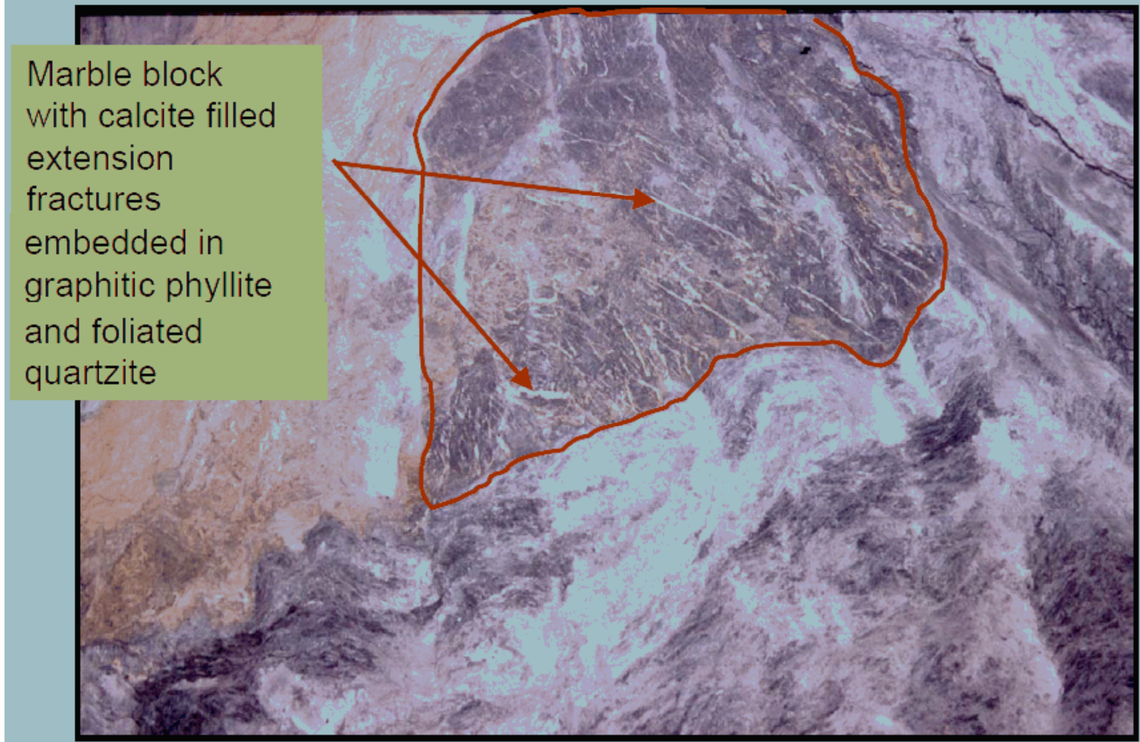
- Geologic/geotechnical conditions, particularly fractures, stress state, water affect cavern (tunnel/drift) performance

- Design and construction will benefit from and actually require adequate knowledge on ground conditions, adequate models (analysis) and adequate design and construction processes

- Proposed research on ground conditions (fractures, stress state, etc.) and proposed research using observed behavior will lead to improved models, design and construction processes

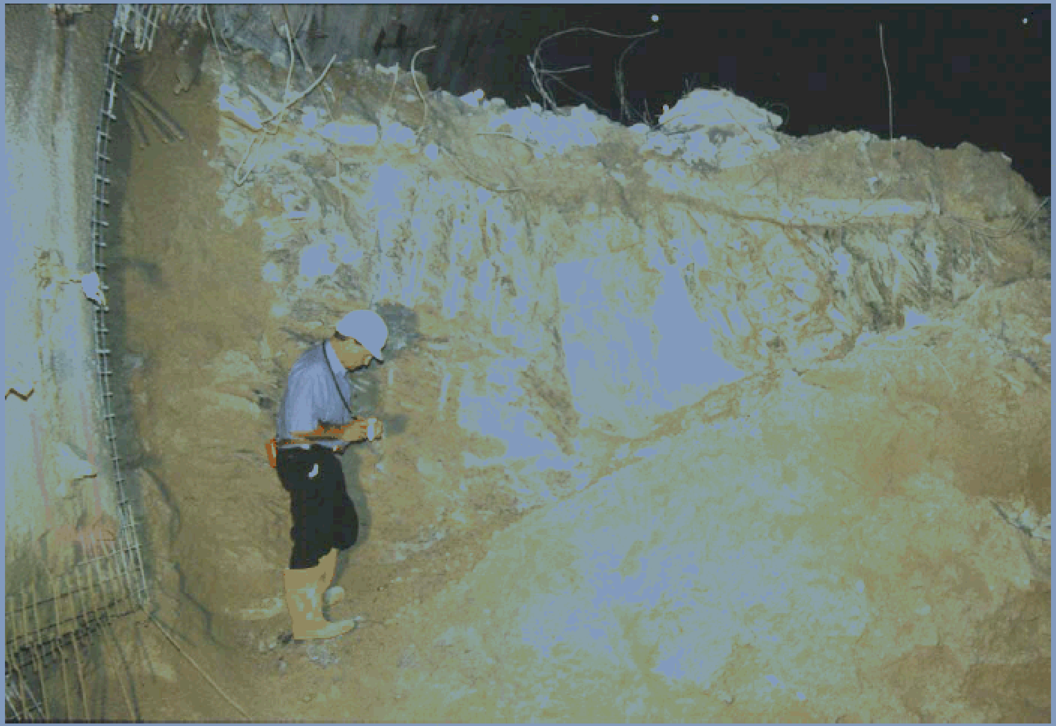
- This research can be integrated in an extended observational approach

- Pre-existing and remaining uncertainties need to be considered.



Tectonic Melange in an Alpine Thrust Setting
Semmering Motorway, Tunnel Steinhaus, Austria

Bench excavation



Tunnel Spital, Austria

Pictures after the collapse of Pinheiros station in Brazil (2007)

Assessing the damage following the collapse, notice the bent lattice girders

Approach:

Use and Adapt Decision Aids for Tunnelling

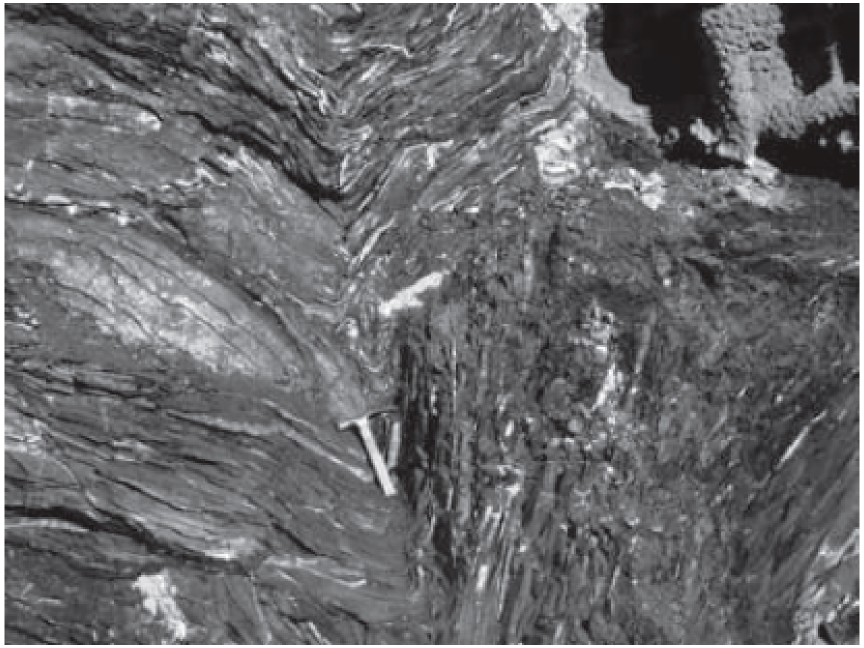
DECISION AIDS FOR TUNNELLING (DAT) - Principles

The DAT allow one to express the effect of geologic, technologic, operational, economic and social uncertainties on tunnel cost, - time - and - resources.

The resulting cost, - time - and resource distributions can be used to assess and mitigate risk.

→ THE DAT ARE AN ESSENTIAL COMPONENT OF RISK MANAGEMENT.

Yacambu Tunnel (tectonically deformed formation at tunnel face)



Tectonically deformed graphitic phyllite at the tunnel face