EOSC433/536:

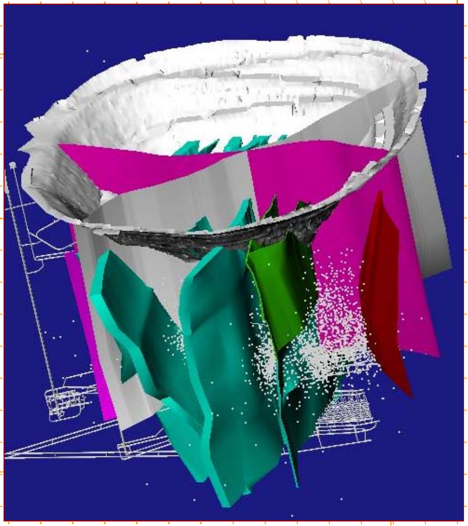
Geological Engineering Practice I – Rock Engineering

Lecture 2: Site Investigation & Data Confidence

Site Investigation & Monitoring

Geotechnical site investigation and monitoring are fundamental to rock engineering projects. Their use extends from prefeasibility through to operations and decommissioning.

Their purpose is multifold, serving both investigative and monitoring functions that are in part a necessity to ensure the economic feasibility of the project and part due diligence to ensure safe operations.



Role of Site Investigation & Monitoring

Investigation:

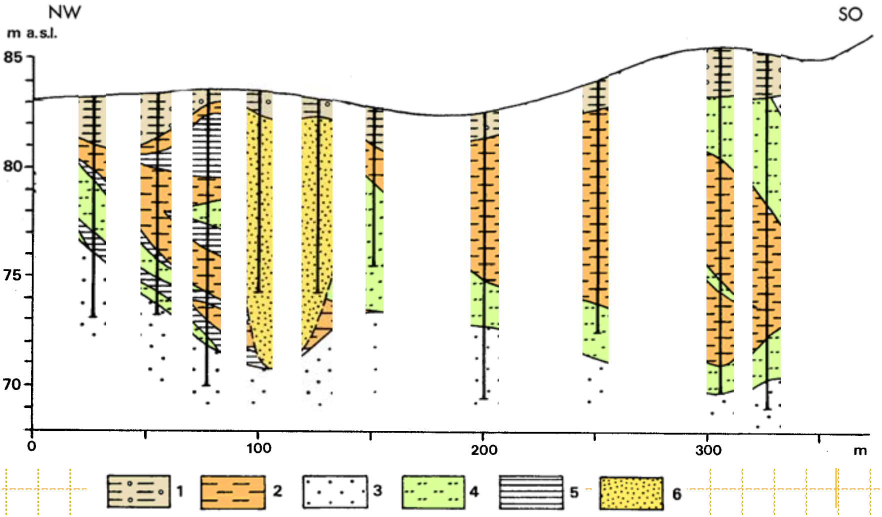
- To provide an understanding of the ground conditions, for prefeasibility and design purposes.
- To provide input values for design calculations.
- To check for changing ground conditions as the project develops, or advance/progress to greater depths.

Monitoring:

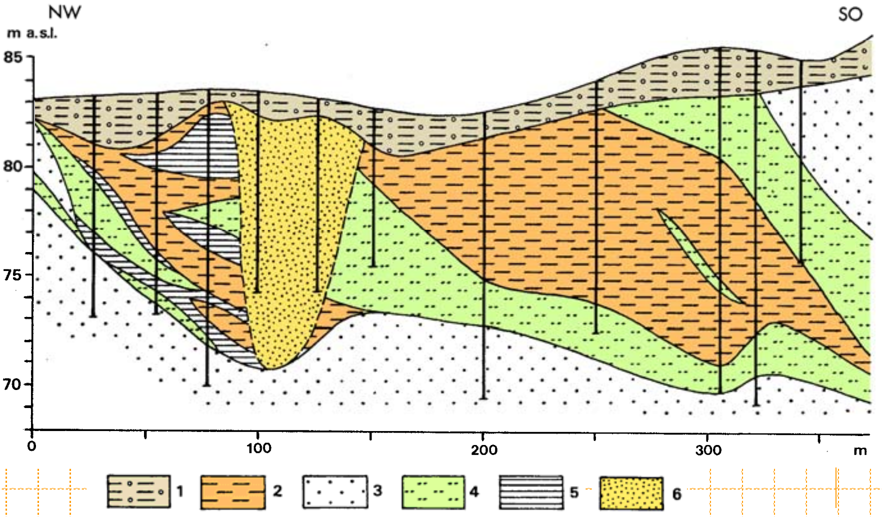
- To assess and verify the performance of the design.
- To calibrate models and constrain design calculations.
- To provide a warning of a change in ground behaviour, thus enabling intervention to improve safety or to limit damage through a design change or remediation measure.

Site Investigation: Boreholes

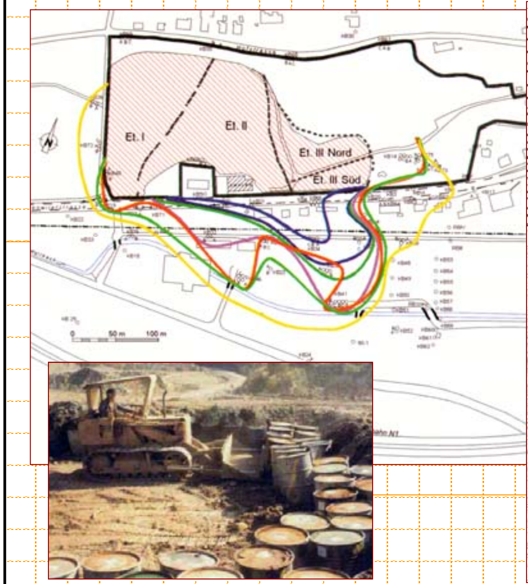
Site Investigation - Boreholes

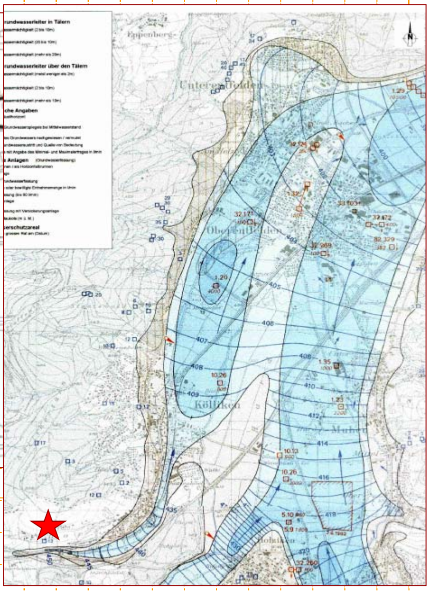


Site Investigation - Boreholes

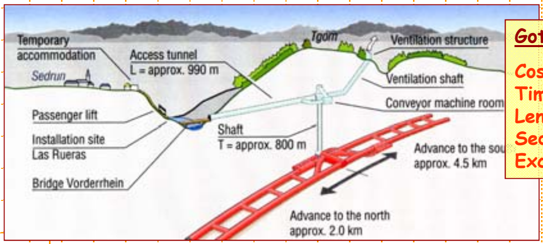


Site Investigation - Boreholes



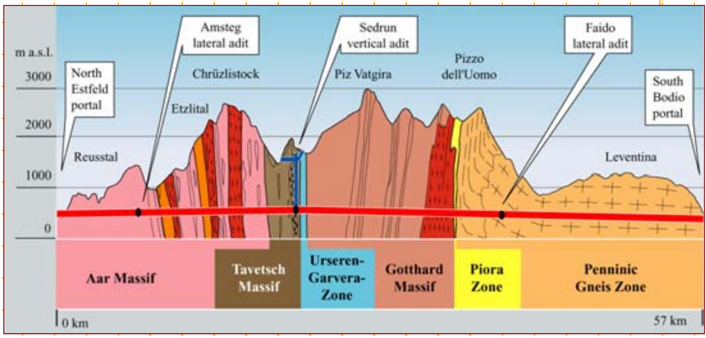


Deep Tunnels - Geological Uncertainty



Gotthard Base-Tunnel (Switzerland)

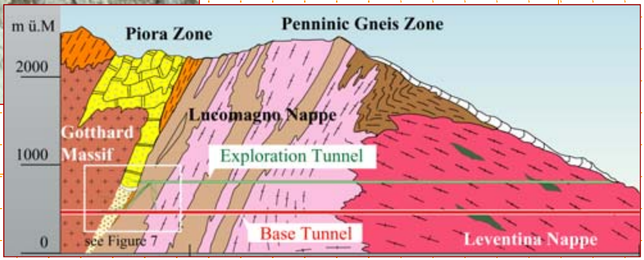
Cost = $15+ billion
Time to build = 17 years
Length = 57.5 km
Sedrun shaft = 800 m
Excavated material = 24 million tonnes



Loew *et al.* (2000)

Deep Tunnels - Geological Uncertainty

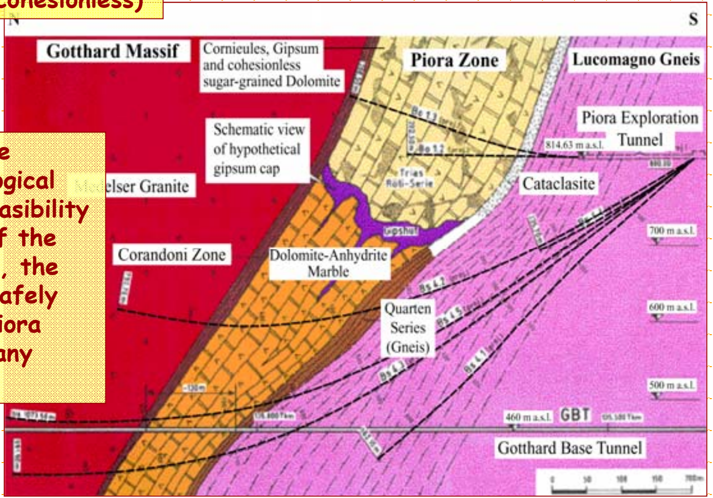
Sugar-grained dolomites (granular & cohesionless)



Deep Tunnels - Geological Uncertainty

Sugar-grained dolomites (granular & cohesionless)

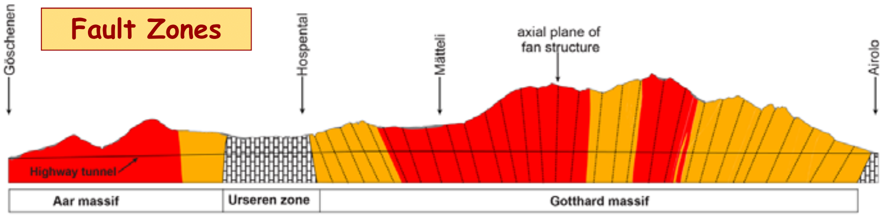
Considered the greatest geological risk to the feasibility and success of the tunnel project, the TBM passed safely through the Piora zone without any problems.

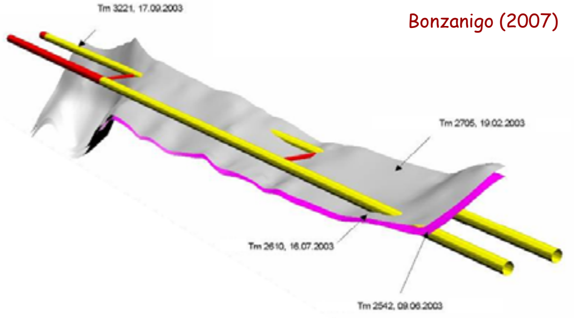


Loew et al. (2000)

Deep Tunnels - Geological Uncertainty

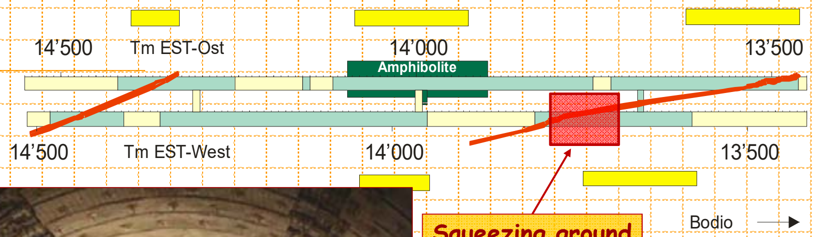
Fault Zones





Bonzanigo (2007)

Deep Tunnels - Geological Uncertainty

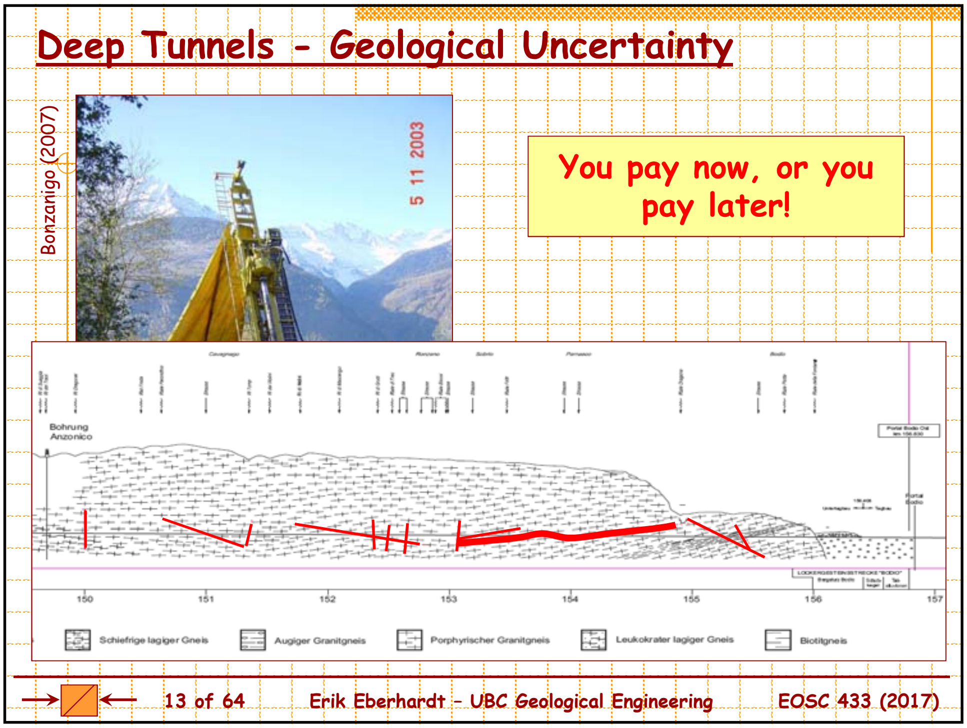


Squeezing ground blocks TBM

The total delay for passing through these faults along this section ... two years.

Budget overrun... more than 200%.

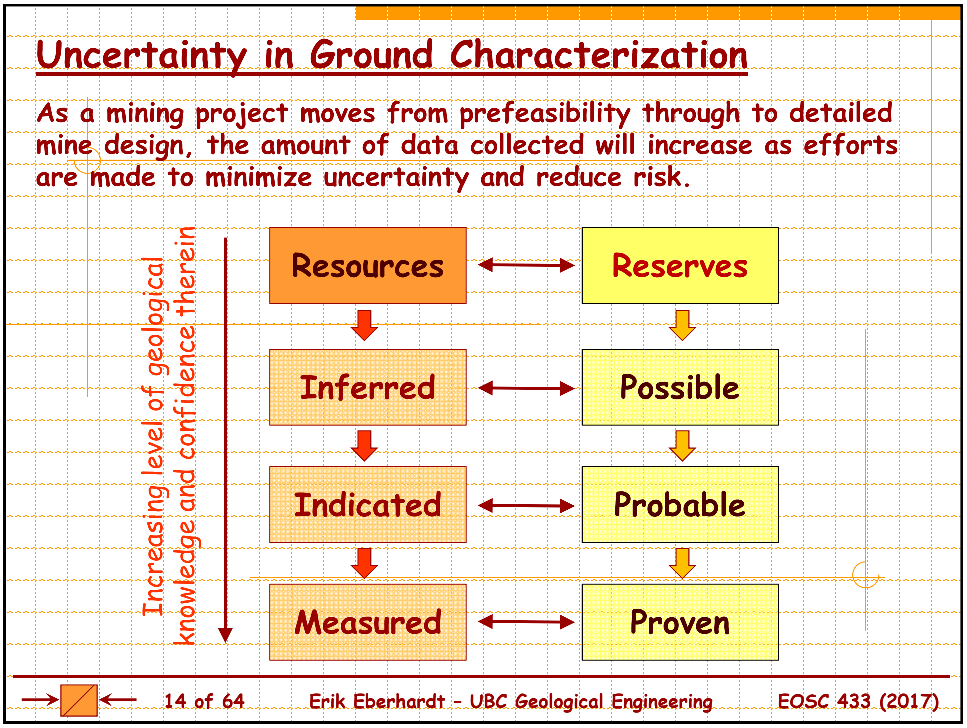
Ehrbar (2008)



Deep Tunnels – Geological Uncertainty

Bonzanigo (2007)

You pay now, or you pay later!

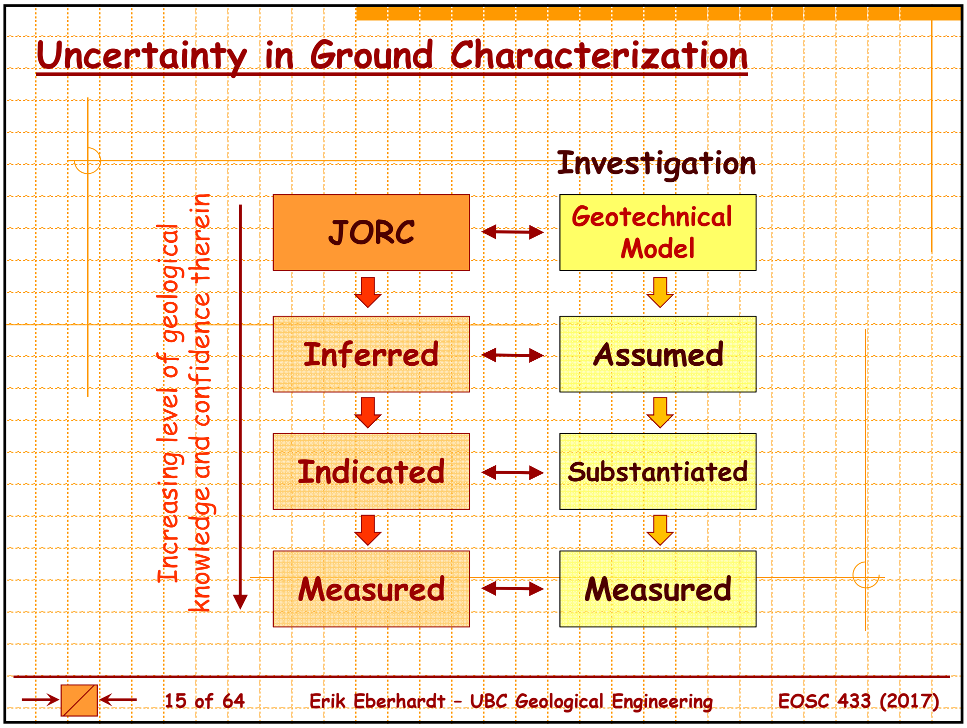


Uncertainty in Ground Characterization

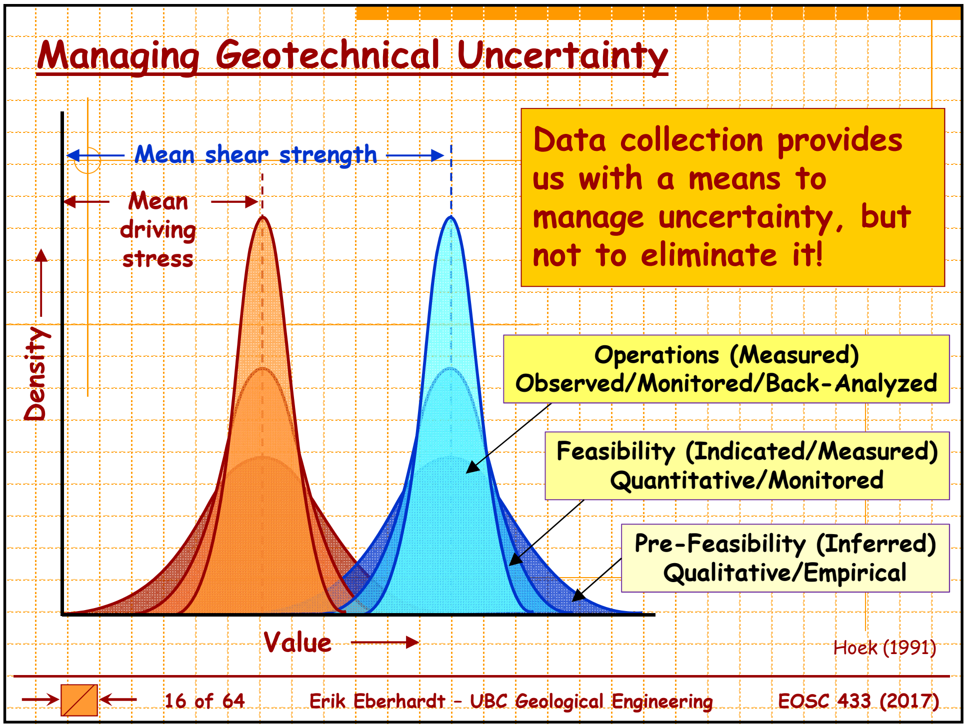
As a mining project moves from prefeasibility through to detailed mine design, the amount of data collected will increase as efforts are made to minimize uncertainty and reduce risk.

Increasing level of geological knowledge and confidence therein

Resources	Reserves
Inferred	Possible
Indicated	Probable
Measured	Proven



Uncertainty in Ground Characterization



Managing Geotechnical Uncertainty

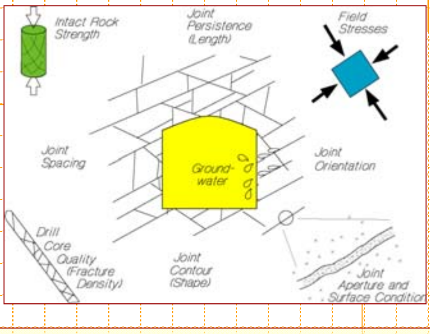
Data collection provides us with a means to manage uncertainty, but not to eliminate it!

Hoek (1991)

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.

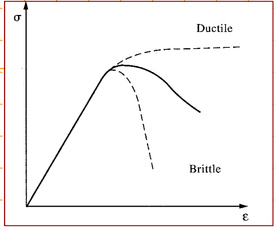
- We have the intact rock which is itself divided by discontinuities to form the rock mass structure.
- We find then the rock is already subjected to an *in situ* stress.
- Superimposed on this are the influence of pore fluid/water flow and time.



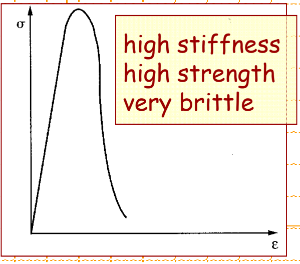
With all these factors, the geological history has played its part, altering the rock and the applied forces.

Laboratory Testing of Rock/Soil Behaviour

Uniaxial Compressive Strength (UCS), or peak strength, is the maximum stress that the rock can sustain. After it is exceeded, the rock may still have some load-carrying capacity, or residual strength.

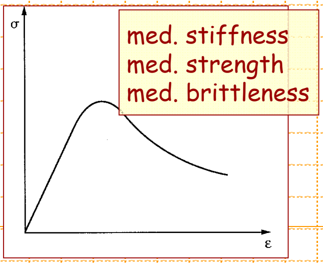


Hudson & Harrison (1997)



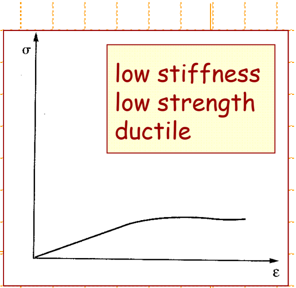
high stiffness
high strength
very brittle

e.g. Granite



med. stiffness
med. strength
med. brittleness

e.g. Limestone

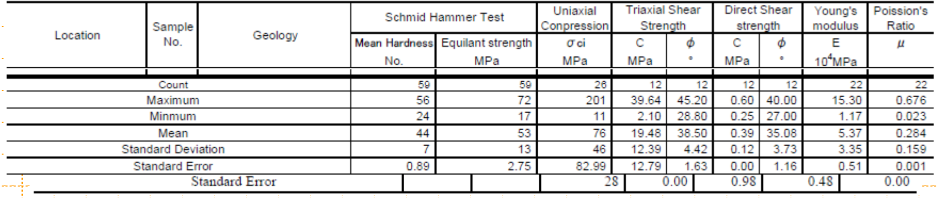


low stiffness
low strength
ductile

e.g. Shale

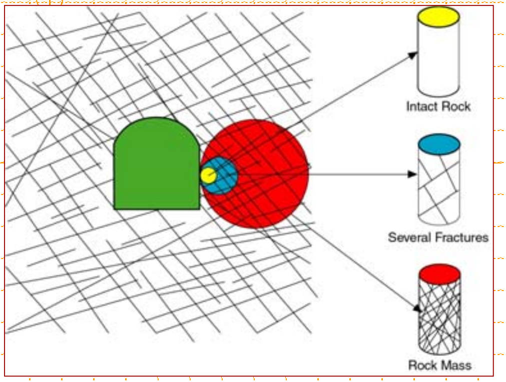
Understanding Rock Behaviour

Parameter	Value (MPa)
Number of Tests	20
Min. Peak Strength, σ_{UCS}	183.0
Max. Peak Strength, σ_{UCS}	231.1
Avg. Peak Strength, σ_{UCS}	206.9 (± 13.5)



Location	Sample No.	Geology	Schmid Hammer Test		Uniaxial Compression	Triaxial Shear Strength		Direct Shear strength		Young's modulus	Poission's Ratio
			Mean Hardness No.	Equilant strength MPa	σ ci MPa	C MPa	ϕ °	C MPa	ϕ °	E 10^4MPa	μ
Count			59	59	26	12	12	12	12	22	22
Maximum			56	72	201	39.64	45.20	0.60	40.00	15.30	0.676
Minmum			24	17	11	2.10	28.80	0.25	27.00	1.17	0.023
Mean			44	53	76	19.48	38.50	0.39	35.08	5.37	0.284
Standard Deviation			7	13	46	12.39	4.42	0.12	3.73	3.35	0.159
Standard Error			0.89	2.75	82.99	12.79	1.63	0.00	1.16	0.51	0.001
Standard Error					28	0.00		0.98		0.48	0.00

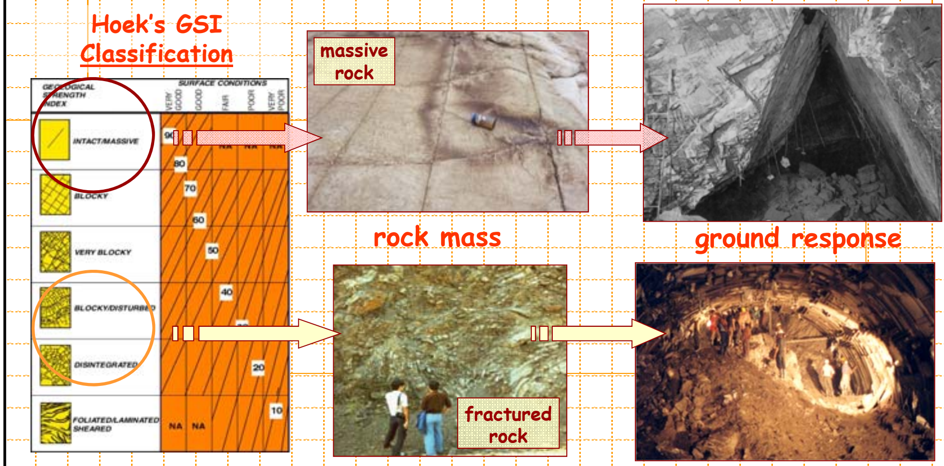
Rock/Soil Behaviour – Scale Effects



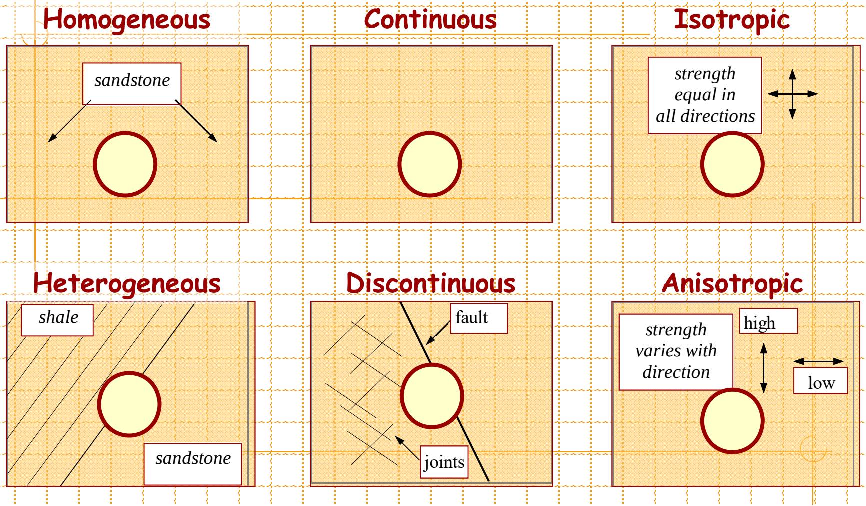
Rock Mass Behaviour

The key factor that distinguishes rock engineering from other engineering-based disciplines is the application of mechanics on a large scale to a pre-stressed, naturally occurring material.

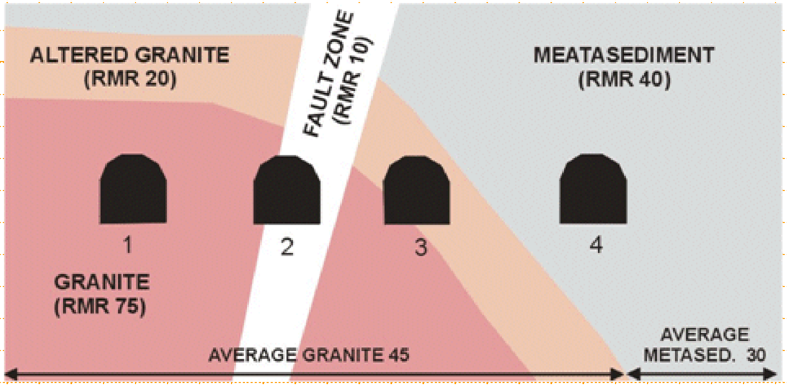
Hoek's GSI Classification



Rock as an Engineering Material

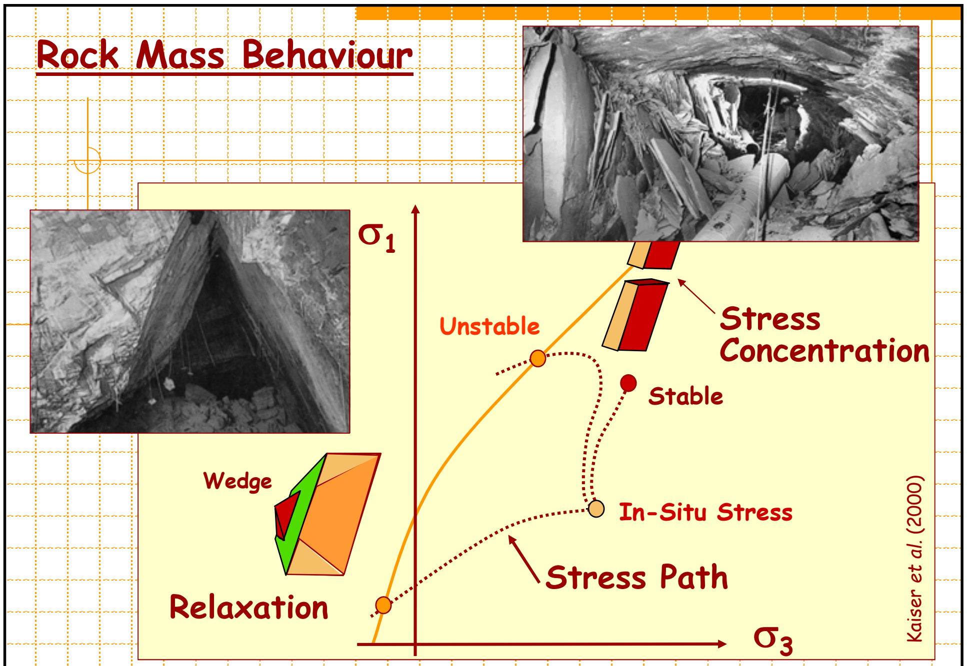


Reporting – Distribution and Variability



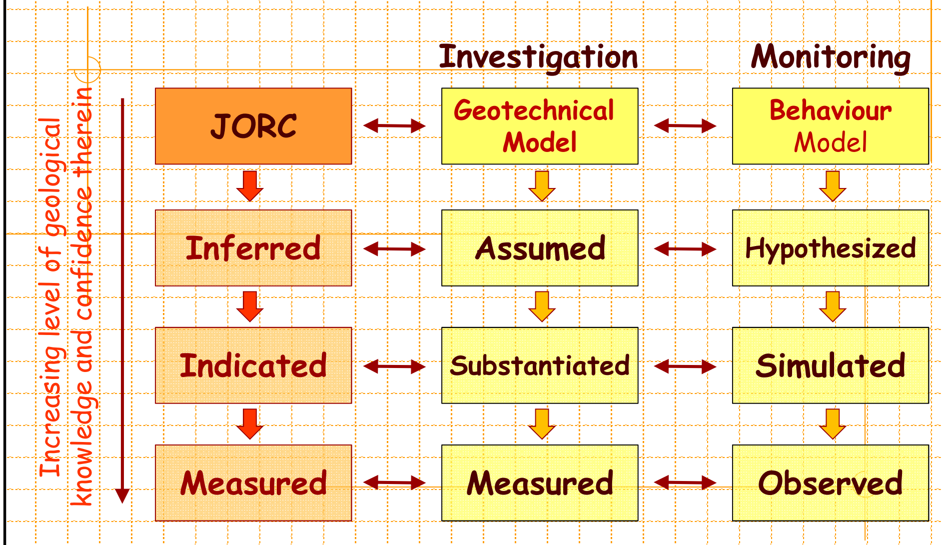
'Averaging' of data that can lead to a misrepresentation of important geological features, particularly major structures.

Rock Mass Behaviour



Kaiser et al. (2000)

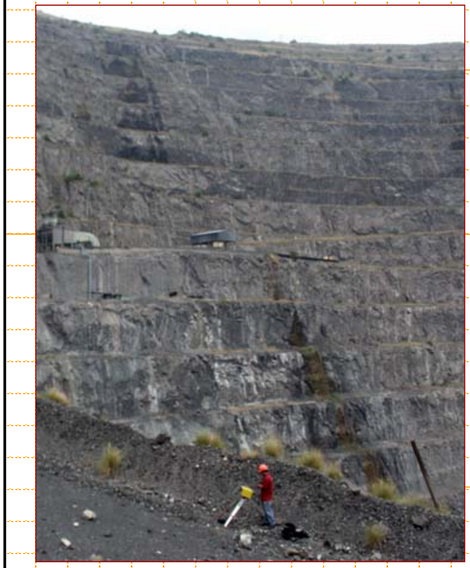
Uncertainty in Ground Characterization

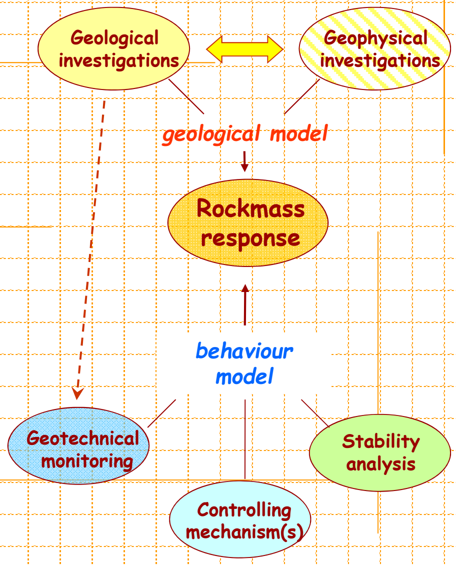


Increasing level of geological knowledge and confidence therein

	Investigation	Monitoring
JORC	Geotechnical Model	Behaviour Model
Inferred	Assumed	Hypothesized
Indicated	Substantiated	Simulated
Measured	Measured	Observed

Site Investigation & Data Collection





Geotechnical Data Collection

- Main Objectives
  - Provide input parameters for geotechnical design calculations
  - Optimize existing operations/construction
  - Limit/manage uncertainty
- Compatibility with the stage of the project
  - Inferred, Probable, Proven
- Practicality
  - Data collection in the context of the engineering design
  - Underground design often has to be completed prior to underground exposure (based on core only)
  - Degree of certainty has to be considered
  - Sensitivities of parameters and consequences must be tested
  - Integral part of the geological investigation
  - Communication between disciplines (geology, engineering, miners)

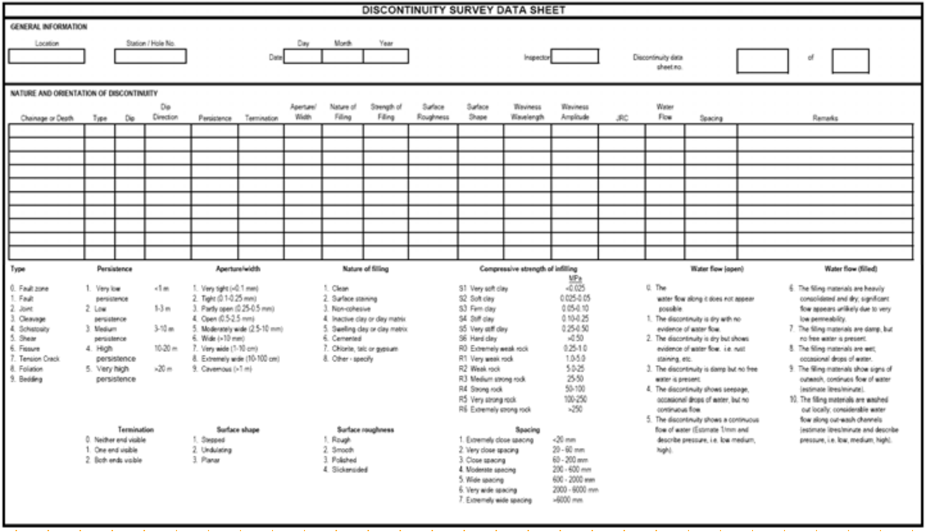
General Data Requirements

Data should be measured and recorded in systematic ways using standardized procedures. Much time and effort can be wasted by collecting data which may be irrelevant or inadequate. The nature of the data will also become more specialized as measurements transition from surface boreholes to excavation/construction.

The quality of the data is critical to the reliability of the interpretation...

... POOR QUALITY OR INACCURATE DATA CAN BE MISLEADING AND IS WORSE THAN NO DATA

General Data Requirements - Standardization



DISCONTINUITY SURVEY DATA SHEET

GENERAL INFORMATION

Location ______ Station / Hole No. ______ Date Day ___ Month ___ Year ___ Inspector ______ Discontinuity data sheet no. ______ of ______

NATURE AND ORIENTATION OF DISCONTINUITY

Chainage or Depth	Type	Dip	Dip Direction	Persistence	Termination	Aperture/ Width	Nature of Filling	Strength of Filling	Surface Roughness	Surface Shape	Waviness Wavelength	Waviness Amplitude	JRC	Water Flow	Spacing	Remarks

Type

0. Fault zone
1. Fault
2. Joint
3. Cleavage
4. Schistosity
5. Shear
6. Fissure
7. Tension Crack
8. Foliation
9. Bedding

Persistence

1. Very low persistence	<1 m
2. Low persistence	1-3 m
3. Medium persistence	3-10 m
4. High persistence	10-20 m
5. Very high persistence	>20 m

Aperture/width

1. Very tight (<0.1 mm)
2. Tight (0.1-0.25 mm)
3. Partly open (0.25-0.5 mm)
4. Open (0.5-2.5 mm)
5. Moderately wide (2.5-10 mm)
6. Wide (>10 mm)
7. Very wide (1-10 cm)
8. Extremely wide (10-100 cm)
9. Cavernous (>1 m)

Nature of filling

1. Clean
2. Surface staining
3. Non-cohesive
4. Inactive clay or clay matrix
5. Swelling clay or clay matrix
6. Cemented
7. Chlorite, talc or gypsum
8. Other - specify

Compressive strength of infilling

	MPa
S1 Very soft clay	<0.025
S2 Soft clay	0.025-0.05
S3 Firm clay	0.05-0.10
S4 Stiff clay	0.10-0.25
S5 Very stiff clay	0.25-0.50
S6 Hard clay	>0.50
R0 Extremely weak rock	0.25-1.0
R1 Very weak rock	1.0-5.0
R2 Weak rock	5.0-25
R3 Medium strong rock	25-50
R4 Strong rock	50-100
R5 Very strong rock	100-250
R6 Extremely strong rock	>250

Water flow (open)

0. The water flow along it does not appear possible.
1. The discontinuity is dry with no evidence of water flow.
2. The discontinuity is dry but shows evidence of water flow, i.e. rust staining, etc.
3. The discontinuity is damp but no free water is present.
4. The discontinuity shows seepage, occasional drops of water, but no continuous flow.
5. The discontinuity shows a continuous flow of water (Estimate 1/min and describe pressure, i.e. low medium, high).

Water flow (filled)

6. The filling materials are heavily consolidated and dry; significant flow appears unlikely due to very low permeability.
7. The filling materials are damp, but no free water is present.
8. The filling materials are wet, occasional drops of water.
9. The filling materials show signs of outwash, continuous flow of water (estimate litres/minute).
10. The filling materials are washed out locally; considerable water flow along out-wash channels (estimate litres/minute and describe pressure, i.e. low, medium, high).

Termination

0. Neither end visible
1. One end visible
2. Both ends visible

Surface shape

1. Stepped
2. Undulating
3. Planar

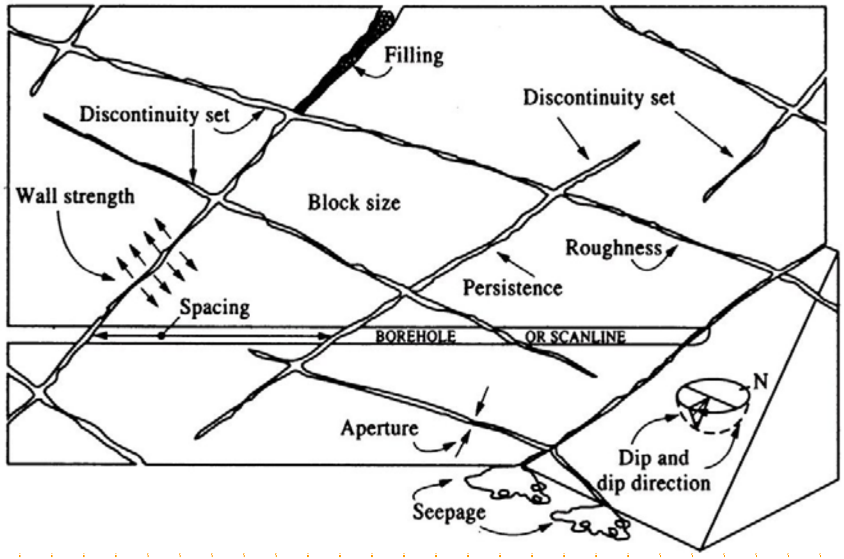
Surface roughness

1. Rough
2. Smooth
3. Polished
4. Slickensided

Spacing

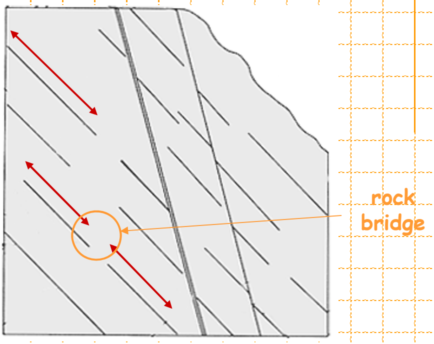
1. Extremely close spacing	<20 mm
2. Very close spacing	20 - 60 mm
3. Close spacing	60 - 200 mm
4. Moderate spacing	200 - 600 mm
5. Wide spacing	600 - 2000 mm
6. Very wide spacing	2000 - 6000 mm
7. Extremely wide spacing	>6000 mm

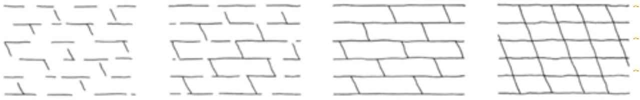
Discontinuity Data Collection



Hudson & Harrison (1997)

Spacing & Persistence



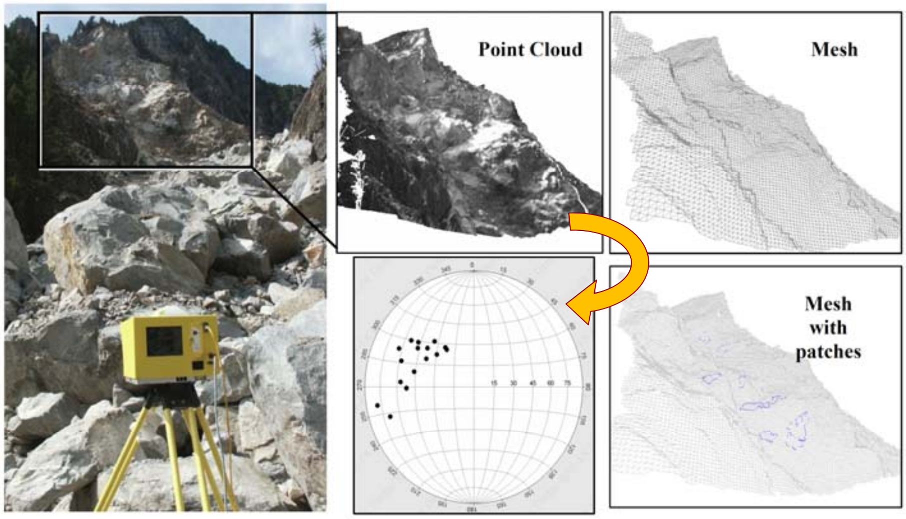


increasing persistence

Remote Sensing – Photogrammetry & LiDAR

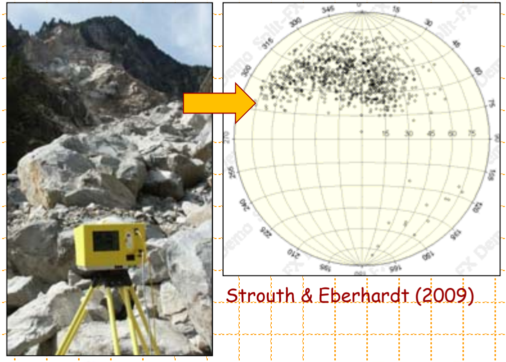
- **Advantage**: able to provide data for remote and inaccessible areas where safety concerns often preclude conventional mapping.
- **Disadvantage**: suffer measurement bias (e.g., orientation, truncation, censoring), which must be fully considered during processing, analysis, and interpretation.

Remote Sensing – Laser Scanning (LiDAR)

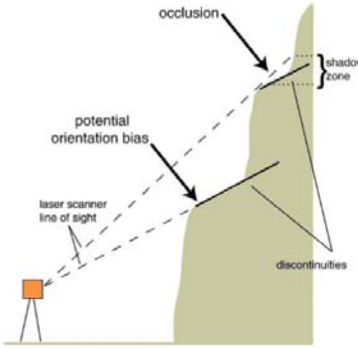


Strouth & Eberhardt (2006)

Remote Sensing – Laser Scanning (LiDAR)



Strouth & Eberhardt (2009)

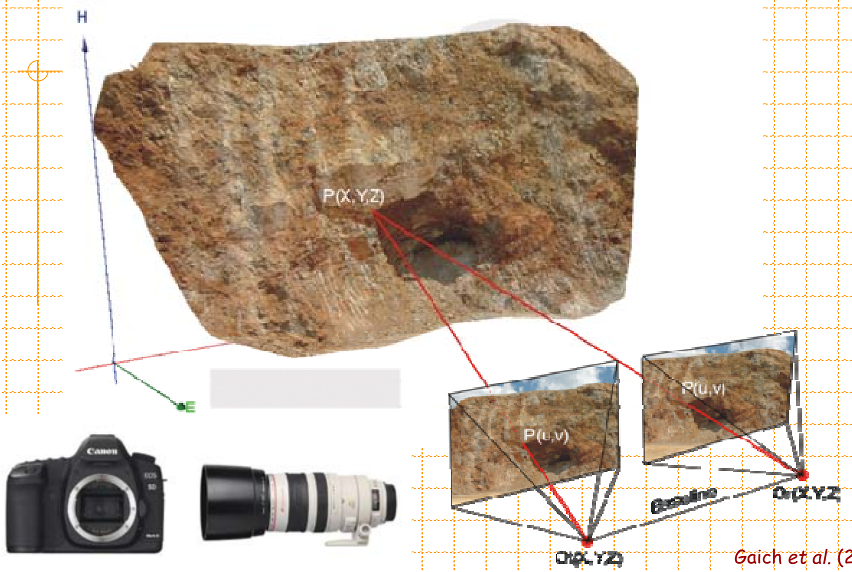


Sturzenegger & Stead (2009a)

Scale bias (or observation scale)	
Effect on discontinuity orientation measurements	Effect on discontinuity persistence measurements
Truncation of non-persistent discontinuity sets resulting in orientation bias	Truncation of non-persistent discontinuities, small compared to ground point spacing
Shift in discontinuity orientation, because of smoothing of step-path geometries	Overestimation of the length of extremely persistent features actually composed of a combination of both smaller discontinuities and intact rock fracture. This results from the smoothing of the step-path geometries at low resolution

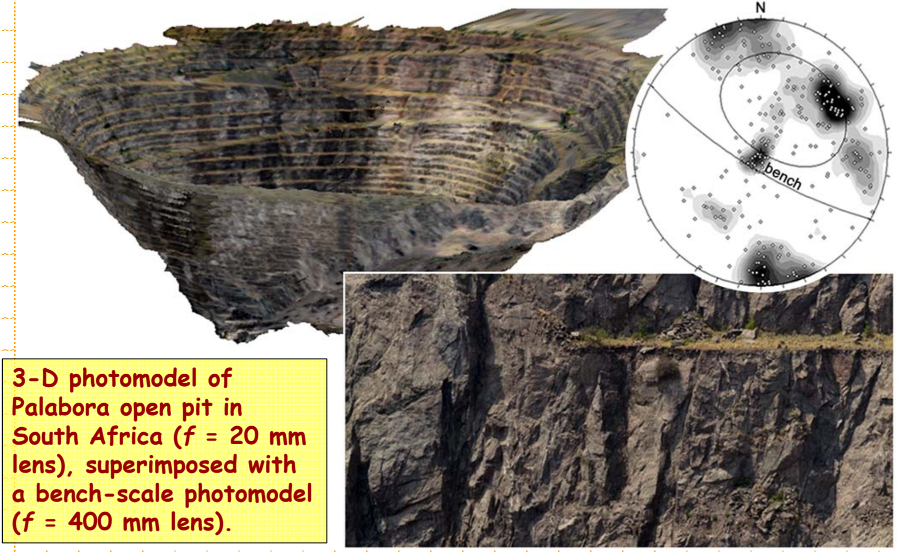
Sturzenegger & Stead (2009b)

Remote Sensing - Photogrammetry



Gaich et al. (2006)

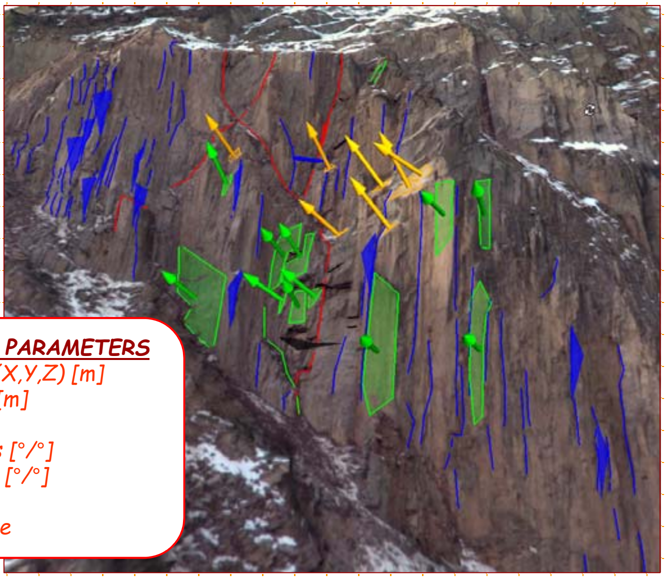
Remote Sensing - Photogrammetry



3-D photomodel of Palabora open pit in South Africa (*f* = 20 mm lens), superimposed with a bench-scale photomodel (*f* = 400 mm lens).

Stead *et al.* (2009)

Remote Sensing – Measured Parameters

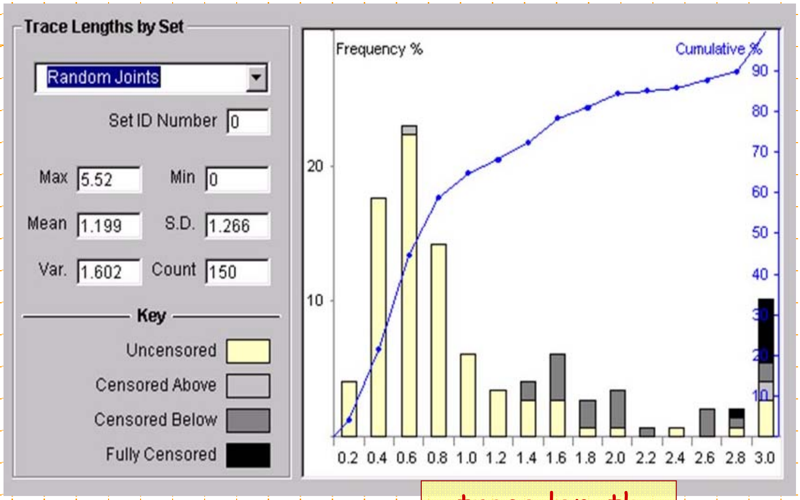


DISCONTINUITY PARAMETERS

Discrete positions (X,Y,Z) [m]
Distances, lengths [m]
Areas [m^2]
Dip / Dip directions [°/°]
Trace orientations [°/°]
Rock bridges
Spacing, persistence

Gaich et al. (2006)

Remote Sensing – Data (Added Value)



Trace Lengths by Set

Random Joints

Set ID Number: 0

Max: 5.52 Min: 0

Mean: 1.199 S.D.: 1.266

Var.: 1.602 Count: 150

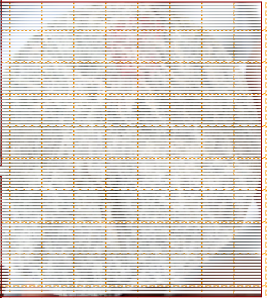
Key

Uncensored 🟨
Censored Above ⬜
Censored Below ▨
Fully Censored ⬛

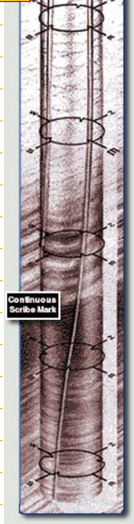
trace length

Discontinuity Mapping at Depth - Oriented Core

Ezy-Mark



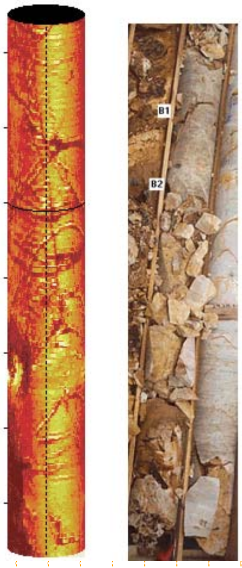
Scribe



Borehole Imaging and Characterisation

Type	Advantages	Disadvantages
Acoustic Televiewer	Provides a continuous record of borehole wall (3-D virtual core); provides high accuracy and confidence in data; can be used in highly fractured rock.	Requires a stable borehole; requires water or mud in borehole to operate.
Optical Televiewer	Provides a continuous record of borehole wall (3-D virtual core); provides high accuracy and confidence in data; can be used in highly fractured rock.	Requires a stable borehole; requires air or clear water to operate.

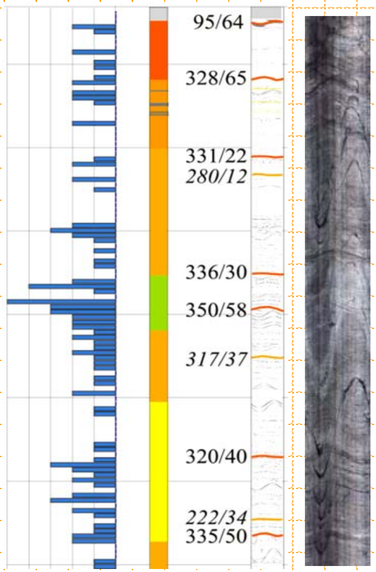
Eberhardt & Stead (2011)



Borehole Imaging and Characterisation

Televiewers are chosen for:

- Defining dip, dip-direction and aperture of fractures, bedding and contacts
- Obtaining critical information from areas with missing core or low core recovery (low RQD)
- Detailing fracture and fault zones regarding depth, size, frequency and attitude
- Depicting the in-situ stress field orientation



Willenberg *et al.* (2008)

Role of Site Investigation & Monitoring

Investigation:

- To provide an understanding of the ground conditions, for prefeasibility and design purposes.
- To provide input values for design calculations.
- To check for changing ground conditions as the project develops, or advance/progress to greater depths.

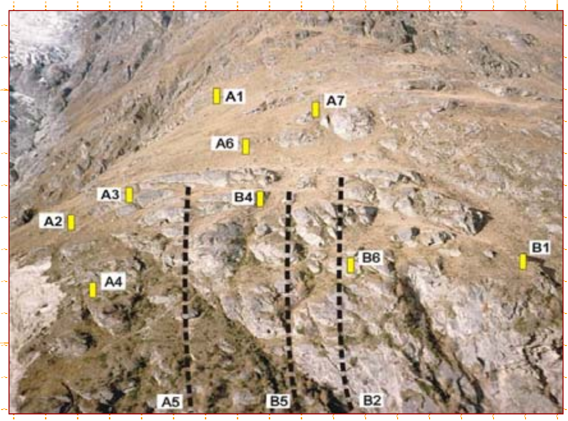
Monitoring:

- To assess and verify the performance of the design.
- To calibrate models and constrain design calculations.
- To provide a warning of a change in ground behaviour, thus enabling intervention to improve safety or to limit damage through a design change or remediation measure.

Field Instrumentation

Geotechnical projects often present the ultimate measurement challenge, in part because of their initial lack of definition and the sheer scale of the problem; often a number of instrumentation types is required.

The ultimate goal is to select the most sensitive measurement parameters with respect to the project objectives. However, because of physical limitations and economic constraints, all parameters cannot be measured with equal ease and success.



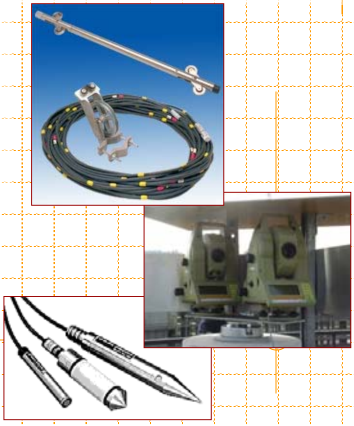
Instrumentation & Monitoring

The use of geotechnical instrumentation is not merely the selection of instruments but a comprehensive step-by-step engineering process beginning with a definition of the objective and ending with implementation of the data.

Engineering objectives typically encountered in soil and rock engineering projects have led to the design and commercial marketing of numerous instrument types, measuring for example:

decreasing reliability

- ***temperature***
- ***deformation***
- ***groundwater/pore pressures***
- ***total stress in backfill and stress change in rock***

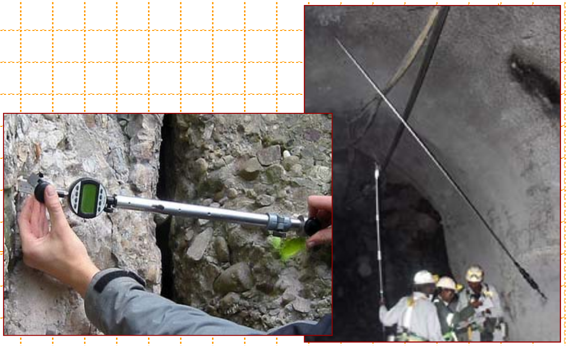


Instrumentation, Monitoring & Design

The required versatility in how instruments can be deployed (on surface, from boreholes, etc.) and what they are meant to measure (rock properties, ground movements, water pressures, etc.) has led to the development of a wide variety of devices.

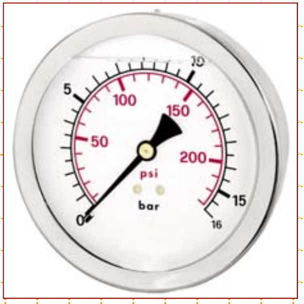
When choosing instruments for a particular project, the engineer must consider and balance the job-related requirements of:

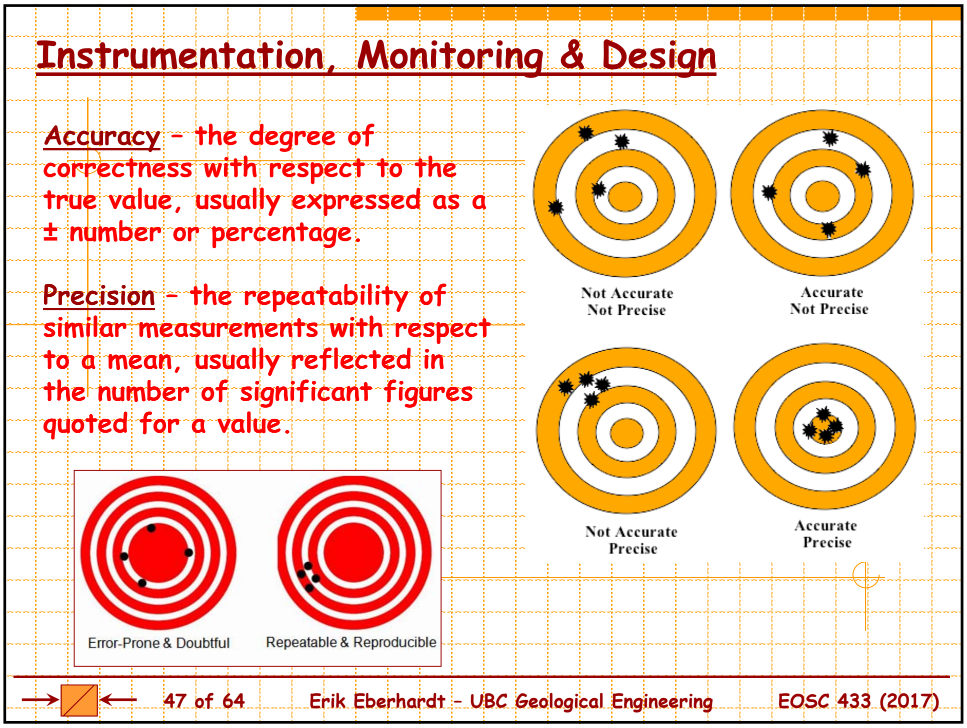
Range – the maximum distance over which the measurement can be performed, with greater range usually being obtained at the expense of resolution.



Instrumentation, Monitoring & Design

Resolution – the smallest numerical change an instrument can measure.

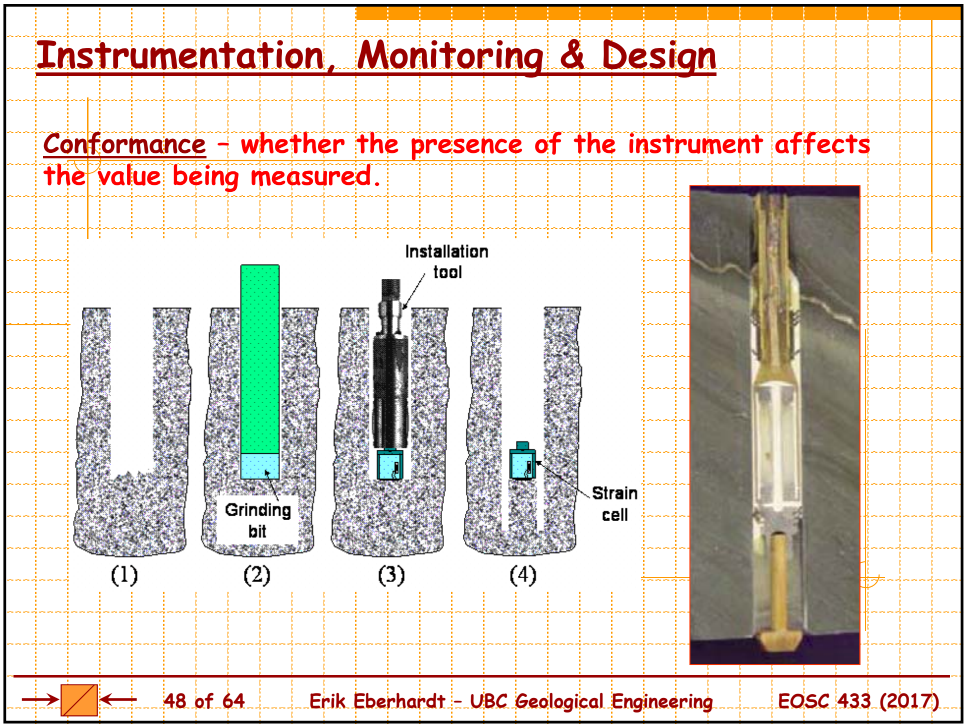




Instrumentation, Monitoring & Design

Accuracy – the degree of correctness with respect to the true value, usually expressed as a ± number or percentage.

Precision – the repeatability of similar measurements with respect to a mean, usually reflected in the number of significant figures quoted for a value.

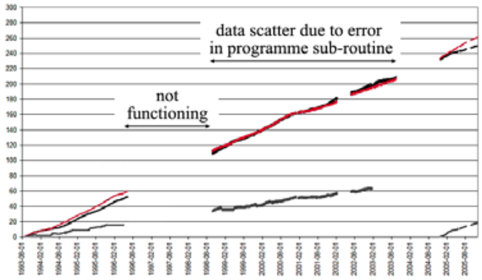


Instrumentation, Monitoring & Design

Conformance – whether the presence of the instrument affects the value being measured.

Instrumentation, Monitoring & Design

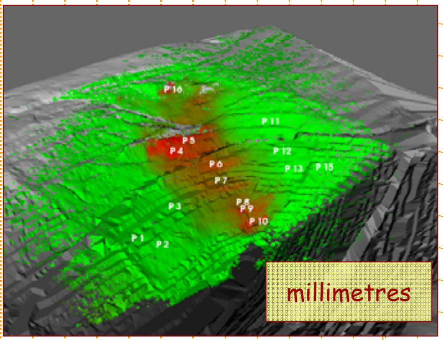
Robustness – the ability of an instrument to function properly under harsh conditions to ensure data accuracy and continuity are maintained.



Reliability – synonymous with confidence in the data; poor quality or inaccurate data can be misleading and is worse than no data.

Instrumentation Planning

Some level of predictions are necessary beforehand so that the required instrument ranges and sensitivities or accuracies can be selected.

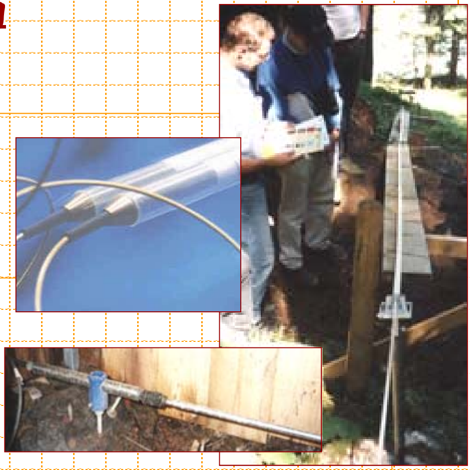


Severin et al. (2011)

> "if you do not know what you are looking for, you are not likely to find much of value"
>
> *R. Glossop, 8th Rankine Lecture, 1968*

Instrumentation Planning

1999 Eibelschrofen rockfall, Austria



Post-failure monitoring of the slope included the installation of a fibre-optic extensometers capable of measuring μm-scale displacements. Was this useful?

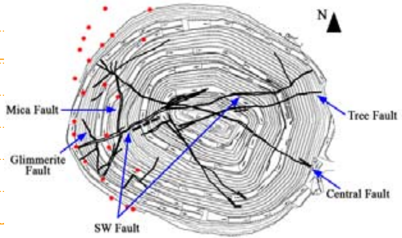
Point versus Area Measurements

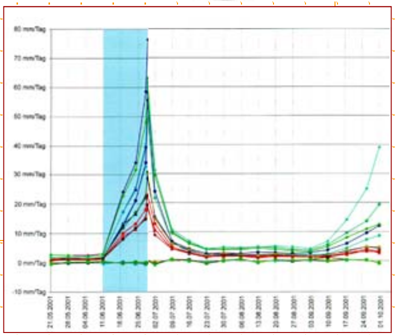
Monitoring systems have traditionally involved *point measurements*, requiring movements and deformations between points to be extrapolated. This may result in:

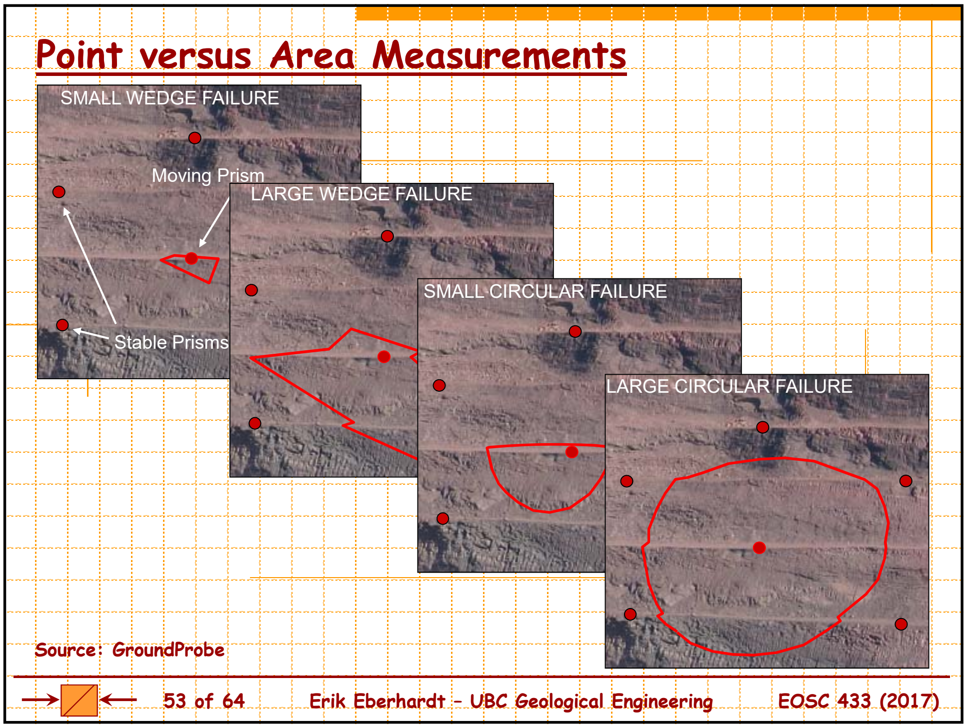
i) the boundaries of areas with high displacement rates to be poorly defined,

ii) smaller scale structurally controlled movements such as wedge or planar sliding to be overlooked, or

iii) the mechanics behind larger and more complex pit-scale failures to be misinterpreted.

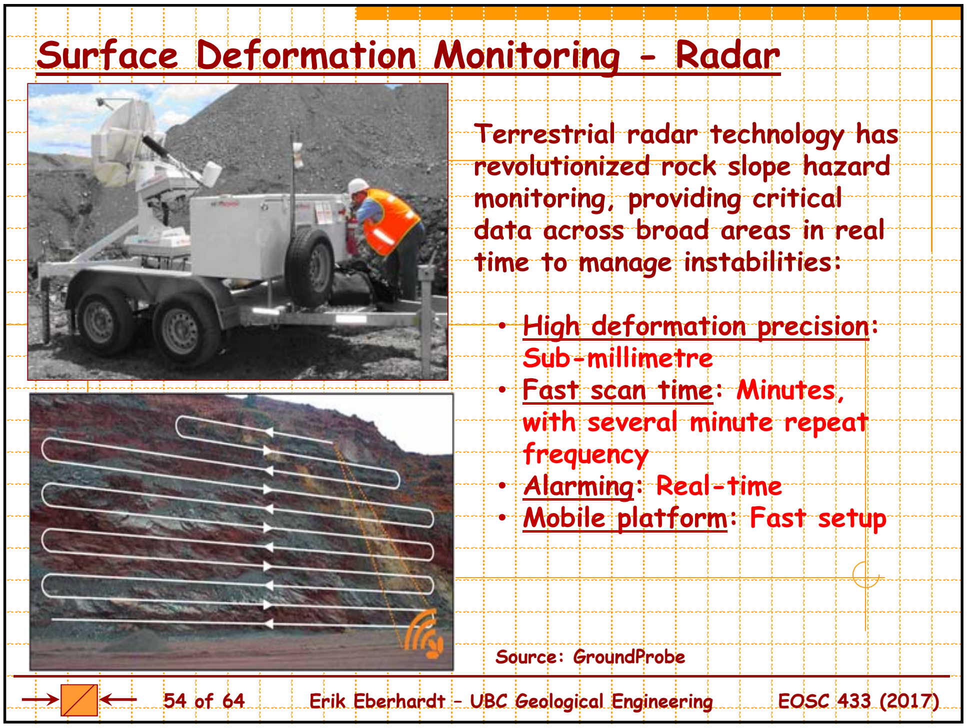






Point versus Area Measurements

Source: GroundProbe

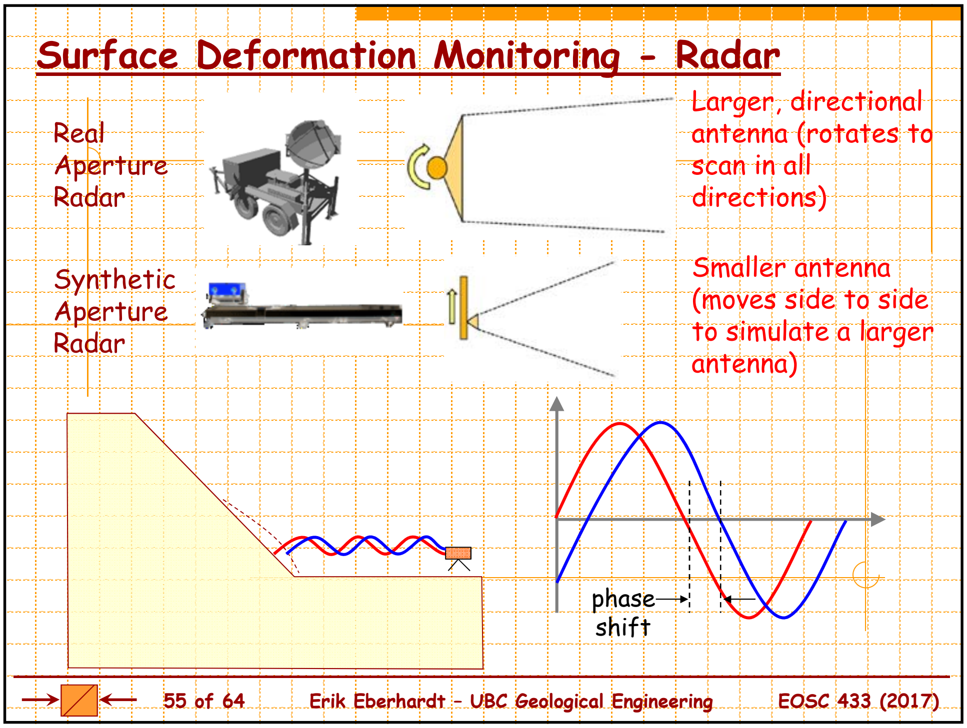


Surface Deformation Monitoring - Radar

Terrestrial radar technology has revolutionized rock slope hazard monitoring, providing critical data across broad areas in real time to manage instabilities:

- High deformation precision: Sub-millimetre
- Fast scan time: Minutes, with several minute repeat frequency
- Alarming: Real-time
- Mobile platform: Fast setup

Source: GroundProbe



Surface Deformation Monitoring - Radar

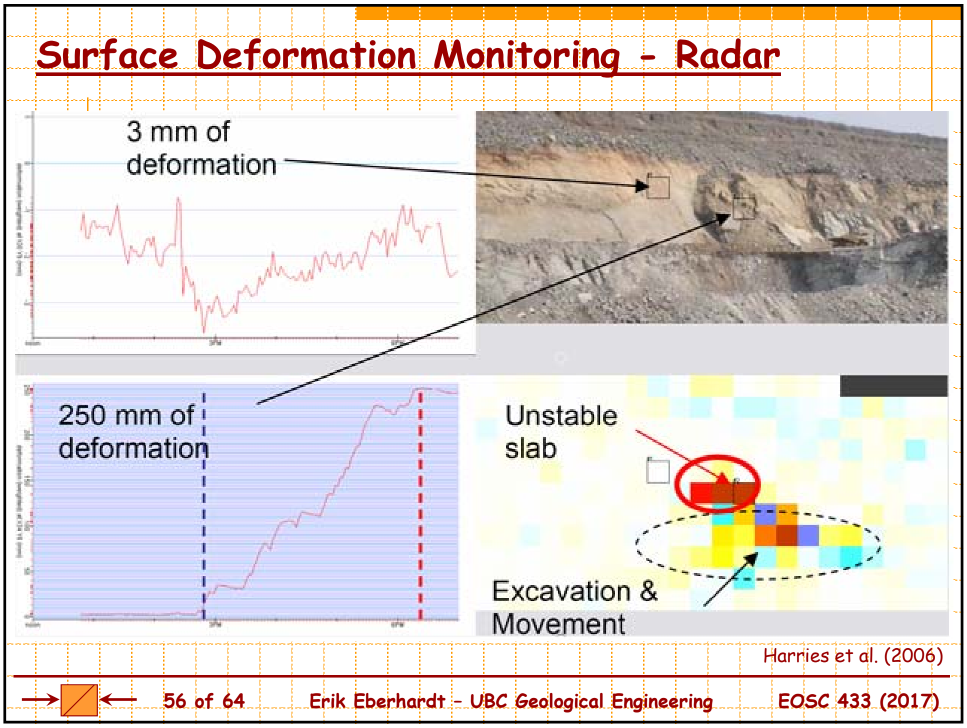
Real Aperture Radar

Larger, directional antenna (rotates to scan in all directions)

Synthetic Aperture Radar

Smaller antenna (moves side to side to simulate a larger antenna)

phase shift



Surface Deformation Monitoring - Radar

3 mm of deformation

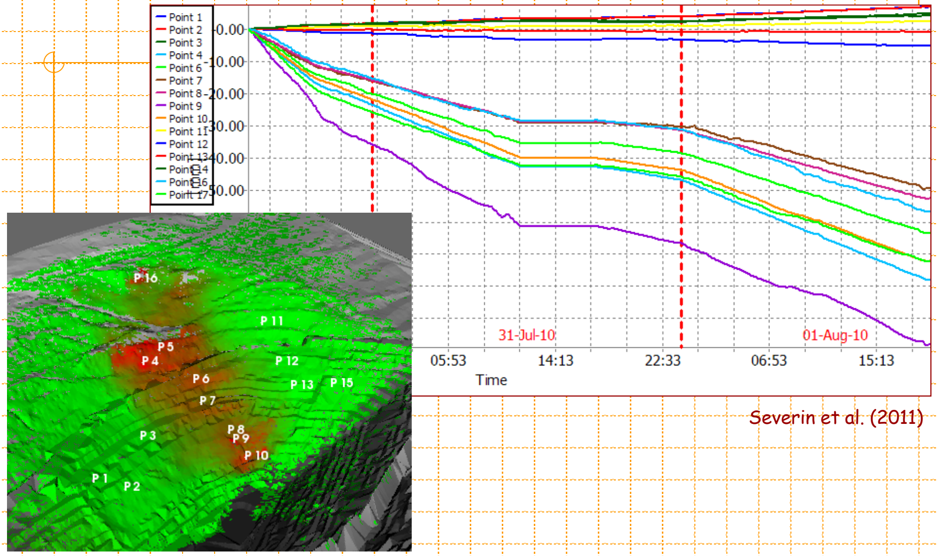
250 mm of deformation

Unstable slab

Excavation & Movement

Harries et al. (2006)

Real Time Monitoring: Radar



Severin et al. (2011)

Trigger Action Response Plans

Inherent in the use of instrumentation for monitoring purposes is the absolute necessity for deciding in advance, a minimum set of actions required by site personnel in response to monitoring alarms being triggered, and a positive means for solving any problem that may be disclosed by the results of the observation.

- 🟥 critical alarm situation; emergency is announced and pit superintendent is notified to evacuate.
- 🟧 geotech alarm situation; movements indicate developing situation that geotech department should provide guidance on.
- 🟨 system failure in radar; pit superintendent notified that radar is unavailable and geotech department notified to assess radar unit.
- 🟩 all systems go and slope movements below alarm thresholds.

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