EOSC433/536:

Geological Engineering Practice I – Rock Engineering

Supplemental Material:

Instrumentation Planning & Design

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.

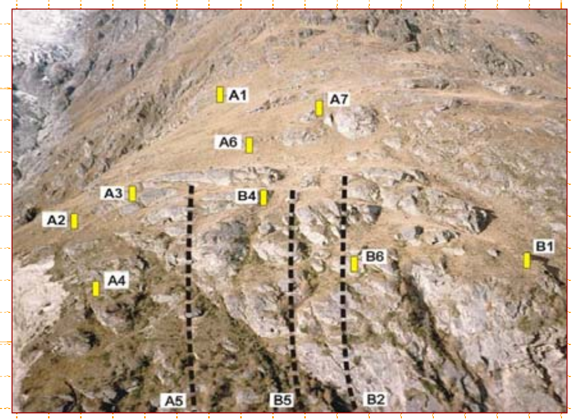
Monitoring:

- 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.



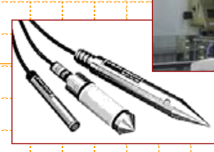
Instrumentation & Monitoring

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

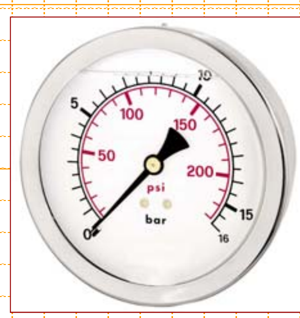
The required versatility in how instruments can be deployed (on surface, from boreholes, etc.) and what they are meant to measure (rock properties, ground movements, water pressures, etc.) has led to the development of a wide variety of devices.

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

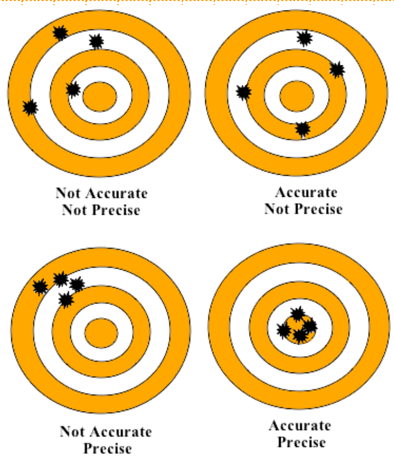
Resolution – the smallest numerical change an instrument can measure.

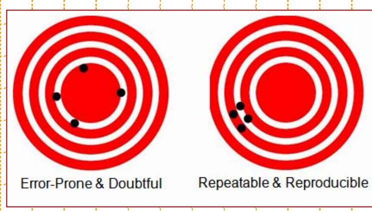


Instrumentation, Monitoring & Design

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

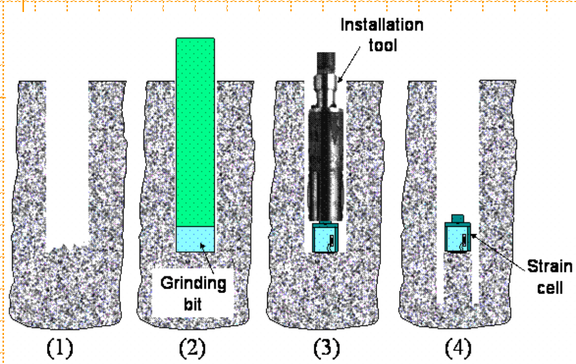
Precision – the repeatability of similar measurements with respect to a mean, usually reflected in the number of significant figures quoted for a value.





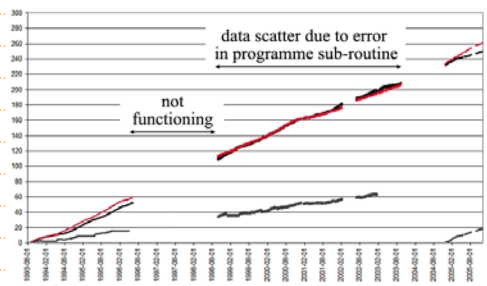
Instrumentation, Monitoring & Design

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



Instrumentation, Monitoring & Design

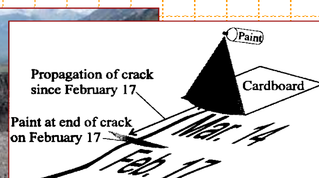
Robustness – the ability of an instrument to function properly under harsh conditions to ensure data accuracy and continuity are maintained.

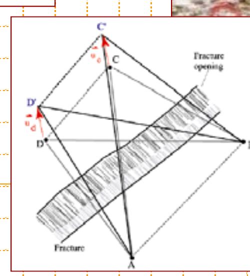


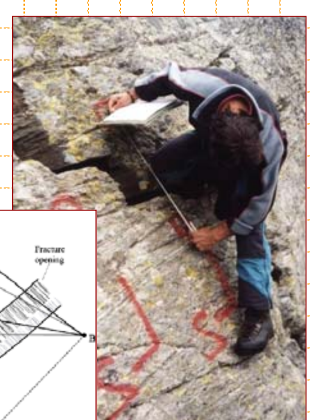
Reliability – synonymous with confidence in the data; poor quality or inaccurate data can be misleading and is worse than no data.

Surface Deformation Monitoring

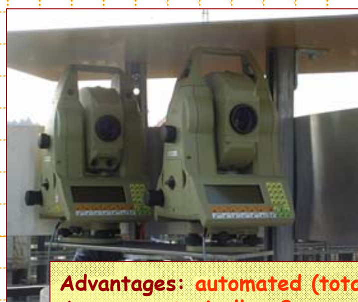
Surface deformation monitoring systems must balance low cost systems and ease of execution with the need for measurement resolution, precision and spatial coverage.





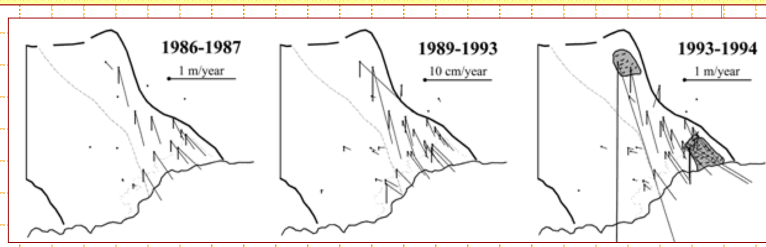


Instrumentation – Geodetic Monitoring



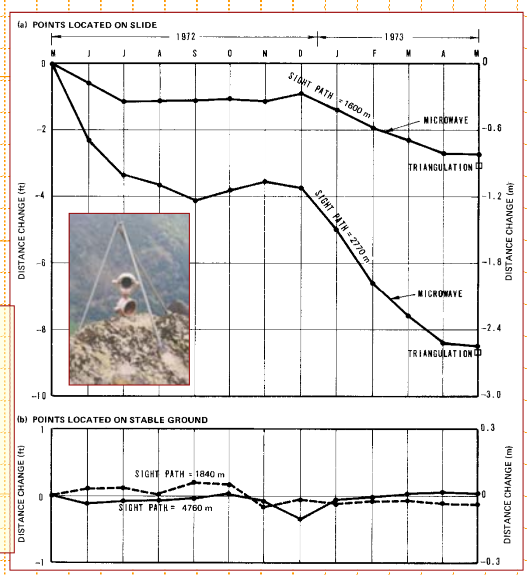
Geodetic monitoring provides a means to measure the magnitude and rate of horizontal and vertical ground movements. Methods are well established, and are often entirely adequate for performance monitoring.

Advantages: automated (total station, robototic), inexpensive, versatile.
Accuracy: typically ±2mm + 2 ppm x D mm over 3000 m



Bonzanigo *et al.* (2007)

Geodetic Monitoring - Benchmarks



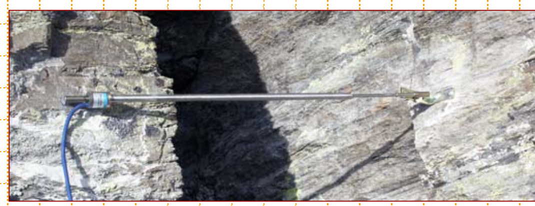
Measurement accuracy (and reliability) is controlled by the characteristics of reference datums and measuring points. Checks are required to make sure these datums are located on stable ground.

Wilson & Mikkelsen (1978)

Instrumentation – Extensometers

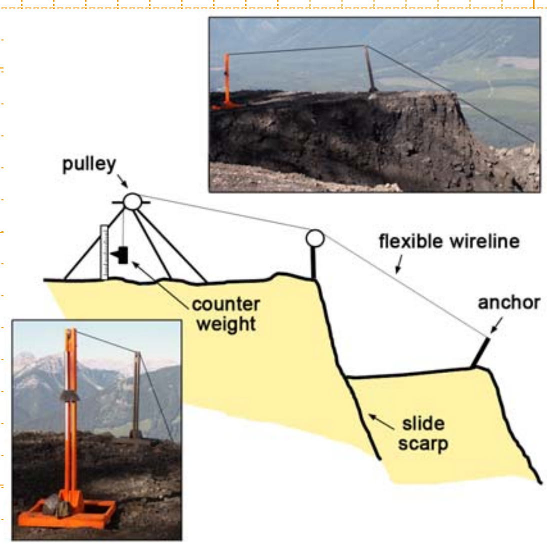
(also: crackmeters, jointmeters, strainmeters, crack gauges, distometers, convergence gauges, siding micrometers)

Extensometers are devices used to measure the changing distance between two points. Measurement points may be located on surface to measure ground movements, for example spanning a tension crack to monitor its opening rate, or in a borehole to measure differential displacements along the borehole. Extensometers vary in type between those that involve manual measurements and those that are automated using vibrating wire electronics, differential transducers, or more recently fiber optics.



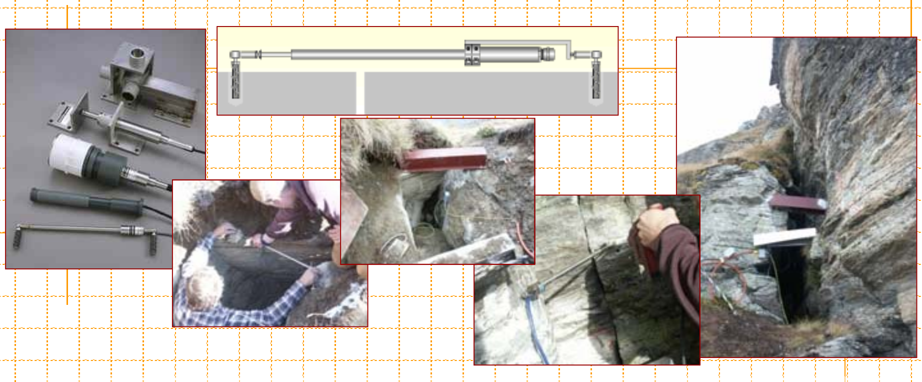
Instrumentation – Extensometers

Wireline extensometers consist of a wire anchored in the unstable ground and tensioned across a pulley located on the stable ground behind the last tension crack using a counter weight. As the unstable portion of the ground moves away from the stable ground, the weight will move and the displacements can be recorded. These devices can be quickly positioned and easily moved, but care must be taken to minimize sag or thermal expansion/contraction in the wire, which can produce measurement errors.



Eberhardt & Stead (2011)

Instrumentation – Crackmeters



… used to measure and monitor the opening of surface fractures and tension cracks.

Advantages: simple, ideally suited for early warning systems.
Sensitivity: <0.01mm with 50-100 mm range

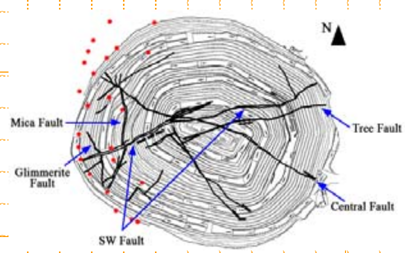
Surface Deformation Monitoring

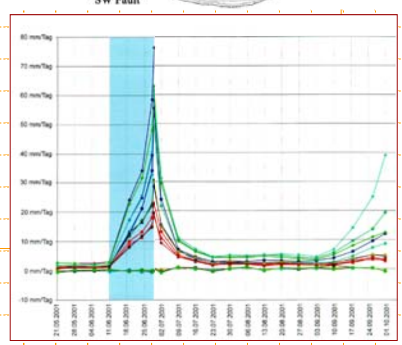
Monitoring systems have traditionally involved *point measurements*, requiring movements and deformations between points to be extrapolated. This may result in:

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.

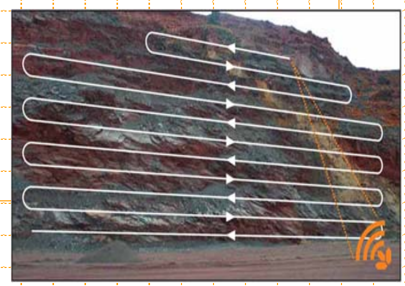




Surface Deformation Monitoring - Radar

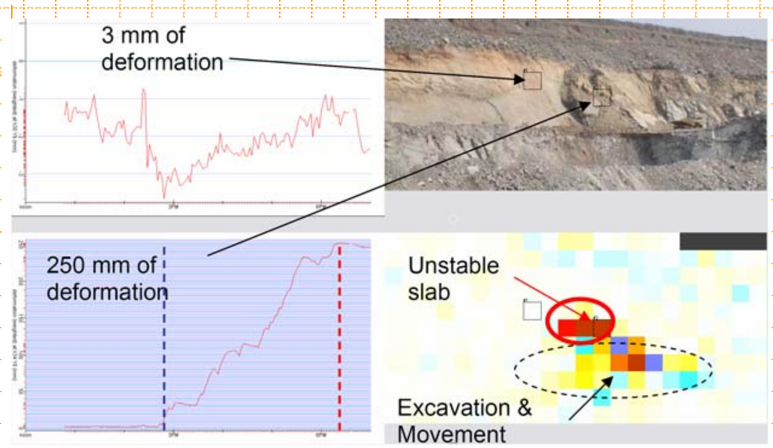
Radar technology has revolutionized open pit mine monitoring, providing real-time full area coverage of a rock slope and offering sub-millimeter measurements of movements.

Radar works by scanning a slope and comparing each point with a reference scan to determine the amount of movement of the slope.



Adverse affects due to rain, dust, and smoke are minimized although reduced precision occurs in pixels due to low coherence between scans for example due to vegetation.

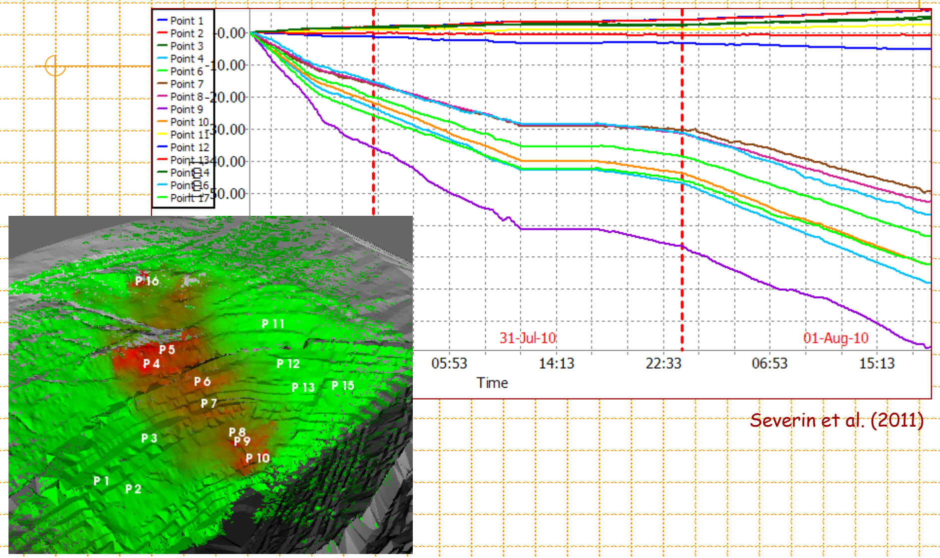
Surface Deformation Monitoring - Radar



Harries et al. (2006)

GroundProbe's Slope Stability Radar (SSR) system showing the continuous monitoring of millimeter-scale movements across the face of an unstable open pit mine slope

Real Time Monitoring: Radar

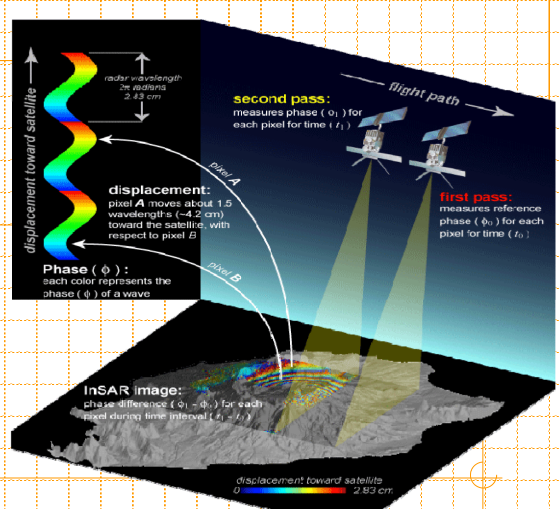


Severin et al. (2011)

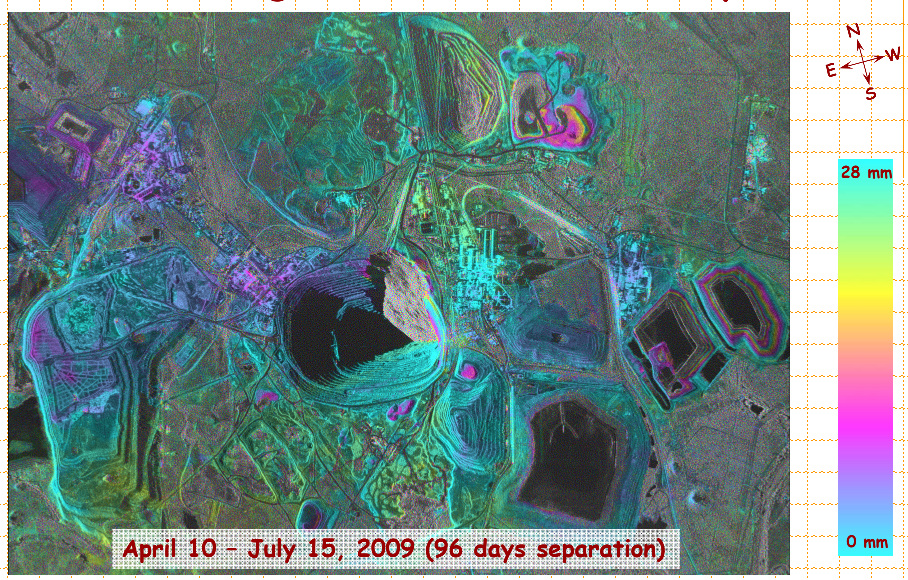
Remote Sensing – Radar Interferometry

Space-borne InSAR involves the use of satellite-based microwave radar. With repeated orbits and image capture (referred to as stacks), interferometric techniques can be used to resolve 3-D surface deformations by analyzing differences in the transmitted and received waves.

Ground deformations on the scale of cm's to mm's can be detected over a surface area resolution of square meters.

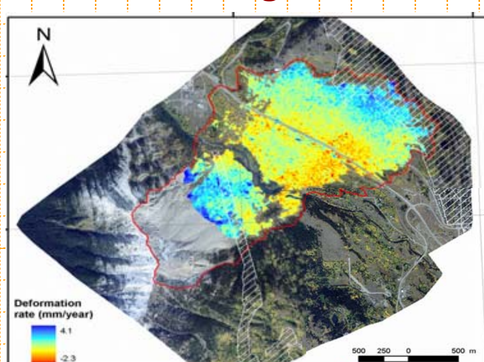


Remote Sensing – Radar Interferometry

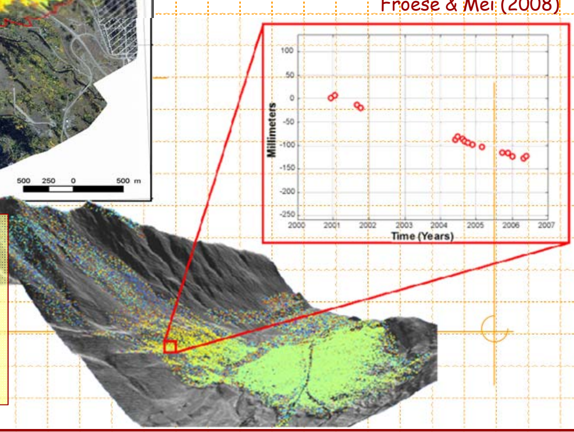


Data courtesy of MDA

Remote Sensing – Radar Interferometry



Froese & Mei (2008)



Deformations detected over old mine workings drawing attention to possible link between movements in the upper slope and de-stressing of the slope's toe due to the slow collapse of the old workings.

Planning and Design: Managing Data Complexity

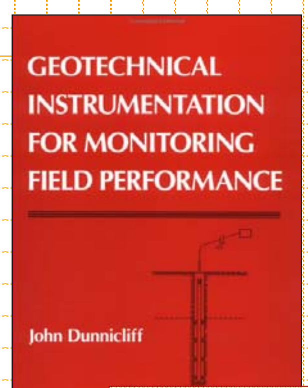
"if you do not know what you are looking for, you are not likely to find much of value"

R. Glossop, 8th Rankine Lecture, 1968

Planning and Design

Monitoring information must be assessed in the context of the physical setting and the conclusions of the site investigation phase.

Planning of a monitoring program should be logical and comprehensive as the measurement problem may require a number of different instrument types collecting information across a range of varying scales. Furthermore, because of physical limitations and economic constraints, all parameters cannot be measured with equal ease and success.



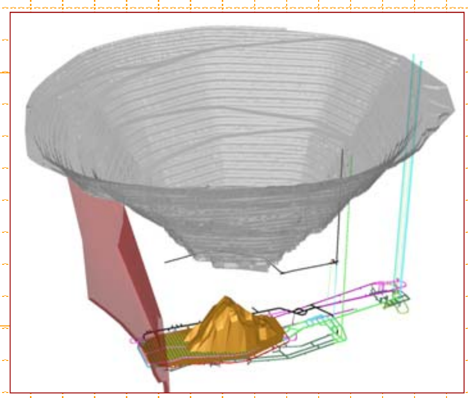
The 'red book' (Dunnicliff 1993)

Planning and Design

Adequate planning is required before proceeding, and these plans should be logical and comprehensive – from defining the objectives to planning how the measurement data will be implemented.

1. Define the project conditions.

   … *these might include project type and layout, geology and structure, engineering properties of materials, groundwater conditions, status of nearby structures or other facilities, environmental conditions, and planned construction method.*

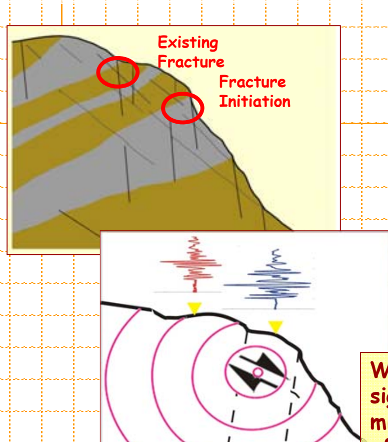


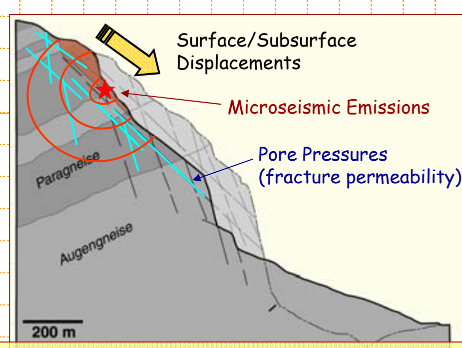
Woo et al. (2012)

Planning and Design

2. Predict mechanisms that control behaviour.

   … *may involve one or more working hypotheses based on a comprehensive knowledge of the project conditions.*





Eberhardt (2008)

Where brittle fracture mechanisms contribute significantly to rock mass deformation and failure, microseismic monitoring may form an integral part of the monitoring strategy.

Planning and Design

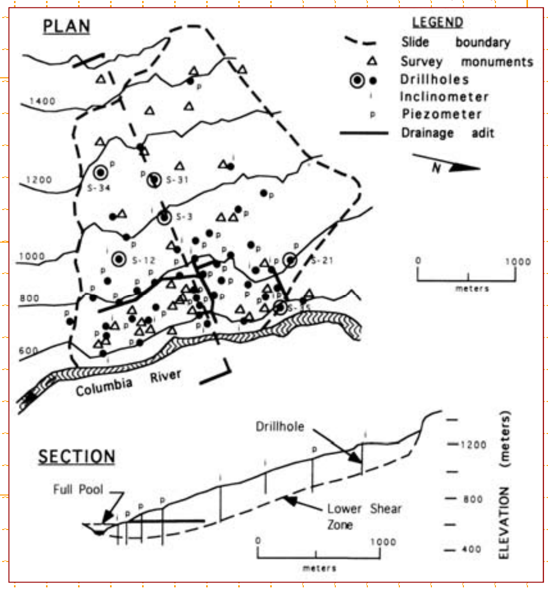
3. Define the geotechnical questions that need to be answered.

… every instrument on a project should be selected and placed to assist in answering a specific question: if there is no question, there should be no instrumentation.

(i) __Investigative Monitoring__: To provide an understanding of the rock mass behaviour and thus enable appropriate actions to be implemented.

(ii) __Predictive Monitoring__: To provide a warning of a change in behaviour and thus enable the possibility of limiting damage or intervening to prevent failure.

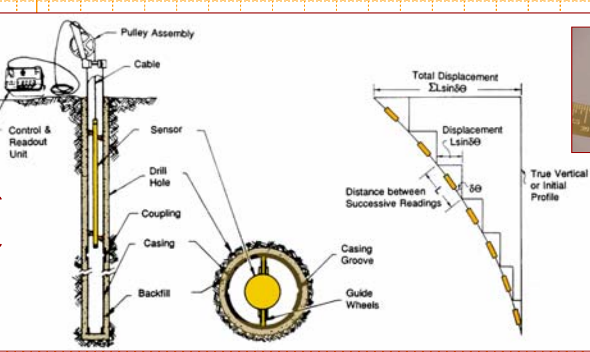
Imrie *et al.* (1992)

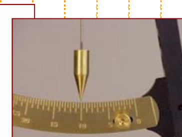


Subsurface Monitoring – Inclinometers

Inclinometers monitor differential subsurface deformations by means of a probe that measures changes in inclination along the length of a borehole.

Dunnicliff (1993)

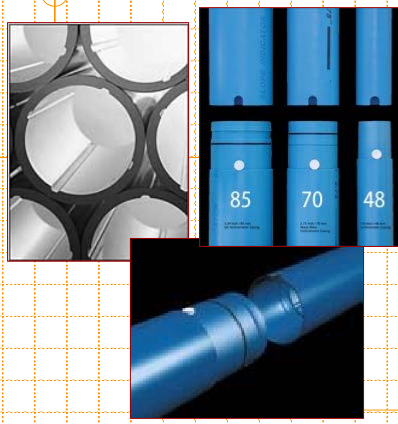


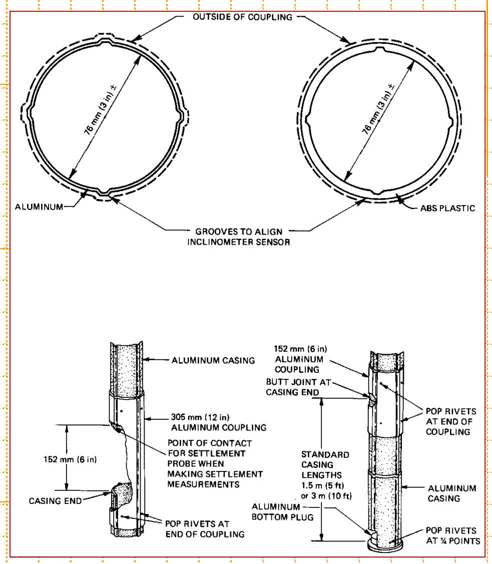


Advantages: can detect and monitor complex slope deformations and displacements along multiple shear planes.

Sensitivity: ±10 arc seconds (±0.05mm/m)

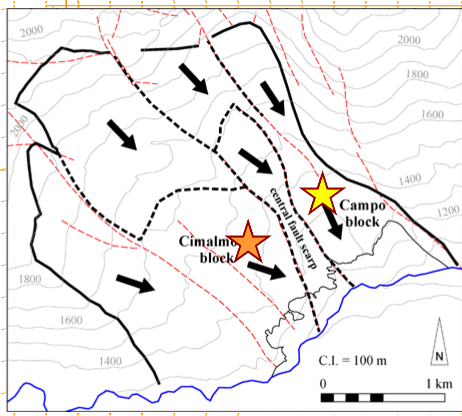
Inclinometer Casing



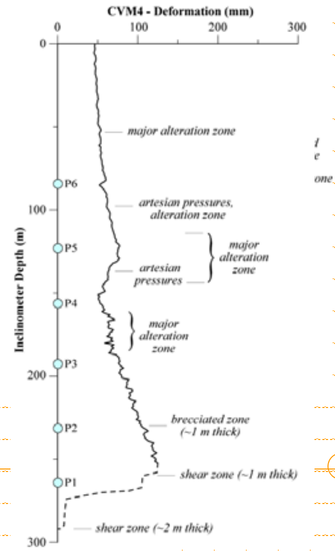


Inclinometer Installation

Campo Vallemaggia – Investigative Monitoring



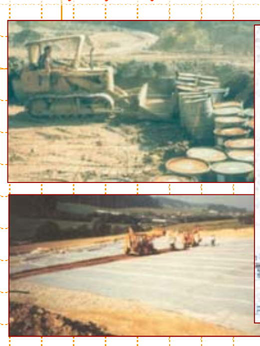
Bonzanigo *et al.* (2007)

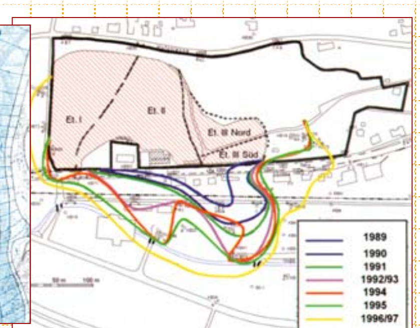


Planning and Design

4. Define the purpose of the instrumentation.

… Peck (1984) stated that, "The legitimate uses of instrumentation are so many, and the questions that instruments and observation can answer so vital, that we should not risk discrediting their value by using them improperly or unnecessarily."



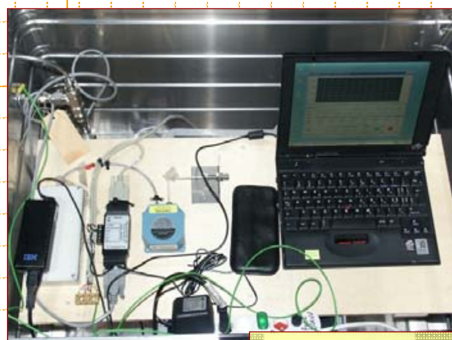


… monitoring the performance of a waste barrier system designed to prevent the polluting of a major aquifer from a chemical waste dump in Kölliken, Switzerland.

Planning and Design

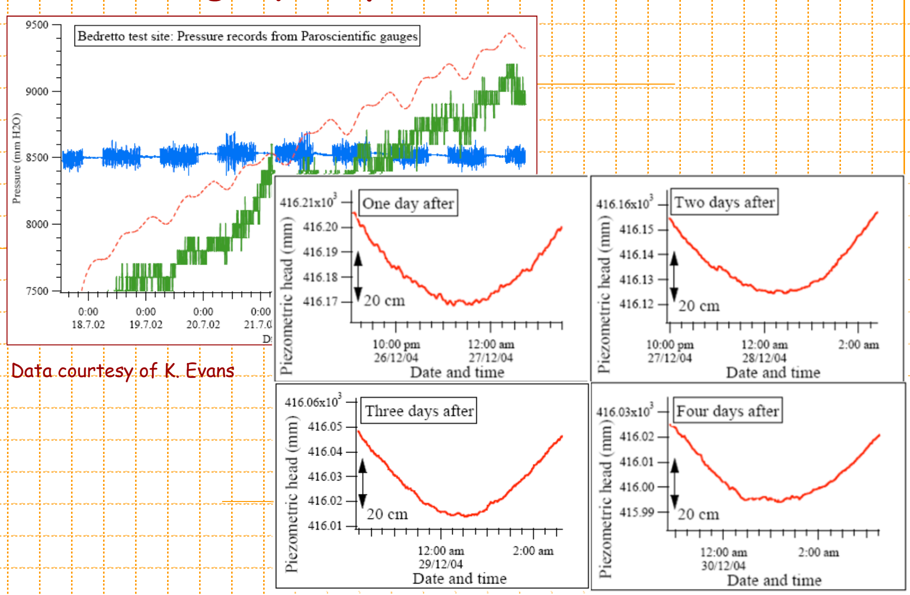
5. Select the parameters to be monitored.

… *Parameters include pore water pressure, joint water pressure, stress change, deformation, and load and strain in structural members, and.*



… high precision joint water pressure measurements from a borehole in the Bedretto tunnel, Switzerland.

Value of high quality instruments…



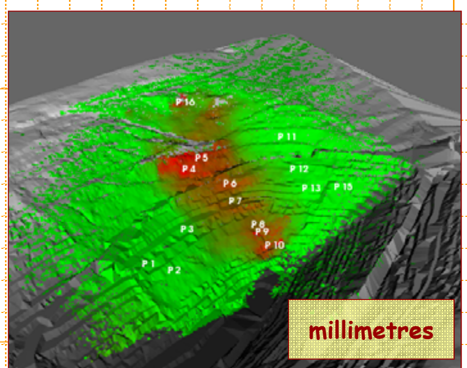
Data courtesy of K. Evans

Planning and Design

6. Predict magnitudes of change.

… *Predictions are necessary so that the required instrument ranges and required instrument sensitivities or accuracies can be selected.*

centimetres

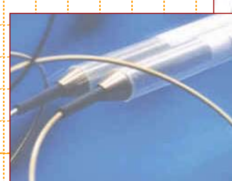


millimetres

Severin et al. (2011)

Planning and Design

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?

Planning and Design

7. Devise remedial action.

… *Inherent in the use of instrumentation for construction purposes is the absolute necessity for deciding in advance, 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.

Planning and Design

8. Assign tasks for design, construction and operation phases.

… *Instrumentation specialists may be the owner's on-site staff or outside consultants/contractors with special expertise. When assigning tasks for monitoring, the party with the greatest vested interest in the data should be given direct line responsibility for producing it accurately.*

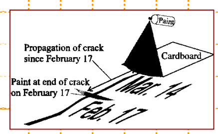
Planning and Design

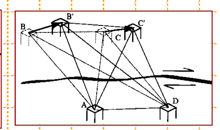
9. Select Instruments.

… When selecting instruments, the overriding requirement is reliability! Inherent in reliability is simplicity.

increasing complexity

- *Optical*
- *Mechanical*
- *Hydraulic*
- *Pneumatic*
- *Electrical*





Instruments should be:

… reliable, rugged and capable of functioning for long periods of time without repair or replacement;

… capable of responding rapidly and precisely to changes so that a true picture of events can be maintained at all times.

Planning and Design – Sensor Types

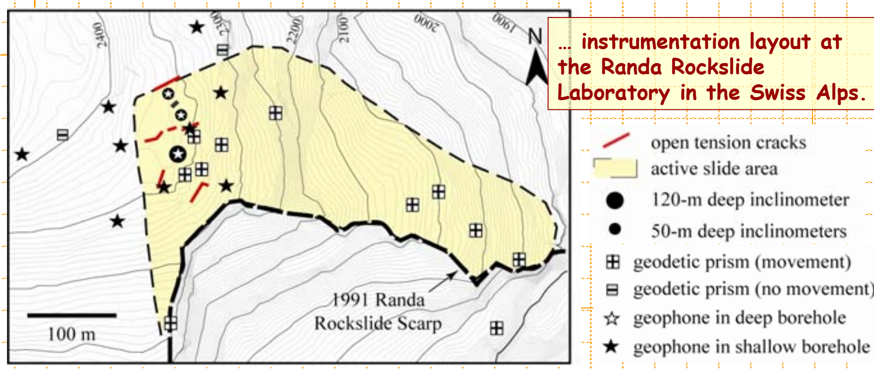
Eberhardt & Stead (2011)

Sensor Type	Operation Principles
LVDT	Linear Variable Differential Transformers (LVDT) consist of a movable magnetic core passing through one primary and two secondary coils. An excitation voltage is applied and a voltage is induced in each secondary coil. When the core moves off center, the output voltage increases linearly in magnitude. LVDTs are commonly used in instruments to measure displacements.
Vibrating wire	Involves a high tensile steel wire fixed at both ends and tensioned so that it is free to vibrate at its natural frequency. The wire is magnetically plucked by an electrical coil and its frequency measured. When one end moves relative to the other the tension in the wire, and therefore measured frequency, changes. Vibrating wire transducers are commonly used in pressure cells, piezometers and deformation gages.
Accelerometers	Consist of a damped mass suspended in a magnetic field; under the influence of external accelerations (or motion) the mass deflects from its neutral position and the deflection measured. Accelerometers are commonly used in tiltmeters and inclinometers.
Fiber optics	Light is emitted into and confined to a glass fiber core and propagates along the length of the fiber. Any disturbance of the fiber alters the guided light which can then be related to the magnitude of the disturbing influence. Fiber optics is finding increased use in piezometers and deformation monitoring instruments.
MEMS	Micro-Electrical Mechanical Systems (MEMS) are small integrated devices that combine electrical and mechanical components on a sub-micrometer to sub-millimeter scale. This allows for transducers, for example accelerometers, that are much smaller, more functional, lighter, more reliable, and are produced for a fraction of the cost of conventional transducers.

Planning and Design

10. Select instrument locations.

… The selection of instrument locations should reflect predicted behaviour and should be compatible with the method of analysis that will later be used when interpreting the data.



… instrumentation layout at the Randa Rockslide Laboratory in the Swiss Alps.

Willenberg et al. (2008b)

Planning and Design

11. Account for factors that may influence measured data.

… Details of each instrument installation should be recorded, because local or unusual conditions often influence measured variables.

12. Establish procedures for ensuring reading correctness.

… When reading an instrument, one should be able to answer the question: Is the instrument functioning correctly? The answer can sometimes be provided by visual observations, duplication of instruments, data consistency or through the use of instruments that internally check their own correct functioning.

Instrument Environments

1. Large deformations—often shearing deformations
2. High pressures—both solids and fluids
3. Corrosive—chemical (groundwater, grouts, concrete additives, bacteria) and electrolytic (electrolysis of dissimilar materials, stray electrical currents)
4. Temperature extremes—subfreezing to 100°F+ in the sun (temperature can be higher in certain instances, such as nuclear waste storage)
5. Shock—blasting, construction activities, rough handling during transportation to and from site
6. Vandalism, destruction by construction equipment, fly rock
7. Dust, dirt, mud, rain, chemical precipitates
8. High humidity, flowing or standing water
9. Erratic power supplies (electrical instruments)
10. Loss of accessibility to instruments when covered by rock, soil, shotcrete, and other supports

Planning and Design

13. List the specific purpose of each instrument.

… It is useful to question whether all planned instruments are justified. If no viable purpose can be found for a planned instrument, it should be deleted.

14. Prepare budget.

… A budget should be prepared for all instrumentation-related tasks to ensure sufficient funds are indeed available. A frequent error in budget preparation is to underestimate the duration of the project and the real data collection and processing costs.

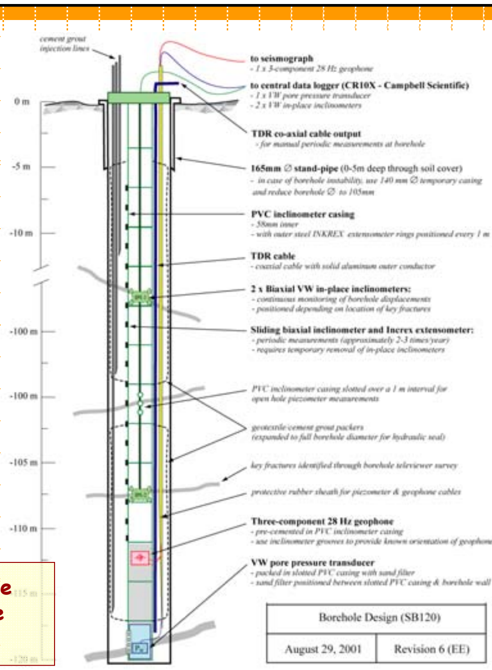
15. Prepare instrument procurement specifications.

… There are several competing instrumentation manufacturers, each offering products designed for similar geotechnical purposes. Be aware of an instrument's capabilities (and limitations), as well as those of competing products. Instruments should be purchased from established manufacturers.

Planning and Design

16. Plan installation, regular calibration & maintenance.

… Installation procedures should be planned well in advance of scheduled installation dates. The step-by-step procedures should include a detailed list of required materials and tools, and installation record sheets for documenting factors that may influence measured data.



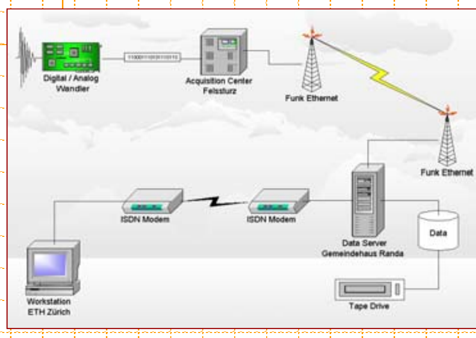
Eberhardt (2008)

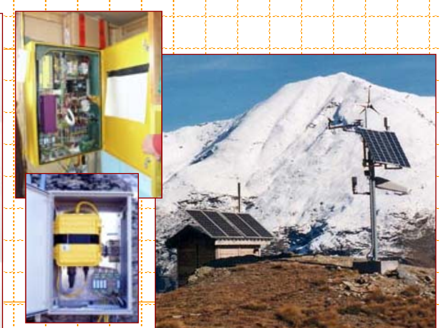
… schematic diagram of the borehole installation design developed for the Randa Rockslide Laboratory.

Planning and Design

17. Plan data collection, processing, presentation, interpretation, reporting and implementation.

… *The effort required for these tasks should not be underestimated. Many consulting firms have files filled with large quantities of partially processed and undigested data because sufficient time/funds were not available for these tasks.*

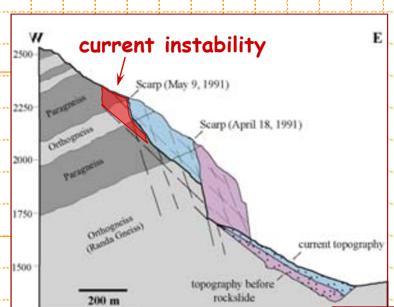


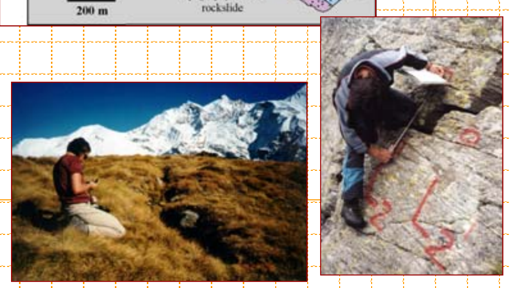


Willenberg et al. (2008b)

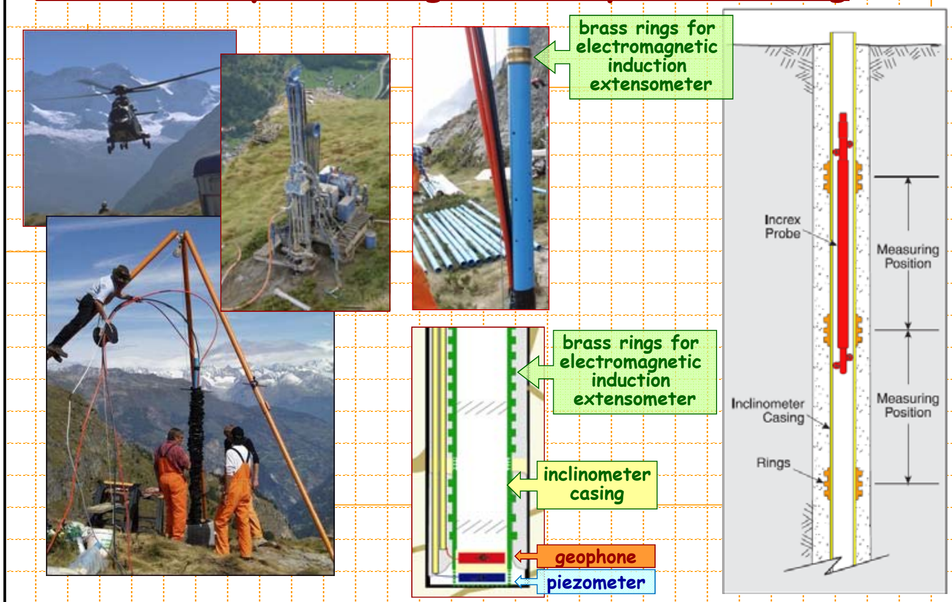
Case History: Investigative Slope Monitoring

Courtesy - H.Willenberg

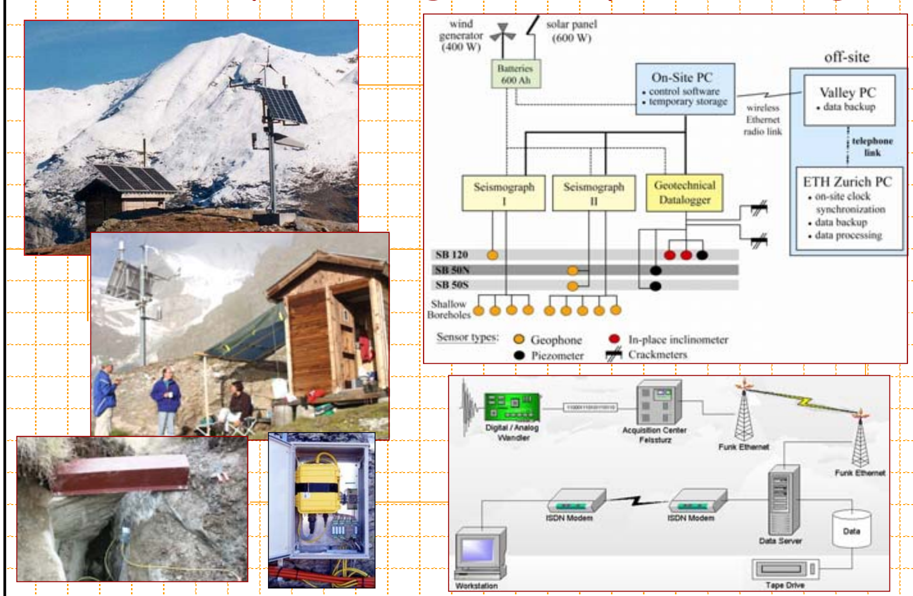




Case History: Investigative Slope Monitoring



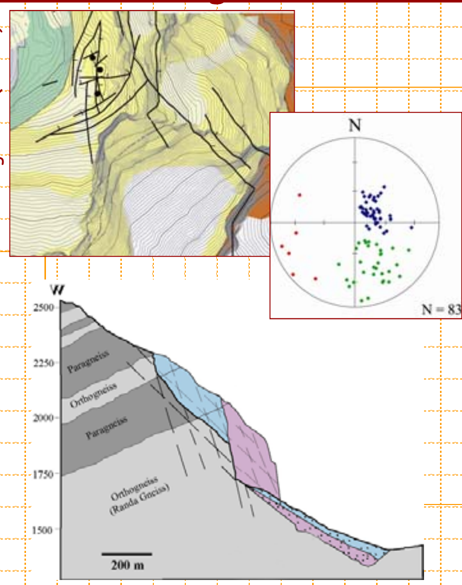
Case History: Investigative Slope Monitoring



Willenberg *et al.* (2008b)

Site Investigation & Data Collection

Willenberg *et al.* (2008a)



Geological investigations ⟷ Geophysical investigations

geological model

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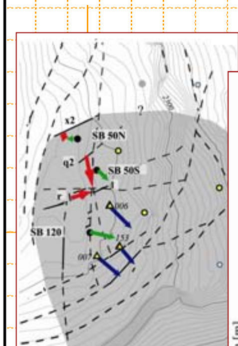
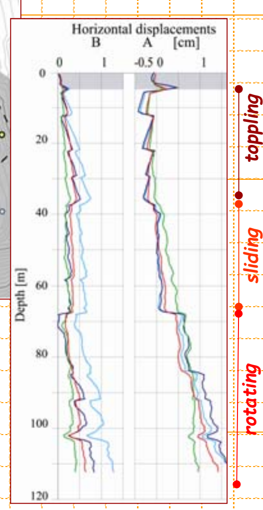
Rockmass processes

Case History: Investigative Slope Monitoring





Geological investigations ⟷ Geophysical investigations

3-D geological model

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Rock Slope Instability

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Kinematics of the rockslide

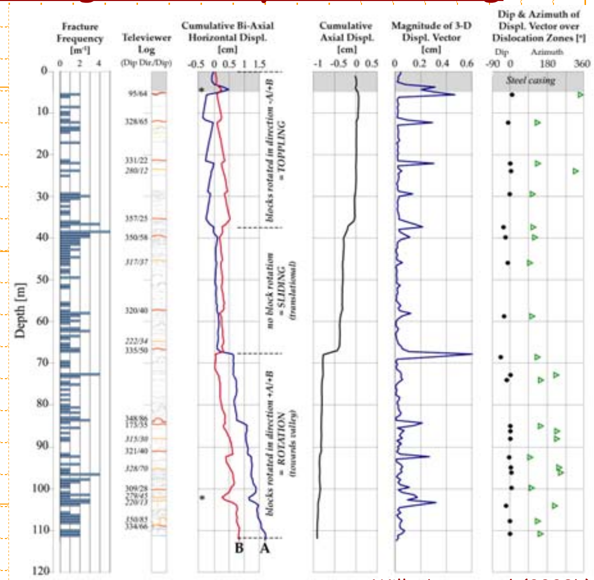
Geotechnical monitoring

Numerical modelling

Microseismic monitoring

Willenberg *et al.* (2008b)

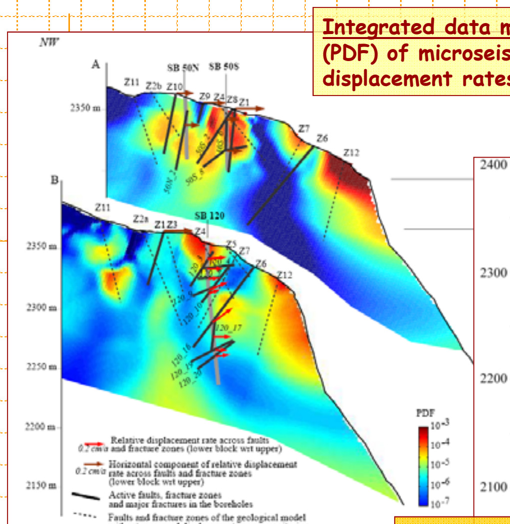
Case History: Investigative Slope Monitoring



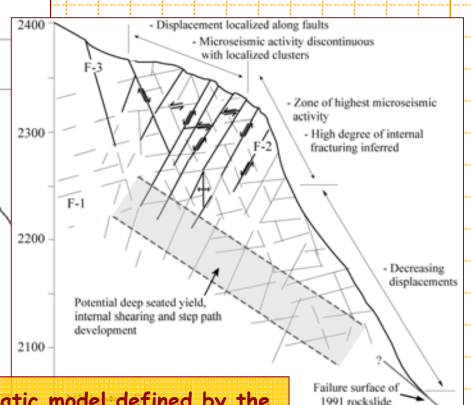
Willenberg *et al.* (2008b)

Case History: Investigative Slope Monitoring

Integrated data model: Probability density functions (PDF) of microseismic event locations, and relative displacement rates of ongoing block movements.

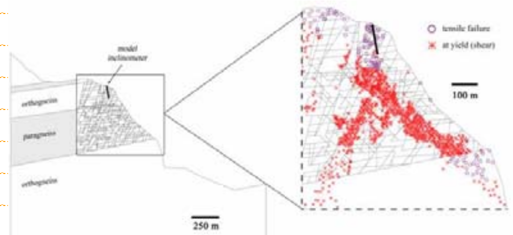


Willenberg *et al.* (2008b)

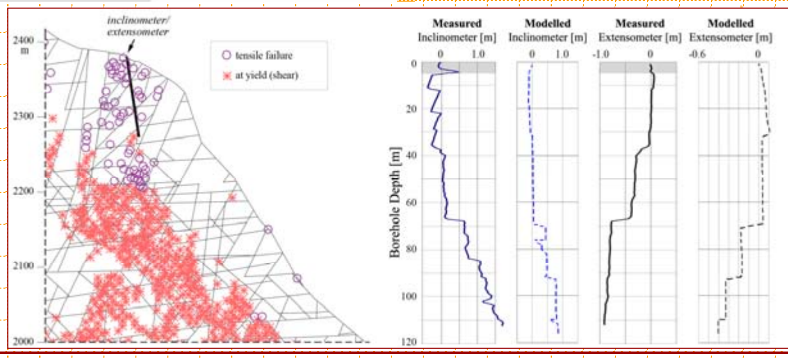


Kinematic model defined by the collective measurements.

Case History: Investigative Slope Monitoring



Monitoring data provides a key means to constrain numerical models. At the same time, numerical modelling provides an ideal means to support and/or refute interpretations drawn from investigative monitoring, as well as to explore possible future behaviour.



Eberhardt (2008)

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