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.

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## 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
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.
Fault Zones

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

Squeezing ground blocks TBM

Budget overrun... more than 200%.
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

- Increasing level of geological knowledge and confidence therein
- JORC
  - Inferred
  - Assumed
  - Indicated
  - Substantiated
  - Measured

Investigation

Geotechnical Model

Mean shear strength
Mean driving stress

Managing Geotechnical Uncertainty

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

Operations (Measured)
Observed/Monitored/Back-Analyzed

Feasibility (Indicated/Measured)
Quantitative/Monitored

Pre-Feasibility (Inferred)
Qualitative/Empirical

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.

- high stiffness: high strength, very brittle
- med. stiffness: med. strength, med. brittleness
- low stiffness: low strength, ductile

- e.g. Granite
- e.g. Limestone
- e.g. Shale
Understanding Rock Behaviour

Parameter | Value (MPa)
---|---
Number of Tests | 20
Min. Peak Strength, $\sigma_{UCS}$ | 183.0
Max. Peak Strength, $\sigma_{UCS}$ | 231.1
Avg. Peak Strength, $\sigma_{UCS}$ | 206.9 ($\pm 13.5$)
**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**

- Massive rock
- Rock mass
- Ground response
- Fractured rock

**Rock as an Engineering Material**

- Homogeneous
  - Sandstone
  - Strength equal in all directions

- Continuous

- Heterogeneous
  - Shale
  - Sandstone

- Discontinuous
  - Fault
  - Joints

- Anisotropic
  - Strength varies with direction
  - High
  - Low
'Averaging' of data that can lead to a misrepresentation of important geological features, particularly major structures.

Rock Mass Behaviour

<table>
<thead>
<tr>
<th>Stress Concentration</th>
<th>In-Situ Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td></td>
</tr>
<tr>
<td>Unstable</td>
<td></td>
</tr>
</tbody>
</table>

Kaiser et al. (2000)
Uncertainty in Ground Characterization

Increasing level of geological knowledge and confidence therein:

- JORC
- Inferred
- Indicated
- Measured

Investigation:
- Geotechnical Model
- Assumed
- Substantiated
- Measured

Monitoring:
- Behaviour Model
- Hypothesized
- Simulated
- Observed

Site Investigation & Data Collection

- Geological investigations
- Geophysical investigations
- Geological model
- Rockmass response
- Geotechnical monitoring
- Stability analysis
- Controlling mechanism(s)
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 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)

Scale bias as observation scale

<table>
<thead>
<tr>
<th>Effect on discontinuity orientation measurements</th>
<th>Effect on discontinuity persistence measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truncation of non-persistent discontinuity set resulting in orientation bias</td>
<td>Truncation of non-persistent discontinuities, small compared to ground point spacing</td>
</tr>
<tr>
<td>Shift in discontinuity orientation, becomes of smoothing of step-path geometries</td>
<td>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</td>
</tr>
</tbody>
</table>

Sturzenegger & Stead (2009b)
3-D photomodel of Palabora open pit in South Africa ($f = 20$ mm lens), superimposed with a bench-scale photomodel ($f = 400$ mm lens).
Remote Sensing - Measured Parameters

**DISCONTINUITY PARAMETERS**
- Discrete positions (X,Y,Z) [m]
- Distances, lengths [m]
- Areas [m²]
- Dip / Dip directions [°/°]
- Trace orientations [°/°]
- Rock bridges
- Spacing, persistence

Remote Sensing - Data (Added Value)
Discontinuity Mapping at Depth - Oriented Core

Ezy-Mark

Scribe

Borehole Imaging and Characterisation

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Televiewer</td>
<td>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.</td>
<td>Requires a stable borehole; requires water or mud in borehole to operate.</td>
</tr>
<tr>
<td>Optical Televiewer</td>
<td>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.</td>
<td>Requires a stable borehole; requires air or clear water to operate.</td>
</tr>
</tbody>
</table>

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:

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Monitoring:

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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:

- 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.

Resolution – the smallest numerical change an instrument can measure.

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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.

**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, sensitivities or accuracies can be selected.

“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

Moving Prism

Stable Prisms

SMALL WEDGE FAILURE

LARGE WEDGE FAILURE

SMALL CIRCULAR FAILURE

LARGE CIRCULAR FAILURE

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

Harries et al. (2006)

3 mm of deformation

250 mm of deformation

Unstable slab

Excavation & Movement

Harries et al. (2006)
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.
Lecture References


Lecture References


