Clay Mineral Neoformation and Transformation in Fault Zones
Formation of Clay Minerals

Sample 1: Smectite 92%
          Illite 8%

Sample 1a: Smectite 87%
           Illite 13%

Sample 2a: Smectite 77%
            Mixed Layer 3%
            Kaolinite 17%
            Illite 3%

Sample 2b: Sample 40%
           Kaolinite 50%
           Illite 10%

Fault Zone in Gneiss („Zentralgneis“)
HPP MALTA – Göß Tunnel, Km 4,615
### Formation of Clay Minerals

<table>
<thead>
<tr>
<th>UNALTERED SOURCE ROCK</th>
<th>Alteration stage (1)</th>
<th>Alteration stage (2)</th>
<th>Alteration stage (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KAOLINIZATION</td>
<td>ILLITIZATION (CHLORITIZATION)</td>
<td>MONTMORILLONITIZATION</td>
</tr>
<tr>
<td><strong>FELDSPAR</strong></td>
<td><strong>KAOLINITE</strong></td>
<td><strong>ILLITE</strong></td>
<td></td>
</tr>
<tr>
<td><strong>MICA</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>BIOTITE</strong></td>
<td><strong>VERMICULITE</strong></td>
<td></td>
<td><strong>SMECTITE</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><strong>CHLORITE</strong></td>
</tr>
</tbody>
</table>

- **INCREASE OF ALKALINITY**
- **DECREASE OF PERMEABILITY**
- **INCREASE OF COMPRESSIBILITY**
- **PROGRESSIVE ARGILLATION**

**Systematic Transformations of Clay Minerals in Fault Zones**

(G. Riedmüller 1976)
Engineering Geological Classification of Fault Rocks
(Riedmüller et al., Felsbau 19 (2001) No. 4)

Classification:

Heavily Fractured Rock Mass
Cataclastic Rocks
Mylonitic Rocks

Cohesive
Cementation
Type of Cement

Strength Ratio:
Block/Matrix

Blocks
Volumetric Block Proportion

Particles Size
< 63 mm

Volumetric Block Proportion

> 75%
Blocky Rock Mass

25 - 75%
Tectonic Bimrock

< 25%

Coarse-grained
> 0.063 mm

G-Cataclasite

S-Cataclasite

M-Cataclasite

C-Cataclasite

Fine-grained
< 0.063 mm

Ferritic

Carbonatic

Siliceous

Glassy

Pseudo-tachylyte

Fault Breccia

1 Block size depends on scale of engineering interest
2 Subsequent differentiation is based on grain size and grading
3 Further differentiation according to USCS standard procedure
4 Differentiation is based on plasticity index and liquid limit (A-line)
General Procedure

- **Desk Studies**
  - Satellite Images, Aerial Photographs, Maps etc.

- **Geological Field Survey**
  - Morphological Features
  - Outcrop Studies
    - Rock Mass Characterization
    - Paleostress Analysis

- **Subsurface Investigation**
  - Trenches, Trial Pits
  - Core Drilling
  - Borehole in-situ tests
  - Geophysical Survey

- **Laboratory Analyses**
  - Mineralogical Analyses
  - Mechanical Analyses
Outcrop Studies

Photographic Substantiation of Selected Outcrops
Outcrop 5 - High Angle Faults

Geological Conditions of Selected Outcrops
Outcrop 5 - High Angle Faults

1. Fault Zone with Fault Breccia and Gouge
2. Parent Rock Heavily Fractured

Hydro Power Project Xiaolangdi
Outcrop Studies

Paleostress Analysis

- Fault Slip Data
  - P/T Method
  - Method of Right Dihedra

- Extension Joints
  - Plumose Structure

Hydro Power Project Xiaolangdi
Thrust Displaced by Strike – Slip Faults

Bolu Tunnel, Turkey

Low angle faults (SL 293/34, 290/42, 302/37, 331/42, 208/39, 249/39) displaced by conjugated faults (SL 227/84, 329/72, 91/87, 243/84, 226/86)
Strategies

Objective of Investigation

OWNER’S INTEREST:

- Construction schedule
- Construction costs

- Definition of uncertainties
- Geotechnical risk assessment
- Identification of environmental problems
Common understanding

High standards and quality for a site investigation lead to an economical and technical successful construction.
Quality is a relative attribute and depends upon the specific circumstance. In the sense of a technical sound and economic investigation quality is determined to be either adequate or inadequate. What is an acceptable quality investigation in one situation can be an inadequate and unacceptable investigation in another.
Strategies

- Design Requirements
- Project Phases

Quality Data
Quality Analyses
Quality Investigation

Complexity of Rock Mass
Complexity of Geology
Strategies

Quality Data Collection
Quality Data Analysis

- geotechnically relevant
- statistically representative
- legally defensible
Strategies

Quality Data Collection
(with adequate quality control and quality assessment)

- Office Data Collection
- Field Survey
- Subsurface Exploration
- In Situ Testing
- Laboratory Testing
Strategies

Quality Data Analysis
(with adequate quality control and quality assessment)

- Statistical Evaluation
- Assessment of Probabilistic Confidence
- Geologic Modelling
- Kinematic Modelling
- Mechanical Modelling
A QUALITY INVESTIGATION needs more than just QUALITY DATA and QUALITY ANALYSES.

It requires:

1. Specific sequence of investigative procedures
2. Design phase and rock mass specific investigations
3. Input from experienced professionals
Strategies

Cost - Benefit Relation of Investigation
Procedure related to Project Phases

Costs

Information

Office Data Collection
Field Survey
Preliminary Site Ass.
Subsurface Exploration
Final Site Assessment

Feasibility
Route Selection
Preliminary Design
Detail Design
## Strategies

### Project Phases - Geotechnical Objectives

<table>
<thead>
<tr>
<th>Pre-Feasibility Feasibility</th>
<th>Conceptual Design Route Selection</th>
<th>Preliminary Design</th>
<th>Detail Design Tender</th>
<th>Final Design Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comparison of Routes</td>
<td>Assessment of Routes</td>
<td>Environmental Impact Assessment</td>
<td>Bill of Quantities</td>
<td>Update of Construction Schedule and Costs</td>
</tr>
<tr>
<td>First Cost Estimate</td>
<td>Cost Estimate</td>
<td>Cost Estimate</td>
<td>Contractual Set-Up</td>
<td>Final Cost Estimate</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Final Cost Estimate</td>
<td></td>
</tr>
</tbody>
</table>
Analytical Procedure in Each Design Phase

Assessment of Geological Models

Rock Mass Characterisation
Rock Mass Types

Stresses, Groundwater, Orientation
Size & Shape of Tunnel

Mechanical Modelling
Rock Mass Behaviour

Geotechnical Design Assumptions
Conceptual **Geological Models** include three-dimensional interpretations of the distribution and orientation of structures and rock types. The models are presented as geological maps, vertical and horizontal sections and, most recently, as 3D-models.
Strategies

Rock Mass Characterisation

Rock Mass Types

- Rock Type
  - Mineralogical Parameter
  - Mechanical Properties

- Discontinuities
  - Geometrical Properties
  - Mechanical Properties
  - Hydraulic Properties

ROCK MASS TYPE
Strategies

Definition of Rock Mass Types

Rock Mass Types are defined by

“KEY PARAMETERS“
Key Parameters depend on

- Rock Type
- Project Phase
- Design Requirements
Granite

Rock Type

Key Parameters

- Grain size
- Texture
- UCS
- Joint sets (orientation, number)
- Persistence, spacing

Strategies
# Strategies

<table>
<thead>
<tr>
<th>Basic Rock Types</th>
<th>Key Parameters</th>
<th>Intact Rock Properties</th>
<th>Discontinuities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanic Rocks</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21</td>
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</tr>
<tr>
<td>Plutonic Rocks</td>
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<tr>
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<tr>
<td>Sulfatic Rocks</td>
<td></td>
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<tr>
<td>Metam. Rocks (massive)</td>
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<td></td>
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</tr>
<tr>
<td>Metam. Rocks (foliated)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brittle Fault Rocks</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**LEGEND**

| x | Significant Parameter |
| o | Less Important Parameter |

1. Anisotropy
2. Mineral Composition
3. Grain Size
4. Texture
5. Porosity
6. Secondary Alteration
7. Clay Mineral Composition
8. Clay Content
9. Swelling Properties
10. Solution Phenomena
11. Cementation
12. Strength Properties
13. Ratio Matrix/Components
14. Orientation of Dominant Set
15. No. and Orientation of Sets
16. Fracture Frequency
17. Roughness
18. Persistence
19. Aperture
20. Infilling
21. Shear Strength

**Rock Type Specific Key Parameters**
Faulted Rock Mass

- **Block / Matrix Ratio**

- **Matrix Properties**
  - Particle Size Distribution
  - Clay Mineral Composition
  - Swelling Properties
  - Shear Strength

- **Block Properties**
  - Lithology
  - Size
  - Shape
  - Strength

- **Discontinuities**
  - Type (shear, extension fractures etc.)
  - Orientation
  - Fracture Degree
  - Relative Movements on Slickensides

**Key Parameters**
AUSTRIAN GUIDELINE FOR THE GEOTECHNICAL DESIGN OF UNDERGROUND OPENINGS

Published by the Austrian Society for Geomechanics
OBJECTIVE

- Transparent, consistent procedure for the design and construction of tunnels
- Design phases, rock mass types and influencing factors have to be considered
- Decisions during construction have to be based on objective and systematic collection, evaluation and interpretation of quality data
Gruppe Geotechnik Graz ZT GmbH

Geomechanically relevant properties (key parameters)

**ROCK MASS TYPE (RMT)**

- ground water
- stresses
- orientation

size & shape of opening

**BEHAVIOUR TYPE (BT)**

- boundary conditions (BC) & requirements (RQ)

excavation & support

**SYSTEM BEHAVIOUR (SB)**

- RQ

  - excavation & support class

  heterogeneity

**GEOTECHNICAL DESIGN**
## Key Parameters

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<td></td>
</tr>
<tr>
<td>(8) Clay Content</td>
<td></td>
<td></td>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>(10) Solution Phenomena</td>
<td></td>
<td></td>
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<tr>
<td>(21) Shear Strength</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Legend

- **x** Significant Parameter
- **o** Less Important Parameter
# BASIC BEHAVIOUR TYPES

<table>
<thead>
<tr>
<th>Basic Behavior Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable</td>
<td>Stable rock mass with small local gravity induced falling or sliding of blocks</td>
</tr>
<tr>
<td>2 Stable with the potential of discontinuity controlled block fall</td>
<td>Deep reaching discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure</td>
</tr>
<tr>
<td>3 Shallow shear failure</td>
<td>Shallow stress controlled shear failures in combination with discontinuity and gravity controlled failure of the rock mass</td>
</tr>
<tr>
<td>4 Deep seated shear failure</td>
<td>Deep seated, stress induced shear failures and large deformations</td>
</tr>
<tr>
<td>5 Rock burst</td>
<td>Sudden and violent failure of the rock mass, caused by highly stressed rock and the rapid release of accumulated strain energy</td>
</tr>
<tr>
<td>6 Buckling failure</td>
<td>Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure</td>
</tr>
<tr>
<td>7 Shear failure under low confining pressure</td>
<td>Potential for excessive overbreak and progressive shear failure with the development of dead loads, caused mainly by a deficiency of side pressure</td>
</tr>
<tr>
<td>8 Raveling ground</td>
<td>Flow of cohesionless dry or moist material</td>
</tr>
<tr>
<td>9 Flowing ground</td>
<td>Flow of material with high water content</td>
</tr>
<tr>
<td>10 Swelling</td>
<td>Time dependent volume increase of the rock mass, caused by physical-chemical reactions of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter</td>
</tr>
<tr>
<td>11 Rock mass with frequently changing deformation characteristics</td>
<td>Rapid variations of stresses and deformations, caused by block-in matrix situation of a tectonic melange (brittle fault)</td>
</tr>
</tbody>
</table>
BEHAVIOUR TYPES (examples)
TRANSFER OF GEOLOGICAL MODELS INTO GEOTECHNICAL DESIGN

GEOLOGICAL LONGITUDINAL SECTION

ROCK MASS TYPES
stepwise assigned (e.g. 20 m intervals)

ANALYTICAL CALCULATIONS
for each 20 m step
Input: influencing factors, geotechnical properties
Output: displacements, depths of broken zones, etc.
DETERMINATION OF BEHAVIOUR TYPES

OUTPUT OF ANALYTICAL CALCULATIONS

eleven parameter groups for the determination of the basic BEHAVIOUR TYPES

BEHAVIOUR TYPE determined for each 20 m step
## Distribution of BEHAVIOUR TYPES along the tunnel alignment

<table>
<thead>
<tr>
<th>Chainage from</th>
<th>Chainage to</th>
<th>Rock Mass Type</th>
<th>Behaviour Type</th>
<th>Displacement Category</th>
<th>Support Pressure</th>
<th>System Behaviour</th>
<th>Excavation Category</th>
<th>Support Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>G10</td>
<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
</tr>
<tr>
<td>20</td>
<td>40</td>
<td>G10</td>
<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>G10</td>
<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
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<td>60</td>
<td>80</td>
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<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
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<td>100</td>
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<td>1</td>
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<td>b</td>
</tr>
<tr>
<td>100</td>
<td>120</td>
<td>G10</td>
<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
</tr>
<tr>
<td>120</td>
<td>140</td>
<td>G10</td>
<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
</tr>
<tr>
<td>140</td>
<td>160</td>
<td>G10</td>
<td>7</td>
<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
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<td>160</td>
<td>180</td>
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<td>c</td>
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<td>b</td>
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<td>4</td>
<td>b</td>
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<td>220</td>
<td>G10</td>
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<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
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<td>240</td>
<td>G10</td>
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<td>1</td>
<td>0.7</td>
<td>c</td>
<td>4</td>
<td>b</td>
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<tr>
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<td>260</td>
<td>G10</td>
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<td>c</td>
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<td>1</td>
<td>0.7</td>
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<td>4</td>
<td>b</td>
</tr>
</tbody>
</table>

**Graph:**

The graph illustrates the distribution of behaviour types along the tunnel alignment, detailing the chainage, rock mass type, and various categories such as displacement and support pressure. Each segment indicates the range of chainage and the corresponding behaviour type, displacement category, and support conditions.
Heavily broken primary lining

Galgenberg Tunnel, Austria
DETERMINATION SYSTEM BEHAVIOUR

Substantial improvement by installing LSC elements

Galgenberg Tunnel, Austria
PROCEDURE DURING CONSTRUCTION
Definition/monitoring of relevant rock mass type specific parameters

**ROCK MASS TYPE (RMT)**
- Stresses, kinematics, water quantity & pressure
- Update model, failure mechanisms
- Short term prediction

**BEHAVIOUR TYPE (BT)**
- Selection of excavation and support
- Prediction of system behaviour (SB)
- Monitoring results

Reevaluate & modify criteria

\[ SB_o = SB_d \]

Additional support

Reevaluate & modify criteria

**EXCAVATION & SUPPORT ✓**
EXAMPLE CONSTRUCTION

### Lithology and Aperture

<table>
<thead>
<tr>
<th>Area</th>
<th>Lithology</th>
<th>Bedding Thickness</th>
<th>Deg. of Fract.</th>
<th>Aperture</th>
<th>R. M. Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>MS</td>
<td>X</td>
<td>X</td>
<td>+</td>
<td>9</td>
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<tr>
<td>B</td>
<td>LD</td>
<td>X</td>
<td>X</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>C</td>
<td>LD</td>
<td>X</td>
<td>X</td>
<td>+</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>LD</td>
<td>X</td>
<td>X</td>
<td>+</td>
<td>3</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Area</th>
<th>Interlocked</th>
<th>Water Inflow</th>
<th>Behav. Type</th>
<th>Dominating Regions</th>
</tr>
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<tbody>
<tr>
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<td>X</td>
<td>X</td>
<td>4</td>
<td>A, C</td>
</tr>
<tr>
<td>B</td>
<td>X</td>
<td>X</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>X</td>
<td>X</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>X</td>
<td>X</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

### Displacement Category (cm)

- <5
- 5-10
- >10

### Behavior Type 2

- Rock mass with potential for systematical and voluminous overbreak, no stress induced failures

### Support & Excavation Concept

- Round length: 1.3 m
- Support type: ST 3
Case Studies

Conceptual (Route Selection) and Feasibility Study

Mae Kuang Inflow Augmentation Project
Conceptual (Route Selection) and Feasibility Study

Project Data and Tasks
Chiang Mai flood protection project. Deviation of water from the Mae Ngut reservoir through TBM tunnels

- No.1 Tunnel (length: 32.6 km, diameter 4.60 m)
- No.3 Tunnel (length: 25.0 km, diameter 4.60 m)
- No.6 Tunnel (length: 28.8 km, diameter 4.60 m)
- Main Tunnel (length: 21.7 km, diameter 5.0 m)

Geological-geotechnical field studies and consulting services, supervision of site investigation, cost estimate and comparison

Geology
Paleozoic and Mesozoic shale, sandstone, limestone and Triassic granitic intrusions were subjected to intense thrusting. Tertiary tectonic events generated pull-apart-basins filled with gravels and sands

Mae Kuang Inflow Augmentation Project
Case Studies

*Mae Kuang Inflow Augmentation Project*

Rock Mass Type

- Rock Type
- UCS
- mi
- GSI

Parameters for Analytical Calculation
Case Studies

Mae Kuang Inflow Augmentation Project

Geological Profile of Route No. 3 Tunnel

Results of Analytical Calculation
## Case Studies

### Mae Kuang Inflow Augmentation Project

The following table represents the geotechnical rating for the No.3 Tunnel:

<table>
<thead>
<tr>
<th>Coh</th>
<th>s</th>
<th>mb</th>
<th>a</th>
<th>E</th>
<th>mxy</th>
<th>prc</th>
<th>Tremendous Risk</th>
<th>Critical Risk</th>
<th>Medium Risk</th>
<th>Minimum Risk</th>
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<tbody>
<tr>
<td>4.64</td>
<td>0.0034</td>
<td>2.96</td>
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<td>1414</td>
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<td>-2.47</td>
<td>0.0035</td>
<td>0.0005</td>
<td>0.0025</td>
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<td>0.1688</td>
<td>17.56</td>
<td>0.30</td>
<td>116866</td>
<td>0.10</td>
<td>-17.22</td>
<td>0.0032</td>
<td>0.0003</td>
<td>0.0009</td>
<td>0.0021</td>
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<td>17.56</td>
<td>0.30</td>
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<td>-17.22</td>
<td>0.0032</td>
<td>0.0003</td>
<td>0.0009</td>
<td>0.0021</td>
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<tr>
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<td>0.0025</td>
<td>0.17</td>
<td>0.63</td>
<td>1257</td>
<td>0.40</td>
<td>4.87</td>
<td>0.0099</td>
<td>0.0009</td>
<td>0.0025</td>
<td>0.0069</td>
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<td>-8.39</td>
<td>0.0004</td>
<td>0.0004</td>
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<td>0.0069</td>
</tr>
<tr>
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<td>56234</td>
<td>0.10</td>
<td>-8.39</td>
<td>0.0004</td>
<td>0.0004</td>
<td>0.0025</td>
<td>0.0069</td>
</tr>
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<td>1.15</td>
<td>0.50</td>
<td>2000</td>
<td>0.29</td>
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<td>0.0006</td>
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<td>0.0003</td>
<td>0.0009</td>
<td>0.0021</td>
</tr>
</tbody>
</table>

**Note:** The table values are representative and should be interpreted within the context of the project's specific requirements and conditions.

### Geotechnical Rating for No.3 Tunnel

- **577.6** 0.988928
- **2750** 0.919888
- **2750** 0.919888
- **2750** 0.919888
- **1149.5** 0.919888
- **919.6** 1.016886
- **334.4** 1.076473
- **917.4** 1.446551
- **919.6** 1.106425
- **906.4** 1.050262
- **680** 1.181781
- **1316** 1.081596
- **2000** 1.028203
- **1044** 1.028203
- **2299** 0.92657
- **2020** 1.028203
- **1738** 1.021948
- **504** 0.914299
- **1227.6** 1.13905
- **1738** 1.190815
- **1529** 1.350347
- **671** 1.072473
- **1100** 1.14007
- **1100** 1.14007
- **605** 1.239269
- **360** 1.160934
- **800** 1.104293
- **800** 1.062382
- **1243** 1.037425
- **438.4** 1.006934
- **800** 1.101101

**Total:** 66585.50

Gruppe Geotechnik Graz ZT GmbH
Case Studies

*Mae Kuang Inflow Augmentation Project*

Mae Kuang Project, 2nd Mission Report

Geotechnical Ratings:

- Tunnel No.1: 51,757
- Tunnel No.3: 66,585
- Tunnel No.6: 59,926
- Main Tunnel: 32,866

Construction costs of No. 1 Tunnel are 10% less than No.3 Tunnel

*Route Selection Study*