Risk oriented design and construction of tunnels

Wulf Schubert

Graz University of Technology

3G-Gruppe Geotechnik Graz ZT GmbH

INTRODUCTION

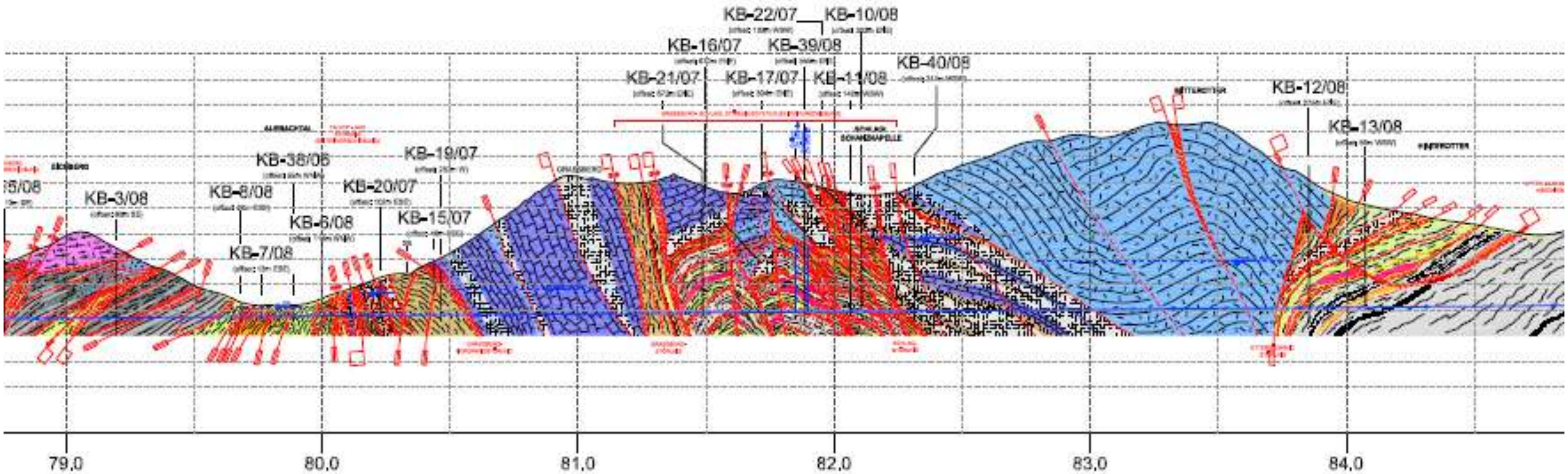
- Risk in engineering commonly is understood as the product of probability of an event and the consequences of such an event
- In tunnelling unfavourable events can be
  - Damage of the support due to excessive deformations or loads
  - Collapses with or without damage to third parties
  - Excessive ground deformations, leading to damage of structures and utilities
  - Lowering of ground water table
  - Immissions by blasting vibrations, noise, dust, etc.

RISK MANAGEMENT IN TUNNEL DESIGN

- It is also understood that in case a risk has an unacceptable level, mitigation measures have to be taken to either eliminate the hazard, reduce the probability of its occurrence, or reduce the consequences
- Using this principle for tunnel design, first of all we would have to identify the hazards, evaluate the probability of occurrence, and the associated consequences
- In the next step, the mitigation measures would have to be designed for cases with unacceptable risk
- In Austria a guideline for risk oriented design approach exists

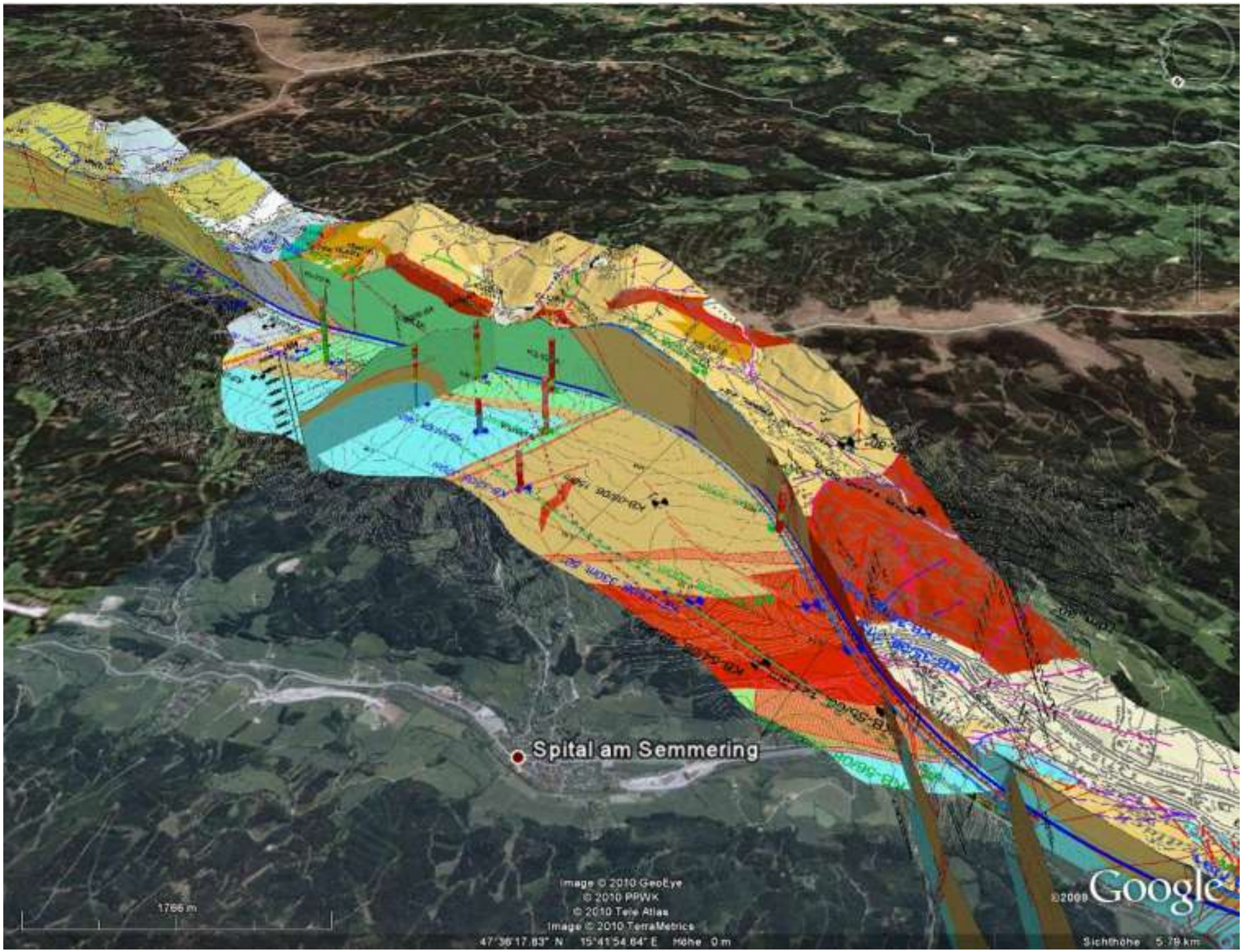
RISK ORIENTED DESIGN PROCESS

- Each tunnel design should be based on a realistic geological model, where also the uncertainties should be indicated



- In a next step, the ground model has to be developed, by characterizing the different geological units

3D Model combined with Google Earth



GEOLOGICAL MODEL

↓

Ground characterization

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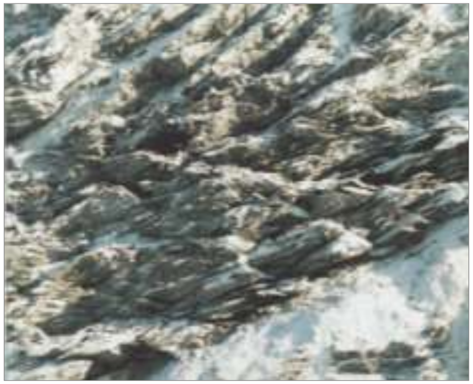
GROUND TYPES (GT)

Ground Types are defined as ground volumes with similar properties

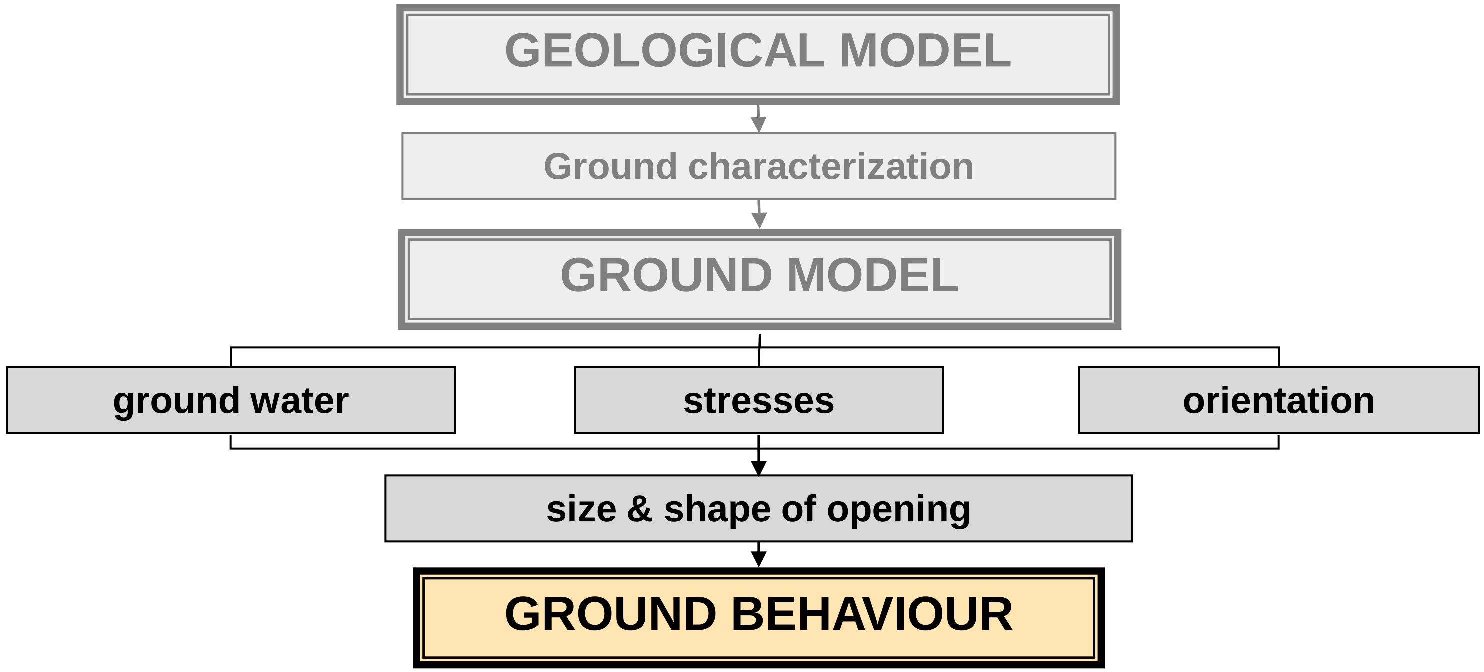


TYPICAL CHARACTERIZATION SHEET

Rock Mass Type – RMT 3		
"Fracture Zone" Heavily fractured, slightly crushed and sheared Granodiorite. Mixture of angular and round pieces. S53E-3 box 1		
Key parameters		**Reference**
Lithology	Anisotropic Granodiorite	-
UCS $_{intact}$ [MPa]	140 (100-200)	Lab tests
Distance of discont. [cm]	2 - 6	Core log
Number of joint sets	3-5	Core log
Block size [m³]	0,0001-0,1	Estimated
Additional parameters intact rock / joints		
Density weight [kN/m³]	27	Lab tests
m_i [-]	29	Literature
Poisson's ratio [-]	0,2	Lab tests
E [GPa]	70 (50-100)	Lab tests
Friction intact rock [°]	51	Lab tests
Cohesion intact rock [MPa]	17	Lab tests
Friction of discont. [°]	30 - 35	Lab tests
JRC [-]	5 - 10	Lab tests
Persistence [m]	n.a.	
Determined parameters rock mass		
GSI [-]	25	Estimated
UCS rock mass [MPa]	15	Estimated - Rocklab
c [MPa]	0.5	Estimated - Rocklab
Friction angle [°]	30	Estimated - Rocklab
E [GPa]	3	Estimated - Rocklab

GROUND MODEL AND INFLUENCING FACTORS

- For assessing of hazards associated with tunnel excavation, a ground model has to be established.
- The model contains information on geological and water conditions, material properties, ground stresses, and orientations of discontinuities and singularities
- Geometrical features of the underground openings, like location, size and shape complete the model
- Once all the basics are defined, the reaction of the ground to the excavation can be assessed and thus hazards identified



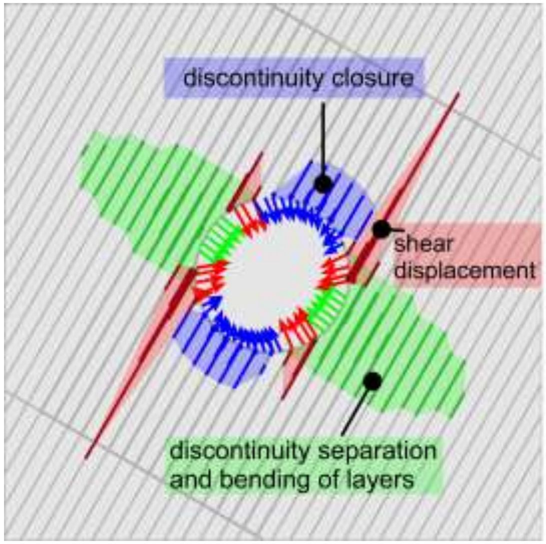
Ground behaviour is defined as the reaction of the ground to the excavation of the tunnel in its full profile without consideration of support or other construction measures = hazard identification

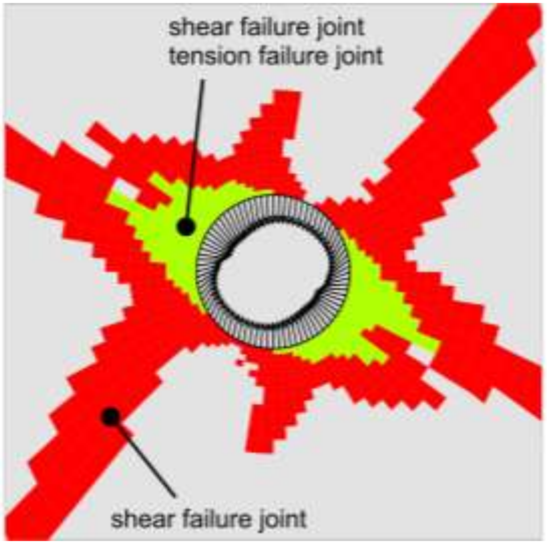
GROUND BEHAVIOUR

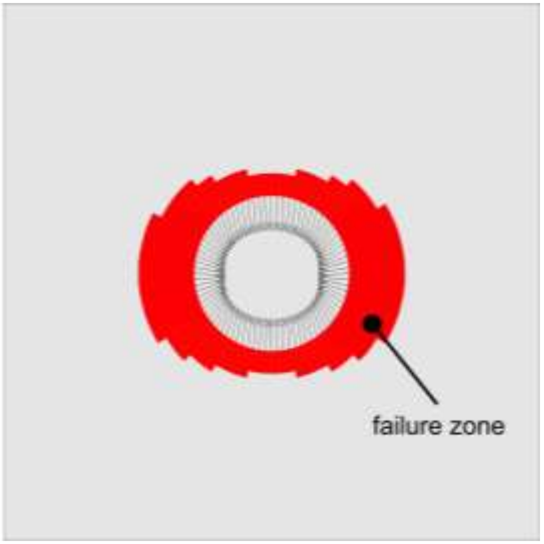
- Ground behaviour assessment should include type of potential failure modes, as well as magnitude and characteristics of displacements
- Method of evaluation must capture the essential features, and allow identifying relevant mechanisms
- Once the hazards are identified, mitigation measures in the form of appropriate excavation and support methods can be selected

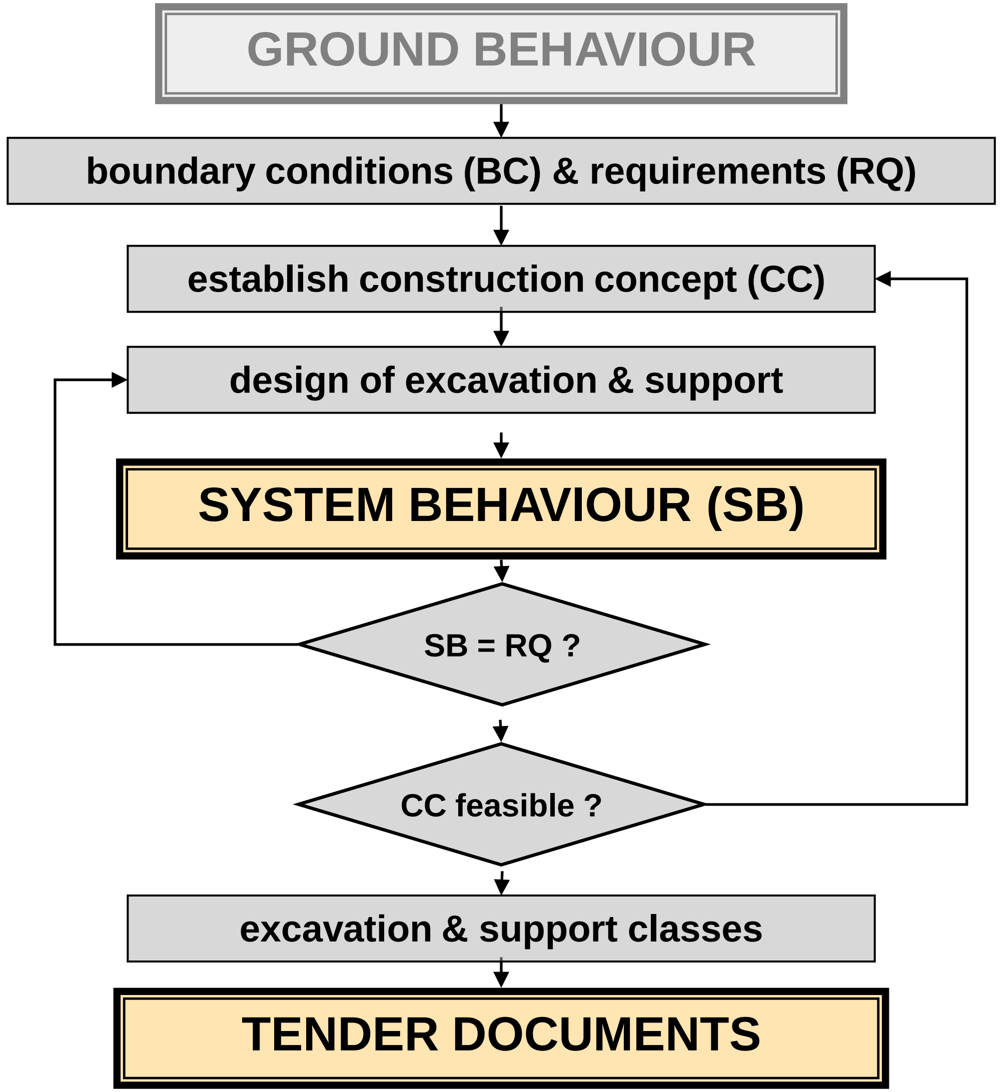
WHICH MODEL ?

- Selection often done according to availability / familiarity rather than problem oriented
- With simplification relevant mechanisms often lost, and thus neglected in the support design

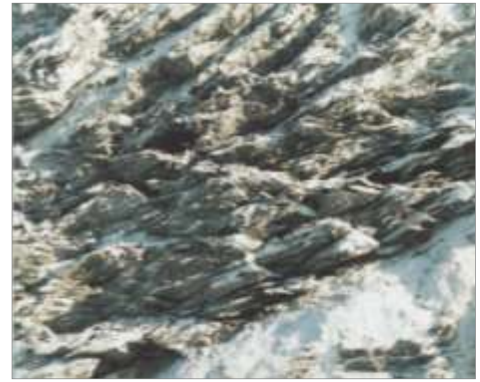







GROUND BEHAVIOUR
boundary conditions (BC) & requirements (RQ)
establish construction concept (CC)
design of excavation & support
SYSTEM BEHAVIOUR (SB)
SB = RQ ?
CC feasible ?
excavation & support classes
TENDER DOCUMENTS

Rock Mass Type



Parameters of GT - B

Parameters of GT - D

Influencing factors

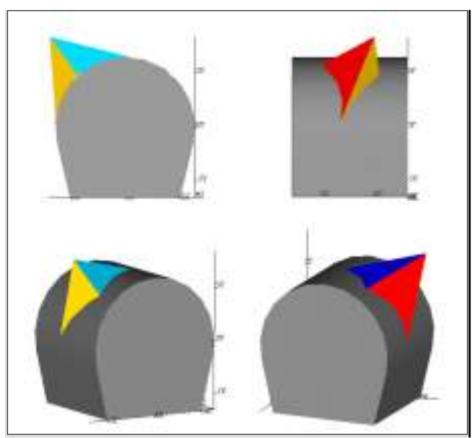
Geometry of excavation

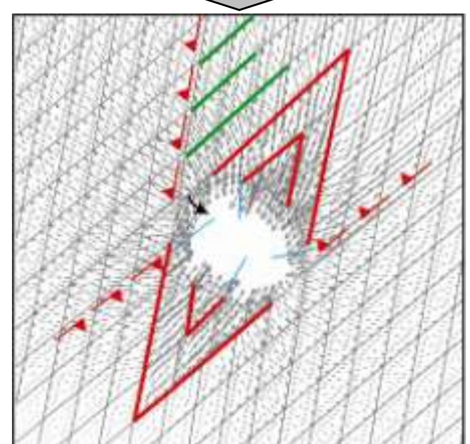
Relative orientation of discontinuities to excavation

Primary stress condition

Water condition

Modeling of ground behavior



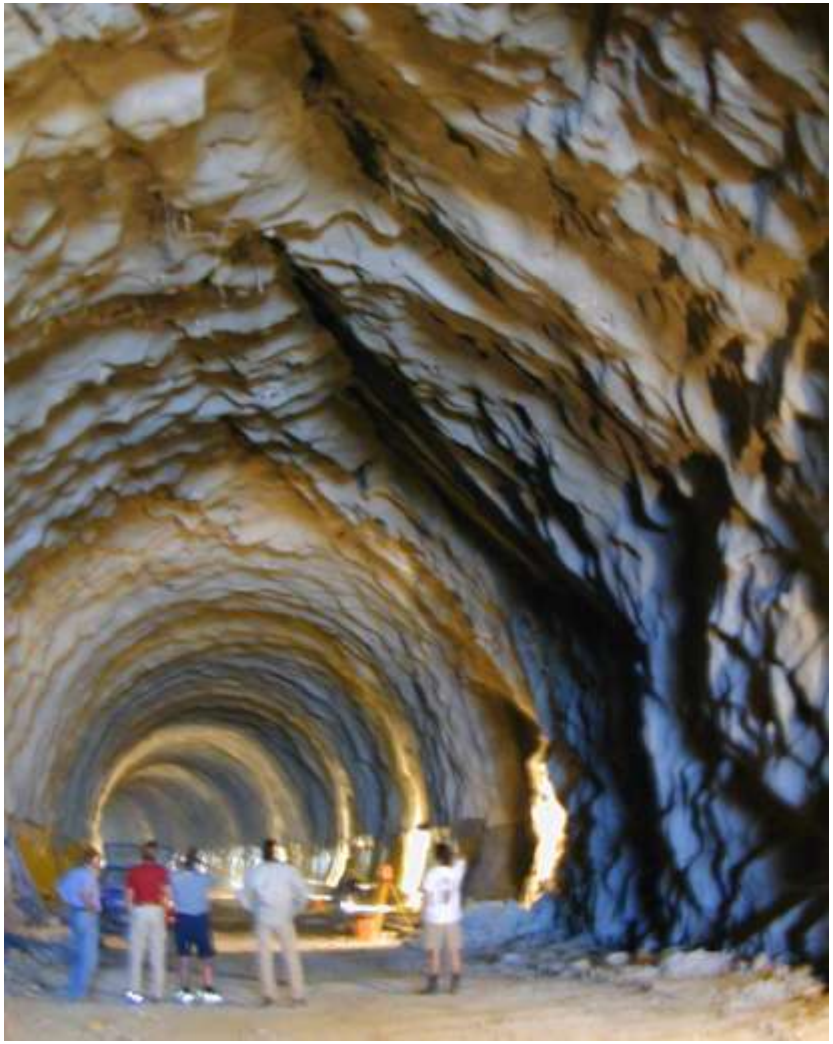


TYPES OF FAILURE MODES

- Failure modes can roughly be distinguished in:
  - Gravity driven, in general discontinuity controlled falling, sliding, or rotating blocks
  - Stress induced failures with a variety of different modes
- The presence of ground water can have a significant influence on the failure. It can trigger failure, or alter the properties of the ground, leading to failure on the long term

DISCONTINUITY CONTROLLED FAILURE

- Intersection of joints forms a block, which when kinematically free, can move into the opening
- Methods for analysis
  - Stereographic projection (Key Block Analysis)
  - Numerical 2D and 3D models
- Required paramteres
  - Size and shape of block
  - Position to opening
  - Joint properties
  - Stresses

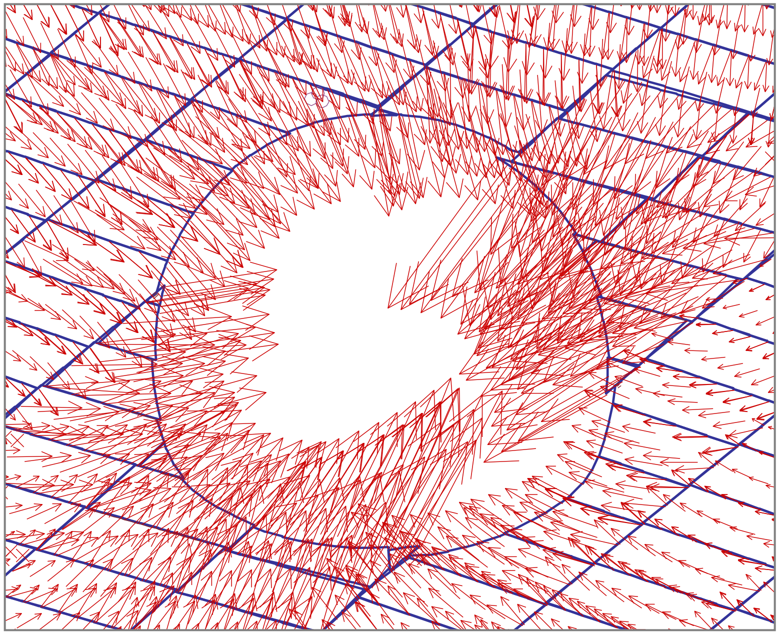


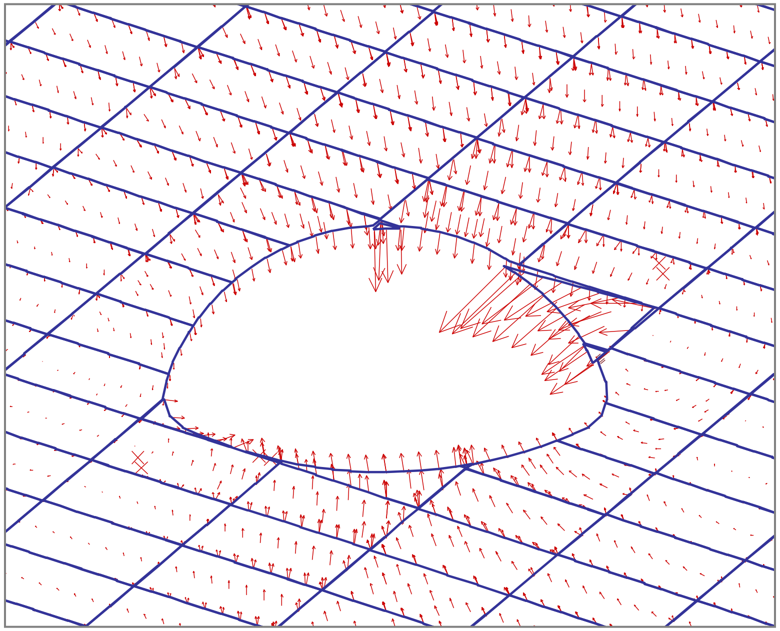
DISCONTINUITY CONTROLLED FAILURE

- Possible measures to control potential failure
  - Rock bolting; bolts shoud be long enough to fix blocks to stable ground
    In case discontinuity controlled failure is not combined with other failure modes, usually bolts with quick efficiency are used (friction bolts, or resin bolts)
  - Separation of excavation into several steps;
    This can reduce size of removable block; potential failing blocks can be supported prior to next exacavation step
  - Supports, like steel arches and/or shotcrete
    (note that shotcrete needs some time to develop strength; in case of high advance rates additionally bolts are recommended)

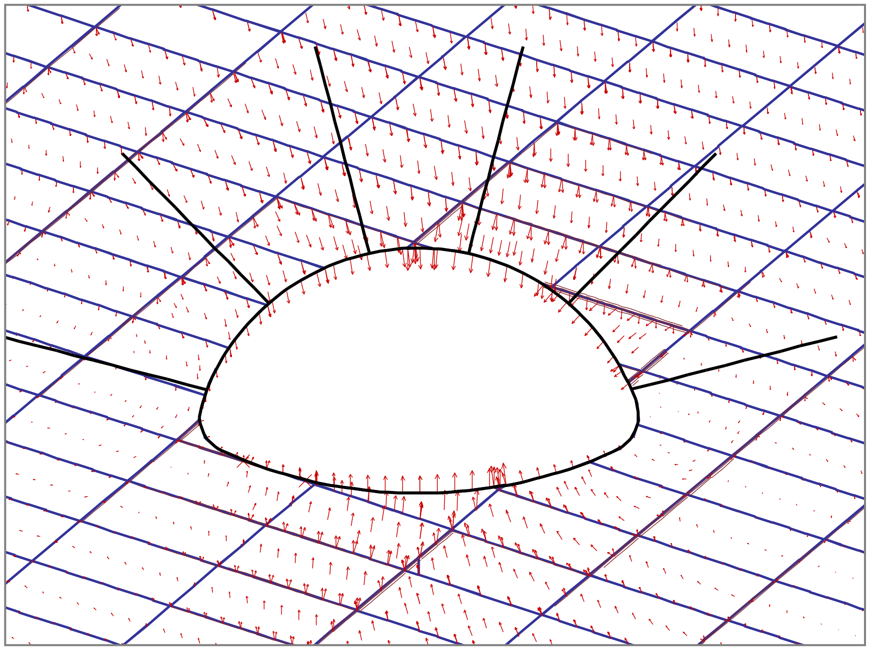
REDUCTION OF SIZE OF REMOVABLE BLOCK

- In full face excavation large removable blocks can exist, which are difficult to control. A sequential excavation can reduce the magnitude of potential failure

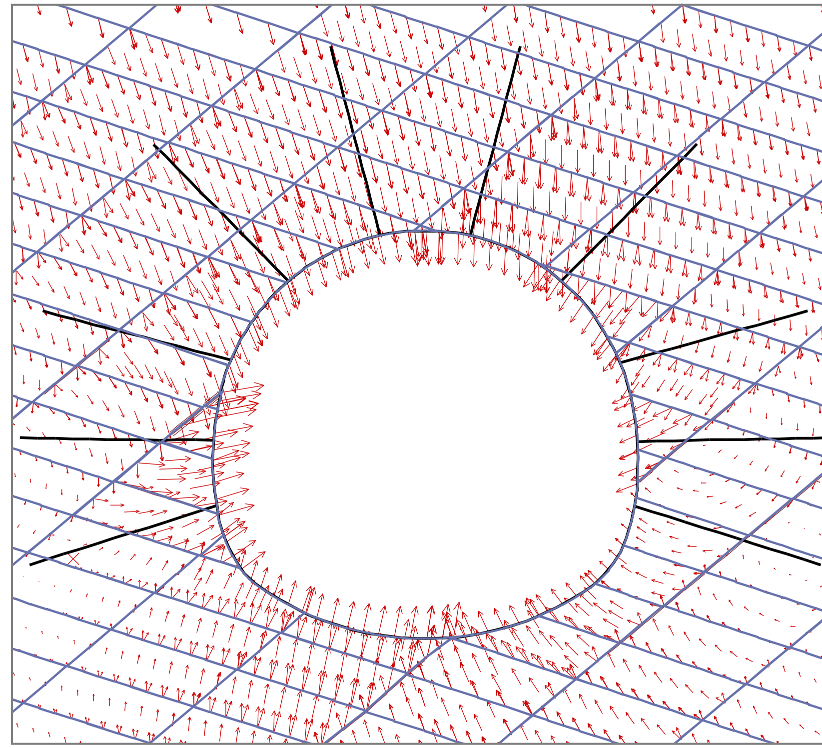




SYSTEM BEHAVIOUR AFTER BOLTING



System Behavior after top heading excavation and support



System Behavior after bench excavation and support

BRITTLE FAILURE WITH LIMITED DEPTH

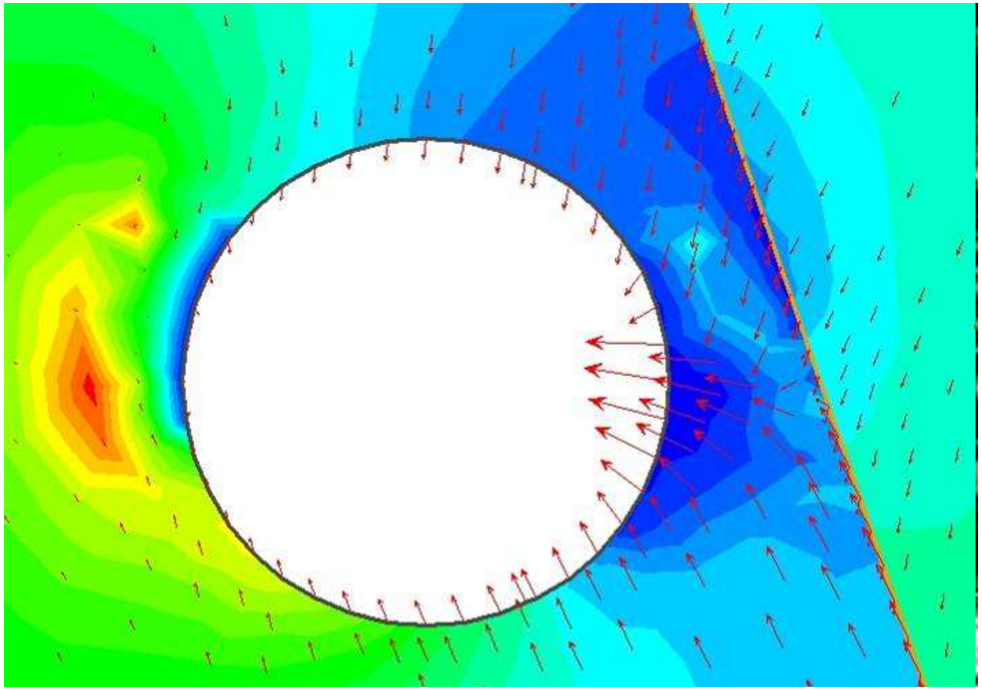
- Excess of stresses leads to spalling of massive or slightly jointed rock
- Methods for analysis
  - Compare strength of rock to stress by closed form solution or simple FE; evaluate possible failure depth
- Required paramteres
  - Strength of rock
  - Size and shape of opening
  - Stresses

BRITTLE FAILURE WITH LIMITED DEPTH

- Possible mitigation measures
  - Check if limited spalling is acceptable. (safety issues may forbid doing just nothing)
  - Bolted wire mesh and/or shotcrete

SHEAR FAILURE

- Excessive stresses cause shearing of rock mass; shearing often initiated at discontinuities
- Methods of analysis
  - Closed form solutions (do not allow modelling of discontinuities)
  - Numerical simulation under consideration of ground structure
- Required input
  - Strength of rock and discontinuities
  - Shape and size of tunnel
  - stresses



SHEAR FAILURE

- Possible measures to prevent potential failure
  - Systematic bolting; bolts should be long enough to cross potential shear plane
  - Shotcrete and arches
  - Combination of bolting and shotcrete
- Shearing may in certain cases be difficult to prevent totally. This may lead to damage of the lining (localized strain). In such cases it can be advisable to use ductile linings or leave gap in shotcrete, where shearing is expected

QUASI DUCTILE DEFORMATION

- High stresses in combination with weak and +/- homogeneous ground lead to large displacements. Pore water pressure can play a role
- Displacements often time dependent
- Methods for analysis
  - Closed form solutions
  - Numerical methods
- Required input
  - Ground properties (time dependent)
  - Stresses
  - Size of tunnel

QUASI DUCTILE DEFORMATION

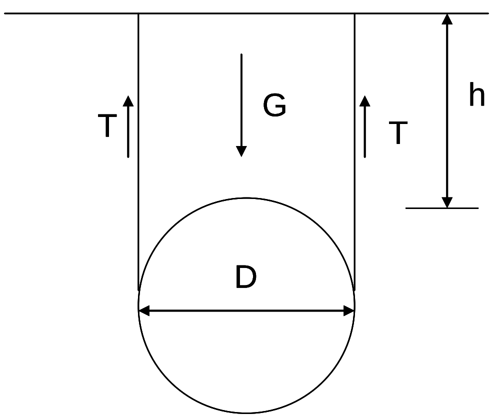
- In general energy involved is beyond reasonable support capacities
- Possible measures to deal with phenomenon
  - Systematic dense bolting to prevent shear failure of rock mass
  - Provide enough overexcavation to allow for expected displacements
  - Use lining, which can sustain the large strains
    (usual shotcrete linings allow a maximum strain of <1%)

APPLICATION OF DUCTILE ELEMENTS

Tauerntunnel, Austria Photo: Vergeiner, 2007

PROGRESSIVE OVERBREAK WITH POTENTIAL TO DAYLIGHTING COLLAPSE

- Failure usually in ground with low cohesion and low stress level.
  In rocks failure mode possible when foliation dips +/- vertical and strikes parallel to tunnel. Ground water can have adverse influence
- Method of analysis
  - Simple limit equilibrium analysis
  - Appropriate numericla model



PROGRESSIVE OVERBREAK WITH POTENTIAL TO DAYLIGHTING COLLAPSE

- Possible measures to prevent potential failure
  - Limit unsupported length and span; divide face in several excavation steps with subsequent support installation prior to next step
  - Forepoling can increase stand up time
  - Shotcrete and arches
  - Bolting through potential shear planes
  - Drainage in case of ground water

FREQUENTLY CHANGING BEHAVIOURS

- Strong local variation of stresses and deformations due to strongly heterogeneous ground, like block in matrix structure, tectonic melange, brittle fault zones
- Methods of analysis
  - Identify heterogeneous conditions from geological investigation
  - 3D numerical simulation with potential to model brittle and ductile behaviours

FREQUENTLY CHANGING BEHAVIOURS

- Behaviour is associated with high contrast in deformations in short sections; large displacements in zones of fault gouge are next to practically no displacements when tunnelling through solid blocks
- Methods to deal with phenomenon
  - Ductile, but strong lining (integration of ductile elements into lining)
  - Dense bolting to reduce/prevent shearing in poor ground and brittle failure in stiff blocks
  - Provide enough overexcavation to prevent the necessity of reshaping; as prediction of final displacements often not easy, be on the safe side

BASIC CATEGORIES OF BEHAVIOUR TYPES

Basic categories of Behaviour Types (BT)		Description of potential failure modes/mechanisms during excavation of the unsupported ground
1	Stable	Stable ground with the potential of small local gravity induced falling or sliding of blocks
2	Potential of discontinuity controlled block fall	Voluminous discontinuity controlled, gravity induced falling and sliding of blocks, occasional local shear failure on discontinuities
3	Shallow failure	Shallow stress induced failure in combination with discontinuity and gravity controlled failure
4	Voluminous stress induced failure	Stress induced failure involving large ground volumes and large deformation
5	Rock burst	Sudden and violent failure of the rock mass, caused by highly stressed brittle rocks and the rapid release of accumulated strain energy
6	Buckling	Buckling of rocks with a narrowly spaced discontinuity set, frequently associated with shear failure
7	Crown failure	Voluminous overbreaks in the crown with progressive shear failure
8	Ravelling ground	Ravelling of dry or moist, intensely fractured, poorly interlocked rocks or soil with low cohesion
9	Flowing ground	Flow of intensely fractured, poorly interlocked rocks or soil with high water content
10	Swelling ground	Time dependent volume increase of the ground caused by physical-chemical reaction of ground and water in combination with stress relief
11	Ground with frequently changing deformation characteristics	Combination of several behaviours with strong local variations of stresses and deformations over longer sections due to heterogeneous ground (i.e. in heterogeneous fault zones; block-in-matrix rock, tectonic melanges)

SUMMARY EXCAVATION AND SUPPORT DESIGN

- Each characteristic mechanism requires targeted measures to mitigate the hazard, or control the consequences to arrive at an acceptable risk level
- Analysis of system behaviour shall show the compliance with requirements. Robustness of design should be checked by considering possible spread of parameters
- Usually more than one method exists to satisfy the requirements. Selection must be based on the overall construction concept, boundary conditions, local regulations, availability of means and methods, and potential of the contractors

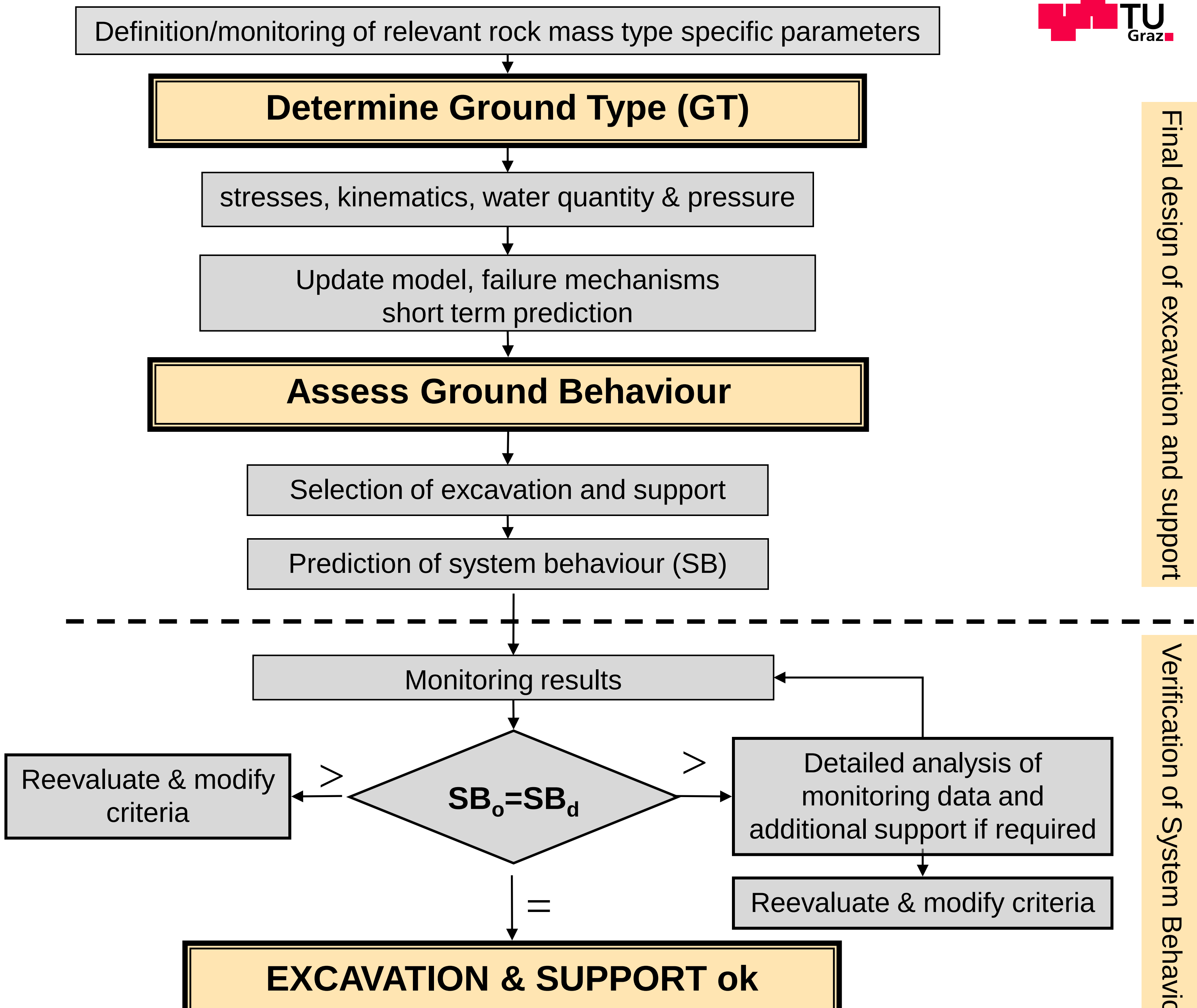
PROCESS DURING CONSTRUCTION

INTRODUCTION

- Uncertainties in the ground model, the physical properties of the ground, as well as the limited accuracy and simplifications in the mathematical models used for design lead to a residual risk during construction
- The resulting inaccuracy of the design calls for an observational approach to allow for a safe and economical construction with minimal risk
- A successful implementation of the observational approach requires sound preparation, including the establishment of a safety management plan
- Focus of observation on verification of assumptions and identification of (predicted or unpredicted) hazards

INTRODUCTION

- Process during construction basically similar to the design process, with focus on potential hazards
- Increased informaton on real ground conditions and behaviour allows refinement of the model and quality of prediction of behaviour
- Observations required to identify deviations from the „normal" behaviour and to optimize construction process
- Organizational provisions must be made to be able to execute an observational approach


Definition/monitoring of relevant rock mass type specific parameters
Determine Ground Type (GT)
stresses, kinematics, water quantity & pressure
Update model, failure mechanisms
short term prediction
Assess Ground Behaviour
Selection of excavation and support
Prediction of system behaviour (SB)
Final design of excavation and support
Monitoring results
Reevaluate & modify criteria
>
SBo=SBd
>
Detailed analysis of monitoring data and additional support if required
Reevaluate & modify criteria
=
EXCAVATION & SUPPORT ok
Verification of System Behaviour

UPDATING OF GROUND MODEL

- Geological tasks during construction
  - Record geological conditions
  - Update geological model
  - Extrapolate rock mass conditions into volume affecting the tunnel behaviour
  - Determine rock mass type

Geotechnical tasks

- Transform the geological model into ground model
- Assess ground quality and determine expected ground behaviour
- Recommend excavation and support method
- Fix layout of monitoring and frequency of reading
- Determine expected system behaviour
- Evaluate and interprete monitoring data
- Observe safety management plan

MONITORING

- Monitoring method must capture the expected behaviours
- Readings in sufficiently short intervals and evaluation of data rapidly enough to allow for detection of deviations in time
- Measurement of absolute displacements allows not only observing the stabilization process, but also predicting the ground quality ahead of the face
- Tools are available to easily check deviations from the normal behaviour

Safety management during construction

BASICS OF SAFETY MANAGEMENT

Hypotheses:

- What can go wrong, usually goes wrong
- Even things happen, which nobody thought could happen at all
- Human beings are all but perfect
- Nothing is unpredictable, but sometimes we are not smart enough to see the signs

Thus:

- Prepare for all possible and apparently impossible events

UNPREDICTABLE ?

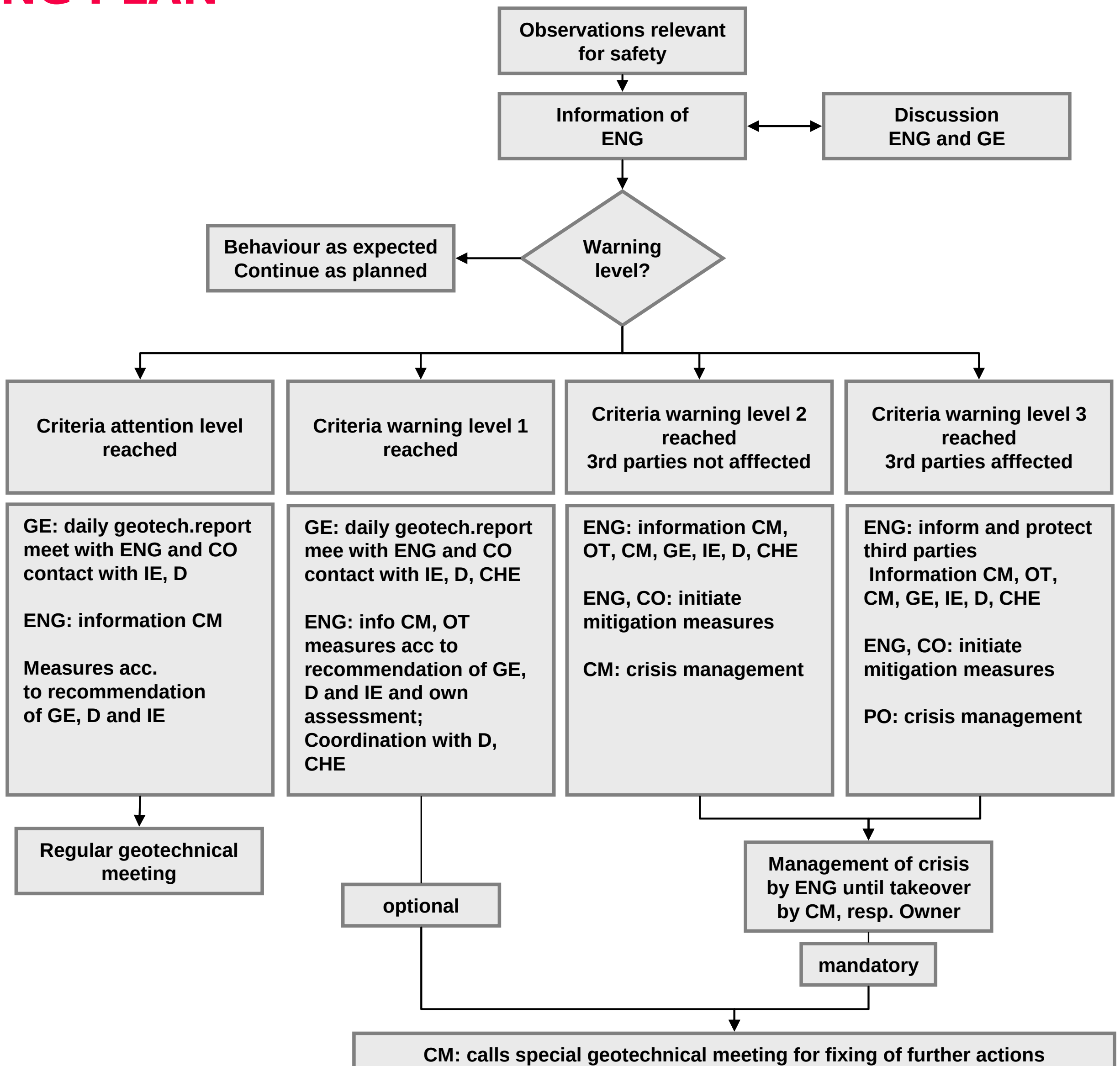
REQUIREMENTS FOR OBSERVATIONAL APPROACH

- Consistent design
- Assessment of possible behaviors; definition of expected behaviour
- Establishment of acceptable limits for expected behaviors
- Adequate monitoring plan
- Appropriate site organization to allow for a short response time in case actual behavior deviates from the predicted/acceptable
- Safety management plan including contingency measures for cases, where actual behaviour deviates from expected

ELEMENTS OF SAFETY MANAGEMENT PLAN

- Identification of safety relevant issues
- Definition of expected behaviour
- Definition of parameters to be observed, observation methods, layout, reading frequency, and evaluation methods
- Definition of warning and alarm levels and criteria
- Definition of contingency measures for each warning level
- Action plan in case of an alarm
- Organisation plan and reporting structure

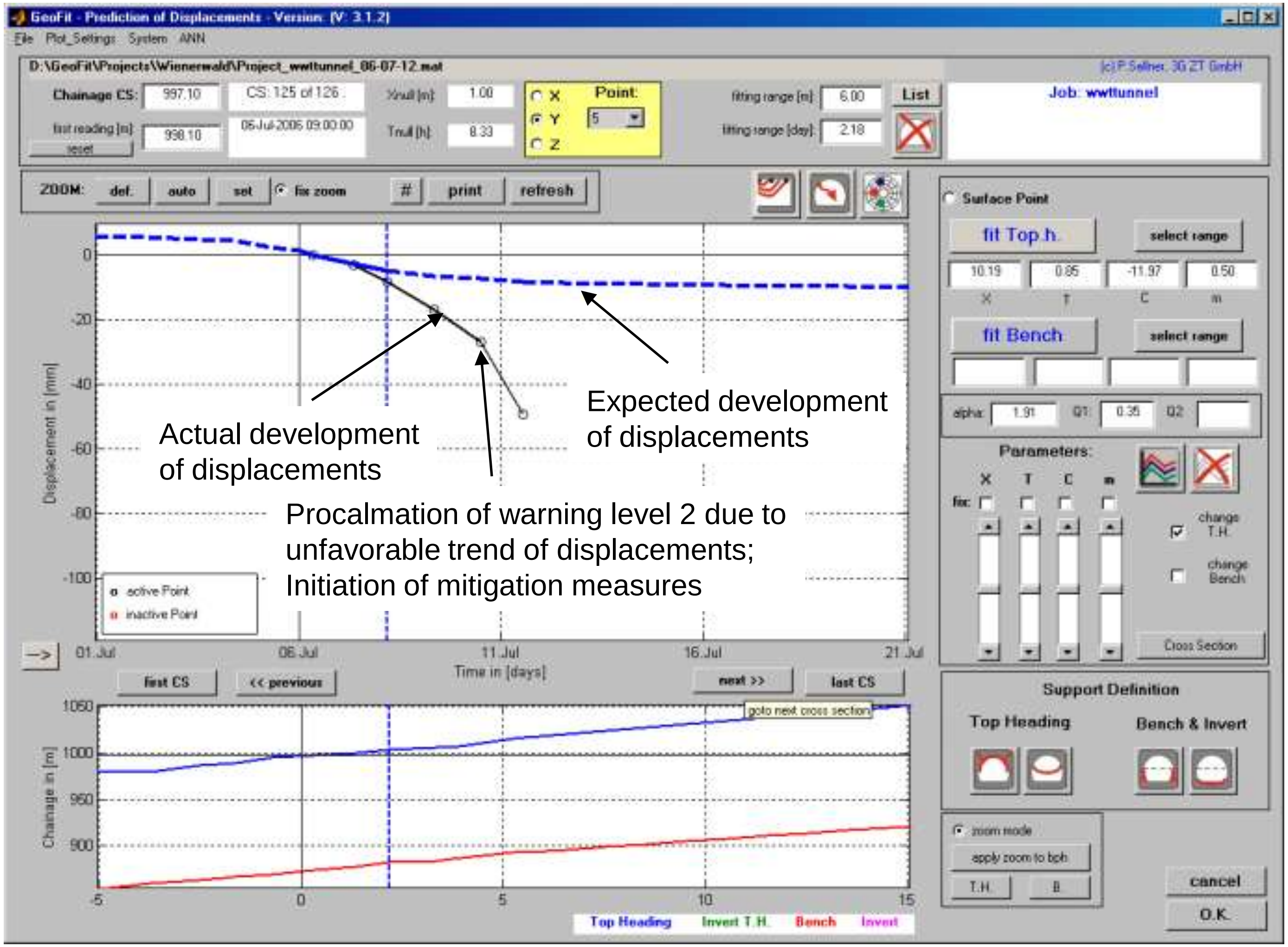
ACTION AND REPORTING PLAN



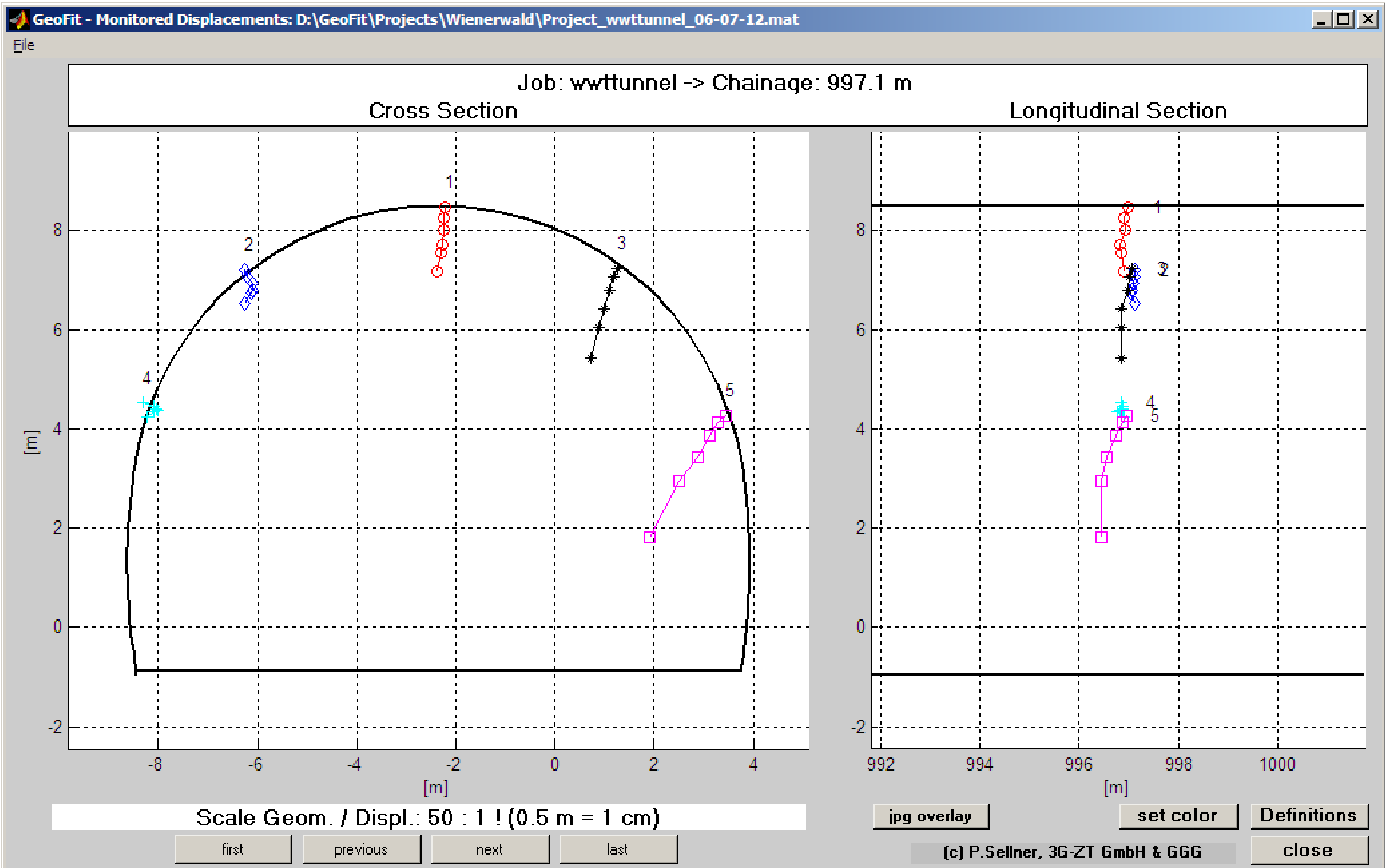
CRITERIA

- Criteria for the single warning levels can be fixed values, combinations of values, or trends
  - Example: criteria for subsidence can be expressed in terms of absolute values of settlement or as maximum slope, or a combination of both
- Expected development of system behaviour in relation to time or advance should be defined to allow for timely reaction
  - Example for surface settlement values:
    - 10 m ahead of face: 3 mm
    - at face: 10 mm
    - 5m behind face: 20 mm
    - 20 m behind face: 30 mm

CASE HISTORY



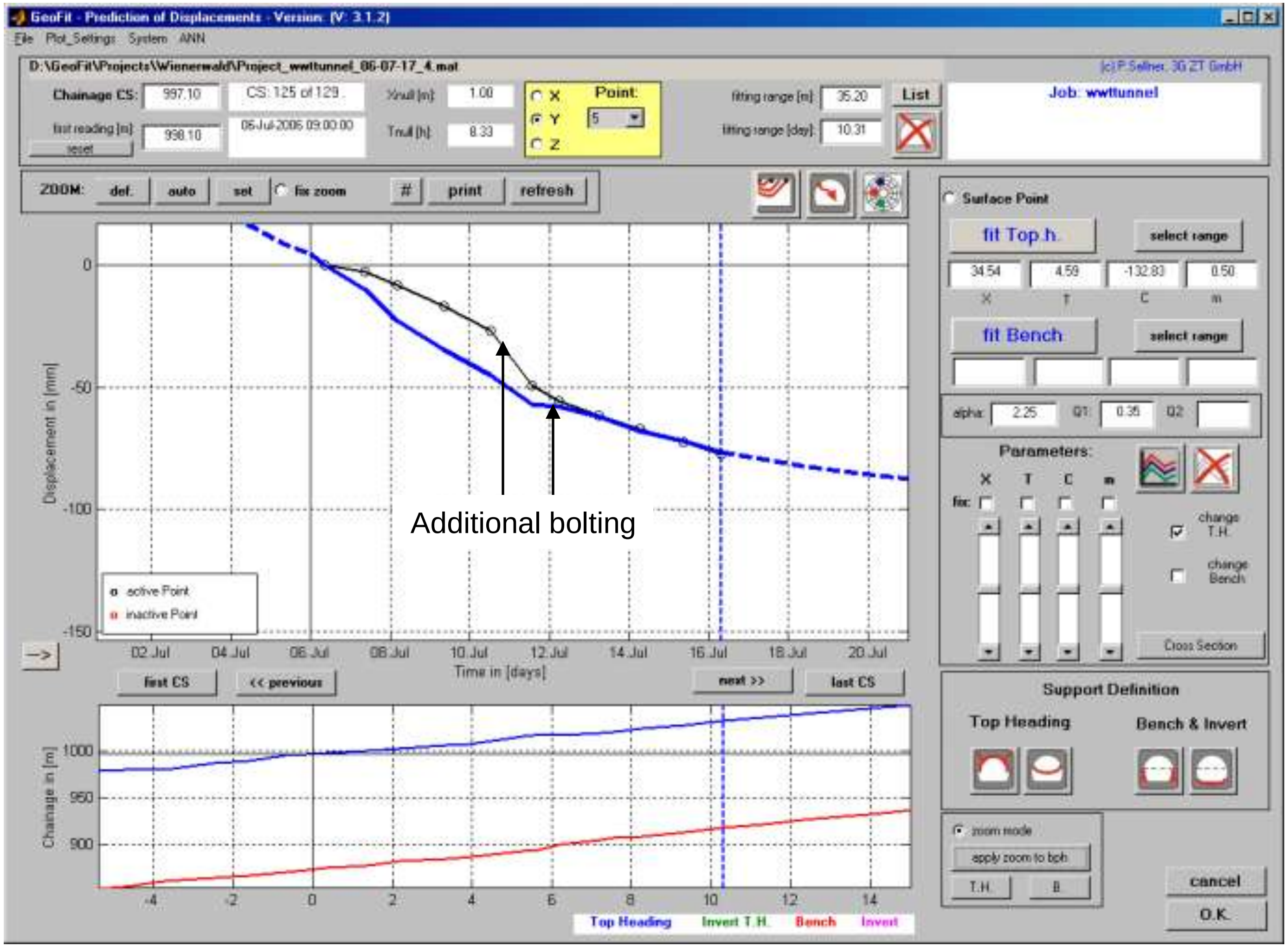
DISPLACEMENT VECTORS CLEARLY INDICATE PROBLEM



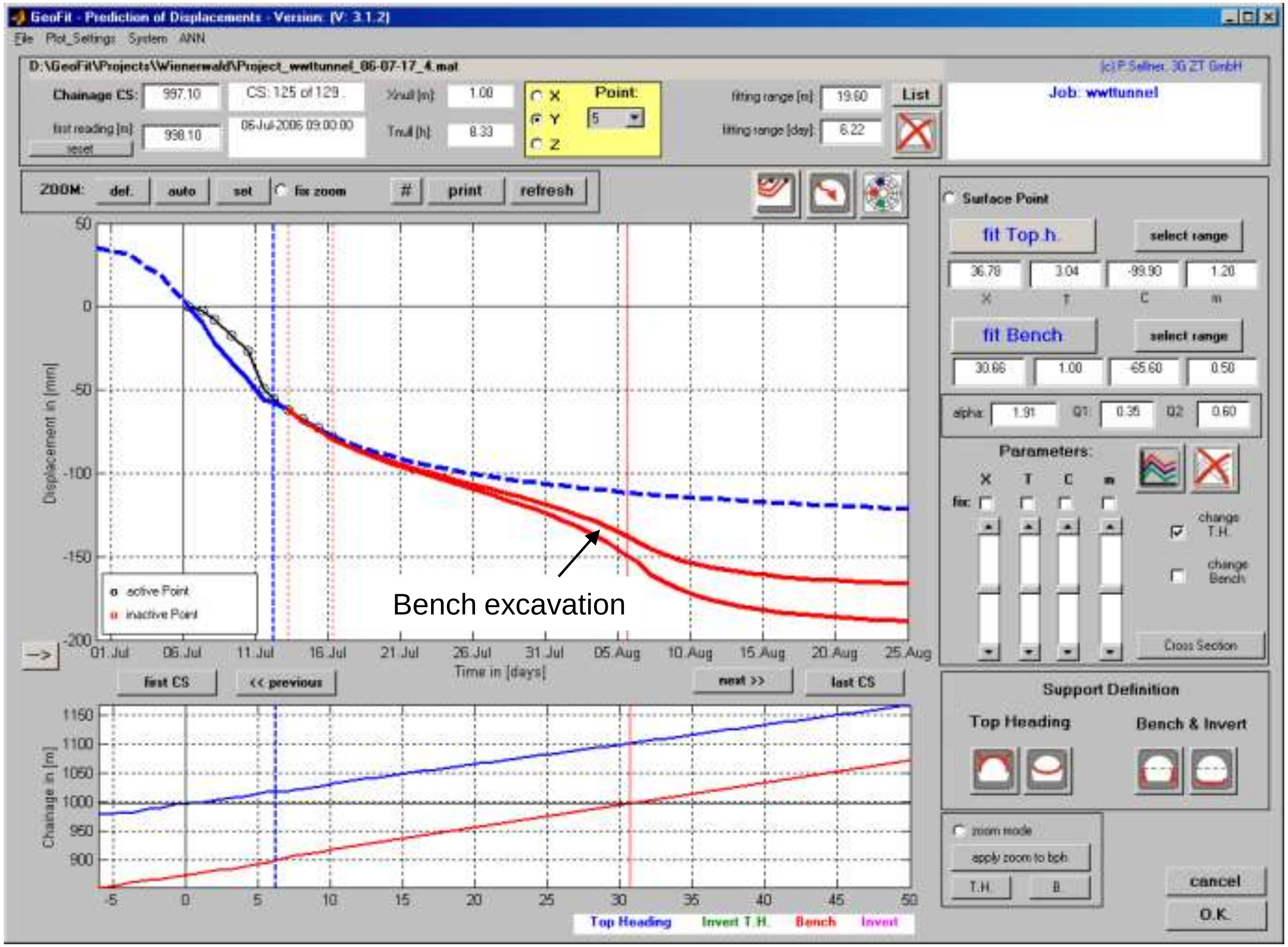
MITIGATION MEASURES

- Additional bolting on a length of about 20m on the richt side was ordered and executed immediately
- A set of additional measures, like installation of a temporary top heading invert was prepared, should the initial mitigation measures not show satisfying effect

EFFECT OF MITIGATION MEASURES



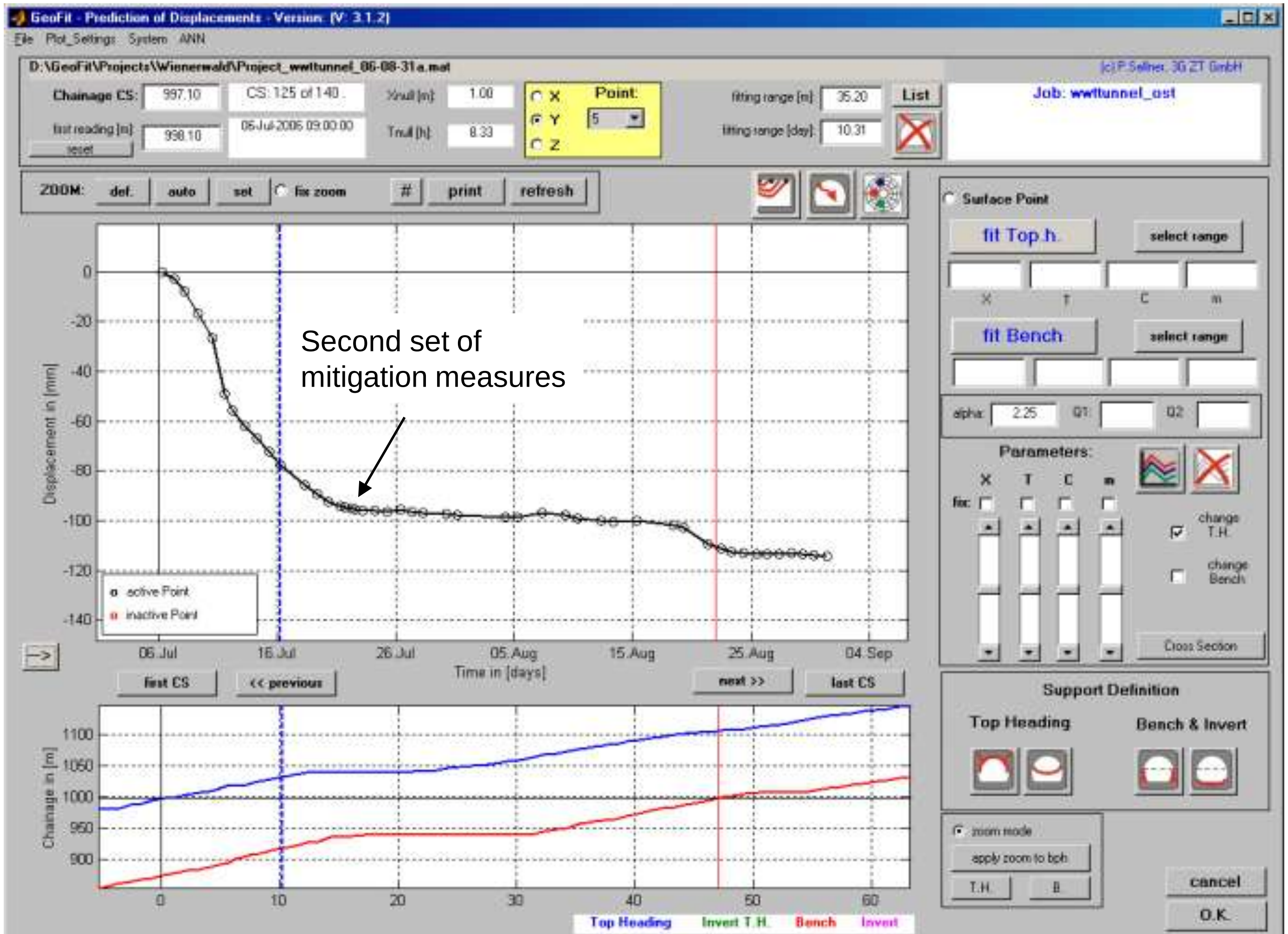
PREDICTION OF FURTHER DEVELOPMENT



FURTHER DEVELOPMENT

- Initial mitigation measures effective, but expected total displacements likely to exceed deformation allowance
- To keep within deformation tolerance, top heading invert was installed
- This stopped deformations practically completely

FURTHER DEVELOPMENT

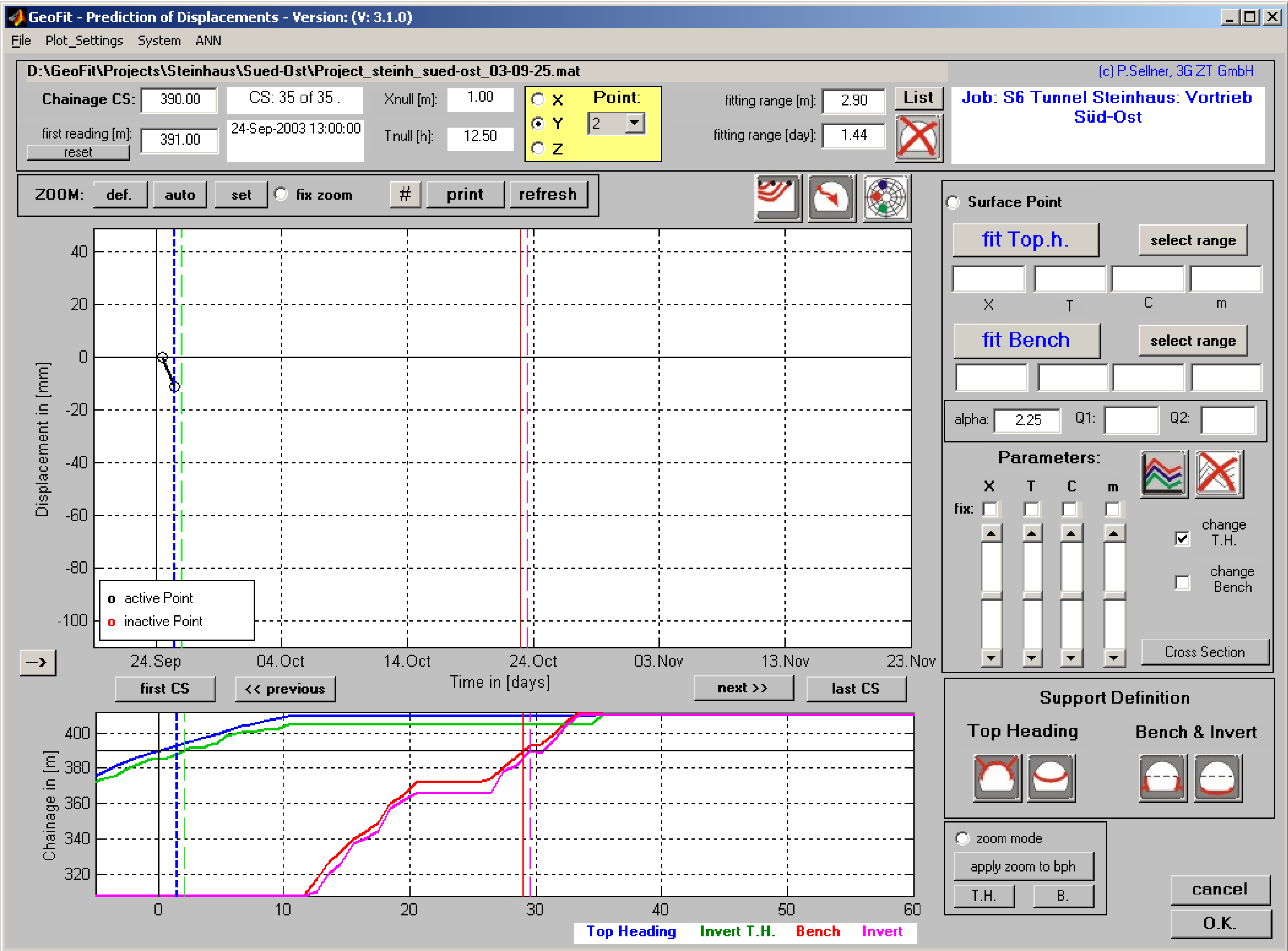


SOME TOOLS TO ASSIST IN GEOTECHNICAL ON-SITE WORK

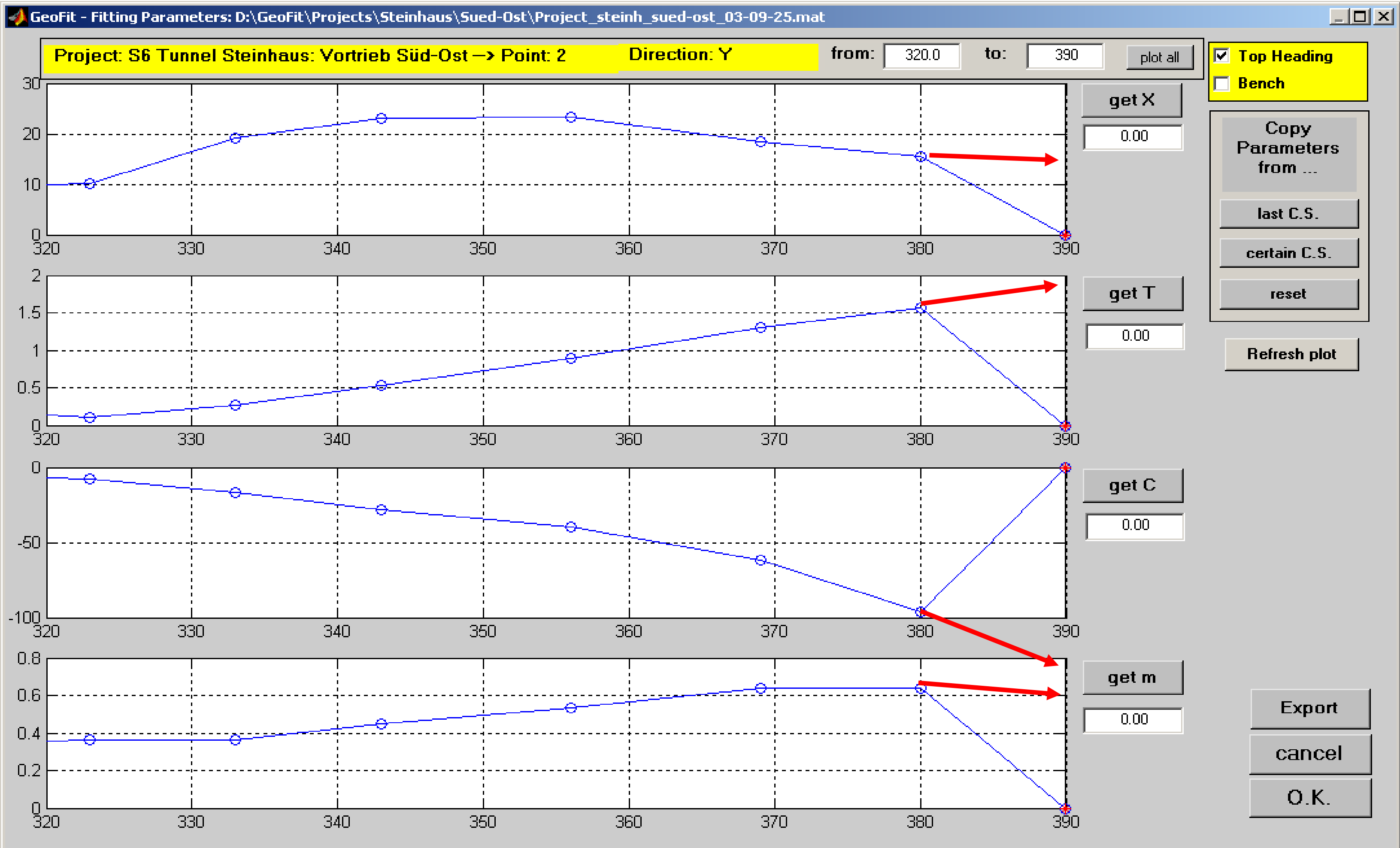
PREDICTION OF DISPLACEMENTS

- Development of displacements is a function of face advance, time, ground structure and quality, excavation sequence and support
- Relatively simple formulations have been proposed by Panet, Sulem, and Guenot in the 1980ies
- Further development of those formulations by Barlow and Sellner to incorporate sequential excavation and different types of support

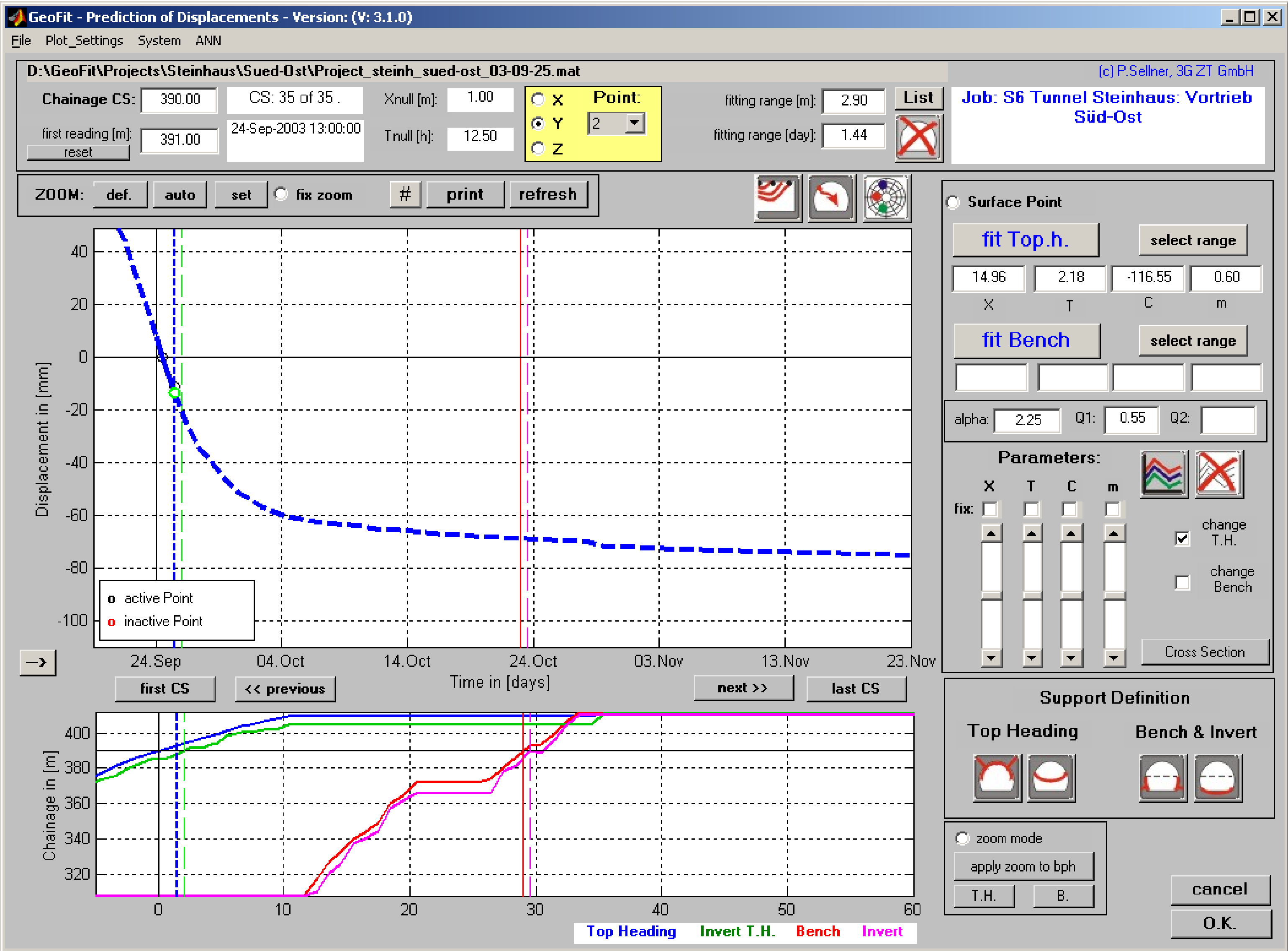
EXAMPLE FOR PREDICTION



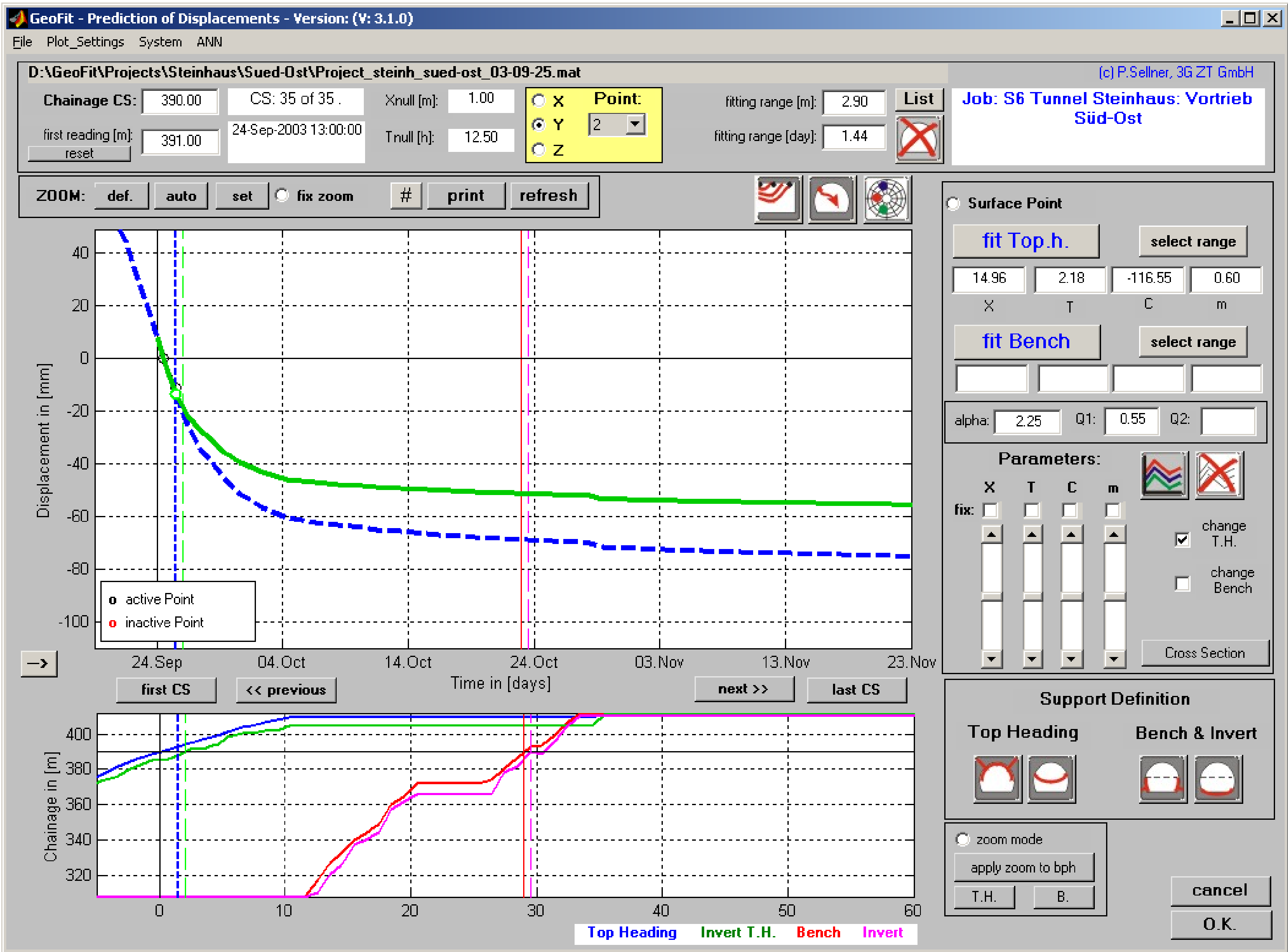
EXTRAPOLATION OF FUNCTION PARAMETERS



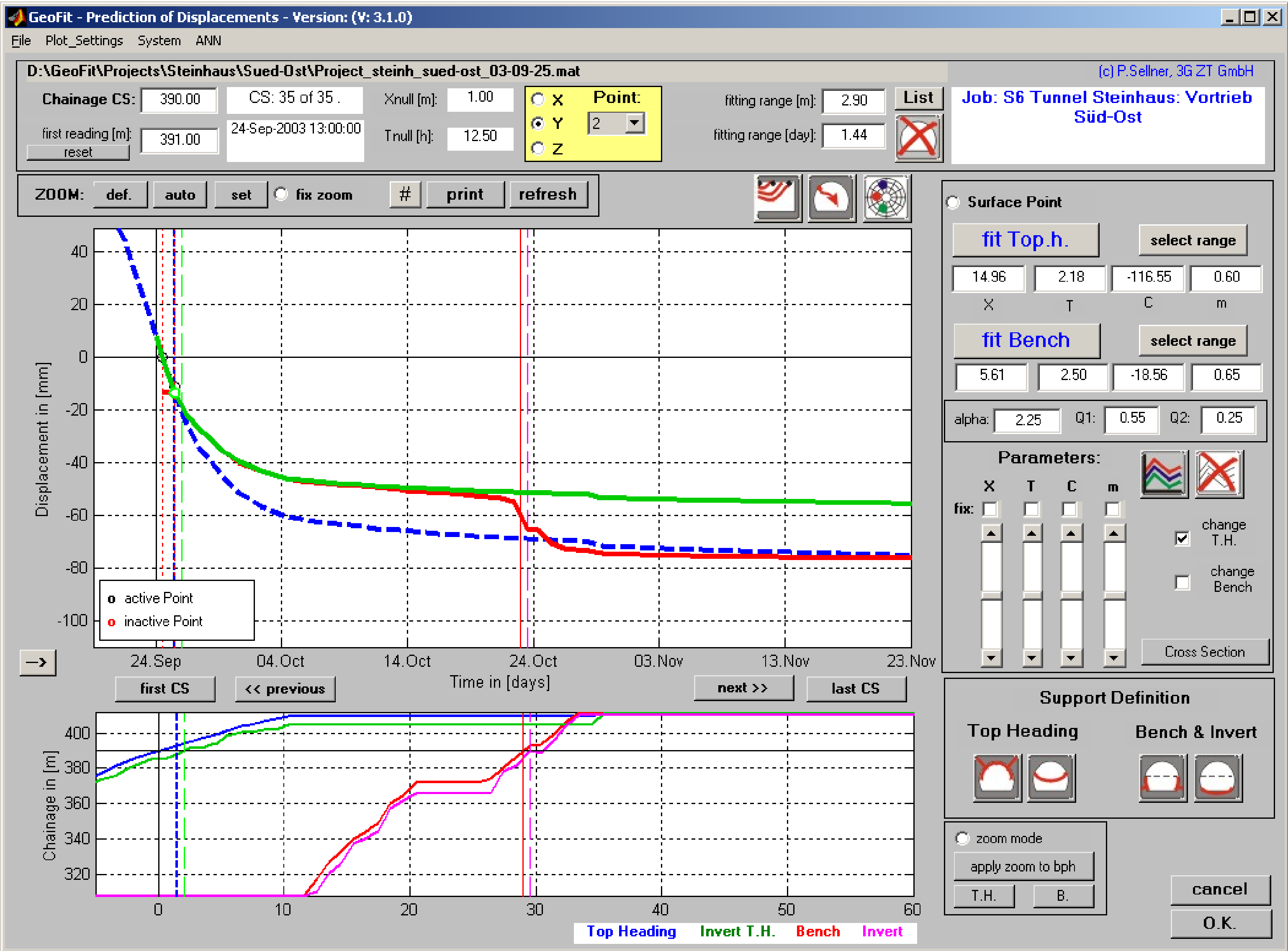
PREDICTION OF DISPLACEMENTS TOP HEADING



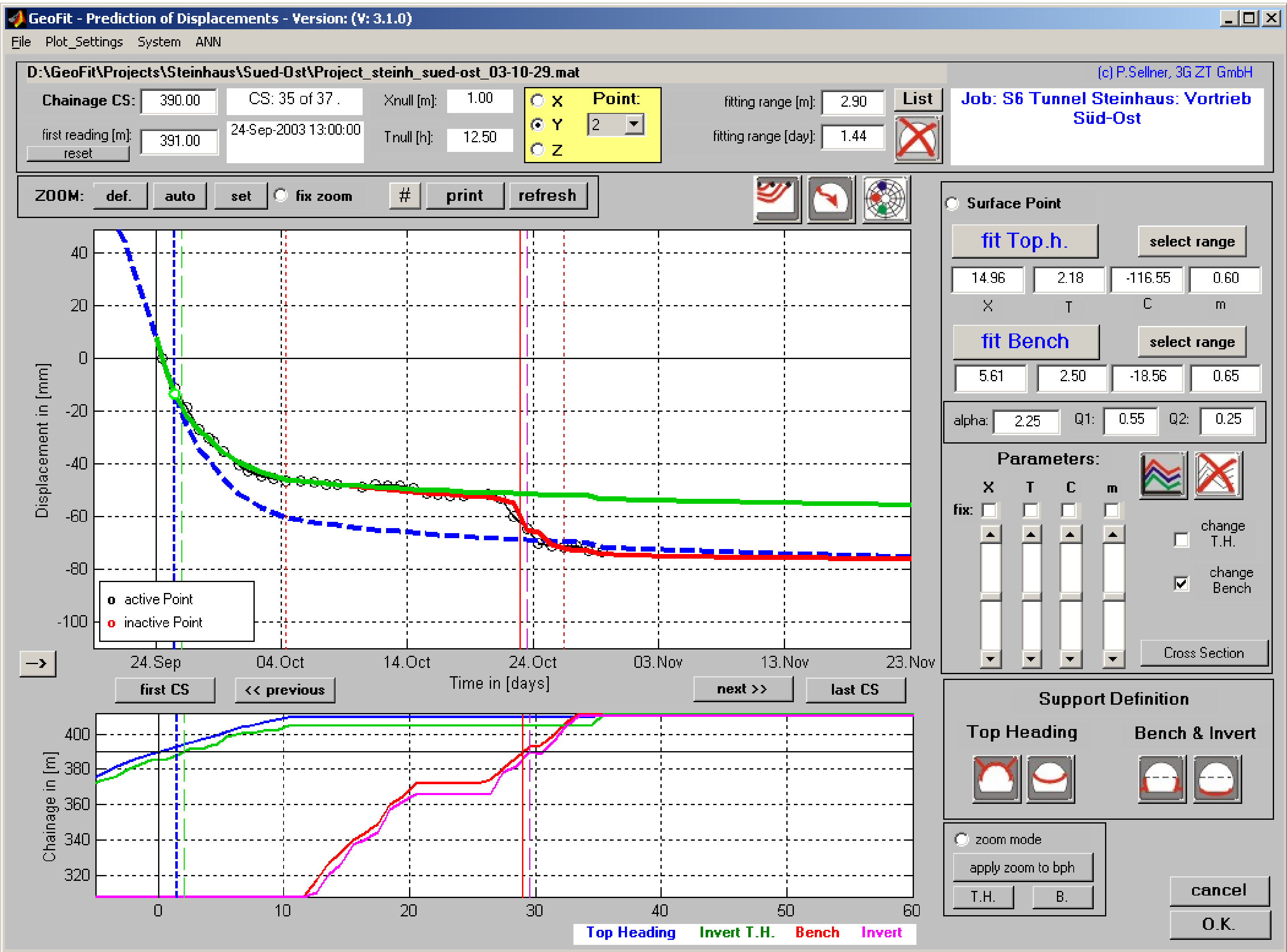
EFFECT OF TOP HEADING INVERT



PREDICTION FOR BENCH AND INVERT EXCAVATION



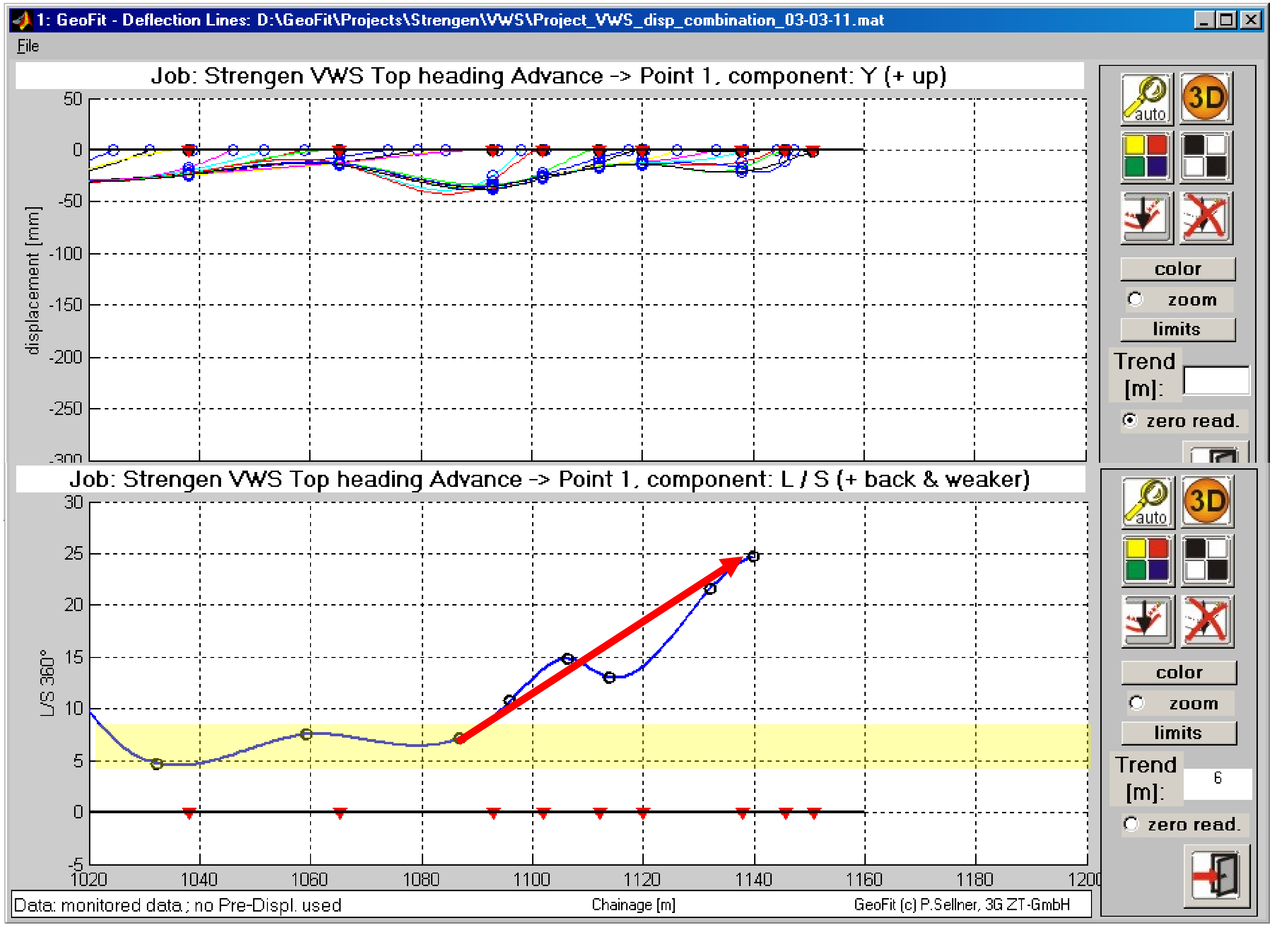
COMPARISON PREDICTION - MEASURED



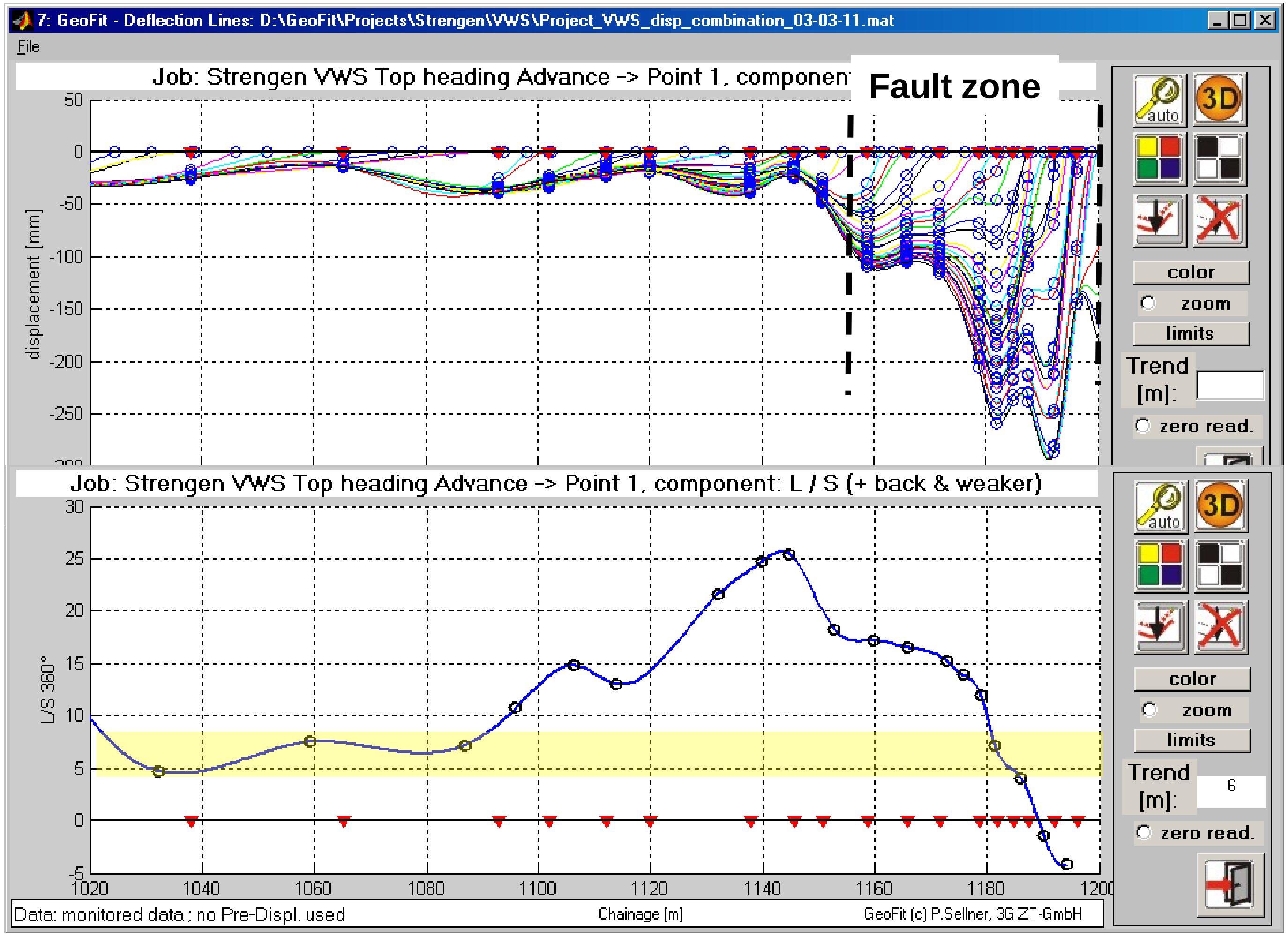
PREDICTION OF GROUND QUALITY AHEAD

- Most costly events associated to „unexpected" changes in the ground quality
- Analysing displacement monitoring data in a non-traditional way, allows to relatively reliabbly predict such changes at practicaly no additional costs
- The idea: if there are no significant changes in the rock mass quality or structure in the vicinity of the tunnel, then displacement characteristics should be similar.
  Vice versa, changing ground conditions should show in changed displacement characteristics

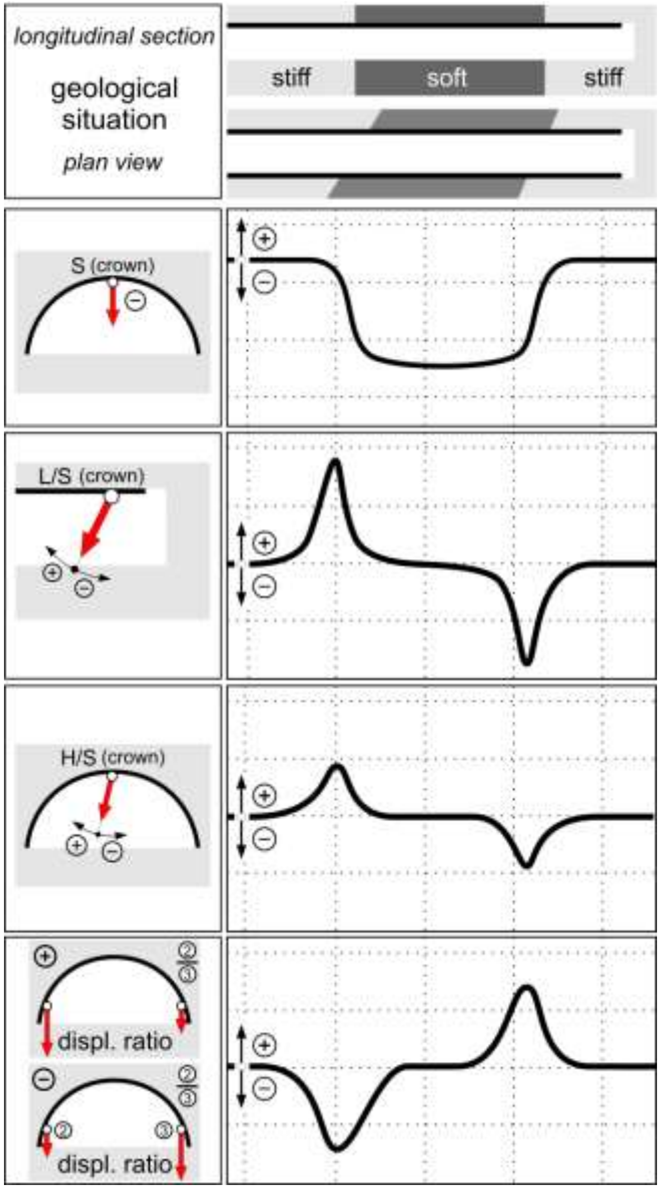
EXAMPLE OF PREDICTING CHANGING GROUND BY EVLAUTION OF DISPLACEMENT TRENDS



CAUSE: FAULT ZONE AHEAD



COMBINATION OF TRENDS FOR SPATIAL ORIENTATION



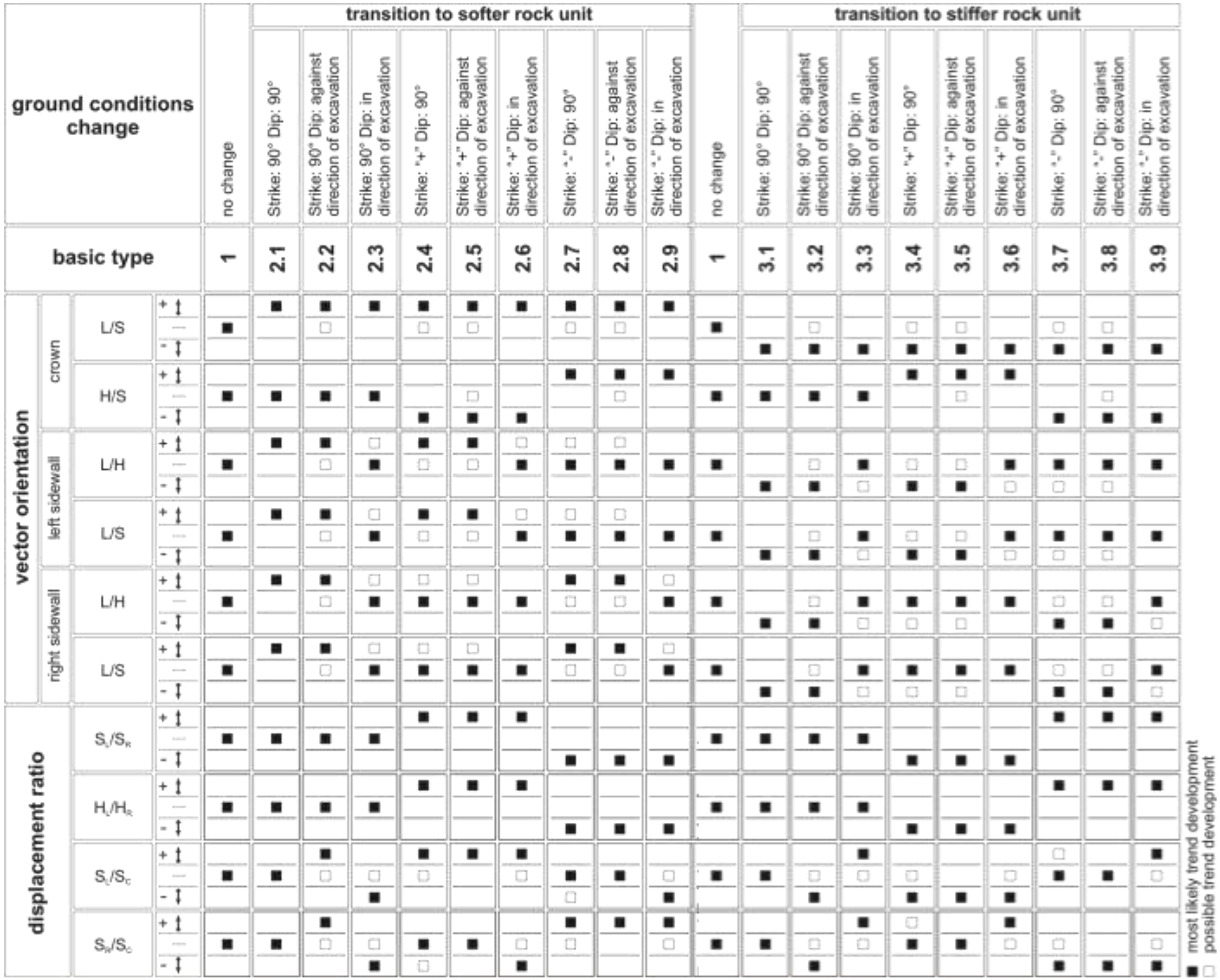
Vertical displacements crown

Deviation of displacement vector orientation in longitudinal section

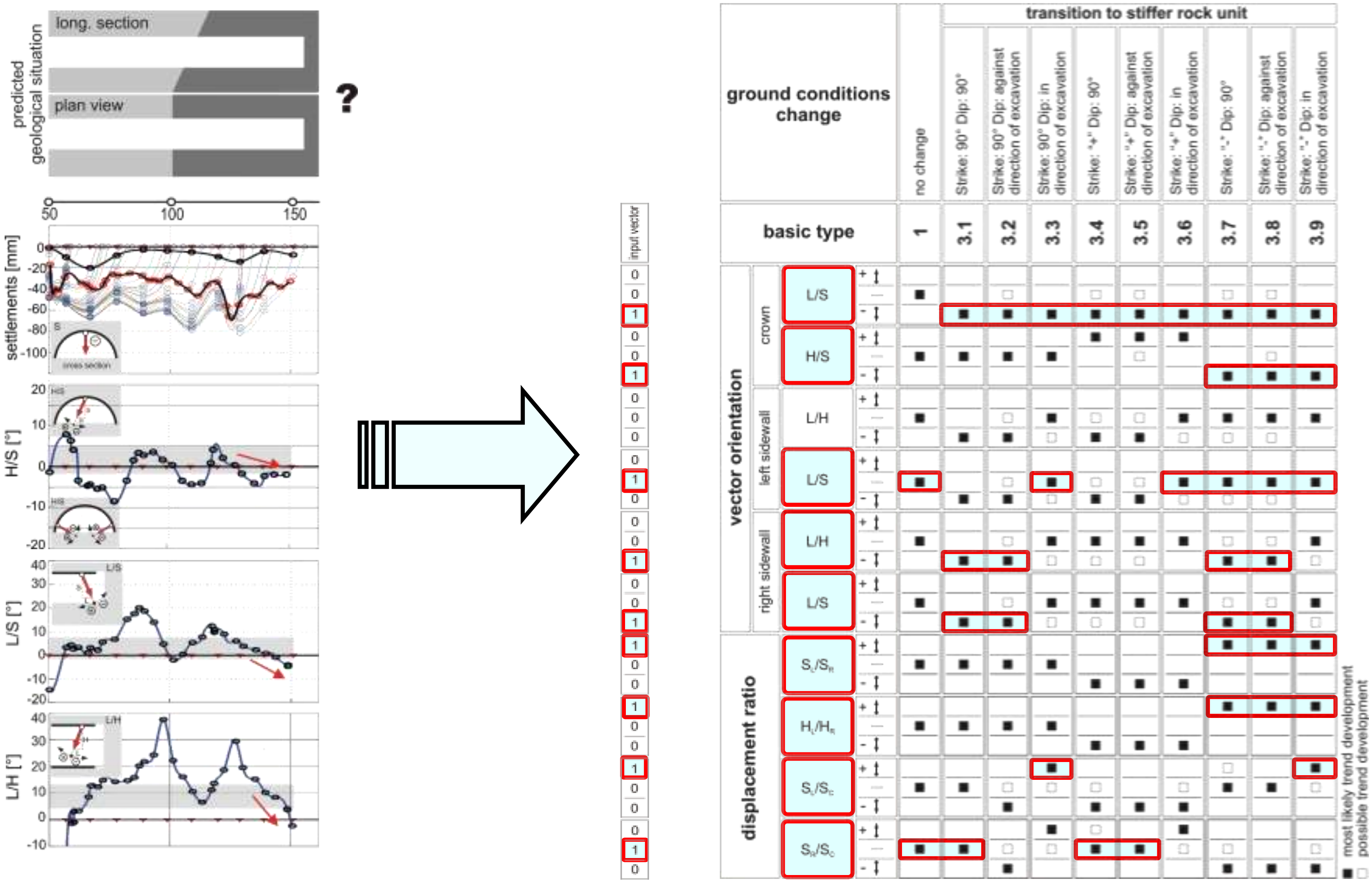
Deviation of crown vector from vertical (cross section)

Variation of ratio of vertical displacements of sidewalls

TREND CORRELATION MATRIX



INPUT OF ACTUAL TRENDS



DETERMINATION OF MAXIMUM CORRELATION

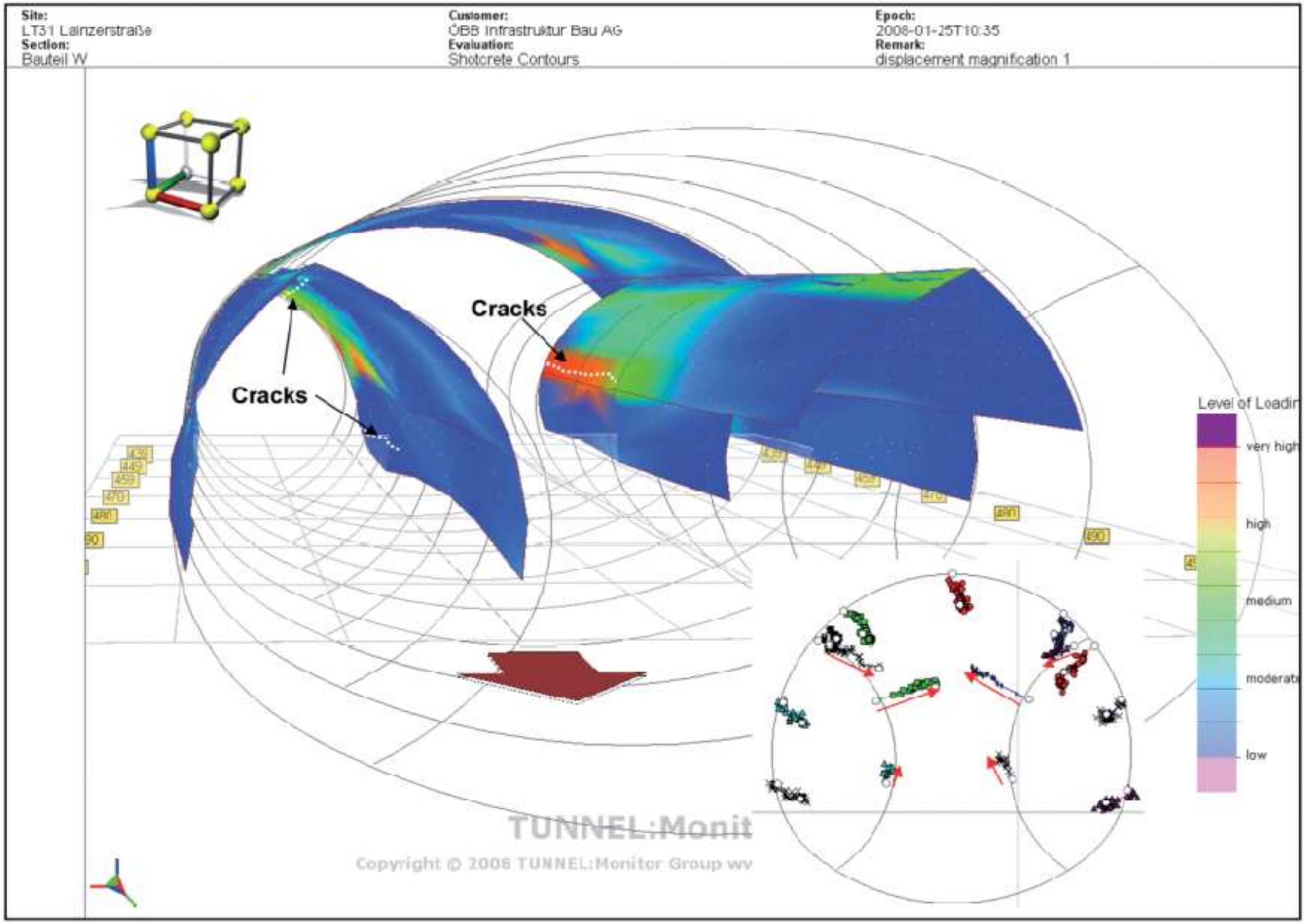
- Compilation of reference table
- Weighting of reference table
  → correlation matrix [C]
- Input of actual trend development
- Multiplication of actual trend development – input vector {a} - with correlation matrix [C]
- Summation of each column
  → actual rating
  $\{r\} = \{a\}^T * [C]$
- Determination of max. correlation
  → related basic type

trend					transition to softer rock unit										transition to stiffer rock unit								
basic type				input vector	1	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9
vector orientation	crown	L/S	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	1	0	0	0	0	0	0	0	0	0	0	10	10	10	10	10	10	10	10	10
		H/S	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	1	0	0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	10	10	10
	left sidewall	L/H	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		L/S	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	1	10	0	5	10	5	5	10	10	10	10	0	5	10	5	5	10	10	10	10
			-↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	right sidewall	L/H	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	1	0	0	0	0	0	0	0	0	0	0	10	10	5	5	5	0	10	10	5
		L/S	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	1	0	0	0	0	0	0	0	0	0	0	10	10	5	5	5	0	10	10	5
displacement ratio		S_L/S_R	+↕	1	0	0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	10	10	10
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		H_L/H_R	+↕	1	0	0	0	0	10	10	10	0	0	0	0	0	0	0	0	0	10	10	10
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S_L/S_C	+↕	1	0	0	10	0	10	10	10	0	0	0	0	0	10	0	0	0	5	0	10
			—	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			-↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		S_R/S_C	+↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
			—	1	10	10	5	5	10	10	5	5	0	5	10	5	5	10	10	5	5	0	5
			-↕	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
actual rating					20	10	20	15	55	55	55	15	10	15	40	40	45	35	35	25	80	70	75
avr. rating					20	28									49								
max. rating					100																		
correlation [%]					20	10	20	15	55	55	55	15	10	15	40	40	45	35	35	25	80	70	75

EVALUATING UTILIZATION OF LININGS

- Back calculating strains from displacement monitoring and using a model for the time dependent properties of shotcrete allows evaluating the utilization of the lining at any time
- This is important information in particular for tunnels with low overburden, where the shotcrete lining is the major means of support

EXAMPLE OF UTILIZATION OF LINING



CONCLUSION

- Risk oriented construction requires understanding of potential failure mechanisms
- Potential stability problems frequently have their cause in features outside the visible area, thus using the information from face mapping only is not sufficient to assess potential behaviour
- Appropriate monitoring and evaluation concept helps in identifying critical developments
- Using modern observation methods significantly reduces the probability of experiencing „surprises“ during excavation, thus saving time and money

CONCLUSION

- Projects with high risk potential require a sound safety management system
- A thorough preparation is required prior to construction to have the system available in time
- Essential information must be available to all parties involved at any time
- Clear definition of responsibilities is essential
- Last, but not least, an efficient safety management system can only be established and executed by persons, who understand the relationships between causes and effects


Thank you for your attention
schubert@tugraz.a