STATE OF THE ART IN TUNNEL MONITORING

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WHY MONITORING ?

- Uncertainties in the geological model
- Uncertainties and spread of ground parameters
- Simplifications in the mathematical models used for design

⇨ inaccurate design and thus residual risk during construction

WHY MONITORING ?

- Observations and measurements are used to
  - Assess the stabilty of the underground structure
  - Verify/falsify assumptions made during the design
  - Adjust excavation and support methods
  - Improve the ground model
  - Detect important features outside of the visible area
  - Quality control and conservation of evidence
  - Basis for back analyses
- In addition measurements are an important basis for the geotechnical safety management

REQUIREMENTS FOR SUCCESSFUL APPLICATION OF OBSERVATIONAL APPROACH

- Expected behaviors and acceptable limits must be defined prior to construction
- Instrumentation, monitoring layout, and reading frequency must be in a way to allow capturing expected behaviors
- Analysis of results must be sufficiently rapid in relation to the possible evolution of the system
- 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 behavior deviates from expected

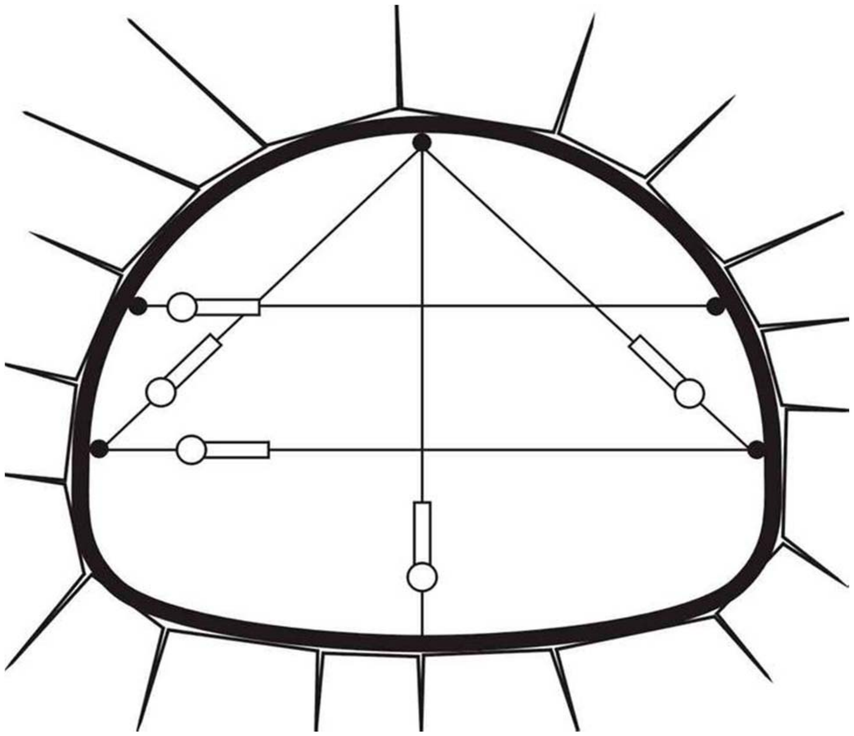
REQUIREMENTS FOR MEASUREMENT DATA COLLECTION

- Take readings as soon as possible
- Make sure face position is recorded correctly
- Process data as quickly as possible in high quality
- Comment on data quality if required
- Be aware that accuracy and quality of data is important for the decision making
- Protect measurement devices and targets against damage

MONITORED PARAMETERS

- Absolute displacements in space
- Relative displacements
  - Tape measurements
  - Extensometer
  - Measuring anchor
- Surface settlements
  - Levelling
  - Horizontal inclinometers
- Inclinations
  - Inclinometers
  - Tilt meters
- Strains (strain gauge)

METHODS OF DISPLACEMENT MONITORING



- Relative displacement measurements
  - Relatively high (sometimes only apparent) accuracy
  - Only information on elongation or shortening of measured length
  - Physilcal access to measurement pins required
  - Hindrance of works by platform and tape across the tunnel

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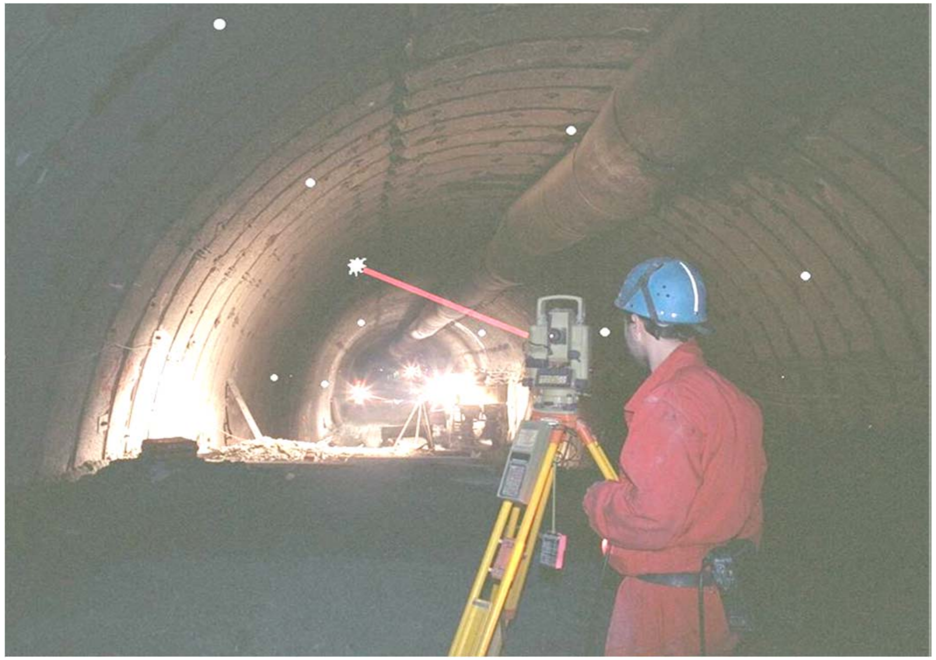
METHODS OF DISPLACEMENT MONITORING



- Absolute displacements
  - Free positioning, thus minimal interference with operation
  - No physical contact to targets required
  - Measurement of spatial movements
  - Accuracy influenced by unfavourable posiion of instrument, refraction, dust, vibrations, stability of „fixed“ points

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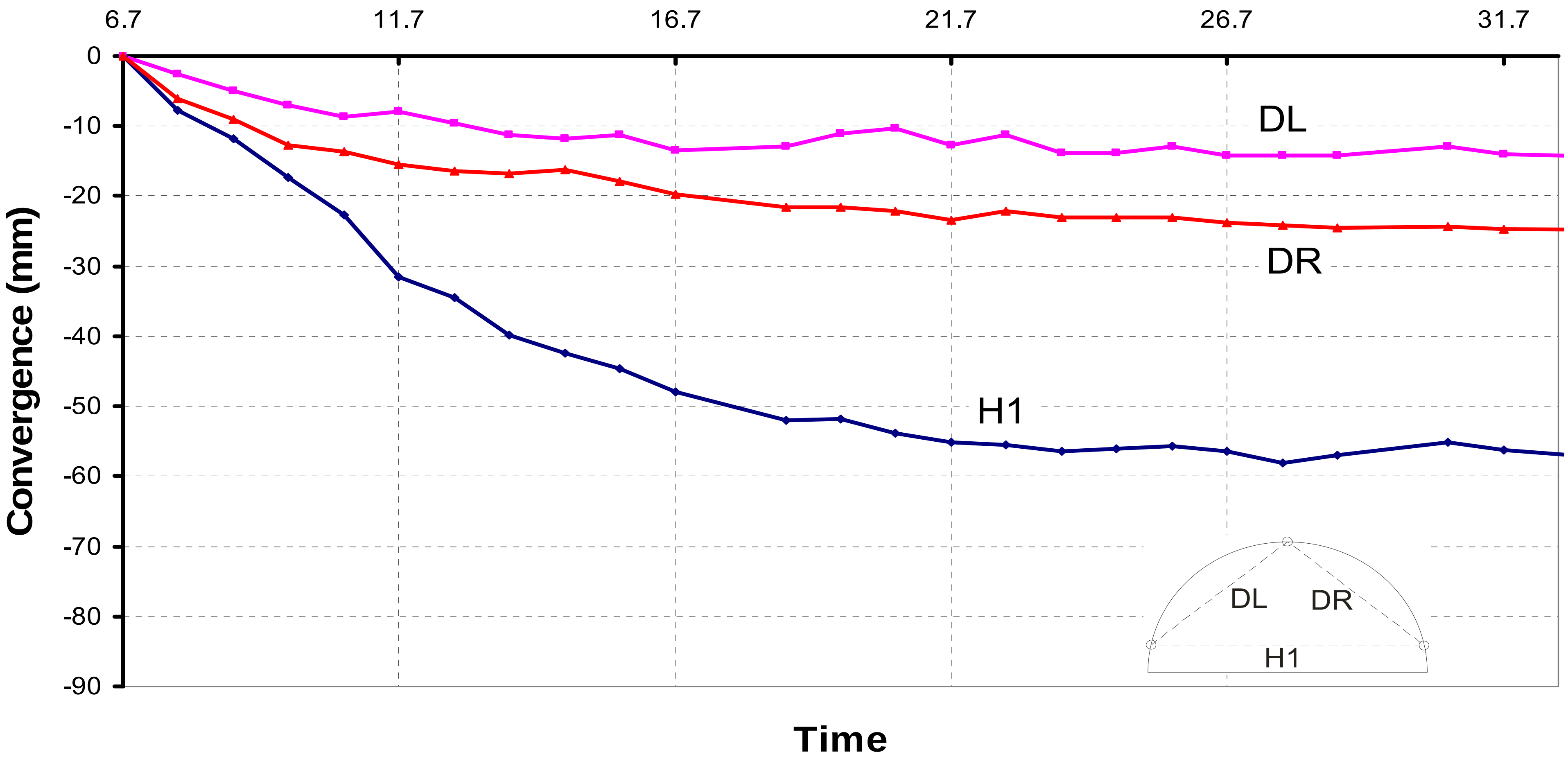
STATE OF THE ART

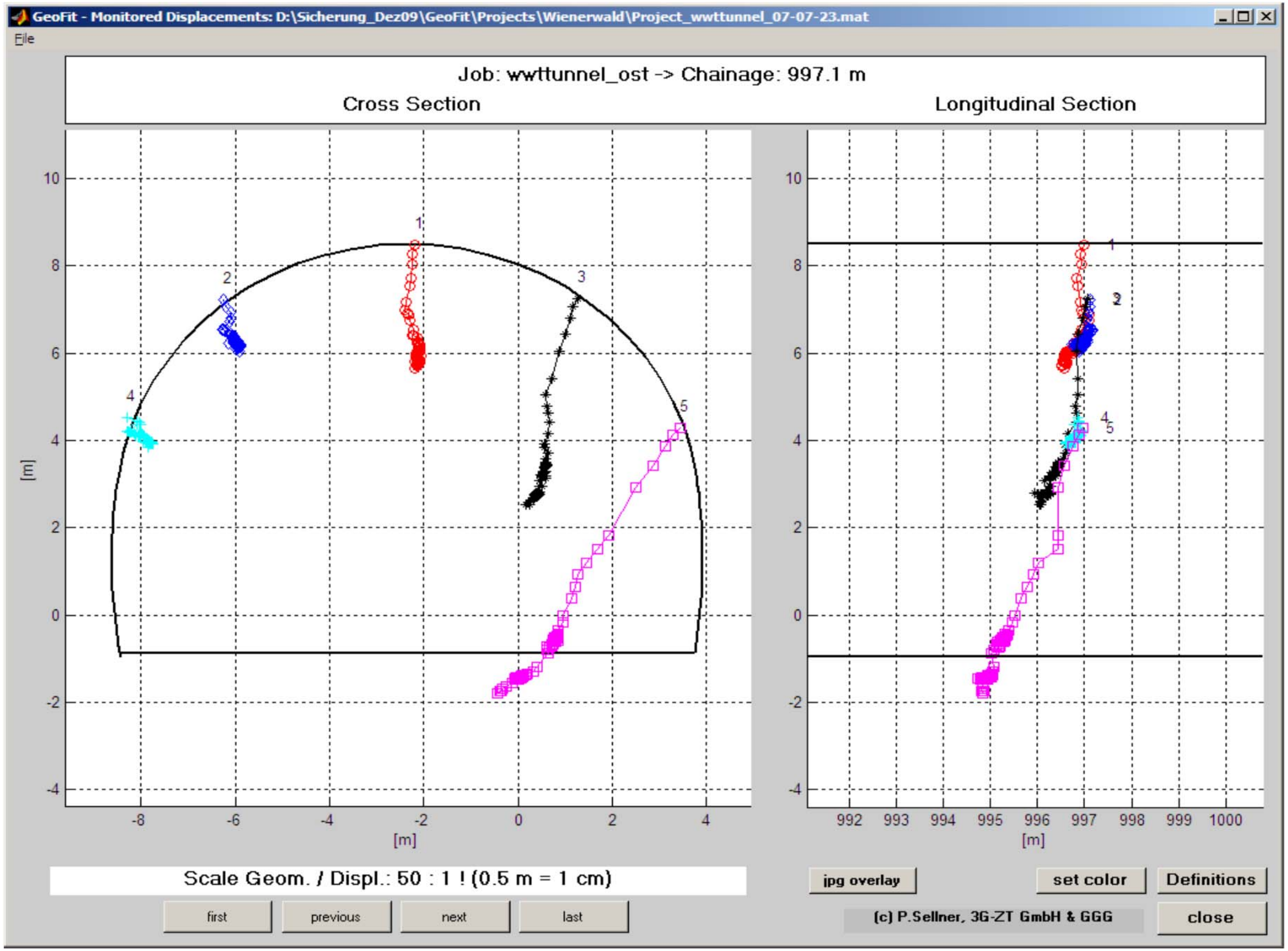
- Measurement of absolute displacements has in many countries replaced the convergence measurements
- The information quality and quantity is much higher than with the traditional methods
- The knowledge of the spatial position of each point at any time has opened a wide field for valuable evaluation methods
- Additional instrumentation (like extensometers) only required in special situations

RESULT OF TRADITIONAL CONVERGENCE MEASUREMENT

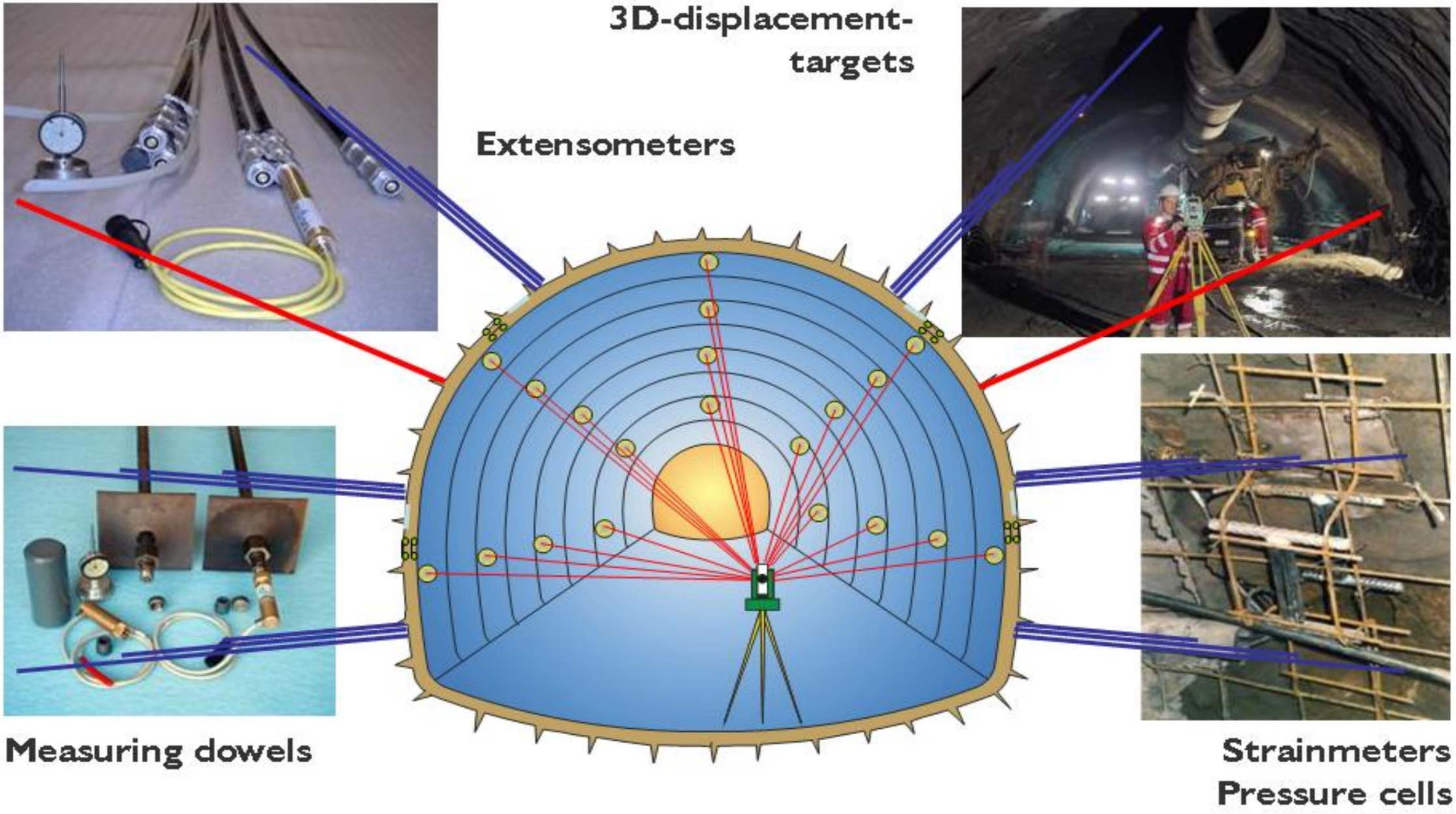
- Display of relative displacements does not allow properly identifying anisotropic displacements



SAME DATA WITH ABSOLUTE DISPLACEMENT MONITORING



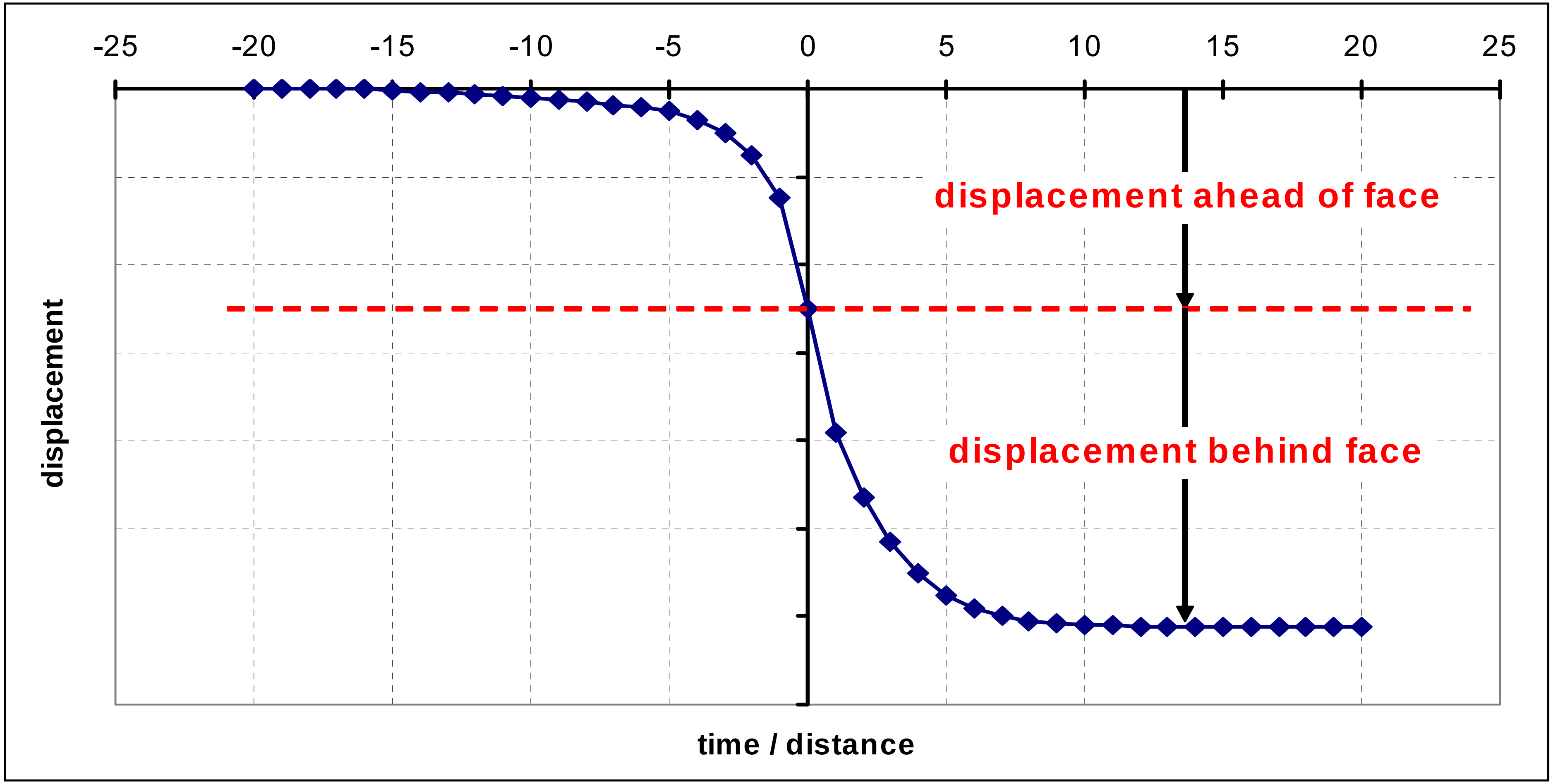
TYPICAL INSTRUMENTATION FOR SELECTED SECTIONS



DATA EVALUATION

- Traditionally displacements are plotted versus time, and the results visually inspected. This makes interpretation of readings difficult in case of an unsteady andvance rate
- It is advisable to plot the displacements against face advance, as this is the most prominent influencing factor, or use a mathematical model, which considers time and advance effects (for example software GeoFit)
- Measurement of spatial displacements has opened a wide field of different assessment methods, like:
  - Spatial orientation of displacement vectors for identification of geological features outside the visible area
  - Assessment of lining loads

TYPICAL DEVELOPMENT OF DISPLACEMENTS

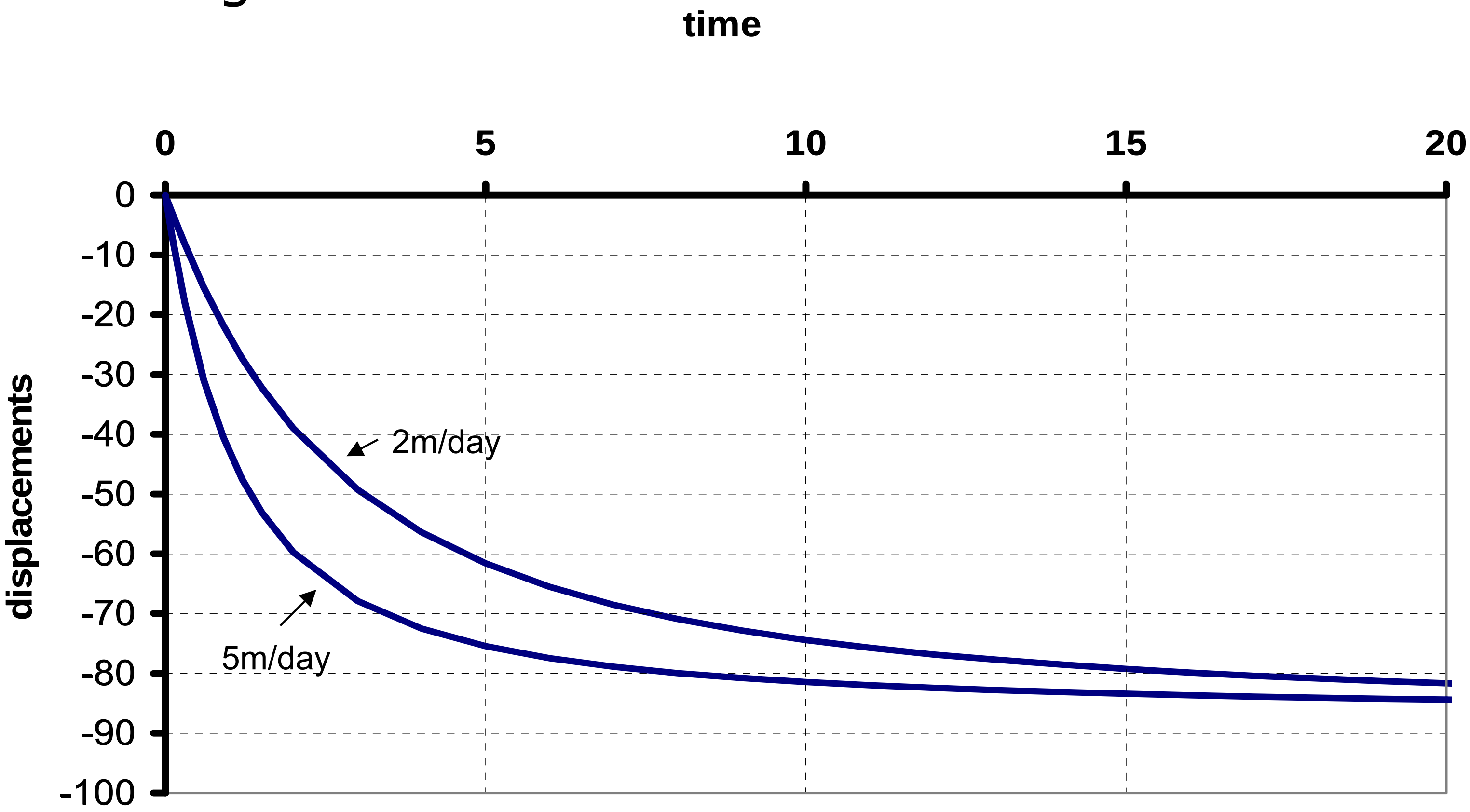


POTENTIAL EVALUATION METHODS

- Displacements versus time or face distance
  - Can give good overview on stabilization process
  - But only one component plotted, thus evaluation cumbersome
- Deflection lines
  - Give good overview of one componenet over longer tunnel section, but also only one component plotted
- Displacement vectors
  - Nicely show influence of ground structure, system response, anisotropic displacements; usually only one section at a time can be shown
  - Spatial displacement vector orientation changes can show changing ground conditions ahead of face

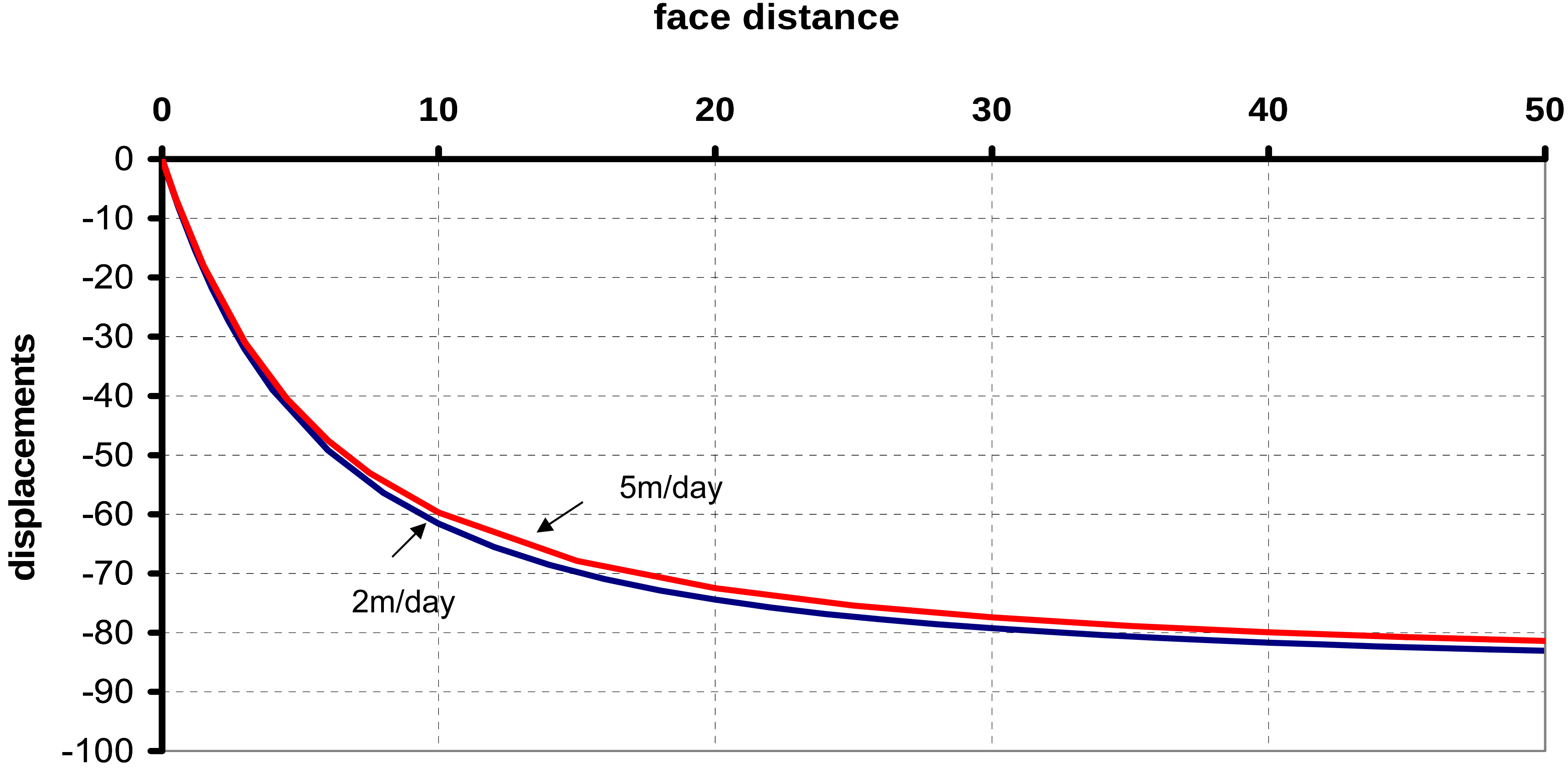
DISPLACEMENTS versus TIME

- With the d/t diagram, apparently larger displacements are interpreted initially. In particular if one estimates final displacements from first day(s) displacements, result may be misleading



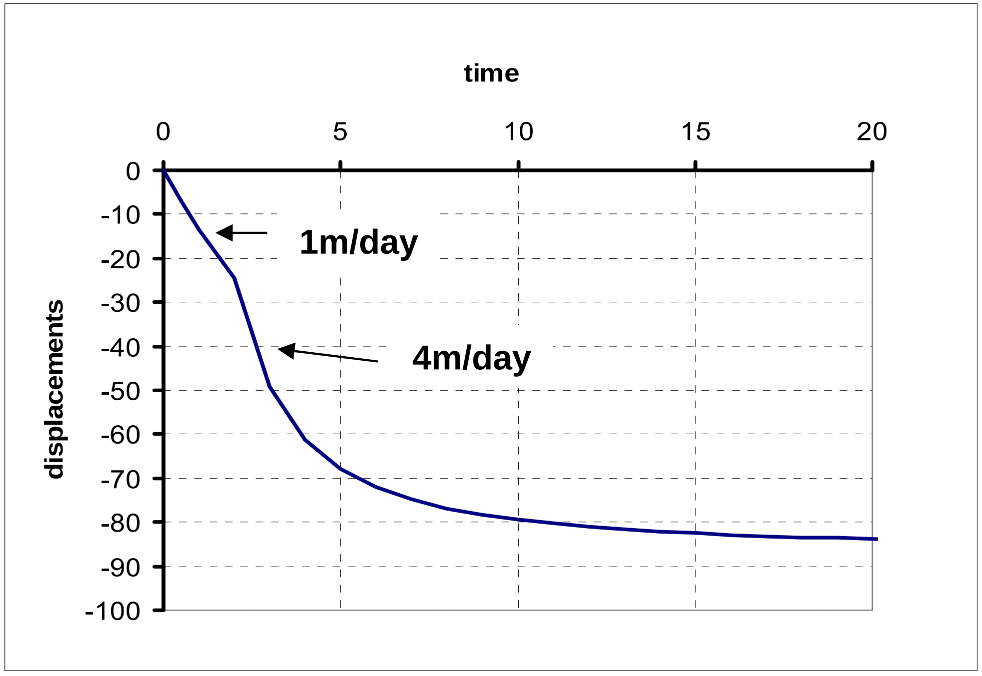
DISPLACEMENTS versus FACE DISTANCE

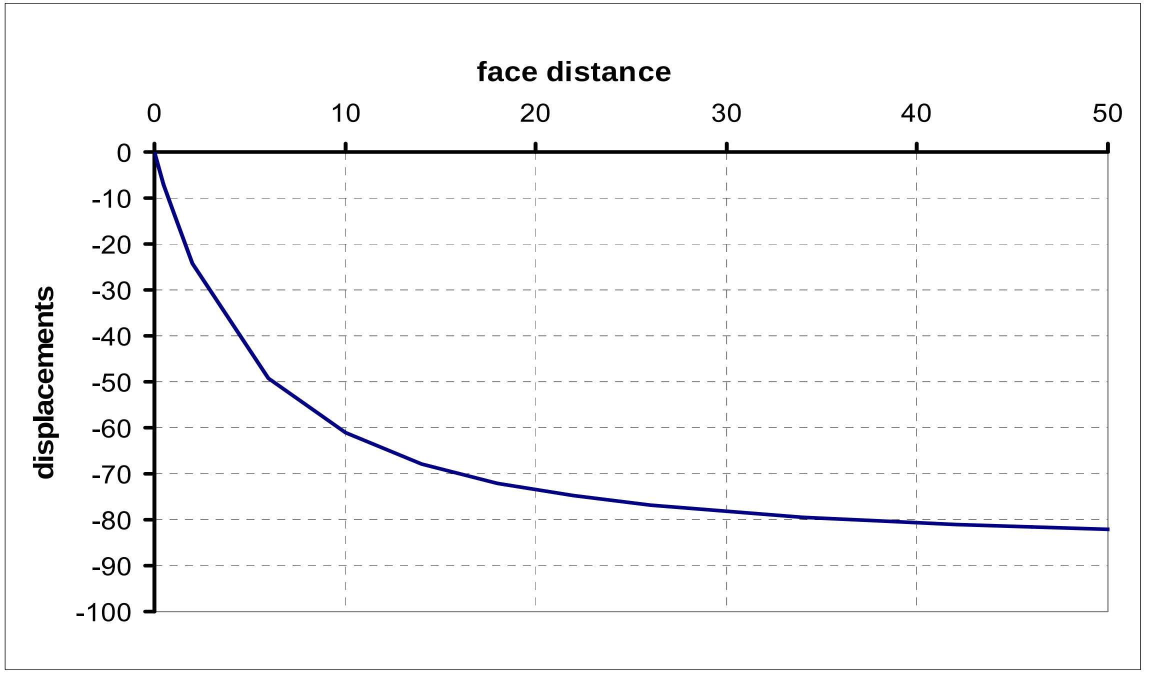
- With the d/x diagram the difference is marginal, provided that time dependent displacements are not dominant



UNSTEADY ADVANCE RATE – DIFFERENT PLOTS

- Displacement – distance diagram not influenced by unsteady advance rate, thus easy to interprete (decreasing displacement rates with increasing distance)





MATHEMATICAL DESCRIPTION OF DISPLACEMENT DEVELOPMENT

- Sulem and Panet have developed an empirical relationship for the displacements behind the face in relation to face advance and time
- General form of function:

$$C(x,t) = C_1(x) * \left[C_{x\infty} + A * C_2(t) \right]$$

$C_1(x)$	Advance dependent component
$C_2(t)$	Time dependent component
$C_{x\infty}$	Final time independent displacement
A	Final time dependent displacement

Panet, M., Guenot, A.: Analysis of convergence behind the face of a tunnel, Tunnelling 1982, The Institution of Mining and Metallurgy, 197 – 204
Sulem J., Panet M., Guenot, A.: Closure Analysis in Deep Tunnels, Int. Journal of Rock Mechanics and Mining Science, 24, 1987, pp 145 – 154, Pergamon Press

MATHEMATICAL DESCRIPTION OF DISPLACEMENTDEVELOPMENT

- The advance dependent function reads as:

$$C_1(x) = \left[1 - \left(\frac{X}{X + x}\right)^2\right]$$

X … shape parameter
x … distance between face and observed section

- The time dependent component reads as:

$$C_2(t) = \left\{1 - \left[\frac{T}{(t+T)}\right]^n\right\}$$

T … shape parameter
t … elapsed time between excavation and observation

MATHEMATICAL DESCRIPTION OF DISPLACEMENTS

- Using $$m = \frac{A}{C_{x\infty}}$$

  and for n=0.3, the function for the development of displacements reads as follows:

$$C(x,t) = C_{x\infty} * \left[1 - \left(\frac{X}{X+x}\right)^2\right] * \left\{1 + m * \left[1 - \left(\frac{T}{T+t}\right)^{0,3}\right]\right\}$$

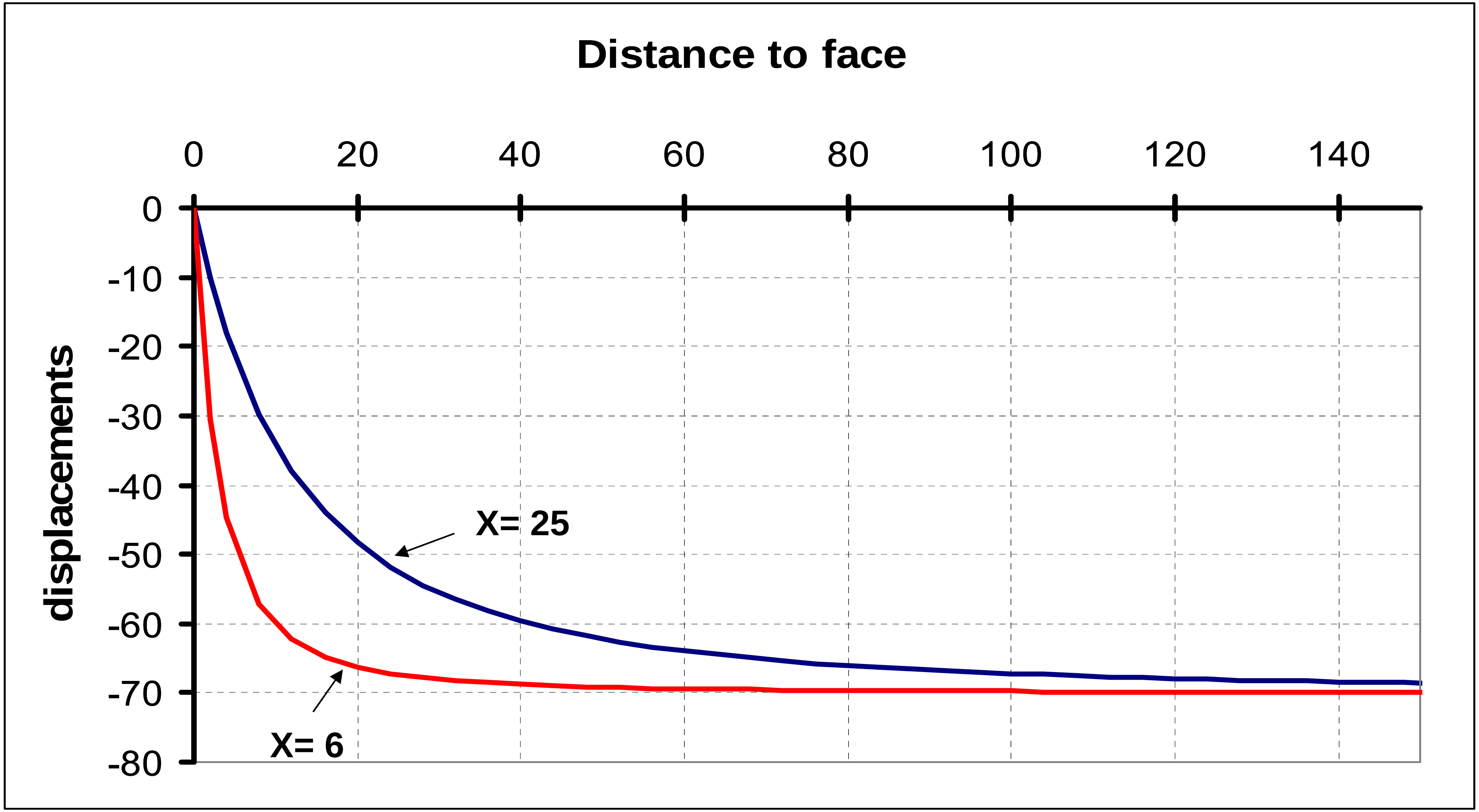
DISCUSSION OF PARAMETER *X*

- *X* describes the shape of the advance dependent function
  the smaller *X* is, the shorter is the length influenced by the excavation
- The value of *X* depends on ground utilization and the ground structure;
  the higher the ground is stressed, the higher is the value of *X*.
  Panet proposed to use for X = 0.84 * plastic radius
  (See also Pilgerstorfer, 2009 and Hoek, 2008)
  Also the relative orientation between tunnel axis and foliation influences the vale X Low values for strike perpendicular to axis, high values for parallel strike

  Range of X for dia 10m tunnels: 4 to 30, usually around 8 to 15

Pilgerstorfer, T. & Schubert, W. 2009. Forward prediction of spatial displacement development.
In Ivan Vrkljan, Rock Engineering in Difficult Ground Conditions
Soft Rocks and Karst, 495-500. London: Taylor \& Francis Group.
Hoek, E., Carranza-Torres, C., Diederichs, M.S. and Corkum, B. 2008.
Integration of geotechnical and structural design in tunnelling.
Proceedings University of Minnesota 56th Annual Geotechnical Engineering Conference. Minneapolis, 29 February 2008, 1-53

EXAMPLE X = 6 / 25; m = 0; C = -70



DISCUSSION OF PARAMETERS *m* AND *T*

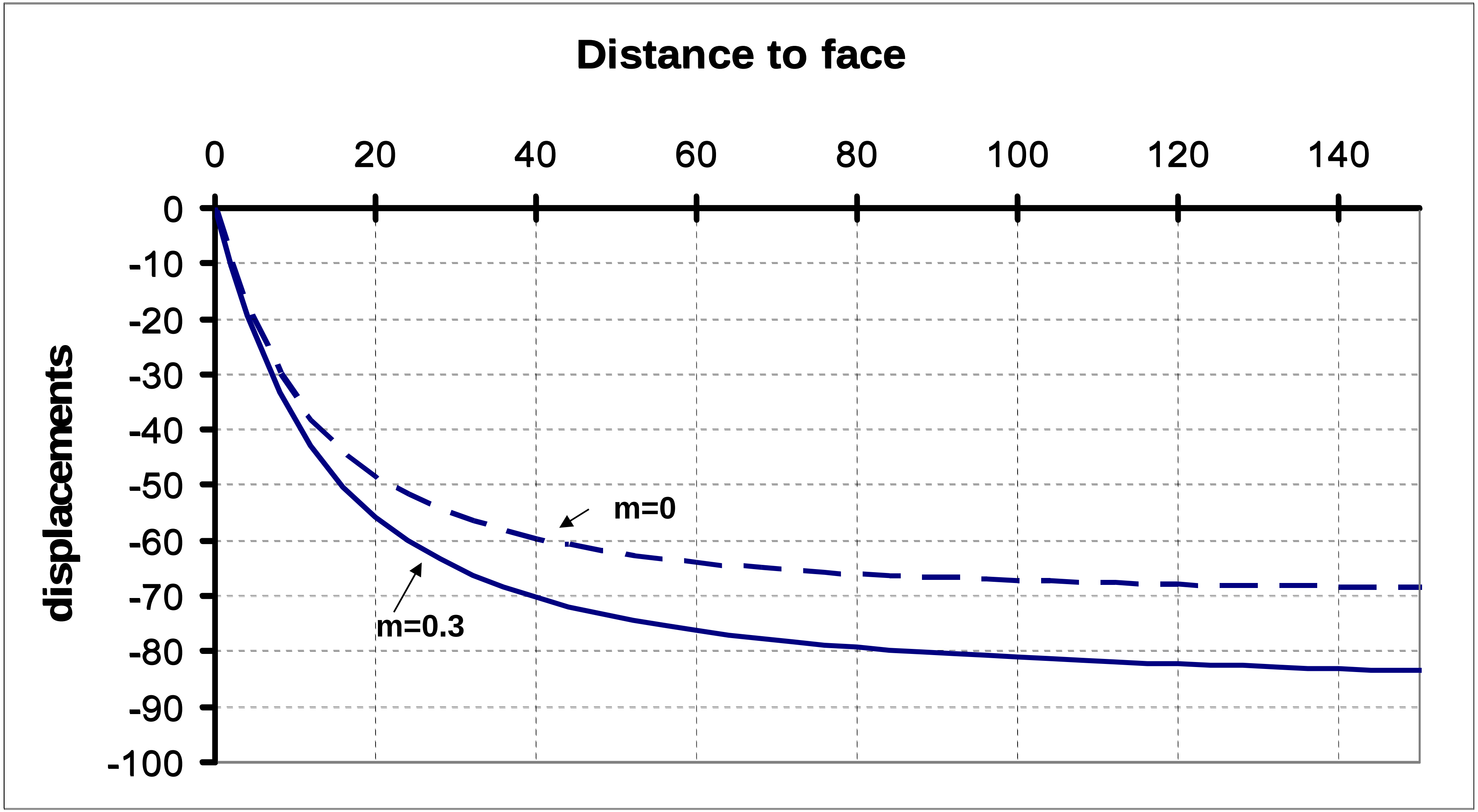
- *m* describes the proportion of the time dependent displacements

  Example:
  time indep. displacement $C_{x\infty}$=100, m=0.3
  C(x,t) for infinite x and infinite t the value of 130)

- The parameter *T*, like the parameter *X* describes the shape of the function (time dependent displacements finished early or last over longer period of time).

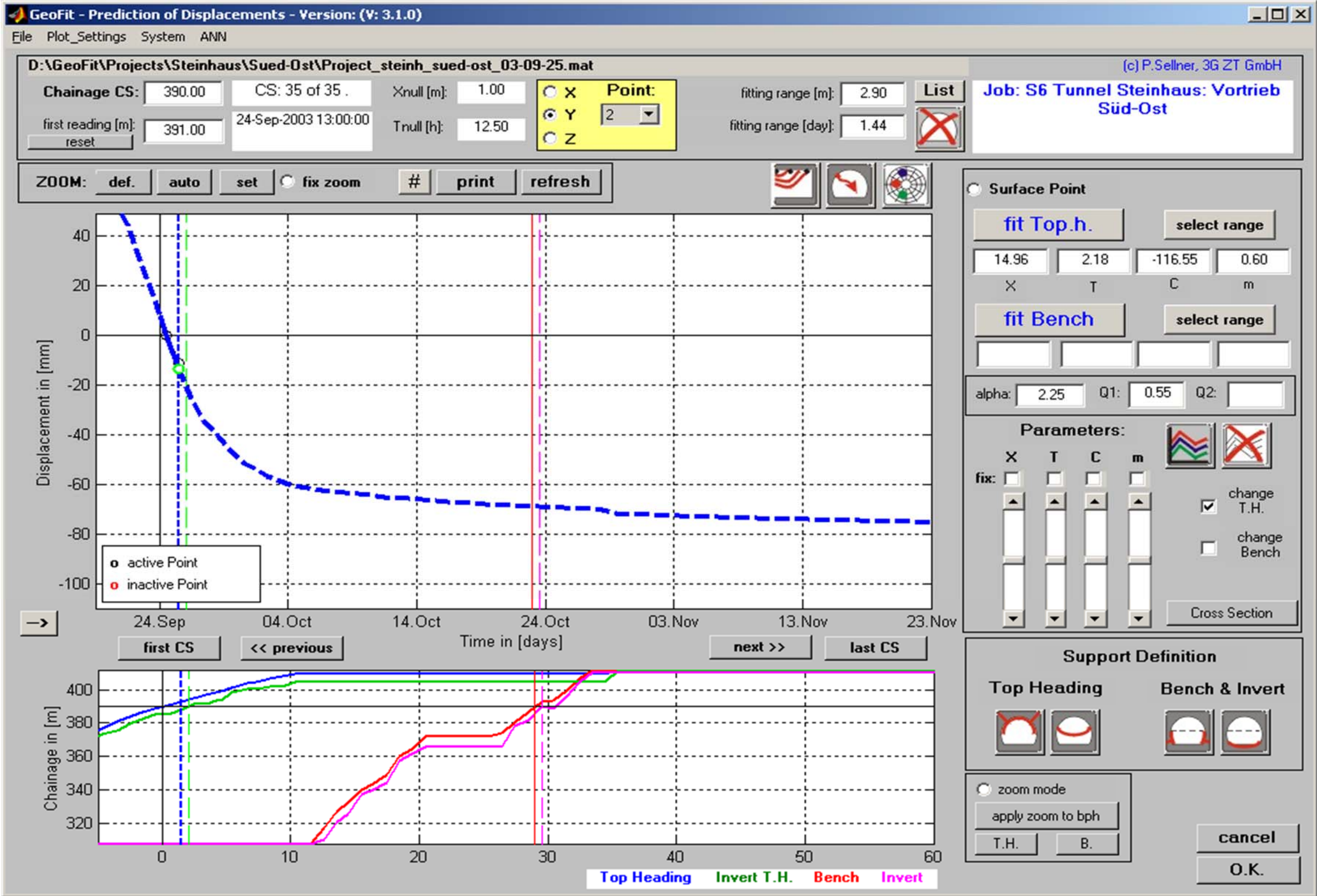
- *Values of m* and *T* very much depend on time dependent characteristics of the ground and the stress level
  Common values for *m* and *T* from fitted measured displacements:
  m=0.1-0.8
  T=0.5-2

Example for X = 25; m= 0.3; T=0.5; C=-70

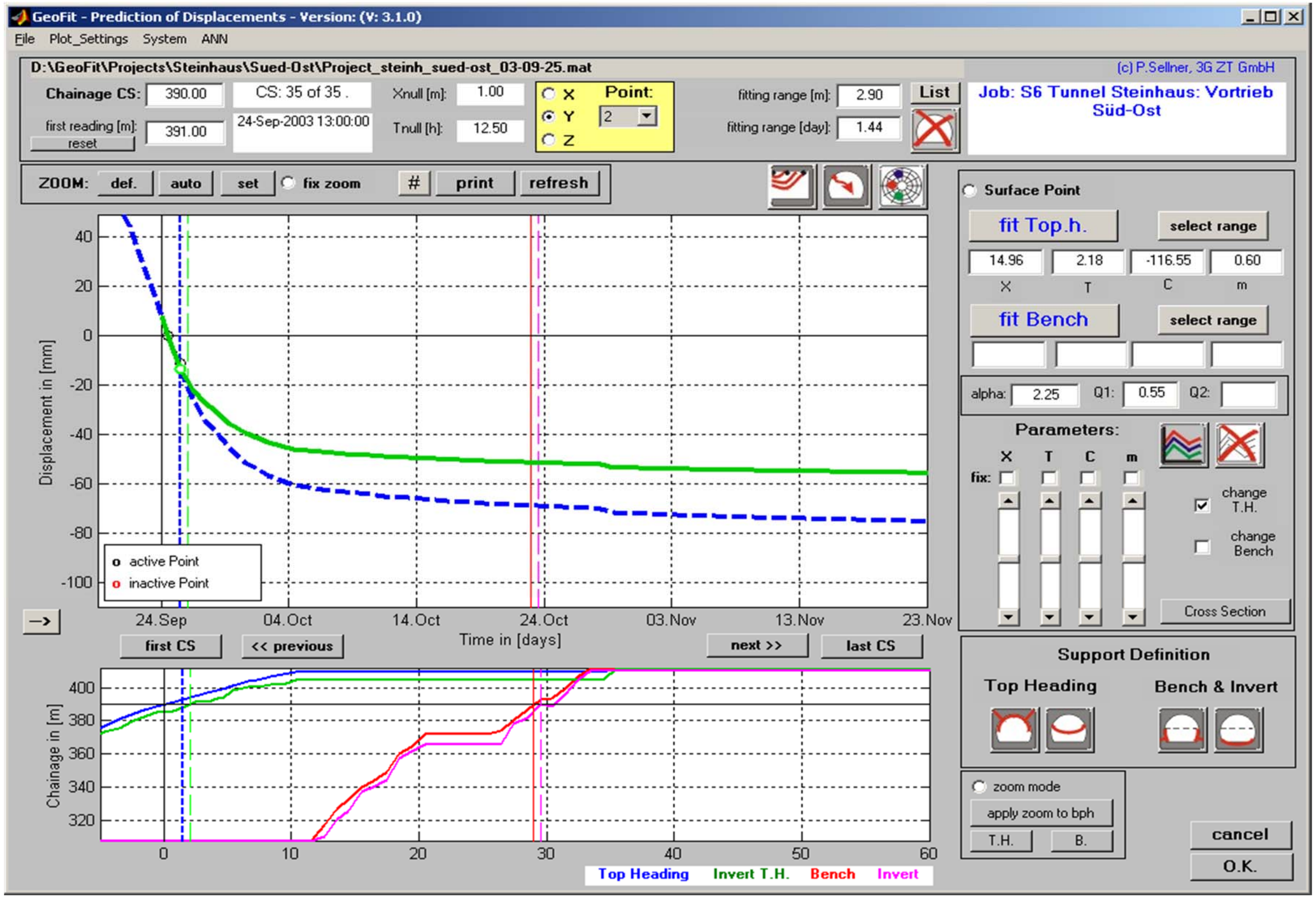


PREDICTION OF DISPLACEMENTS TOP HEADING

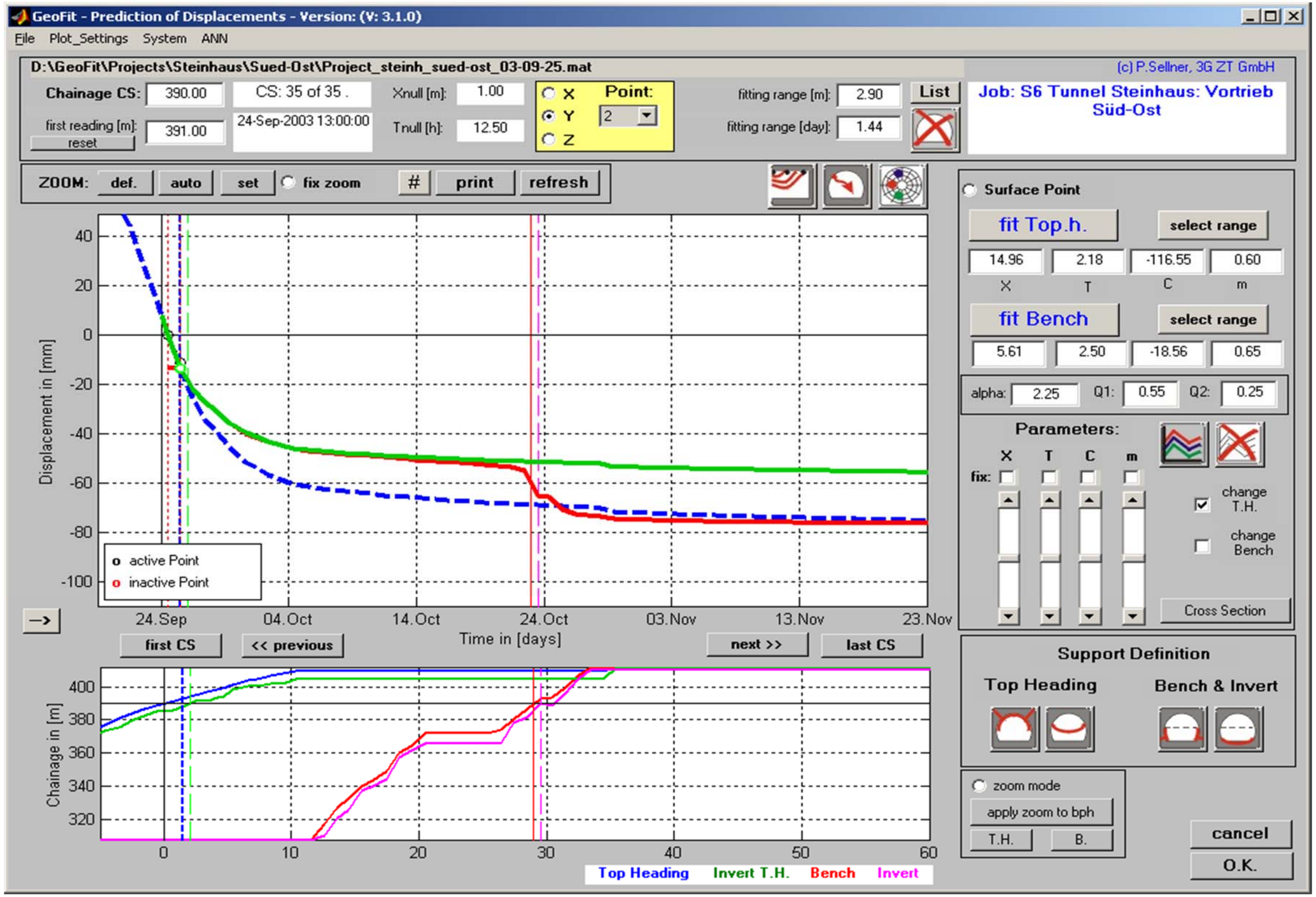
with Software GeoFit



EFFECT OF TOP HEADING INVERT



PREDICTION FOR BENCH AND INVERT EXCAVATION



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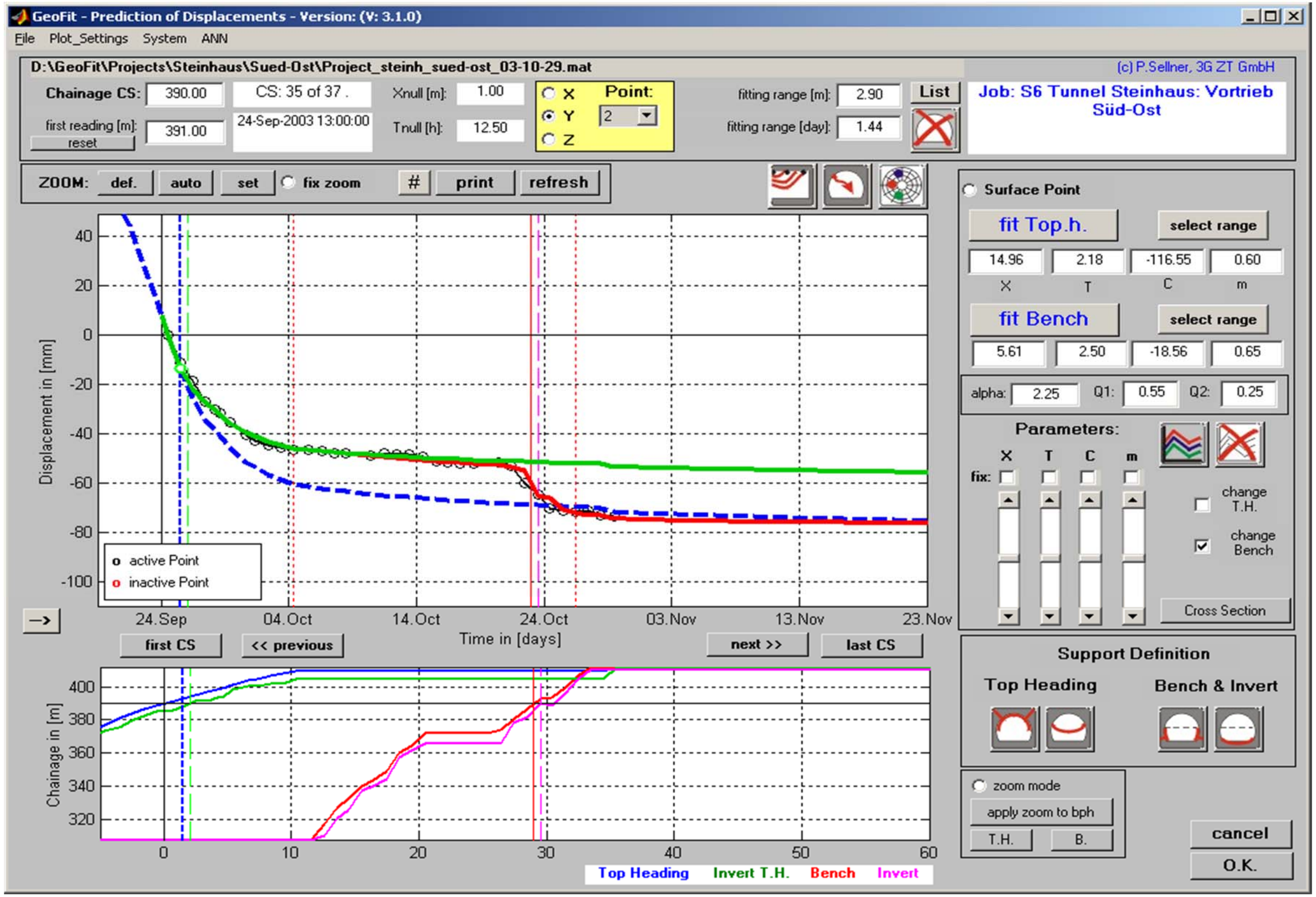
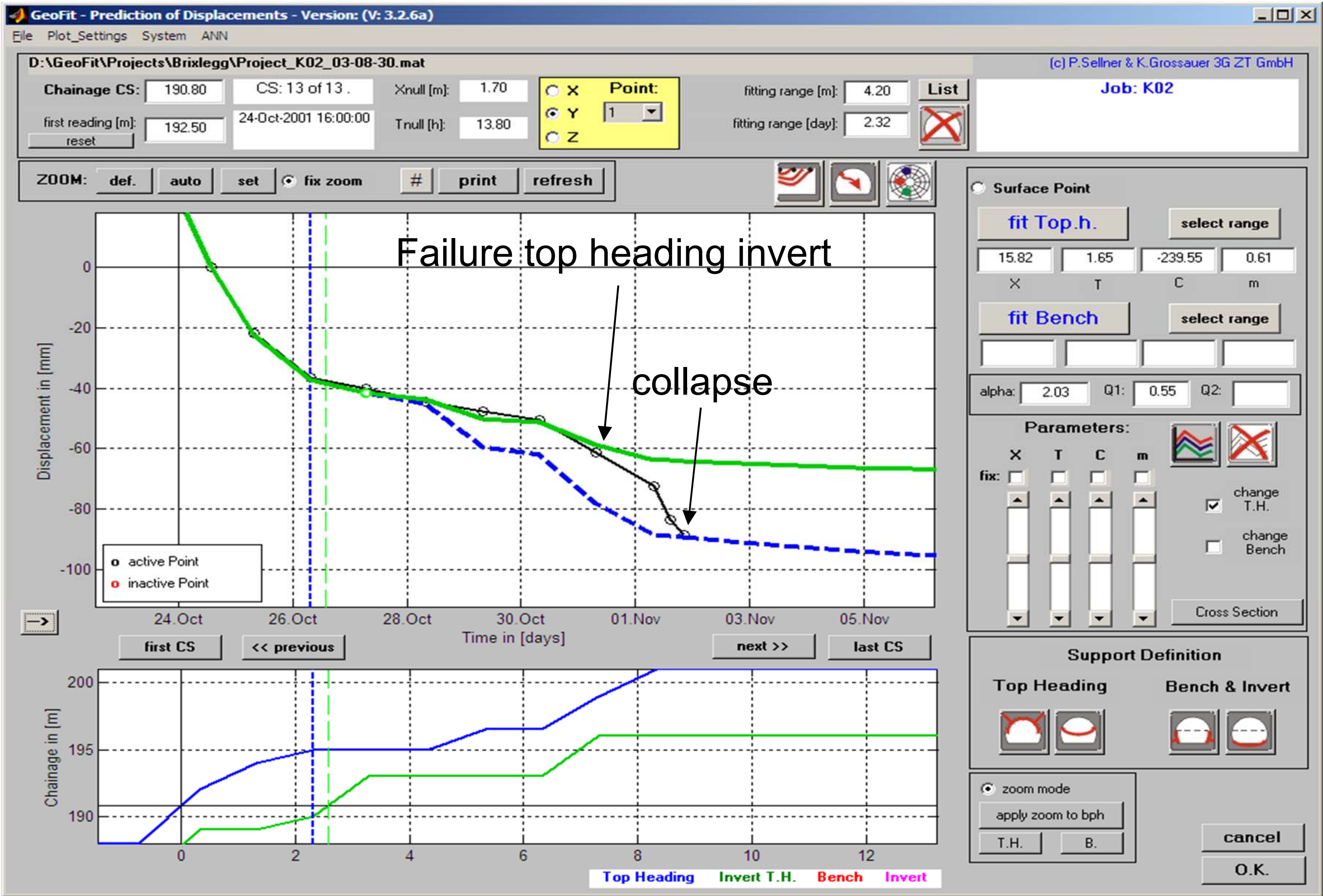
COMPARISON PREDICTION - MEASURED



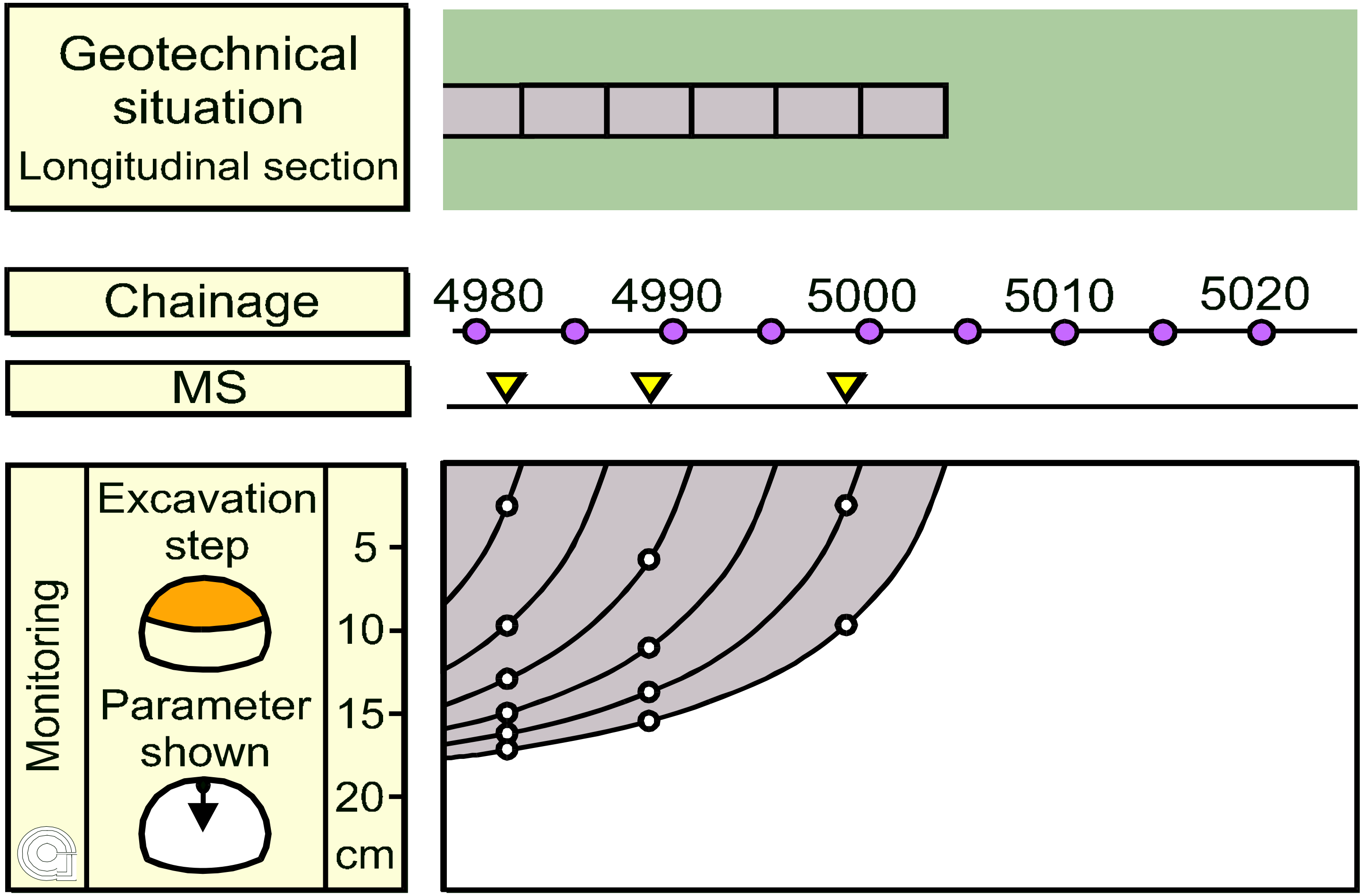
DEVIATION FROM „NORMAL“



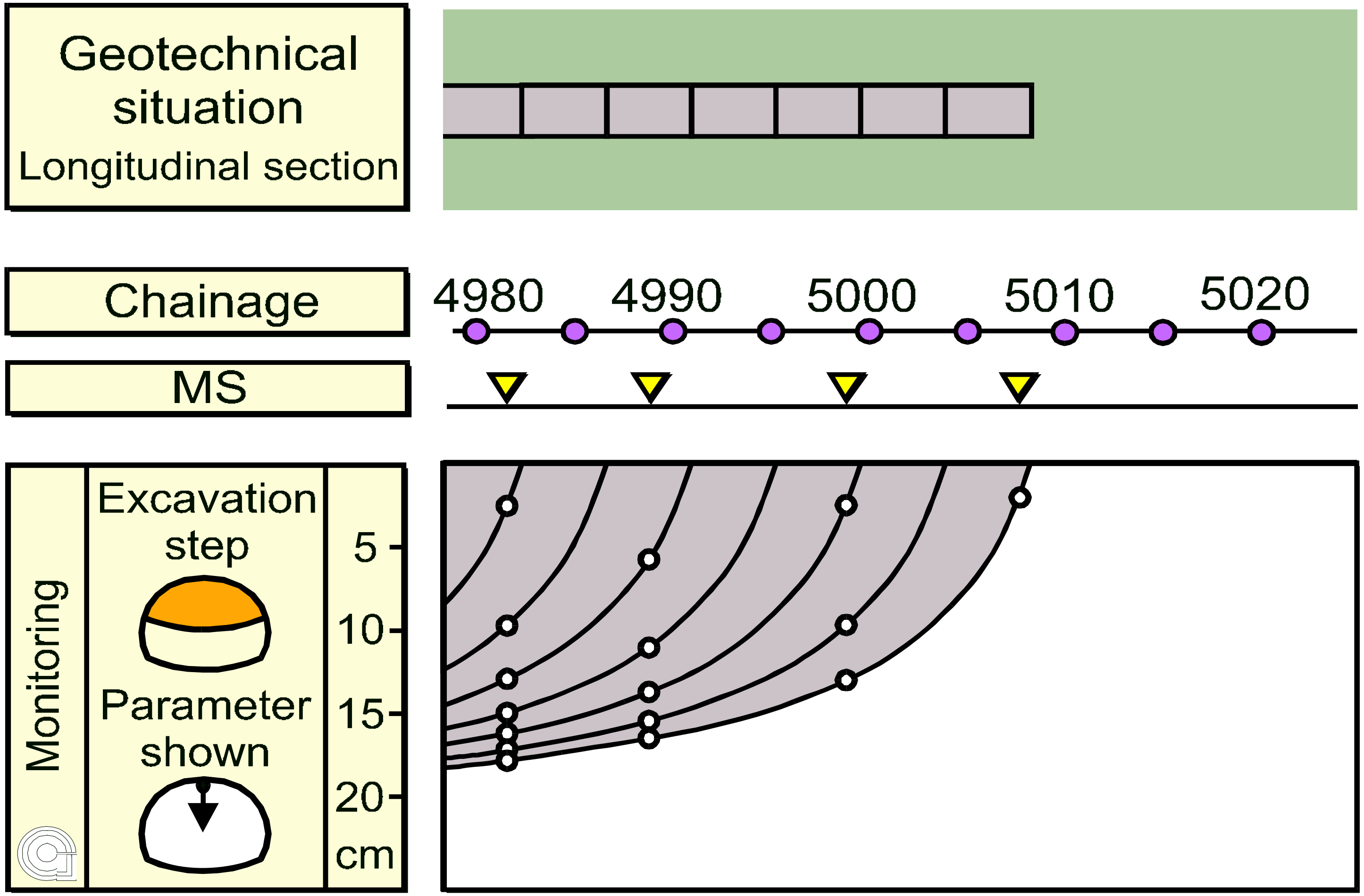
POTENTIAL EVALUATION METHODS

- Trends
  - Information compressed
  - Various trends can be shown (displacements, ratios, orientations, etc)
- Contour plots
  - Presently mainly used for surface settlements and lining utilization
- Lining utilization
  - By recalculating strains from measured displacements, and using an appropriate material model, stresses in the lining can be evaluated

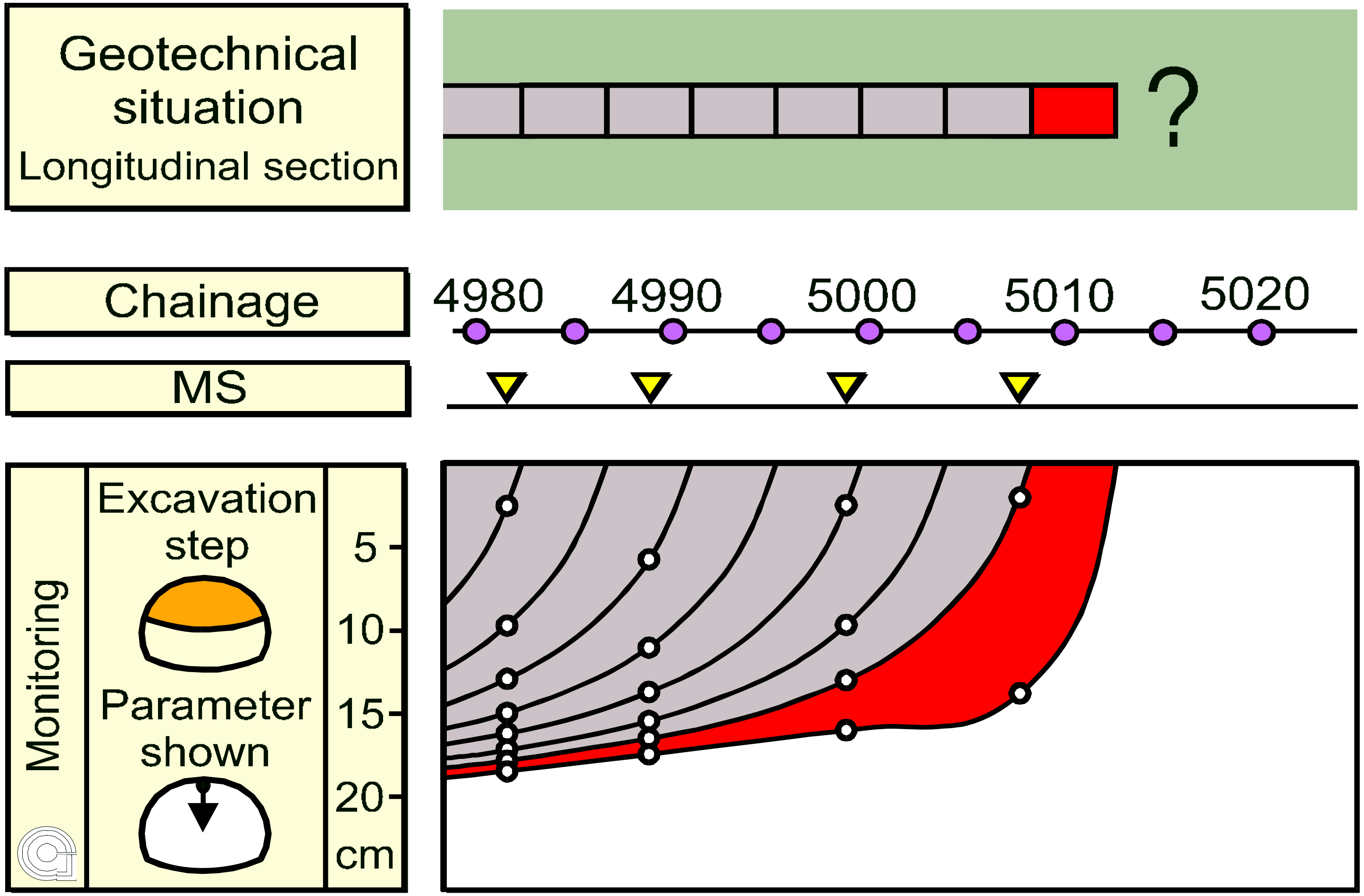
DEFLECTION LINES



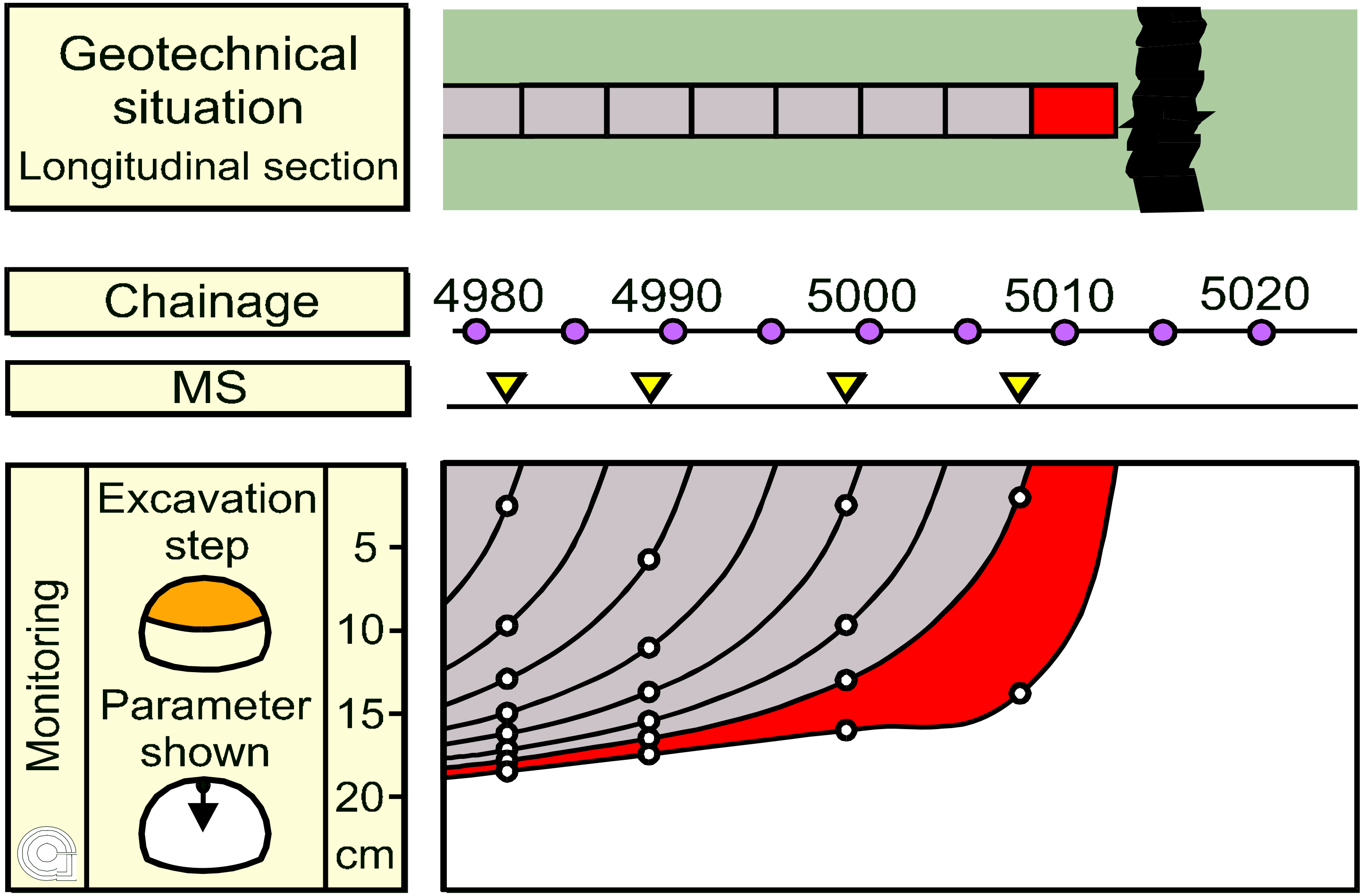
HOMOGENOUS GROUND



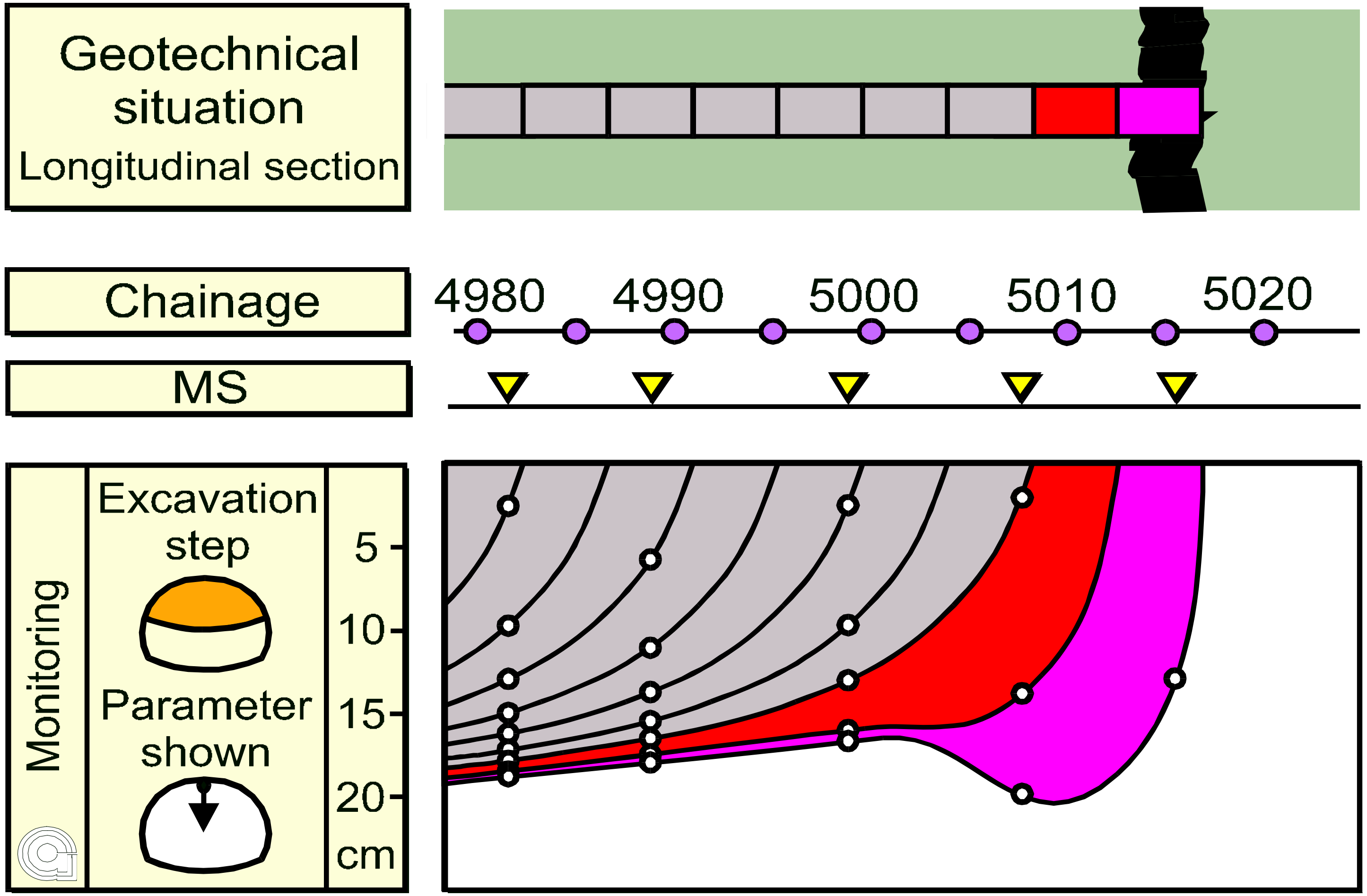
INCREASED DISPLACEMENTS NEAR FACE



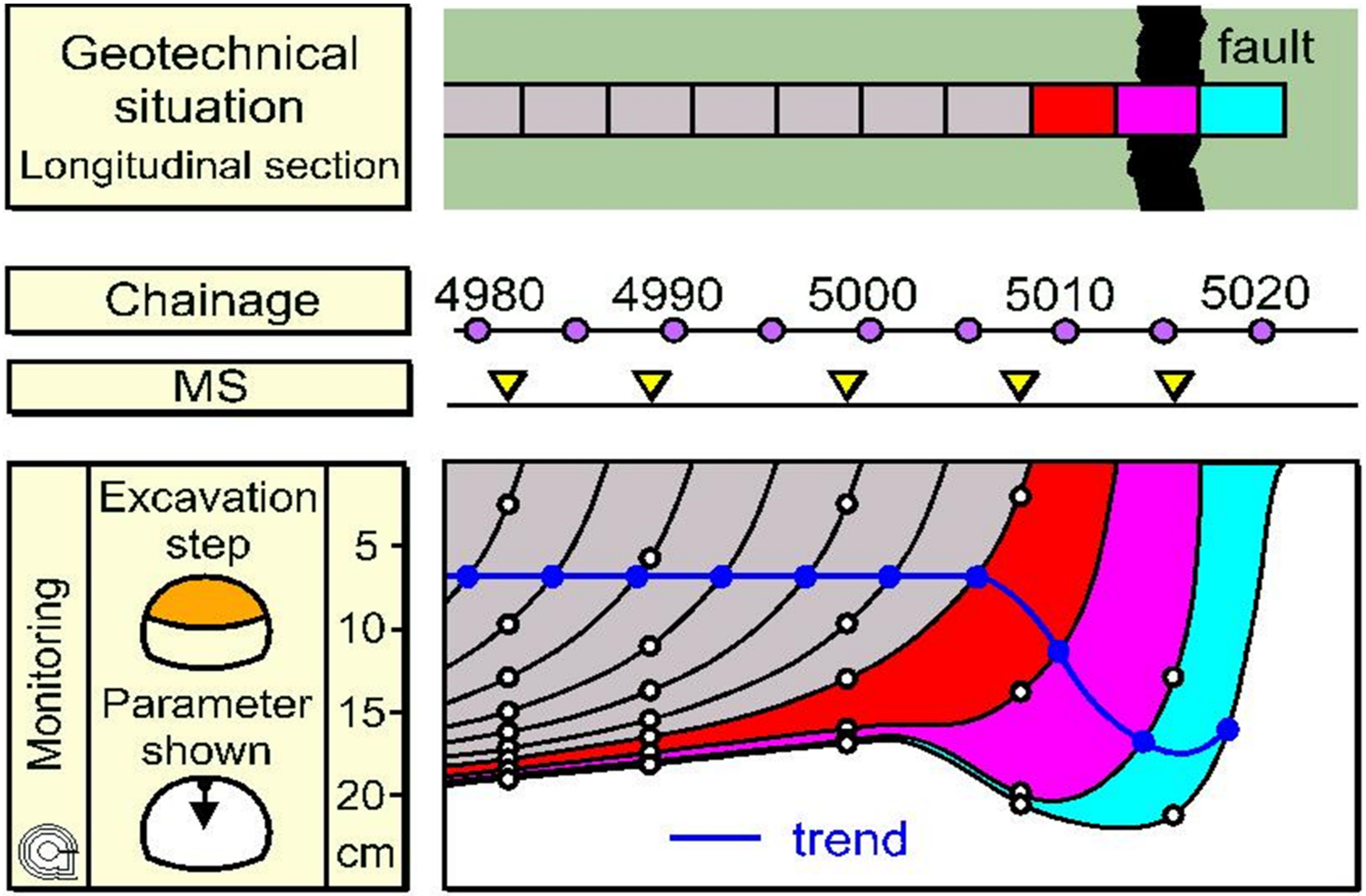
ASSUMPTION: FAULT AHEAD FACE



FURTHER DEVELOPMENT



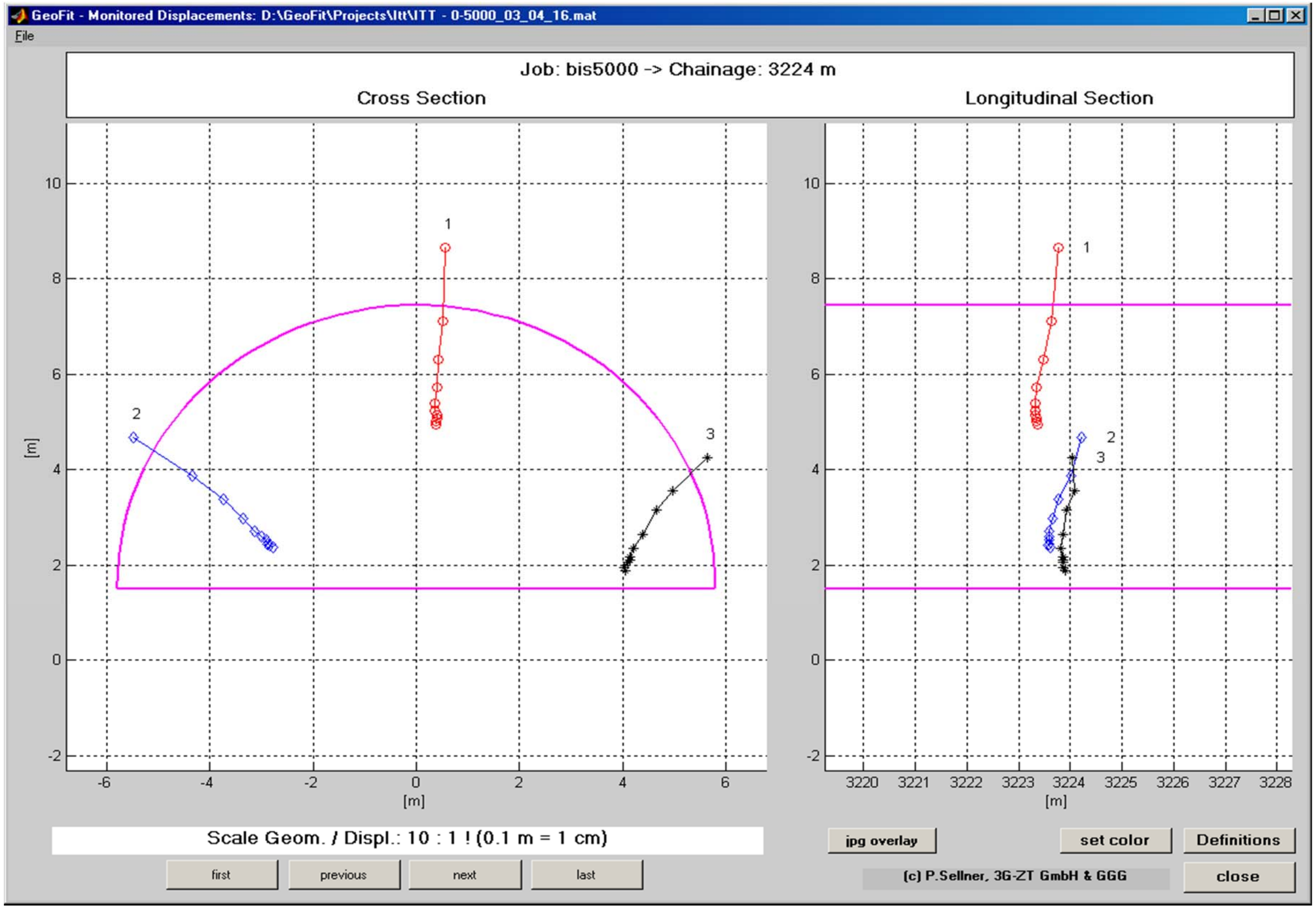
TREND LINE


Geotechnical situation
Longitudinal section
fault
Chainage
4980
4990
5000
5010
5020
MS
Monitoring
Excavation step
Parameter shown
5
10
15
20
cm
trend

DISPLACEMENT VECTORS - GENERAL

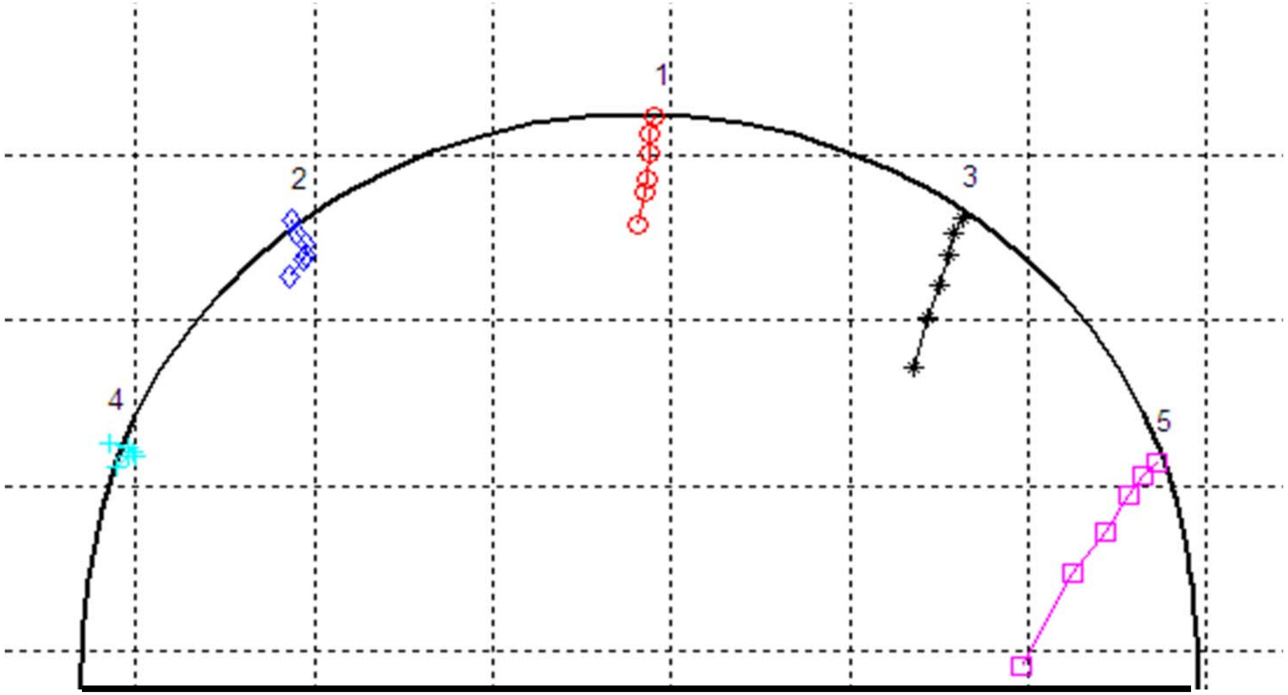
- Measurement of absolute displacements allows to observe the movement of each point in space
- This is very valuable for assessing the influence of ground structure and quality on the system behaviour
- Processes occuring outside the visible area show in the displacements, and can be realtively easily interpreted
- Method less suitable for direct observation of normal stabilization process
- Monitoring targets usually mounted on lining, thus result of mesasurements not always reflects ground behaviour (slip between lining and ground)

PLOT IN CROSS- AND LONGITUDINAL SECTION

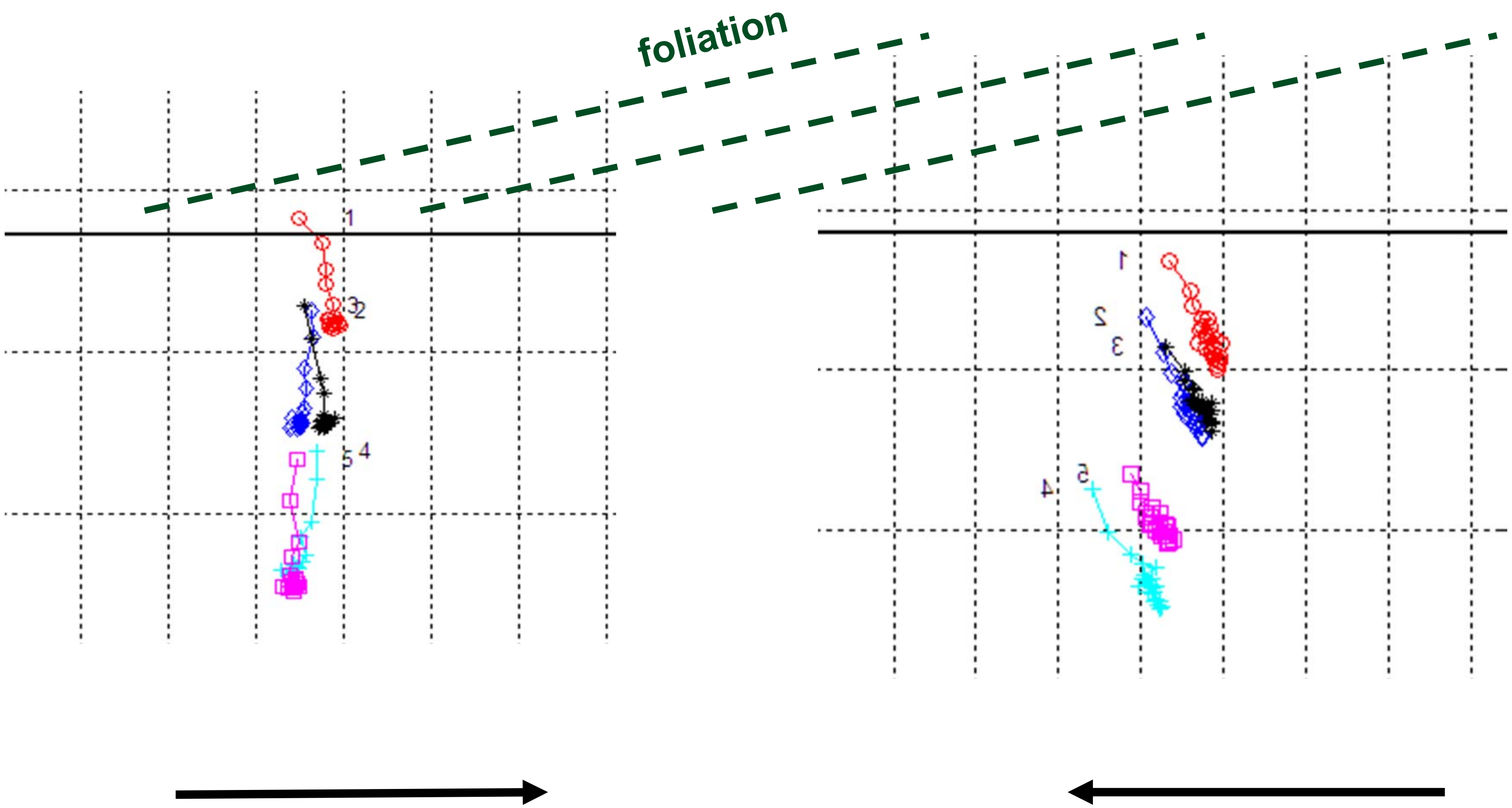


STRONGLY ANISOTROPIC BEHAVIOUR

- Features outside the excavation area (faults, slickensides,…) change the stress situation and/or kinematics, and thus the effects can be seen in the displacement characteristics



INFLUENCE OF FOLIATION ON „NORMAL“ ORIENTATION

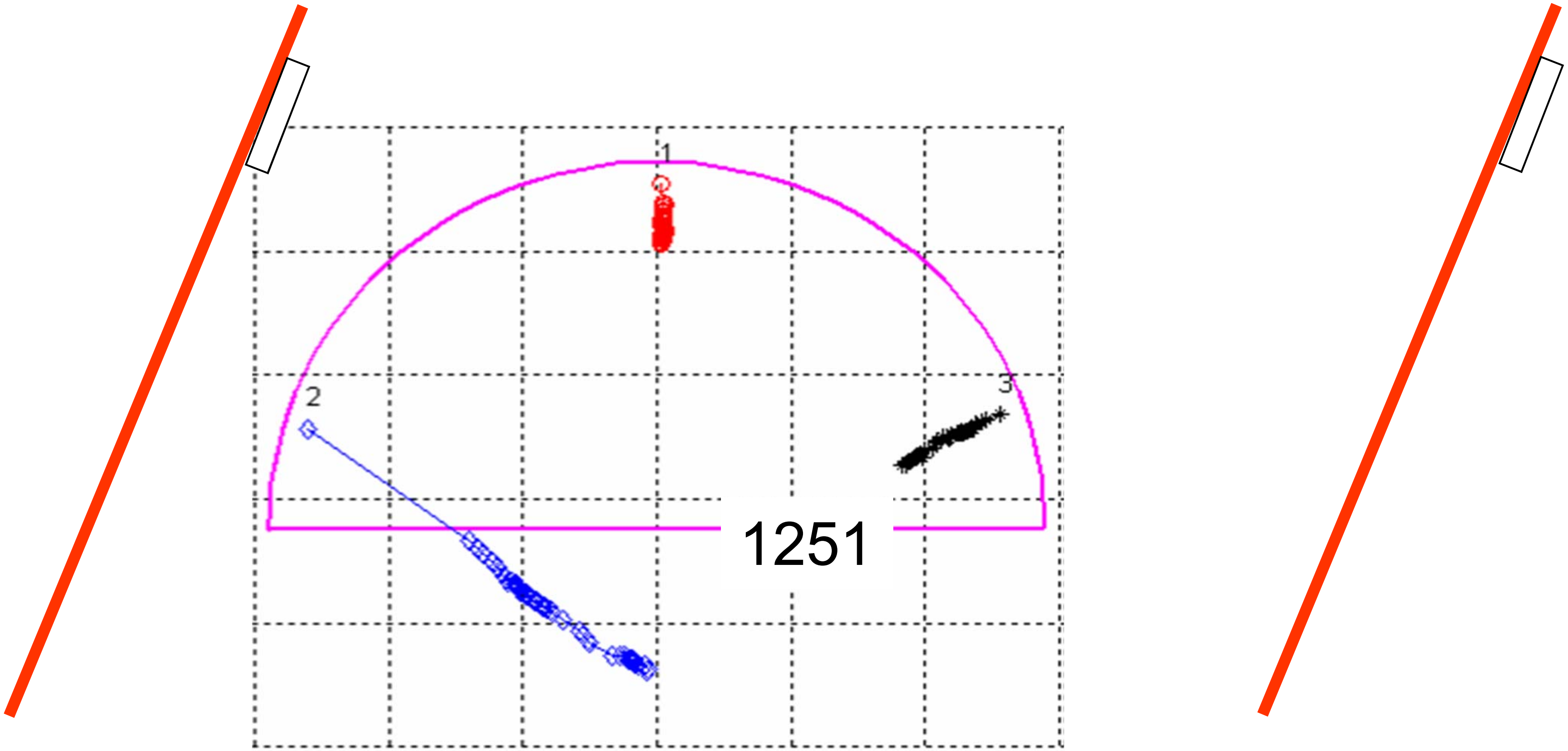


Excavation direction

Excavation direction

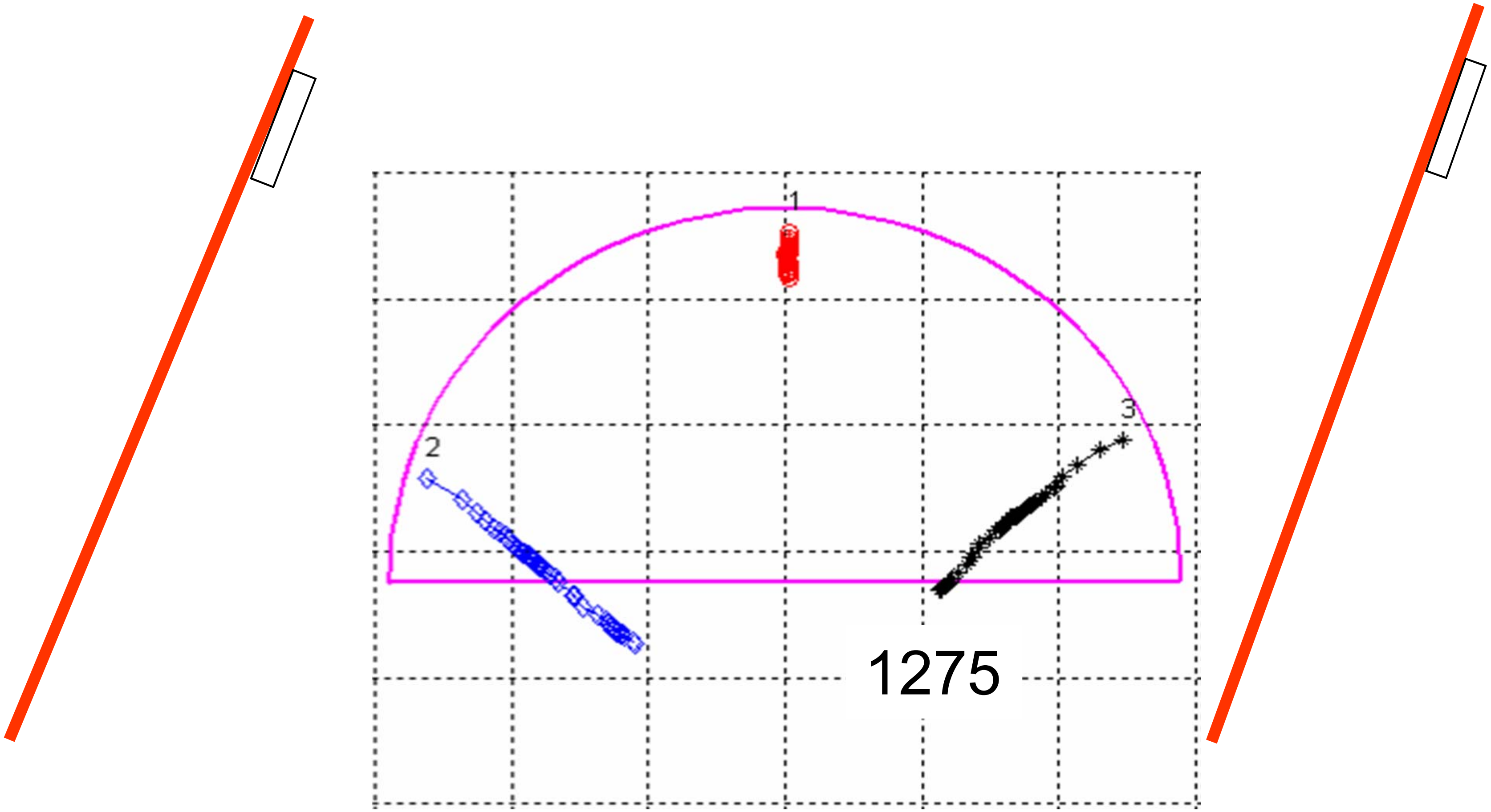
INFLUENCE OF SINGULARITIES

- faults right and left of tunnel, strong influence on left side



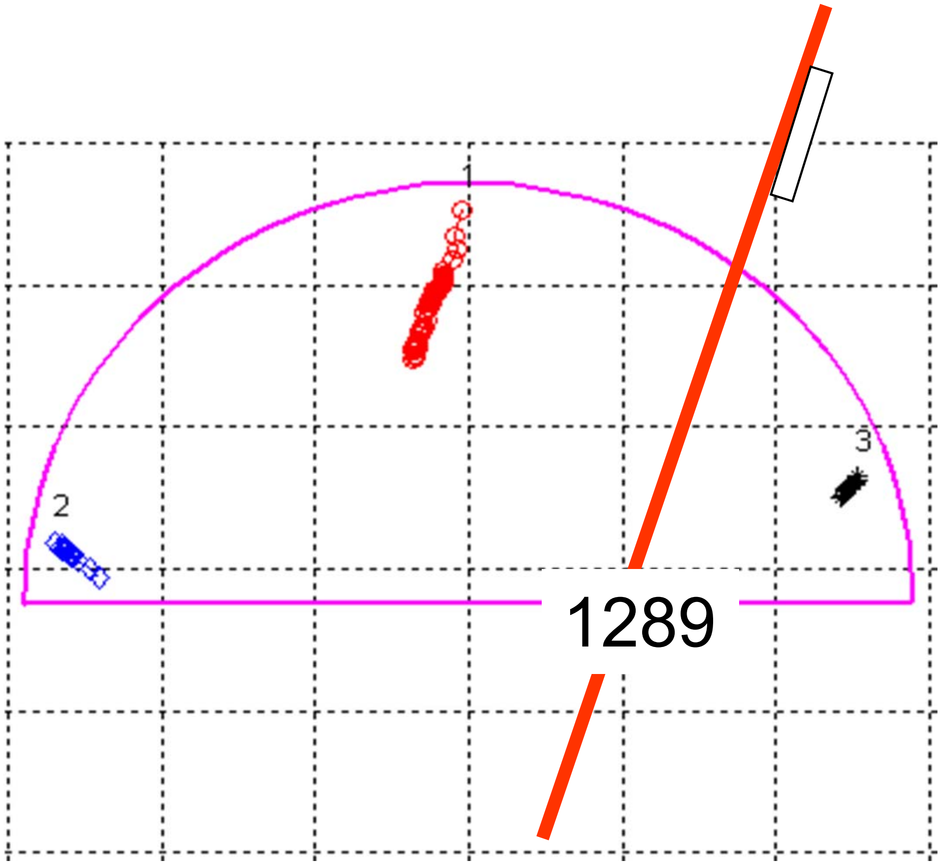
INFLUENCE OF SINGULARITIES

- reduced influence on left side, increased influence on right side



INFLUENCE OF SINGULARITIES

- fault in face, low influence



DISPALCEMENT VECTOR ORIENTATION

- When relatively soft rock mass is ahead of the face, change of displacement vector orientation against direction of excavation
- When relatively stiff rock mass is ahead, change of displacement vector orientation towards direction of excavation
- Stiffness contrast and length of zone up to a critical thickness influences the magnitude of the deviation of the displacement vector orientation

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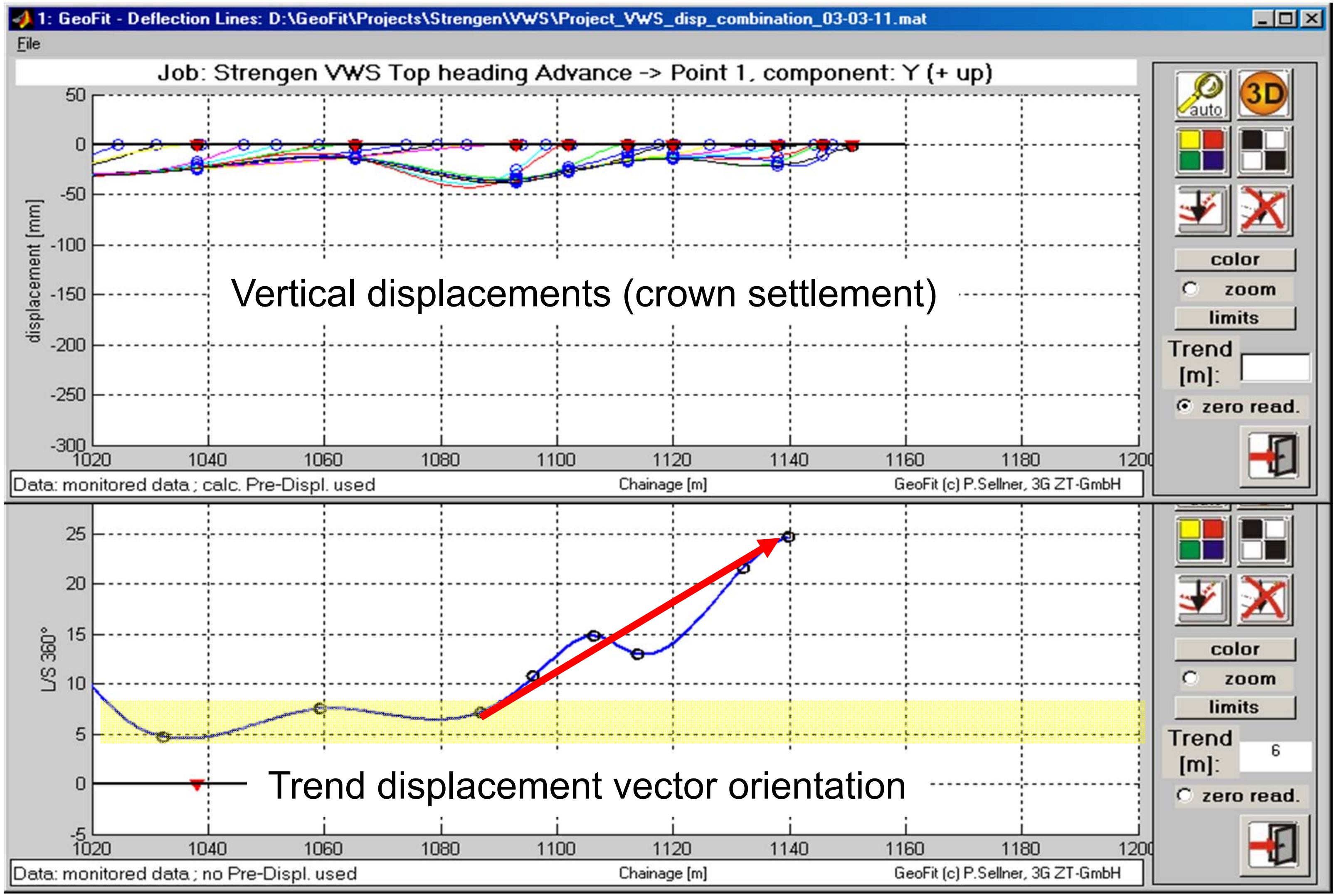
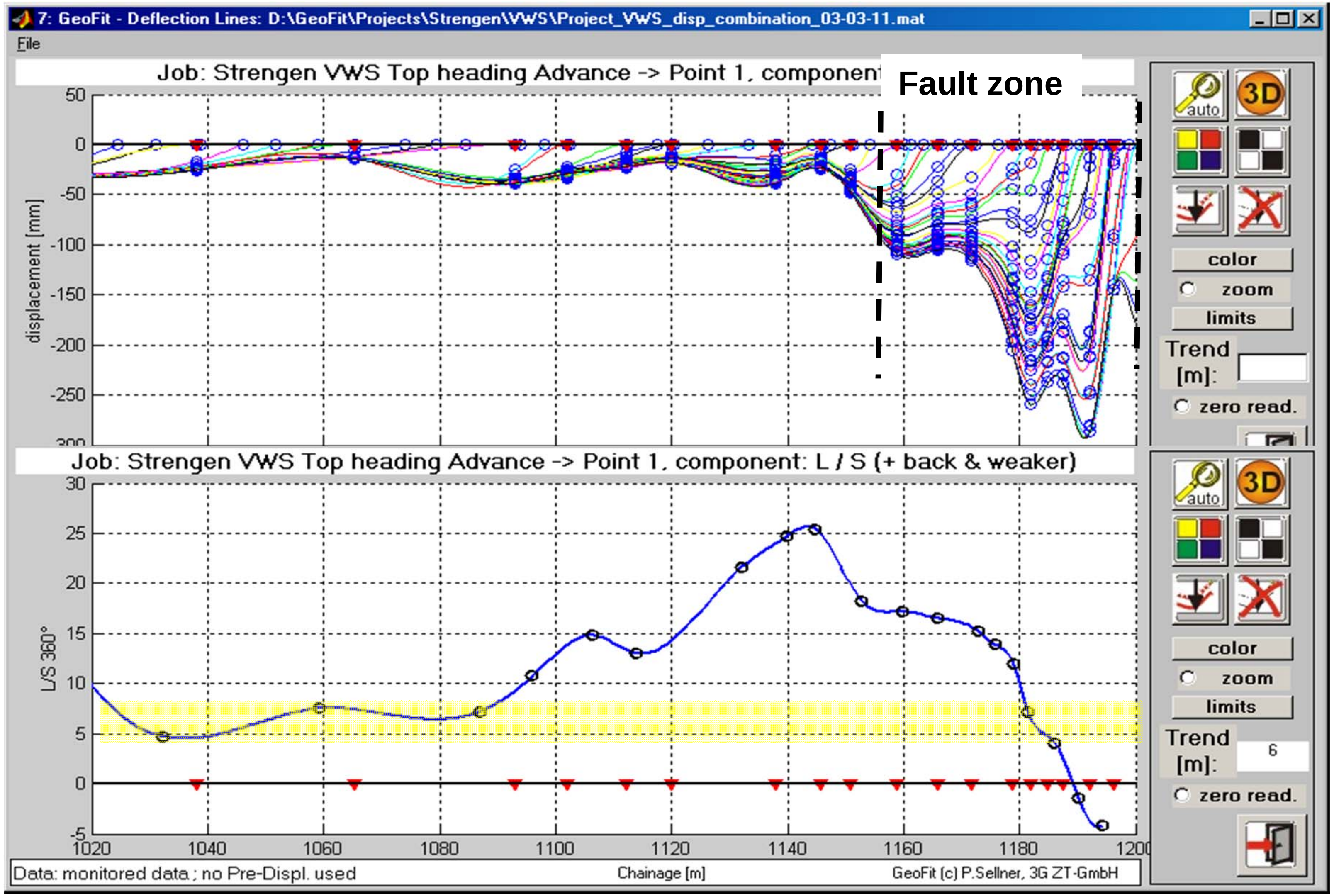
CASE HISTORY



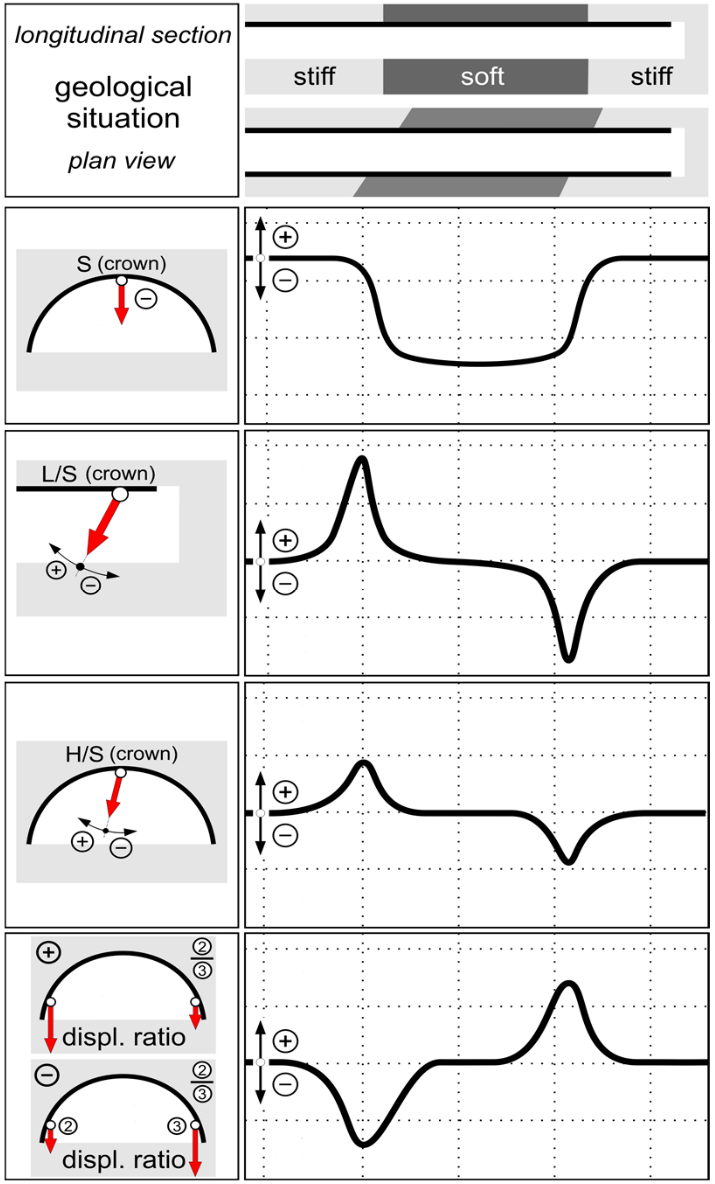
CASE HISTORY



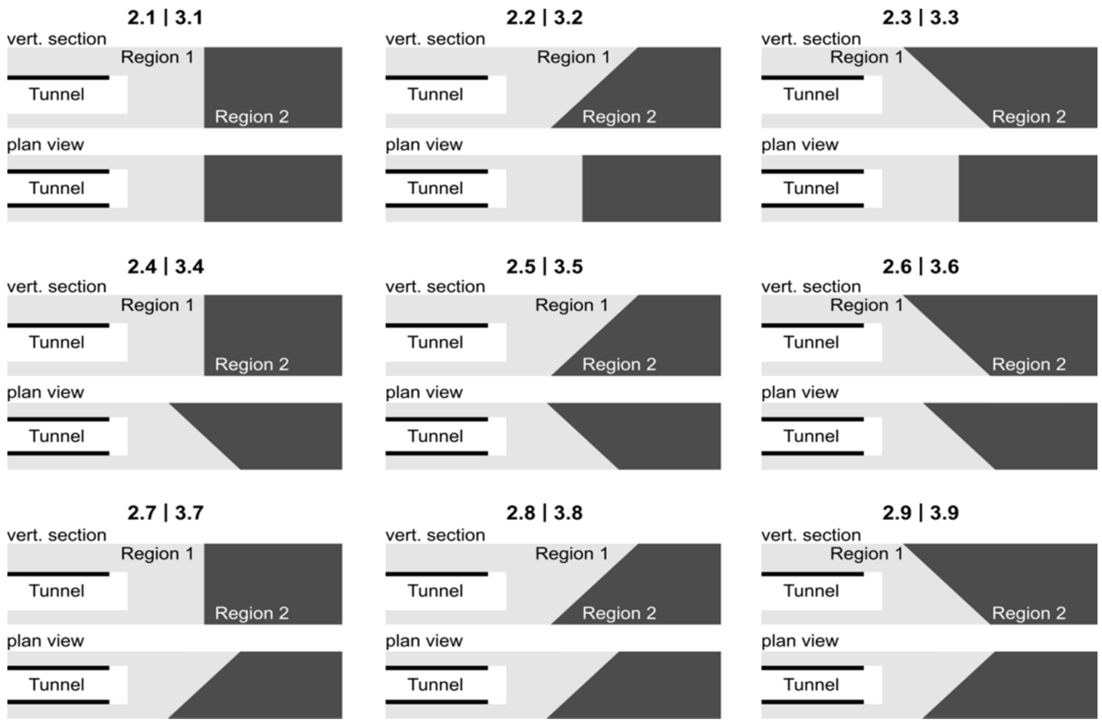
DEVELOPMENT OF EXPERT SYSTEM FOR DATA INTERPRETATION

- Combining several trends allows for identifying also the spatial orientation of single features or zones with fifferent properties ahead of the face
- Existing knowledge is used to establish typical displacement trends for various geotechnical conditions
- Establishment of a correlation matrix allows automated predition of situation ahead

ESTABLISH TYPICAL TREND COMBINATIONS



TREND CORRELATION MATRIX

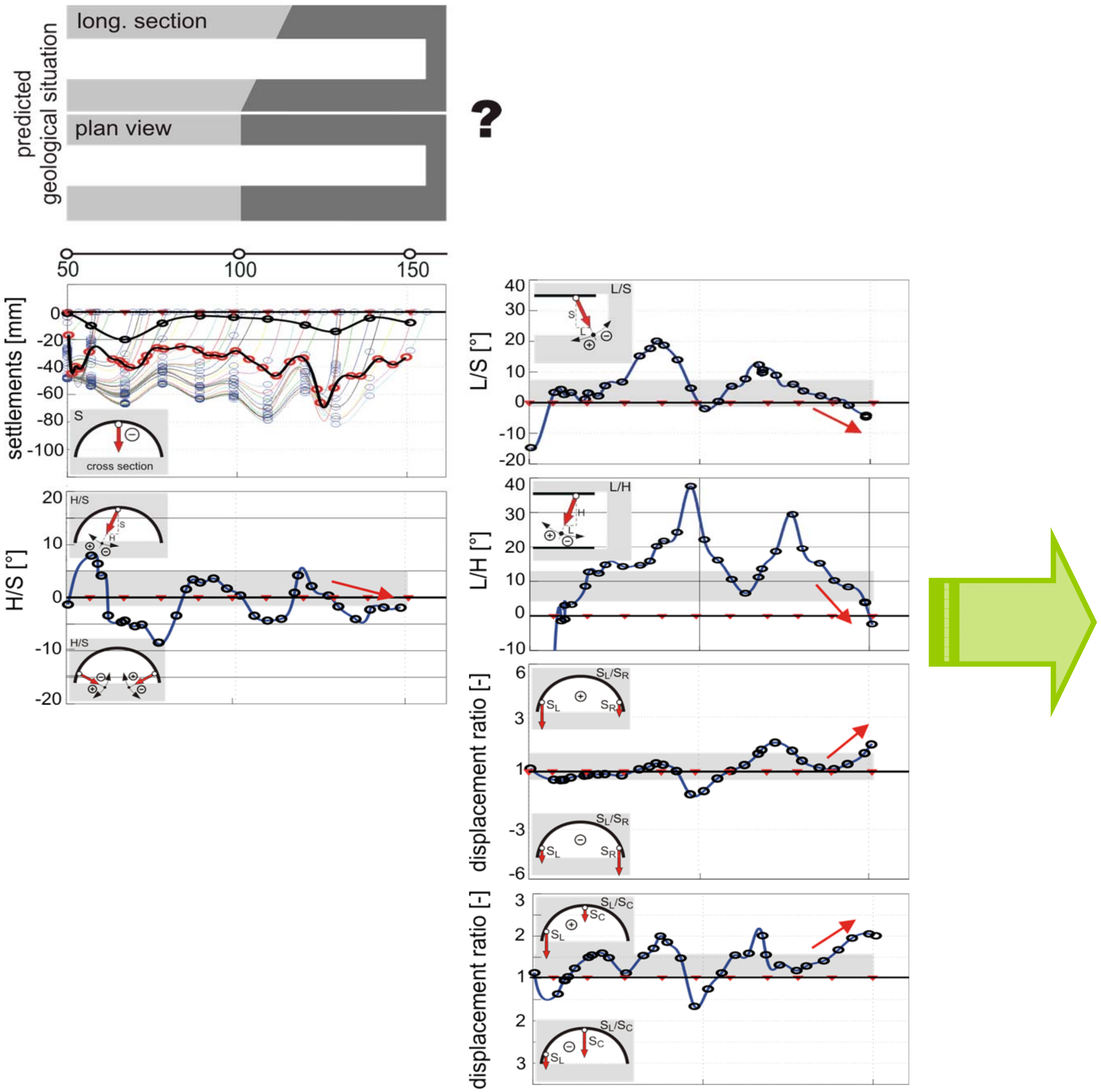


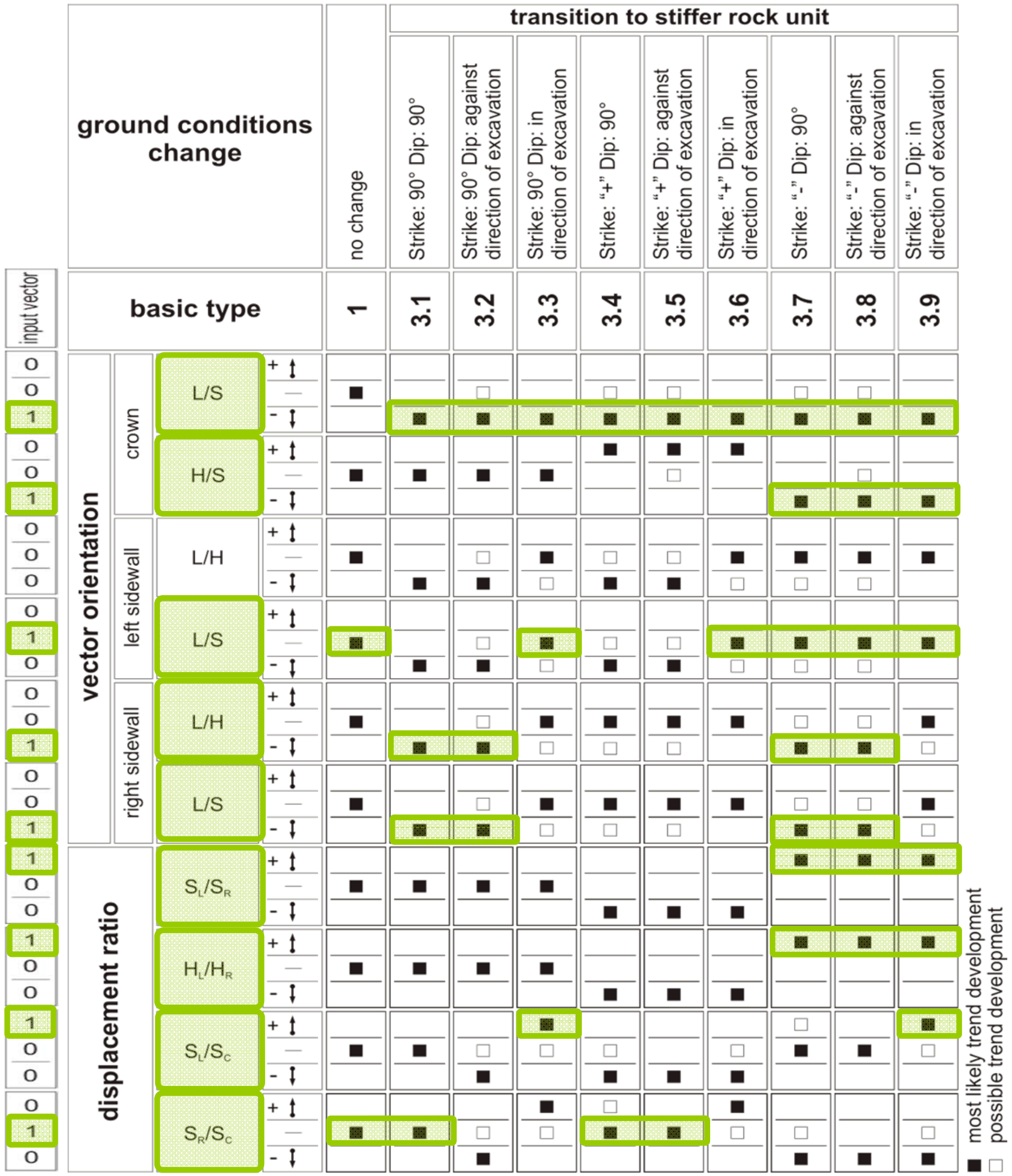
ground conditions change				no change	transition to softer rock unit								
					Strike: 90° Dip: 90°	Strike: 90° Dip: against direction of excavation	Strike: 90° Dip: in direction of excavation	Strike: "+" Dip: 90°	Strike: "+" Dip: against direction of excavation	Strike: "+" Dip: in direction of excavation	Strike: "-" Dip: 90°	Strike: "-" Dip: against direction of excavation	Strike: "-" Dip: in direction of excavation
basic type				1	2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9
vector orientation	crown	L/S	+		■	■	■	■	■	■	■	■	■
			—	■		□		□	□		□	□	
			-										
		H/S	+								■	■	■
			—	■	■	■	■		□			□	
			-					■	■	■			
	left sidewall	L/H	+		■	■	□	■	■	□	□	□	
			—	■		□	■	□	□	■	■	■	■
			-										
		L/S	+		■	■	□	■	■	□	□	□	
			—	■		□	■	□	□	■	■	■	■
			-										
	right sidewall	L/H	+		■	■	□	□	□		■	■	□
			—	■		□	■	■	■	■	□	□	■
			-										
		L/S	+		■	■	□	□	□		■	■	□
			—	■		□	■	■	■	■	□	□	■
			-										
displacement ratio		S_L/S_R	+					■	■	■			
			—	■	■	■	■						
			-								■	■	■
		H_L/H_R	+					■	■	■			
			—	■	■	■	■						
			-								■	■	■
		S_L/S_C	+			■		■	■	■			
			—	■	■	□	□	□		□	■	■	□
			-				■				□		■
		S_R/S_C	+			■					■	■	■
			—	■	■	□	□	■	■	□	□		□
			-				■	□		■			

■ most likely trend development
□ possible trend development

Lenz, G. 2007. Displacement monitoring data in tunnelling.
Development of a semiautomatic evaluation system. Diploma thesis TUG

COMPARISON OF ACTUAL TRENDS TO REFERENCE TRENDS





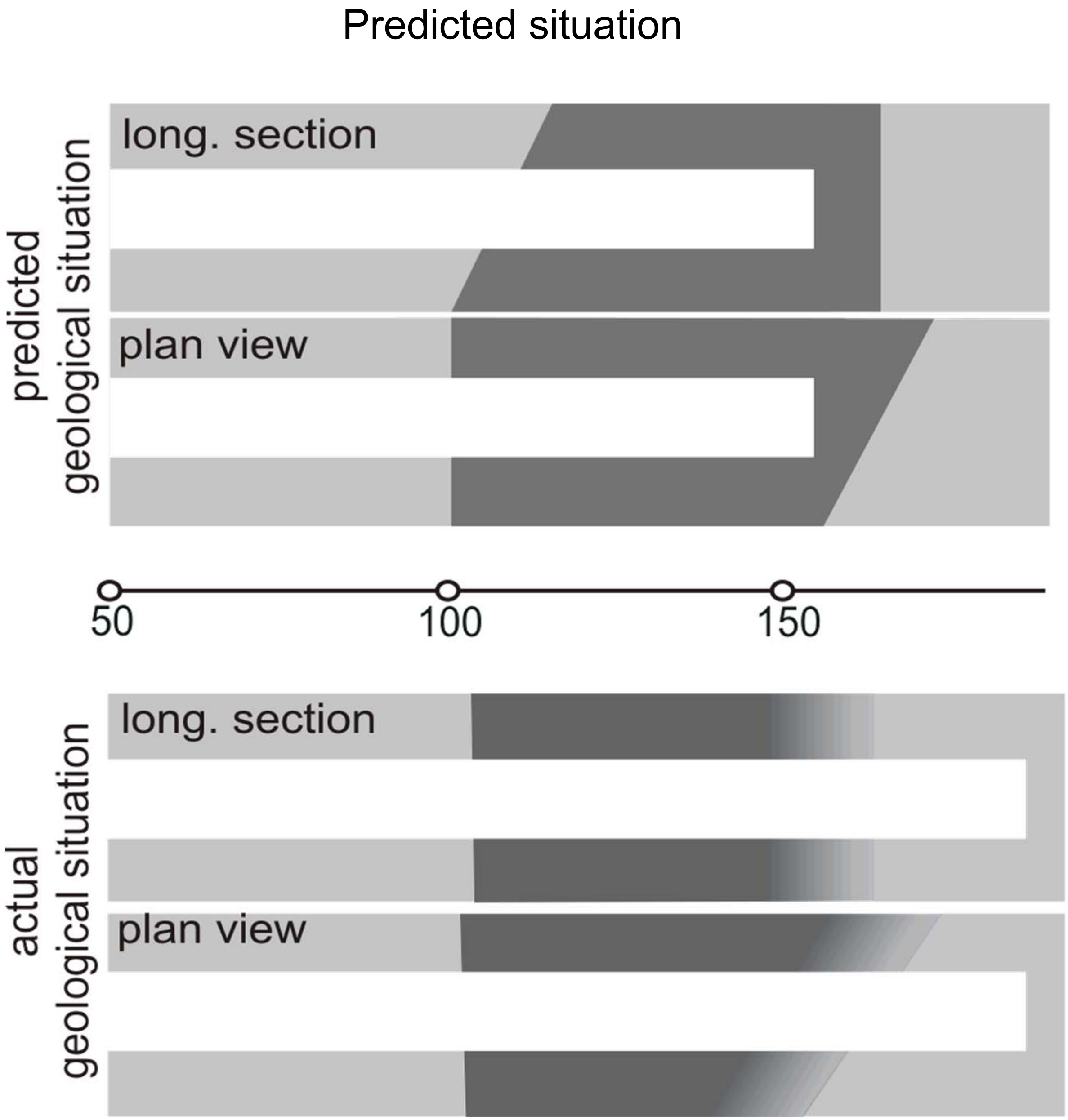
EVALUATION

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

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

PREDICTION

- Reference case 3.7 is most likely to apply. This means stiffer rock mass ahead, with vertical dip and a strike from the right to the left



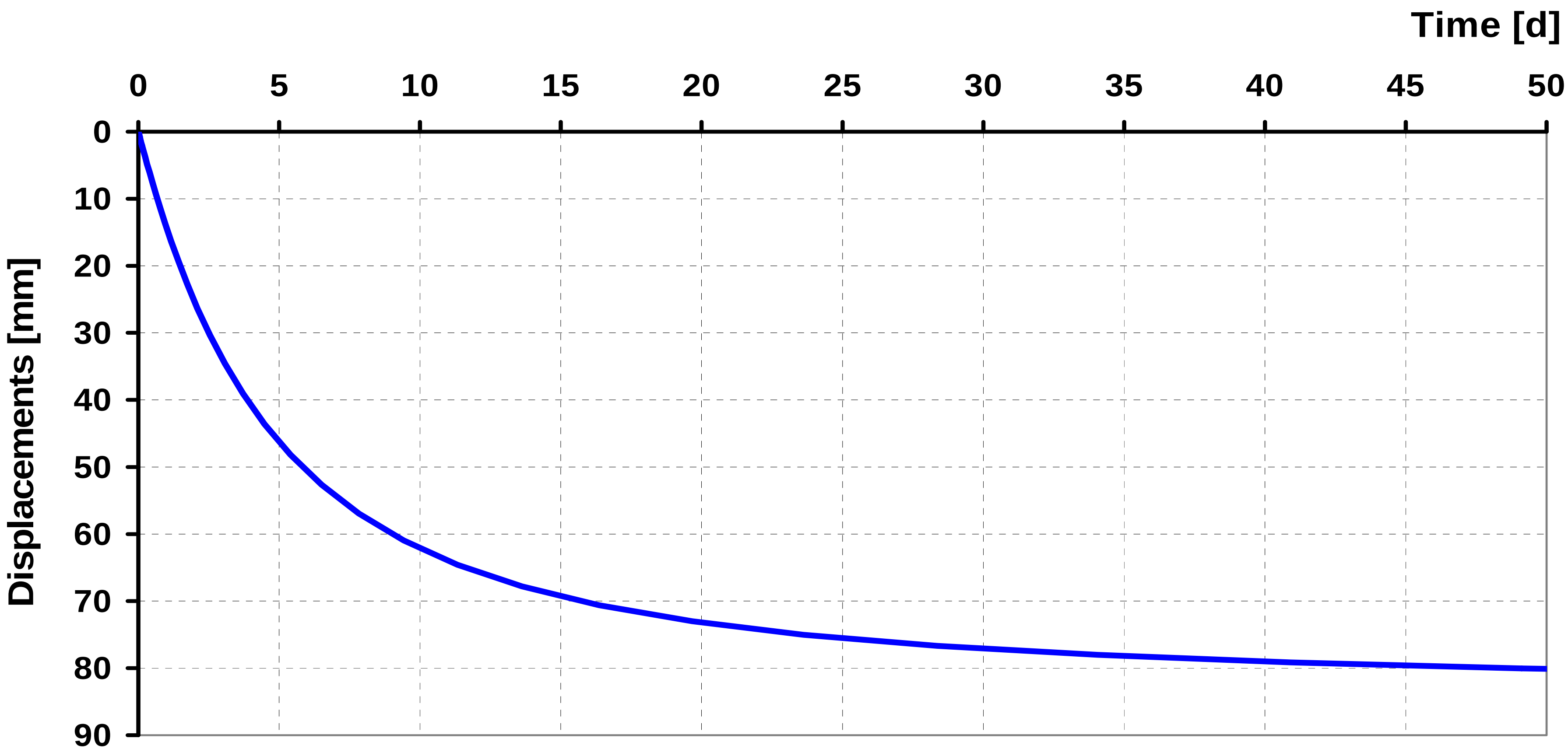
Grossauer, K. 2009. Expert System Development for the Evaluation and Interpretation of Displacement Monitoring Data in Tunnelling. Doctoral thesis TUG

EVALUATION OF LINING UTILIZATION

- Strains in the lining are evaluated from measurement results; as displacements are measured in several points, spline has to be used to assess strains between measurement points
- For minimizing the error, distance between single monitoring points should be small
- Appropriate material model for complex shotcrete properties should be chosen for evaluating stresses in the lining
- Actual strength then is compared to the calculated stress

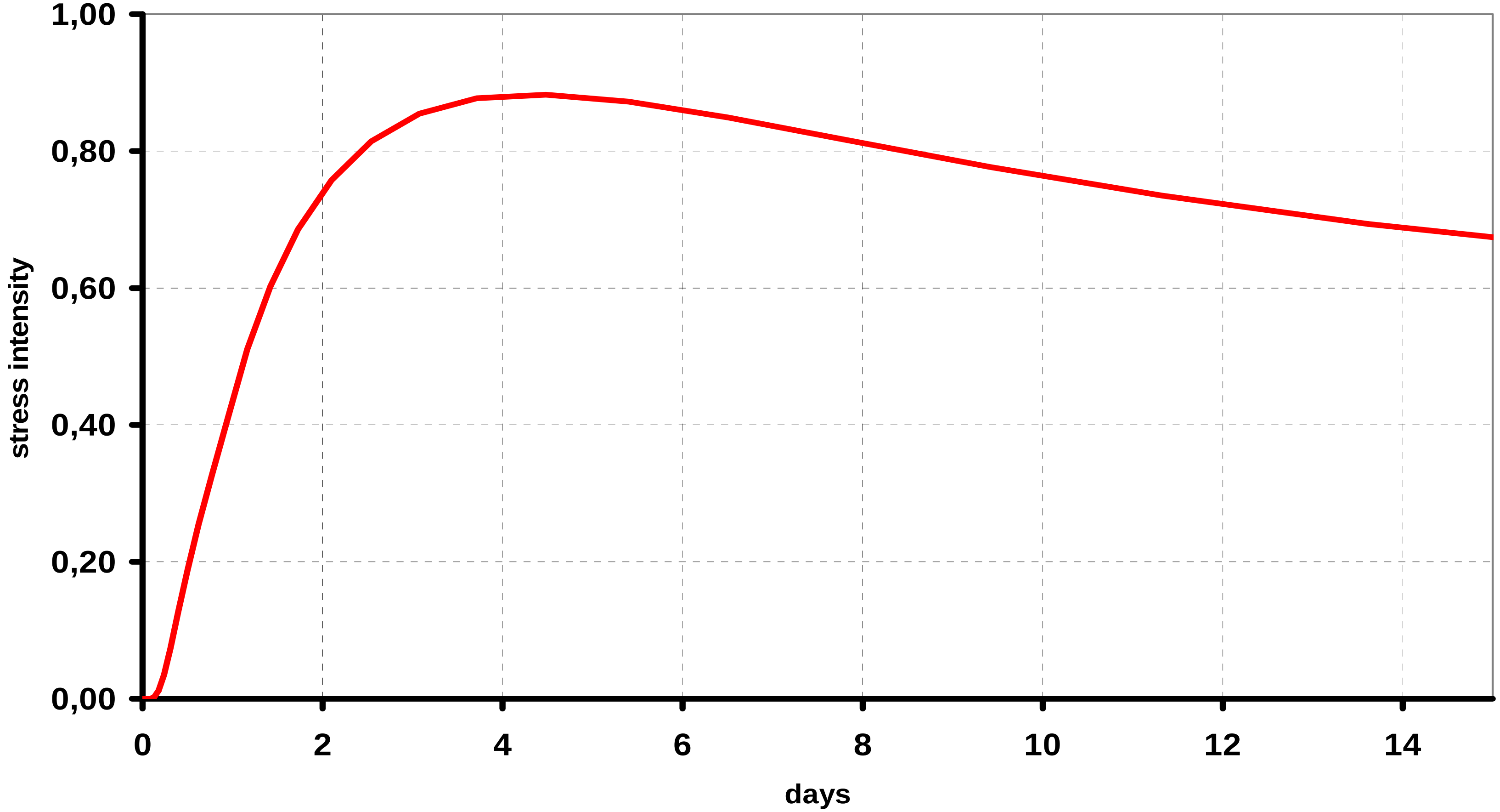
EXAMPLE: circular tunnel, dia 10m; 30cm shotcrete, advance rate 2m/d

- Development of displacements (radial symmetric)

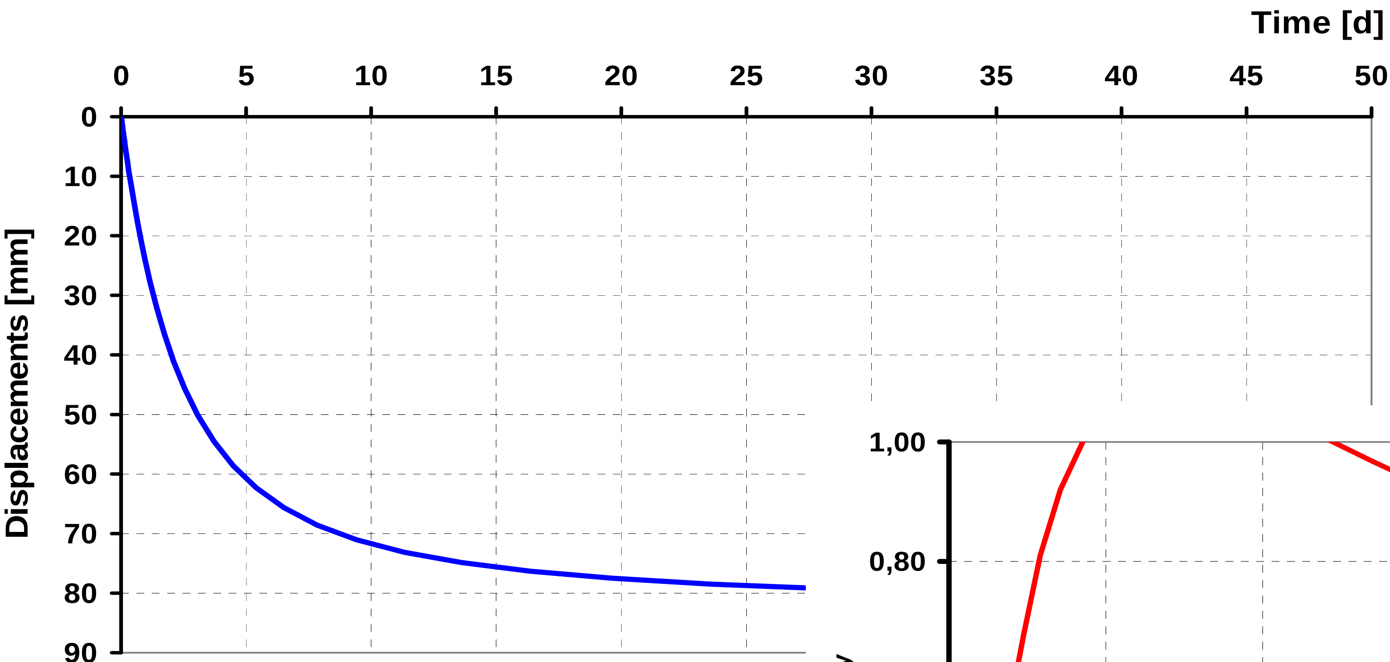


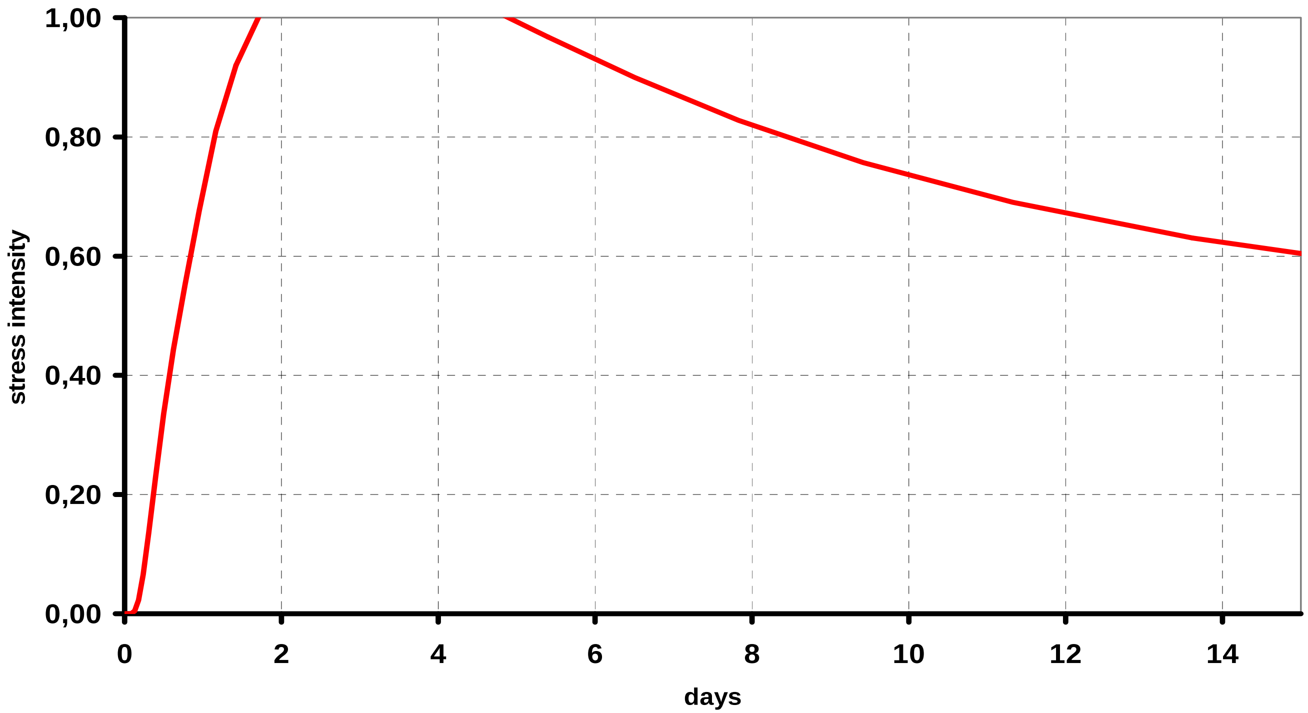
EXAMPLE: circular tunnel, dia 10m; advance 2 m/d

- Lining utilization

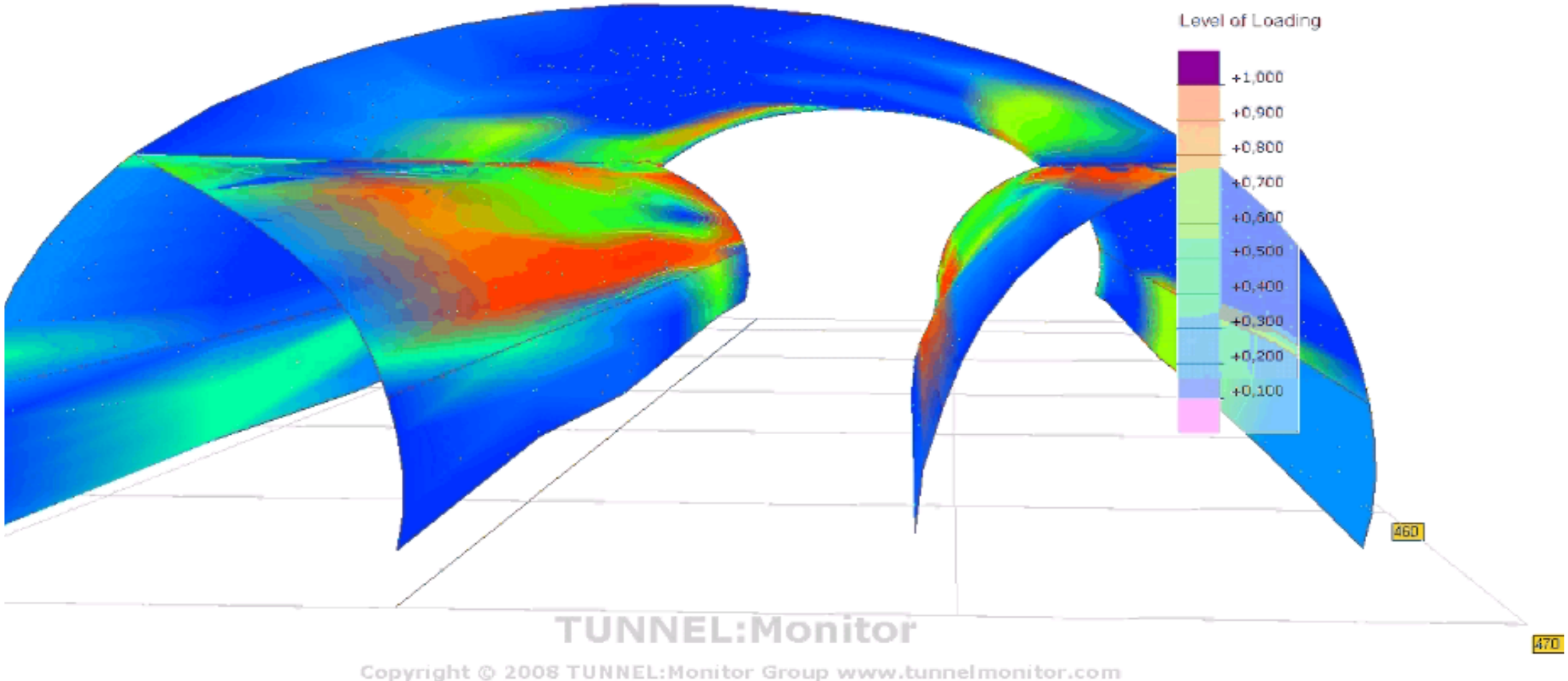


EXAMPLE: same conditions, but advance rate 4 m / d





EVALUATION OF LINING UTILIZATION BASED ON MONITORED DATA (TUNNEL:MONITOR)



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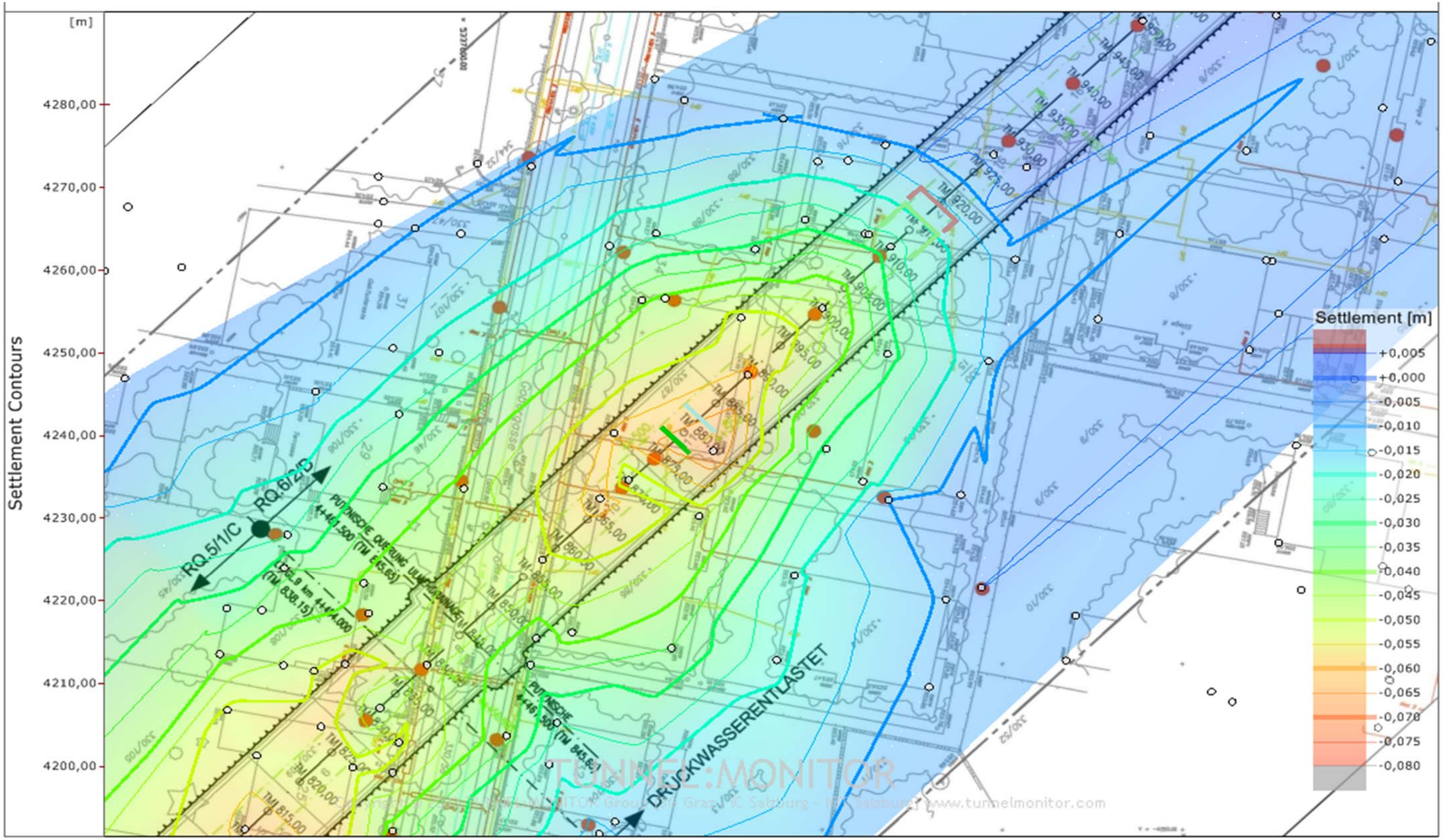
CONTOUR PLOT OF SURFACE DISPLACEMENT



SUMMARY

- For observational methods monitoring is an integral part of the final design
- Monitoring is the key element for observing the system behaviour and predicting the ground conditions
- Monitoring is the basis to verify the design assumptions, detect behaviour deviating from the normal, and implement remedial measures in time
- Modern methods of measurement and data evluation allow controlled tunnel construction
- Necessarily data have to be of good quality, and the persons using the data need to know what they mean
- Appropriately using the available tools significantly reduces the residual risks and allows saving time and money