RISK ORIENTED TUNNEL DESIGN PROCESS

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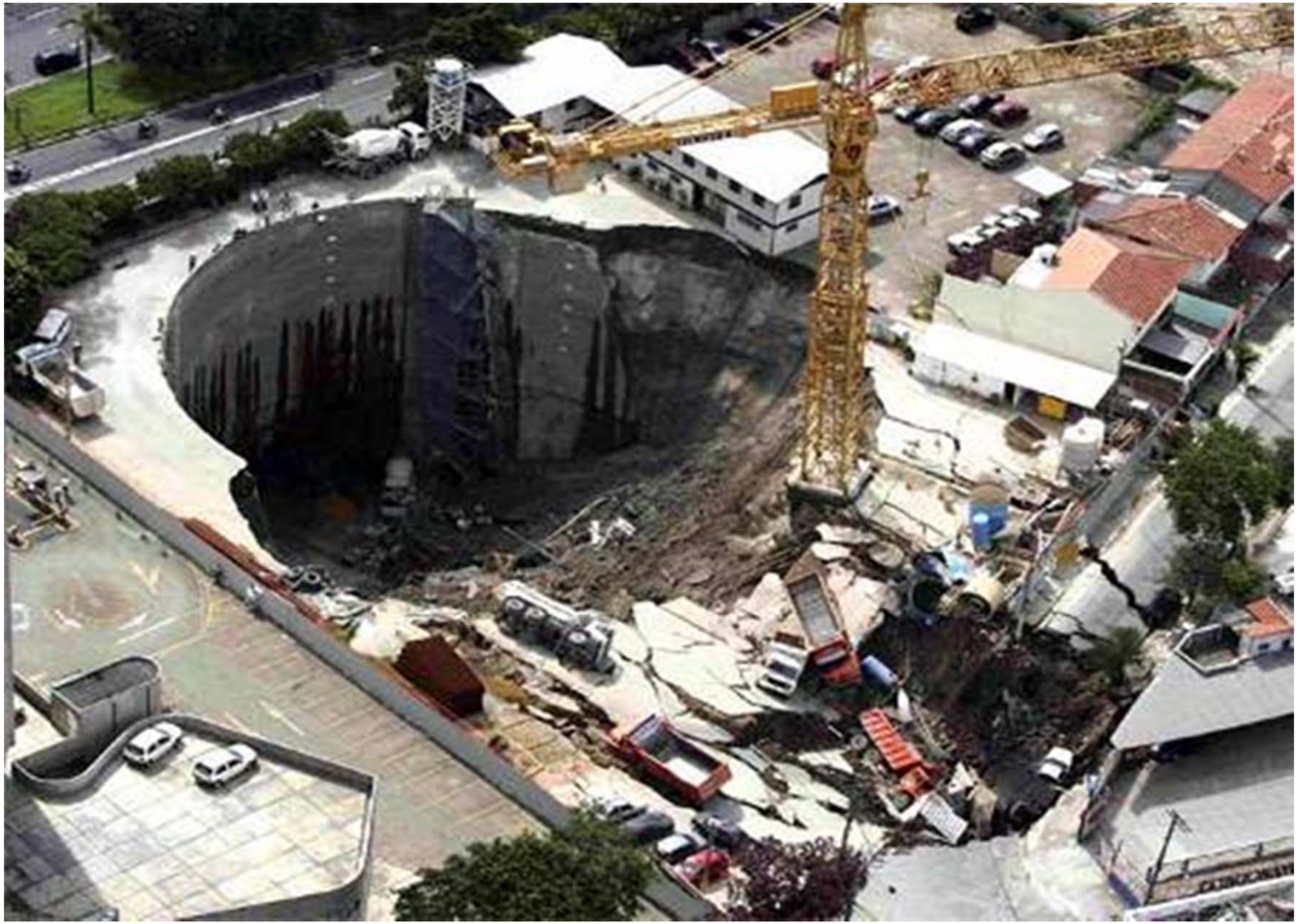
INTRODUCTION

- Accidents during tunnel construction not only have led to cost increase, time overruns, injuries and fatalities, but also contributed to a bad reputation of the industry
- Insurers talk of bad risk
- Regulations become more and more strict
- Lawyers and courts are increasingly involved

EVENTS LIKE THIS



… OR THIS

… OR THIS

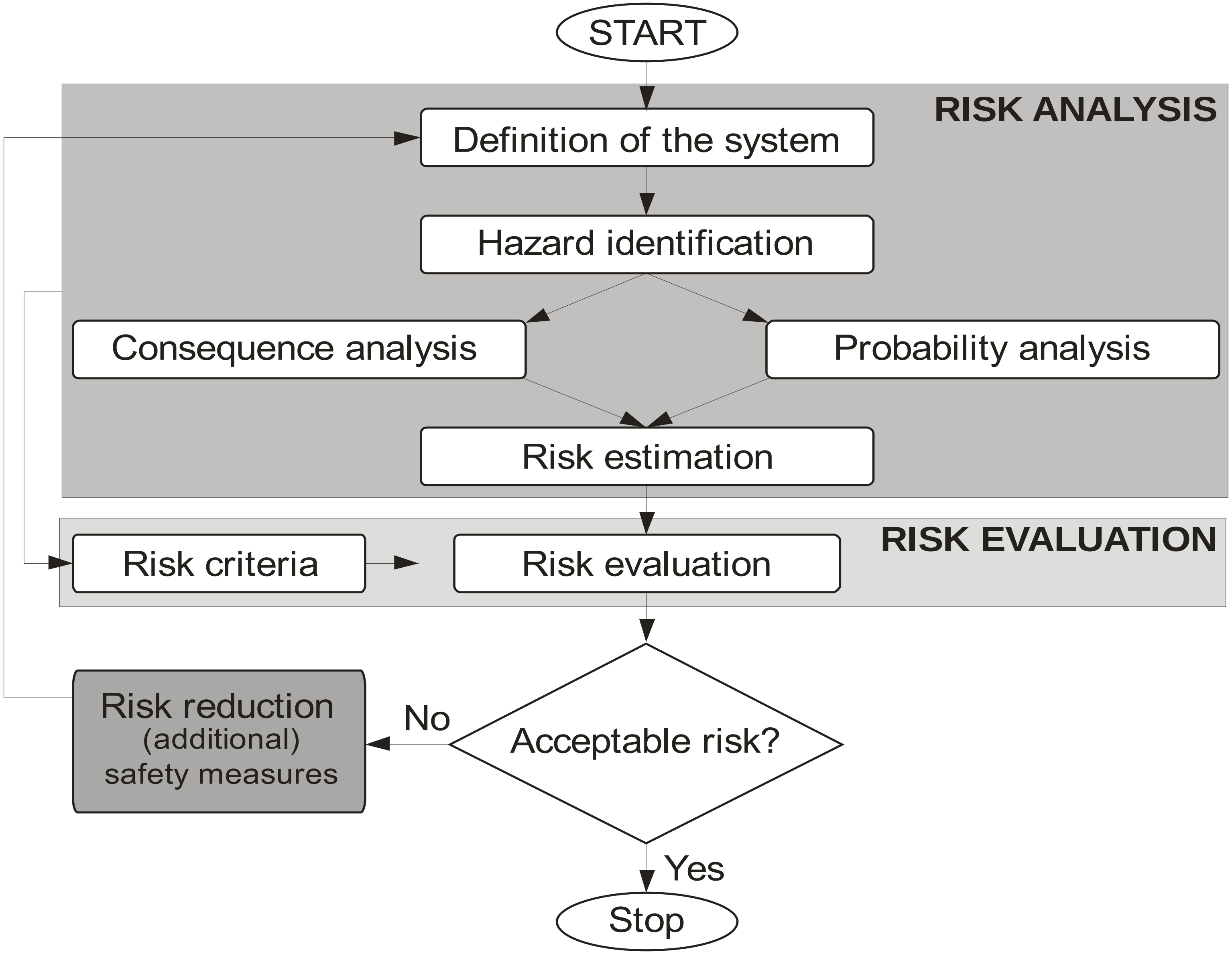
RAISE THE QUESTIONS ...

- Have we acted responsibly during design and construction?
- Have we considered the geological conditons appropriately?
- Are we really aware of the hazards involved?
- Have we used state of the art methods?

RISK ASSESSMENT AND MANAGMENT

- Risk assessment - if conducted at all - is often understood as a separate task
- Underground projects are associated with uncertainties in all stages; even with perfect investigation and design, residual risks remain
- Thus risk assessment and management should be integrated into the whole process, from investigation through design and construction until the completion of the project

GENERAL PROCEDURE OF RISK EVALUATION



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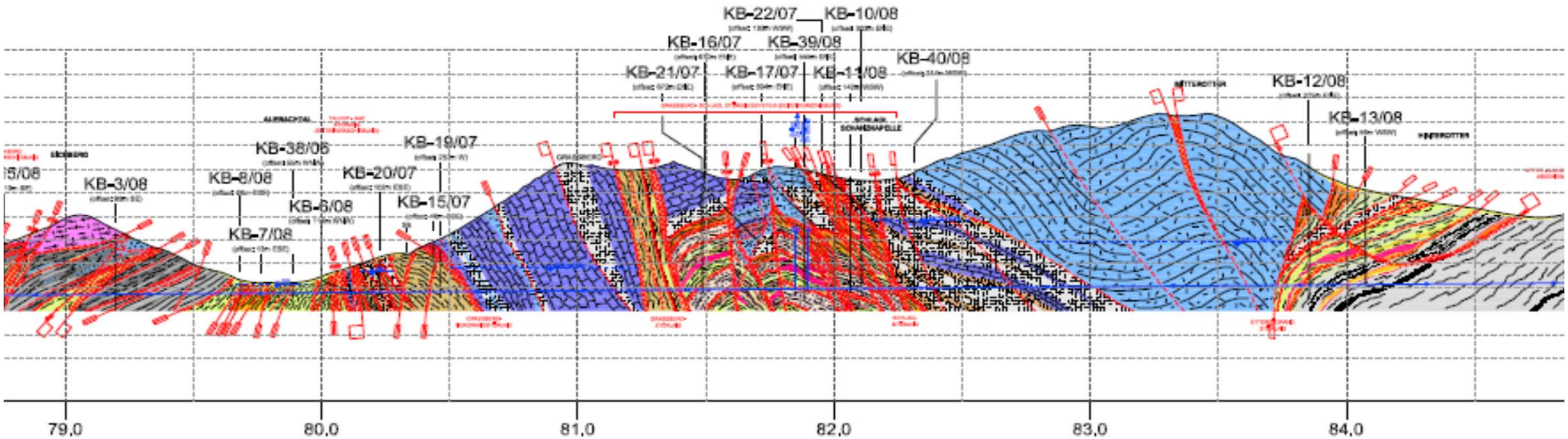
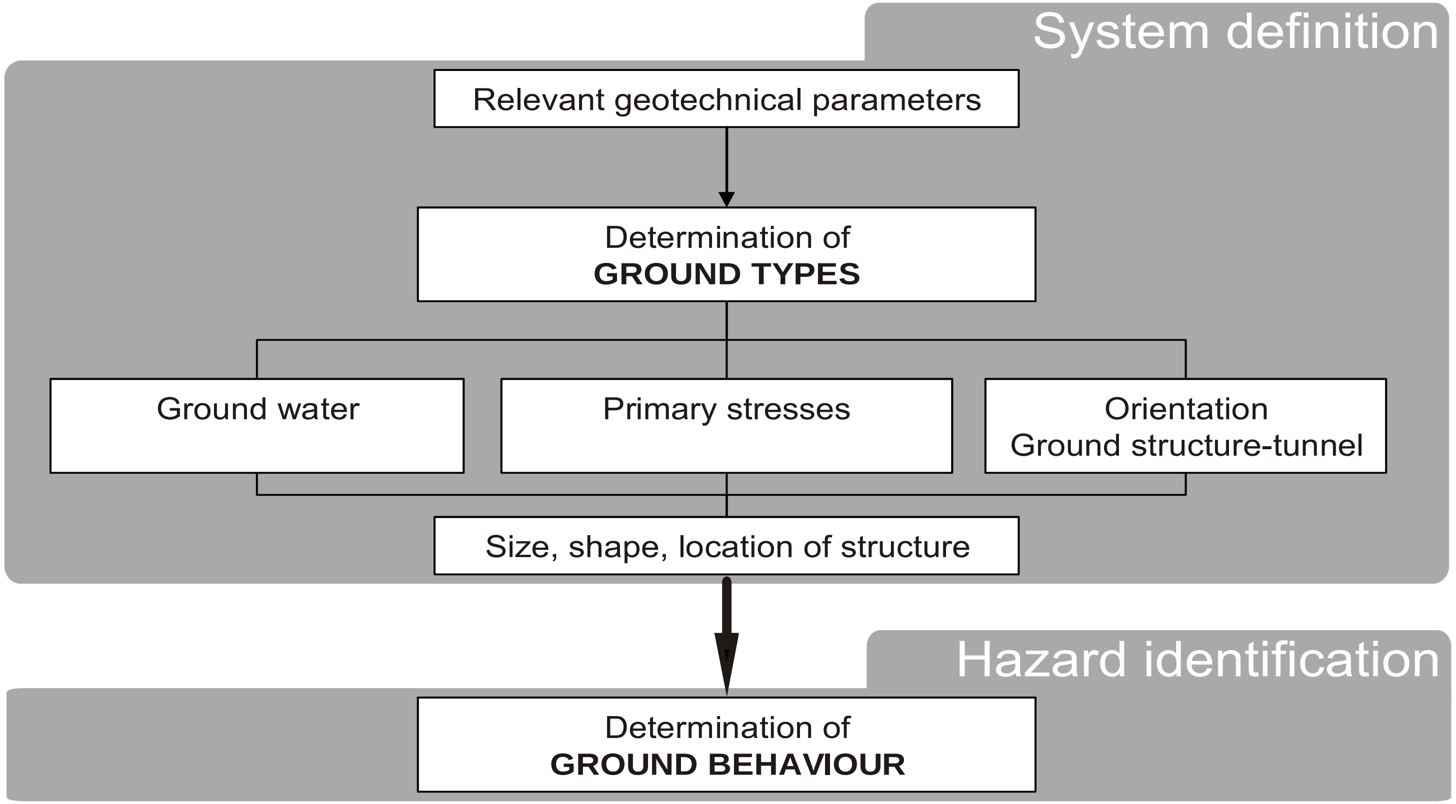
RISK ORIENTED DESIGN PROCESS

- Each tunnel design should be based on realistic geological and ground models, where also the uncertainties should be indicated

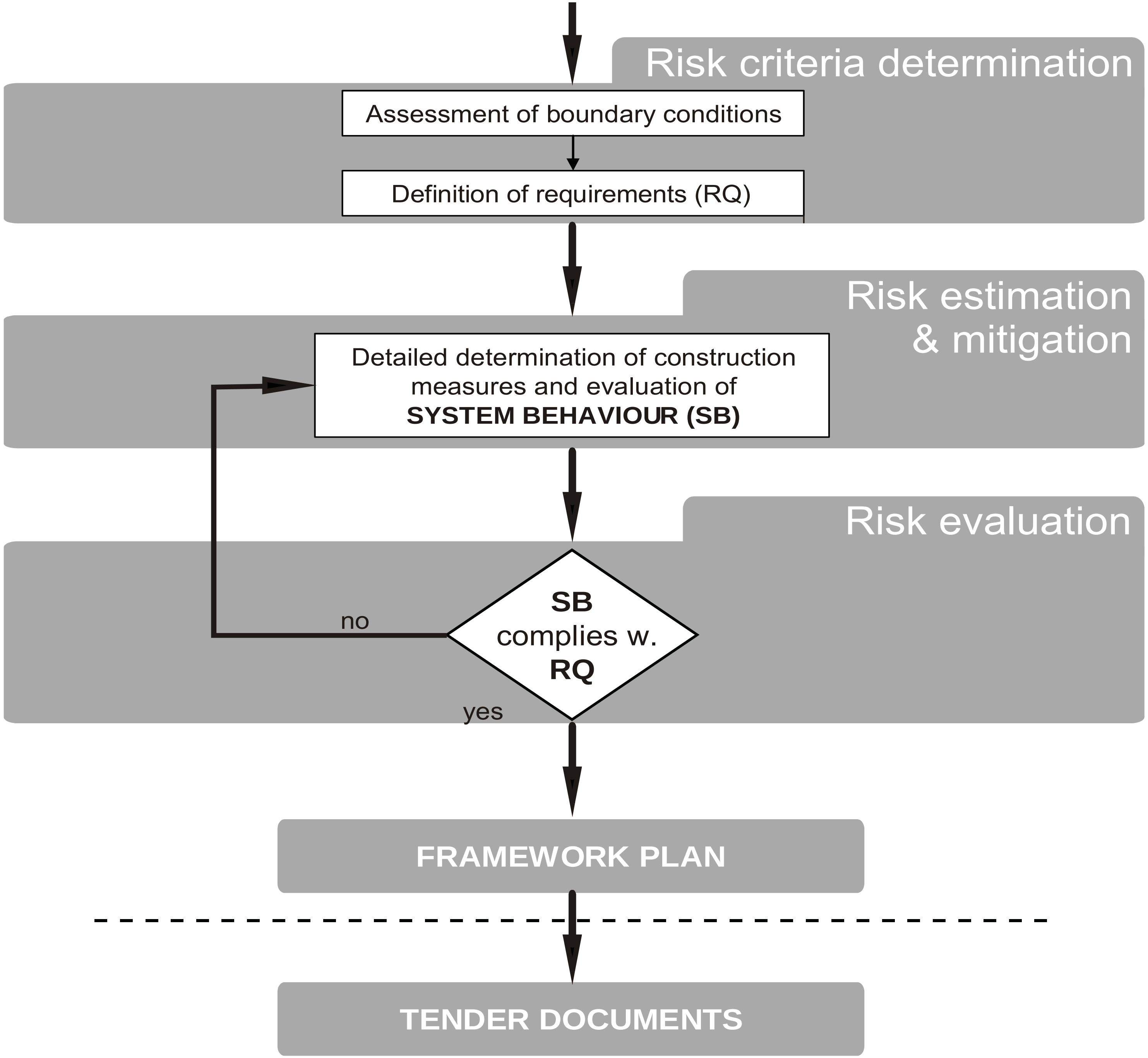


STRUCTURED APPROACH



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 location 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 (eg potential failure modes) identified


Risk criteria determination
Assessment of boundary conditions
Definition of requirements (RQ)
Risk estimation & mitigation
Detailed determination of construction measures and evaluation of SYSTEM BEHAVIOUR (SB)
Risk evaluation
no
SB complies w. RQ
yes
FRAMEWORK PLAN
TENDER DOCUMENTS

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GROUND BEHAVIOUR

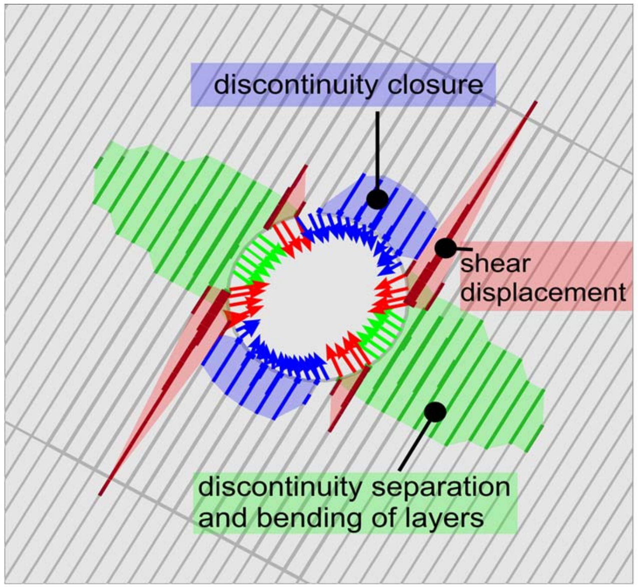
- Ground behaviour assessment should include type of potential failure modes, as well as magnitude and characteristics of displacements
- Method of evaluation must capture the essential features, and allow identifying relevant mechanisms
- Once the hazards are identified, risk mitigation measures in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

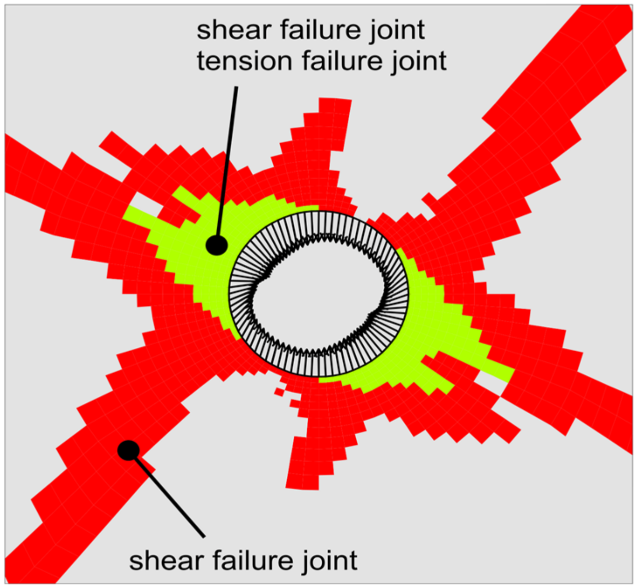
TYPES OF FAILURE MODES

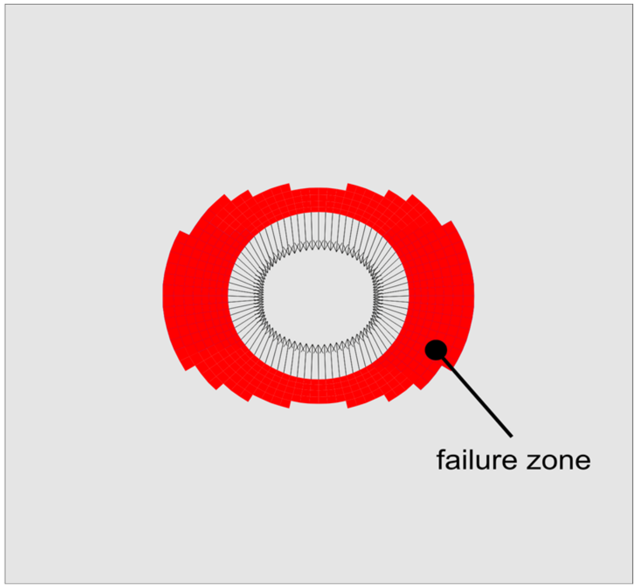
- Failure modes can roughly be distinguished in:
  - Gravity driven, in general discontinuity controlled falling, sliding, or rotating blocks
  - Stress induced failures with a variety of different modes
- The presence of ground water can have a significant influence on the failure. It can trigger failure,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

WHICH MODEL ?

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

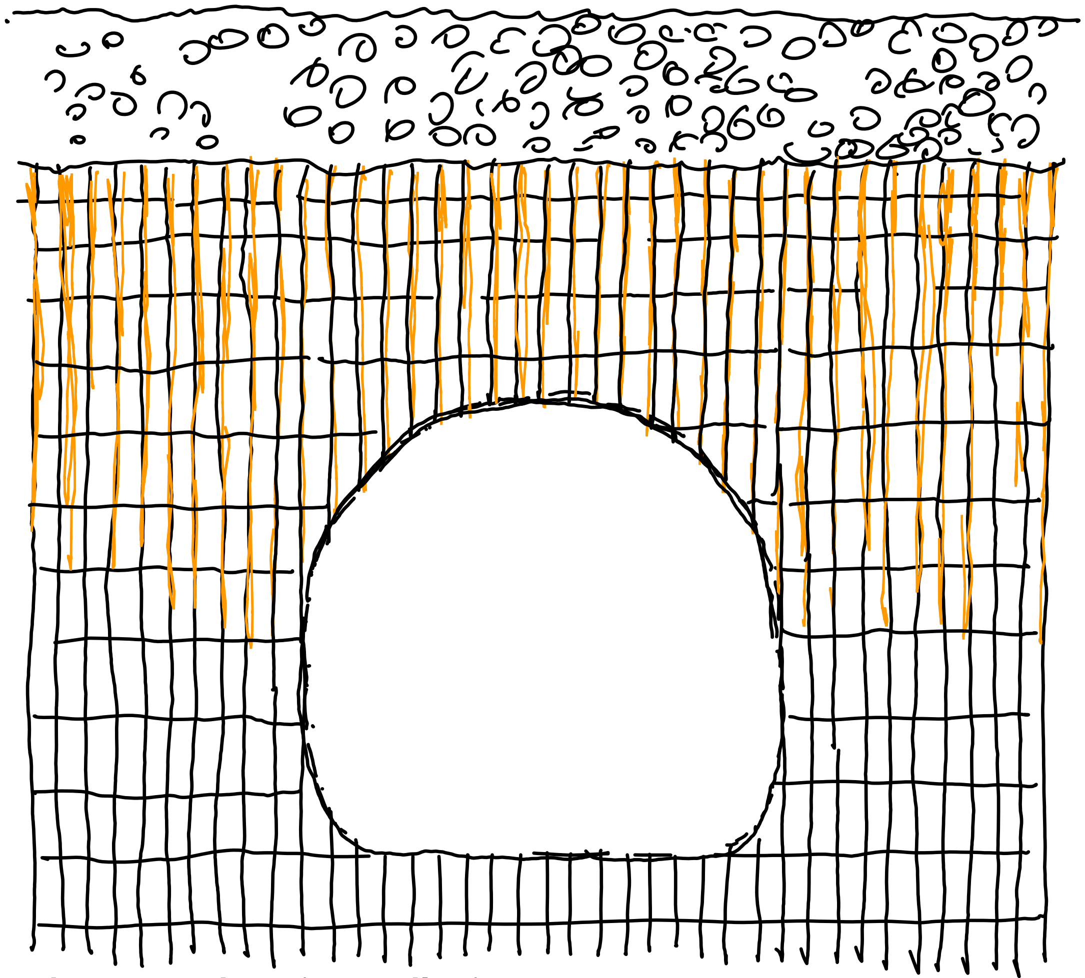






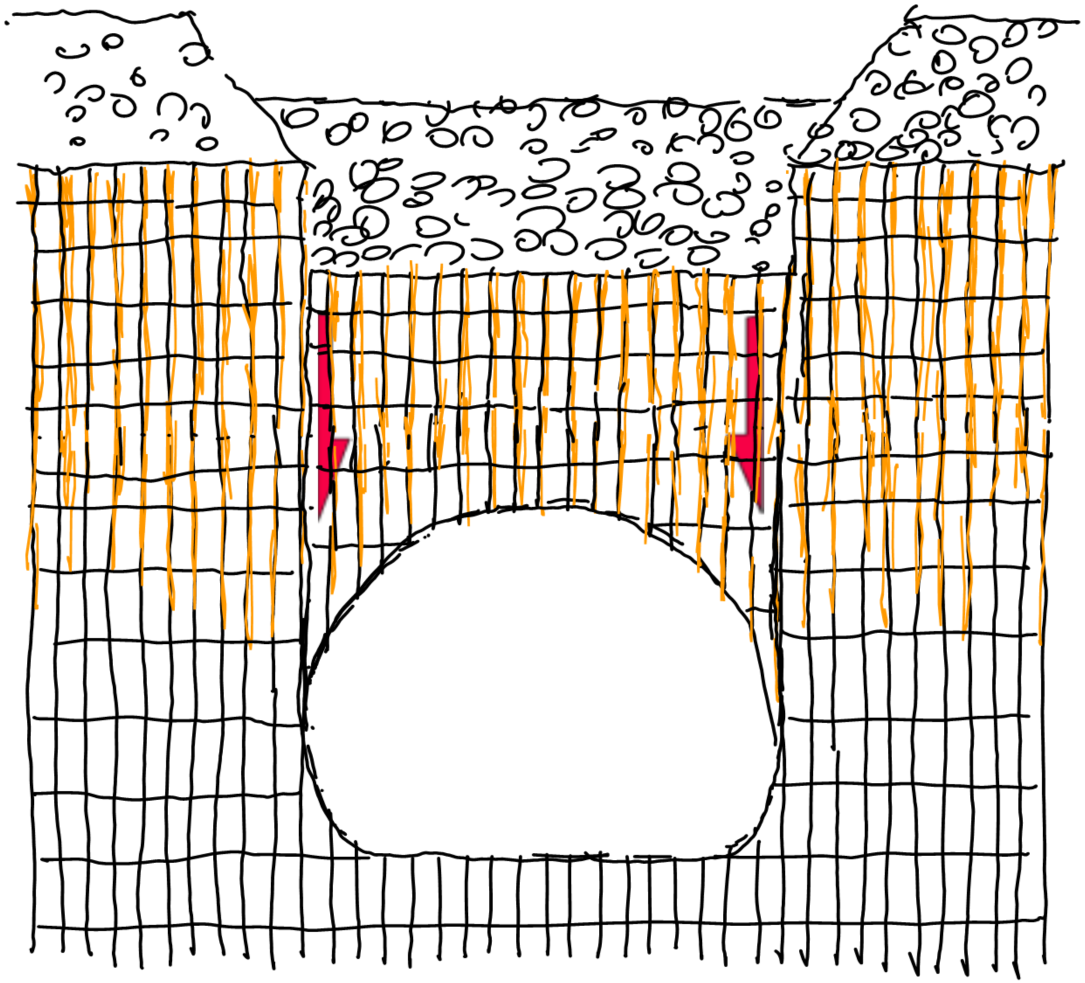
EXAMPLE

- System definition: tunnel of 10m diameter is excavated in gneiss, strike of weathered and occasionally slickensided foliation parallel to tunnel axis, dip vertical



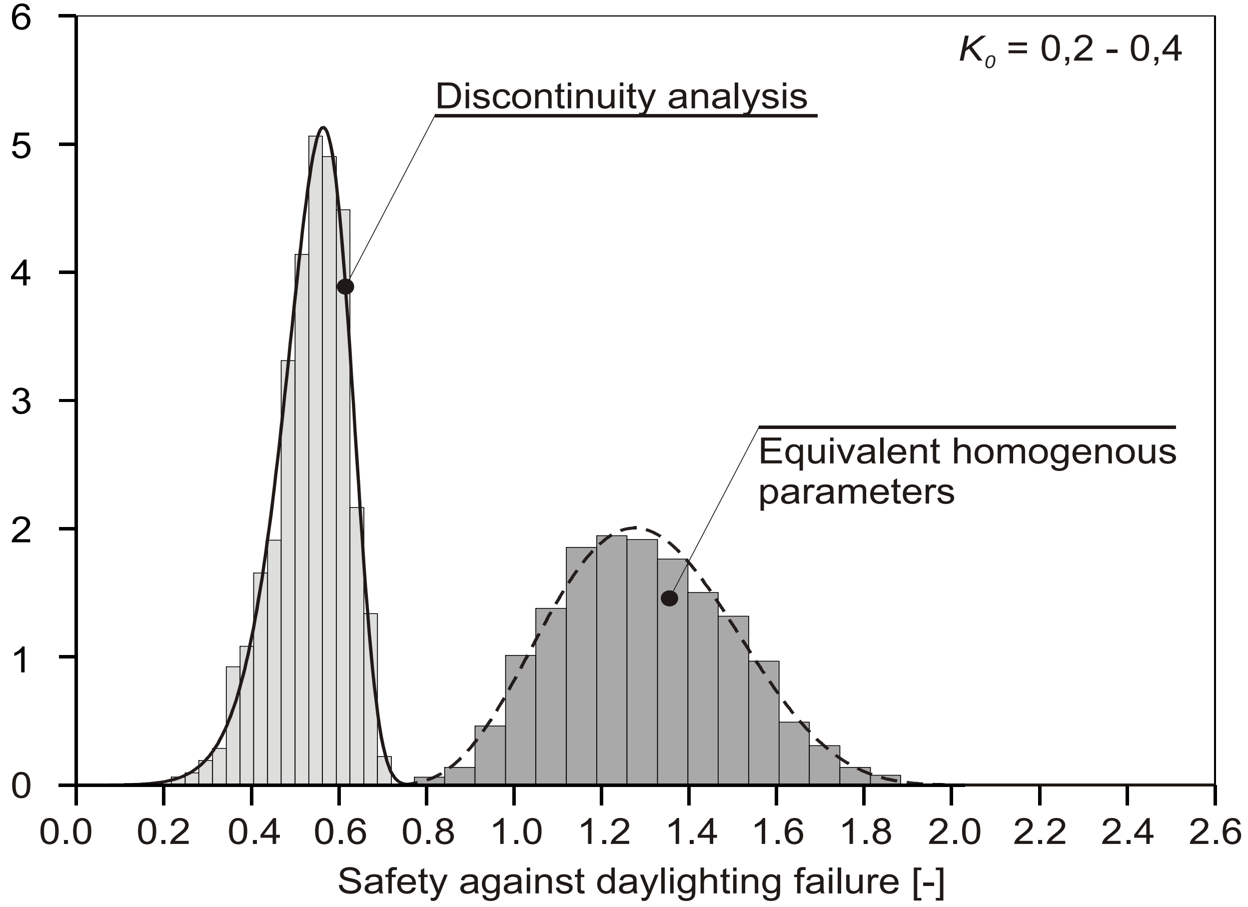
HAZARD ASSESSMENT

- Potential failure mode is shearing along vertical joints, with potential of failure to propagate to surface (daylighting collapse)

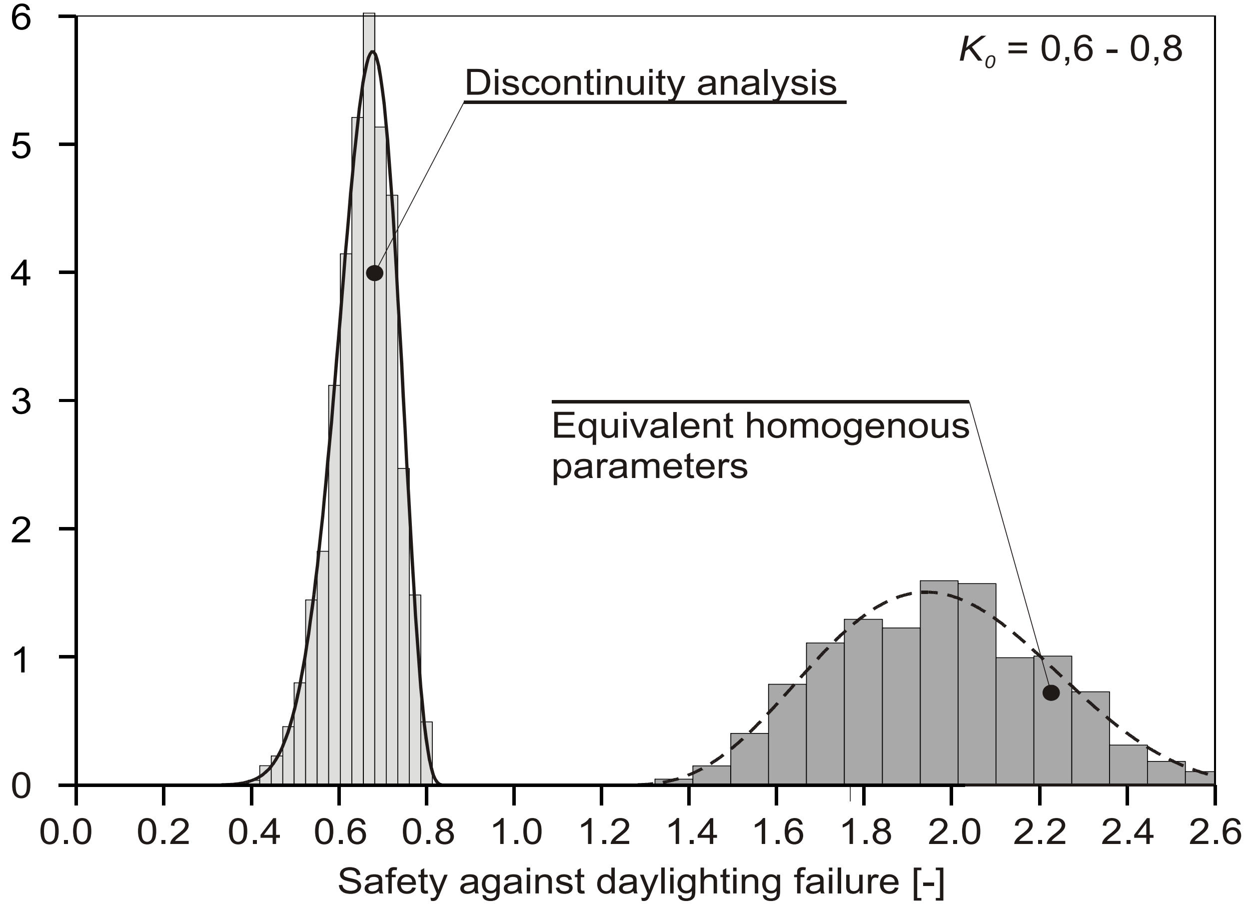


FAILURE PROBABILITY ANALYSIS

- Limit equilibrium analysis for discrete model and model where joints are „smeared“ into continuum. Variation of ground properties and horizontal stress



INFLUENCE OF HIGHER HORIZONTAL STRESS

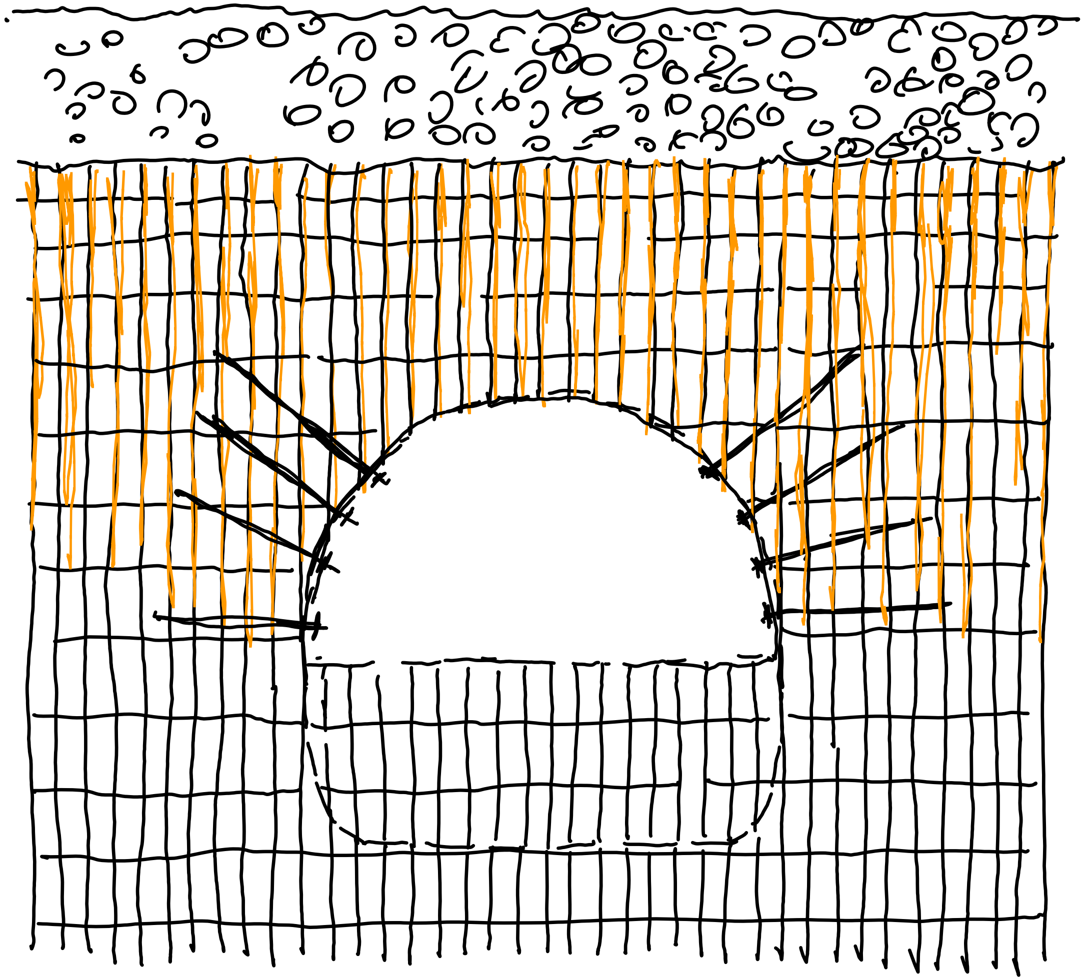


CONCLUSION OF ANALYSIS

- It can be clearly seen that „homogenized“ model yields much lower probability of failure than discrete model
- Basing support design on the results of the homogenized model would most likely result in a rather thin layer of shotcrete to prevent single blocks from falling into the tunnel
- As discrete model shows extremely high potential for failure
- Mitigation measures to reduce probability of failure have to be implemented

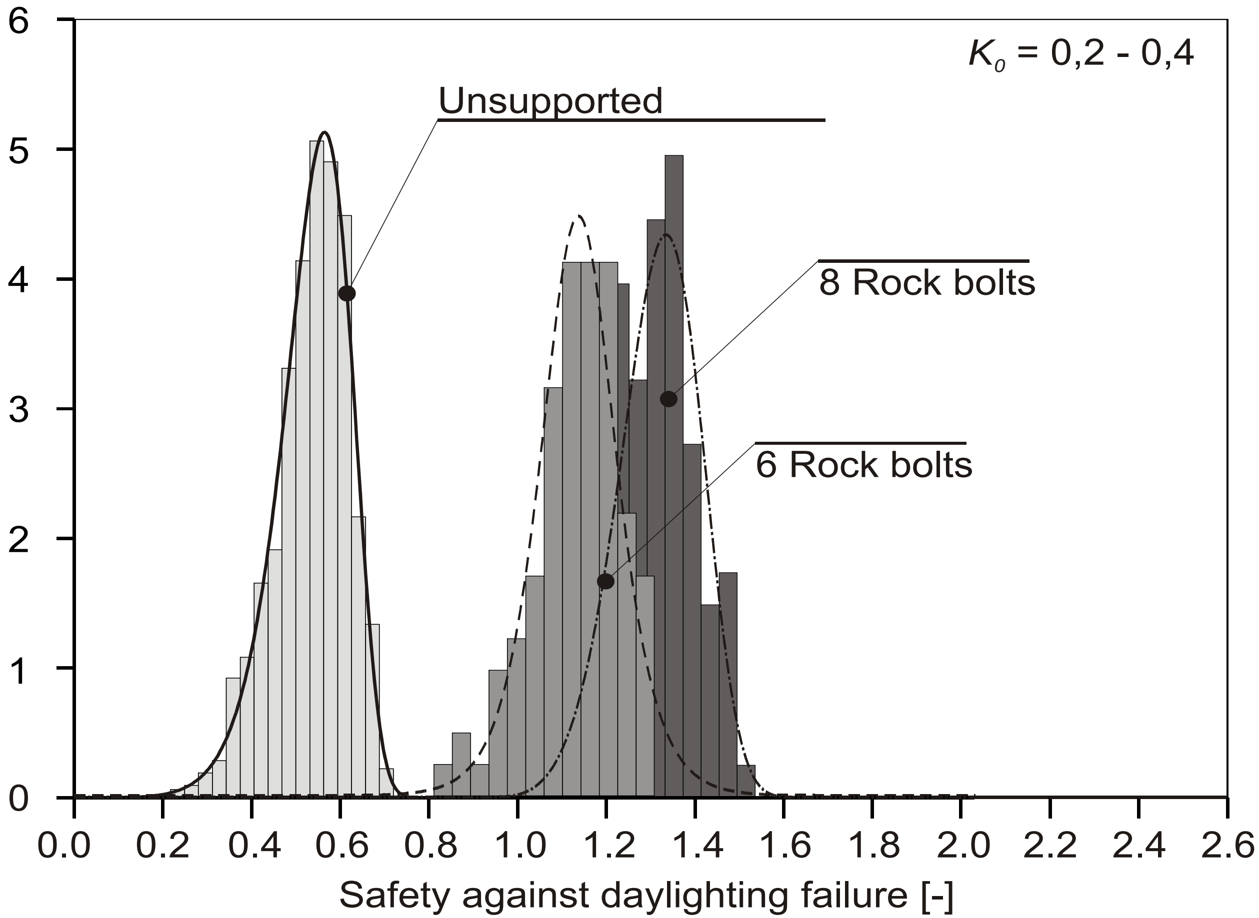
MITIGATION MEASURES

- To reduce probability of shearing along vertical joints, bolting in the sidewalls and shoulders, and a thin layer of shotcrete is applied



ANALYSIS OF SYSTEM BEHAVIOUR

- Again probabilistic approach is chosen for evaluating the effect of the bolts



SUMMARY EXCAVATION AND SUPPORT DESIGN

- Example shows importance of considering important features of the ground explicitely, understanding the problem and selecting appropriate model
- In many cases a good sketch of the situation reveals type of potential failure modes better than a sophisticated, but inappropriate simulation

Tip: use brain before starting the computer!

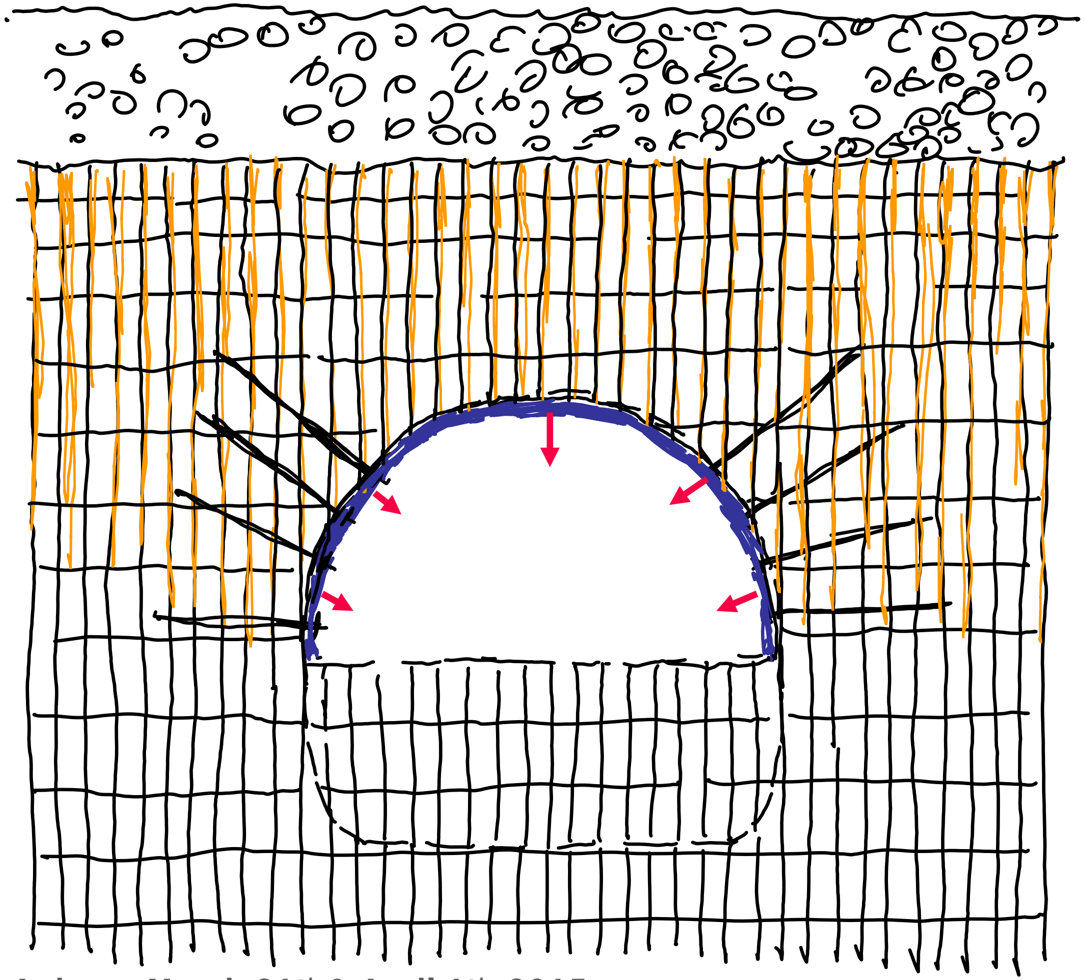
PROCESS DURING CONSTRUCTION

INTRODUCTION

- Even with excellent investigation, characterization and design, residual risks remain
- To be able to identify „abnormal“ behaviour, expected system behaviour must be defined
- Deviations identified by monitoring
- Safety management plan contains all provisions for cases of deviating behaviour

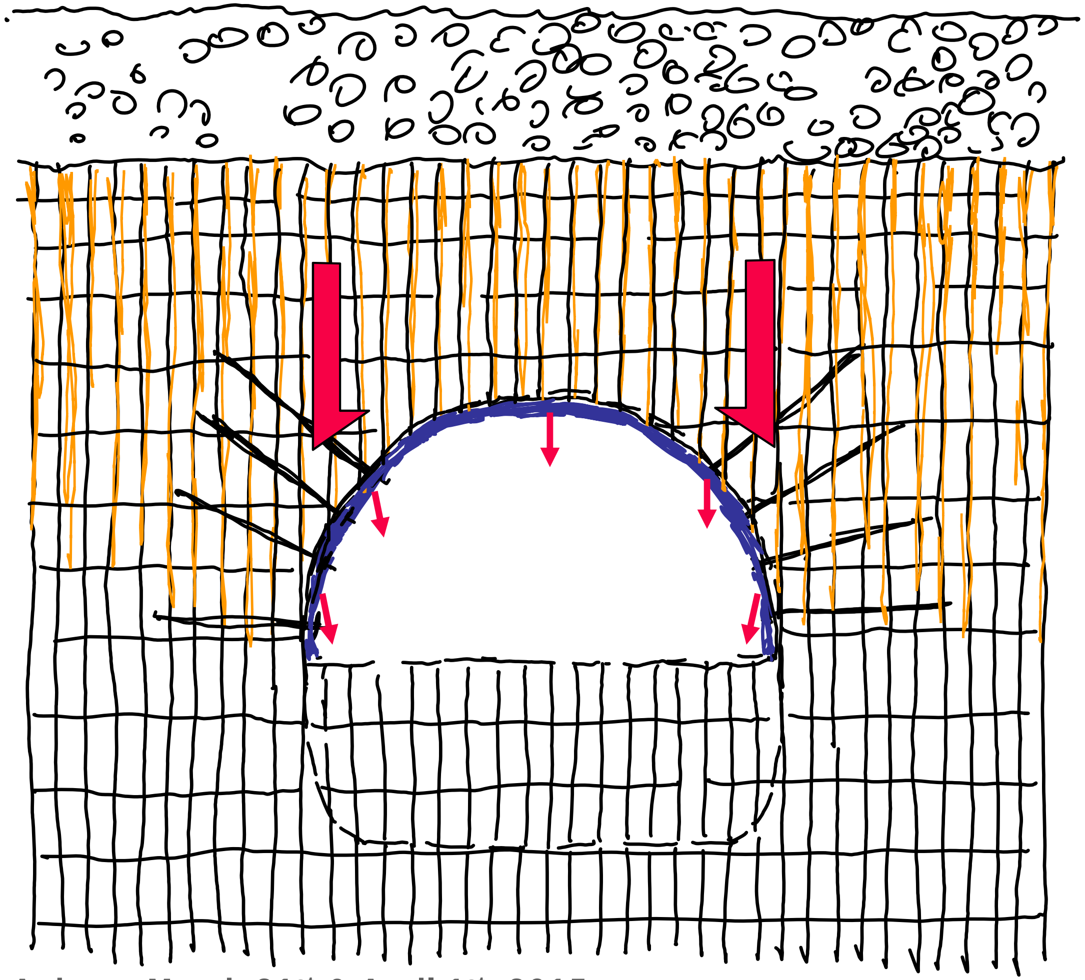
EXAMPLE CONTINUATION

- „Normal“ system behaviour can be defined by displacement characteristics or magnitudes



DETECTION OF DEVIATING BEHAVIOUR

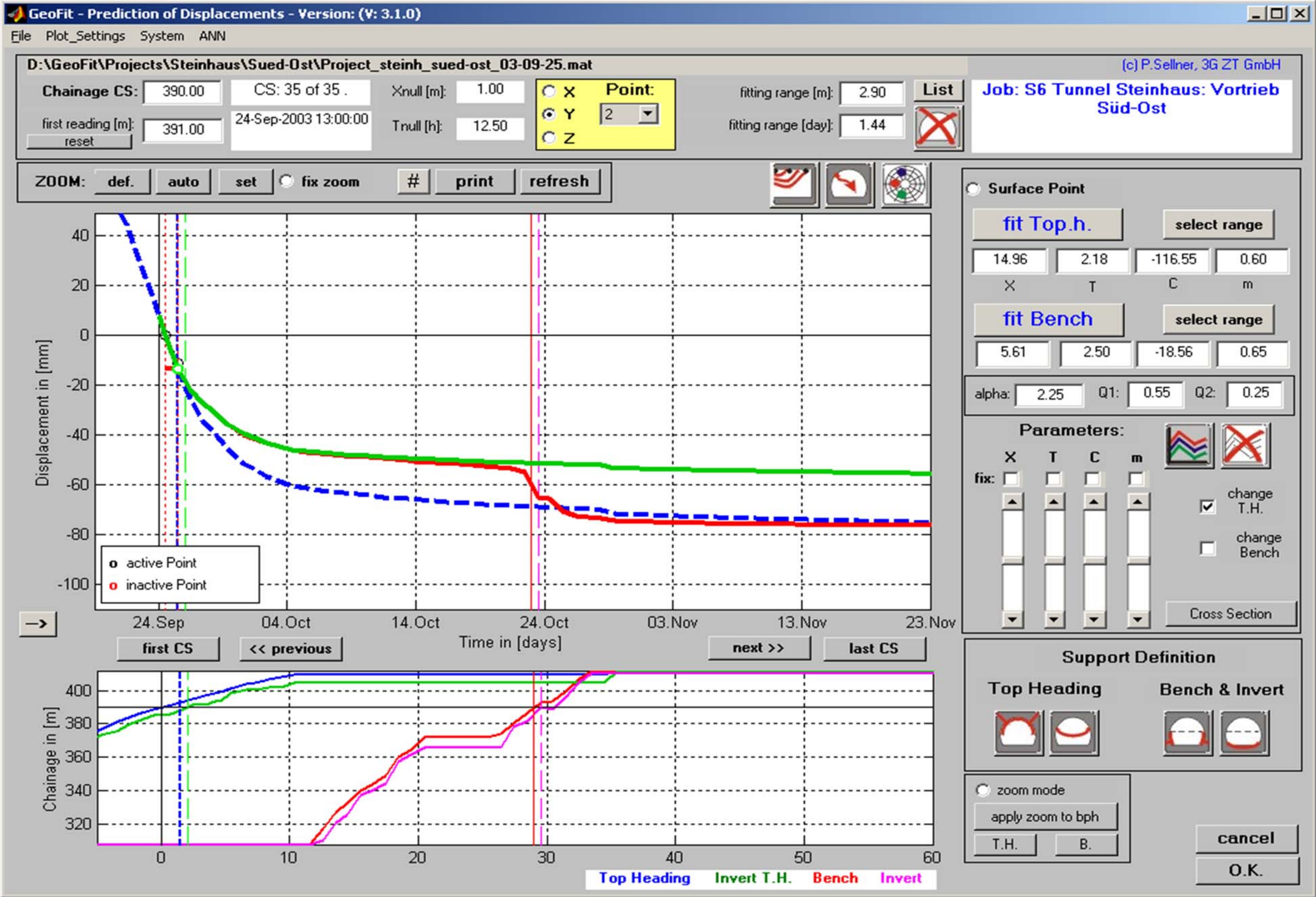
- By observing displacement characteristics, abnormal behaviour can be easily detected



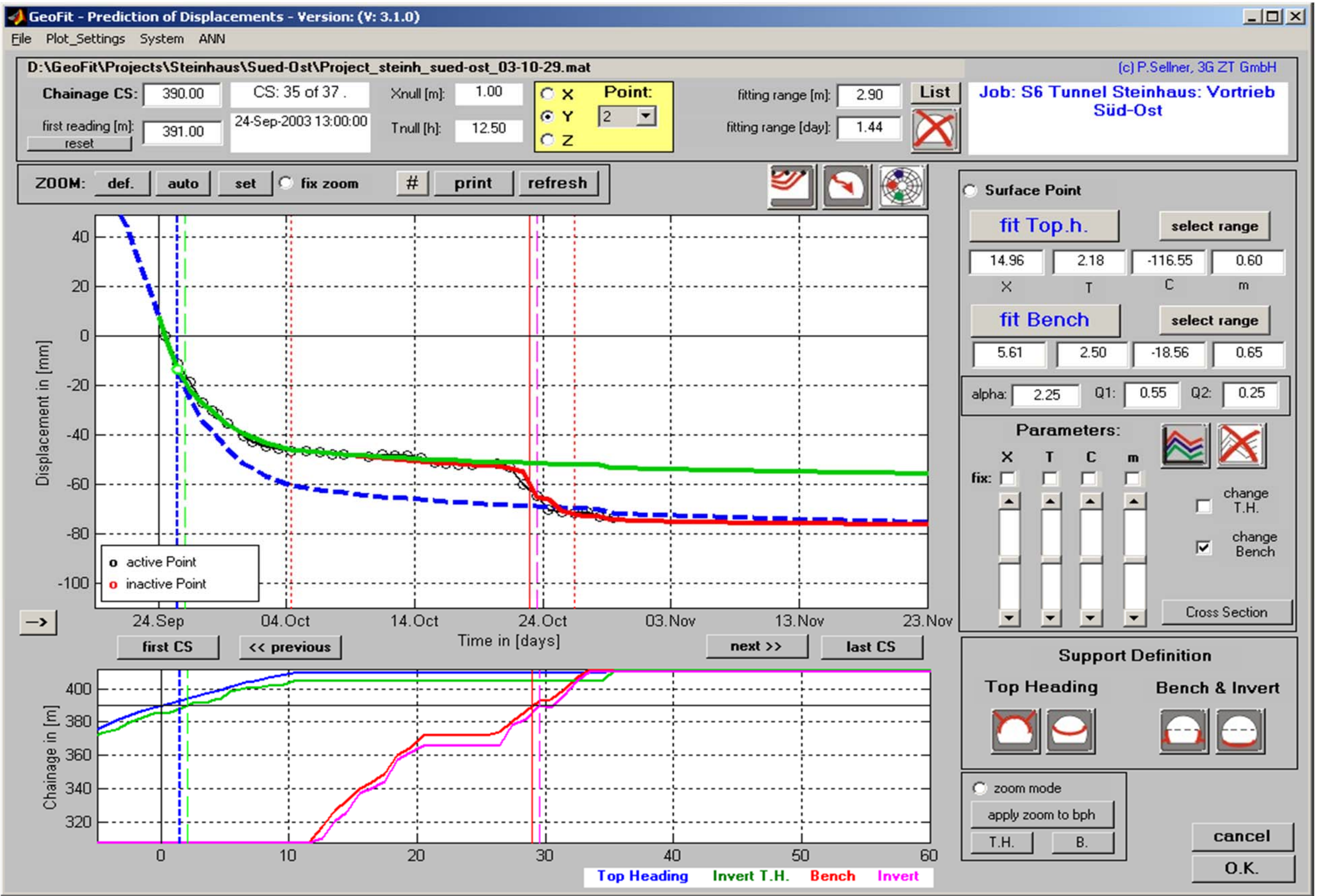
PREDICTION OF DISPLACEMENTS

- Predicting development of displacements as a function of face advance, time, ground structure and quality, excavation sequence and support can be done with relatively simple formulations
- This allows easy check of „normality“ of observed system behaviour

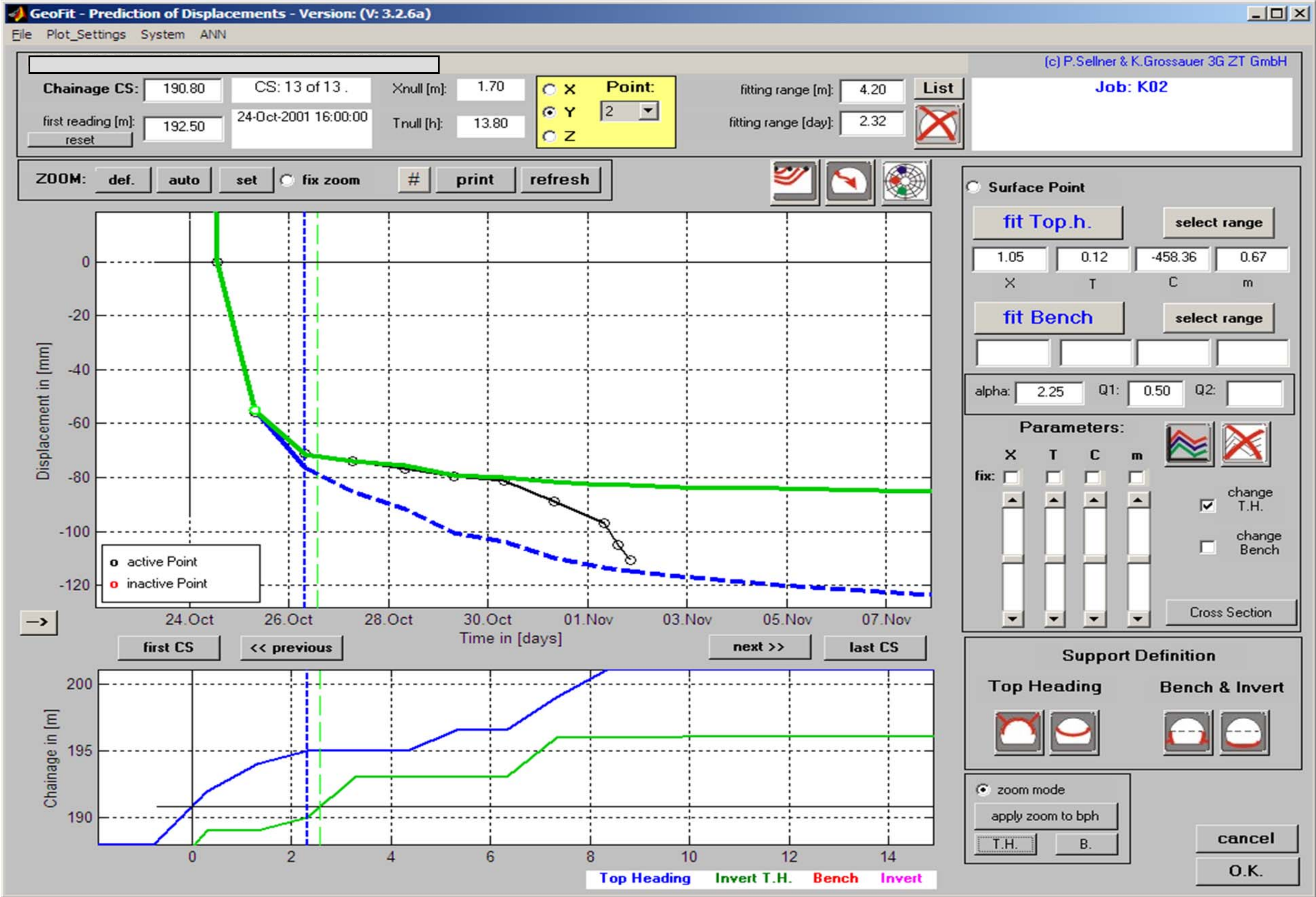
PREDICTION FOR TOP HEADING-BENCH EXCAVATION



COMPARISON PREDICTION - MEASURED

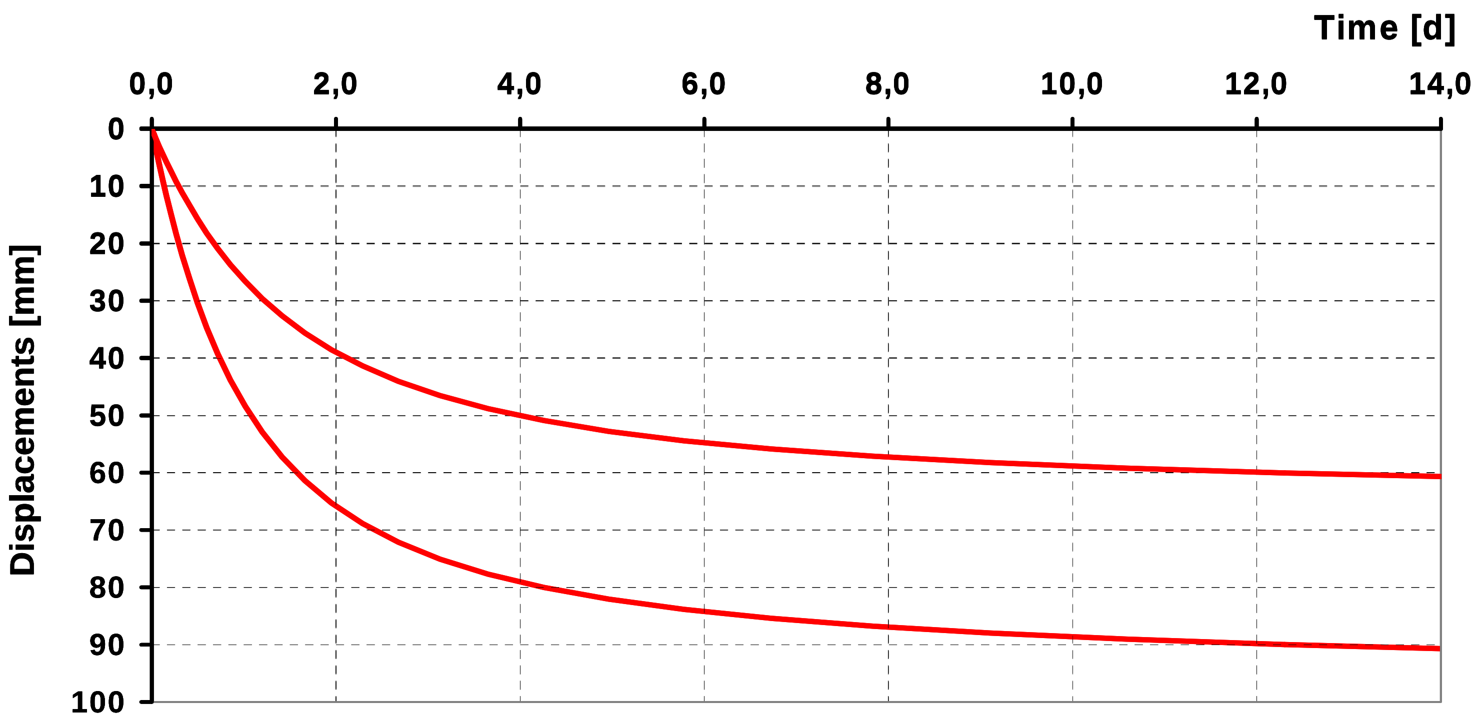


DEVIATION FROM „NORMAL“ BEHAVIOUR



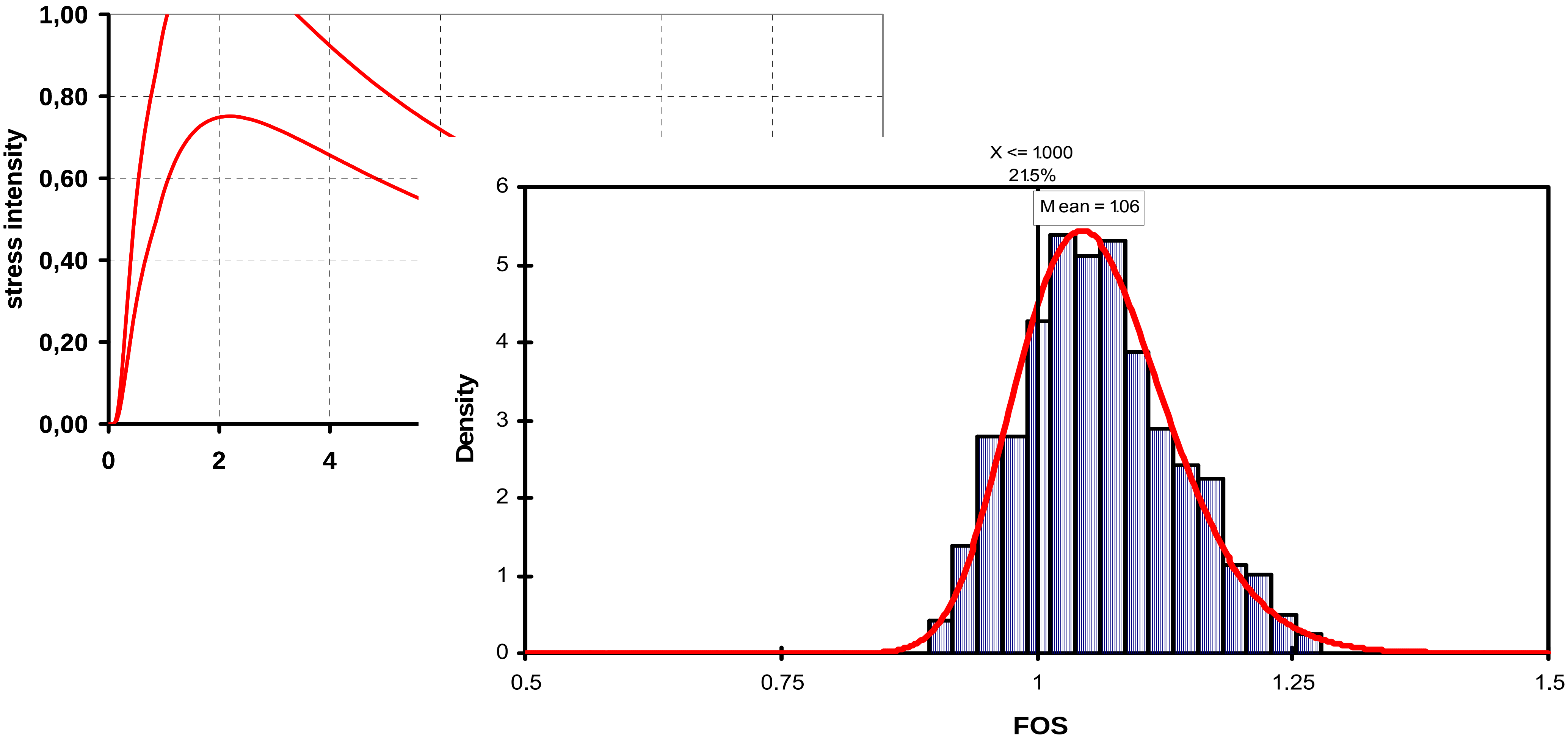
LINING FAILURE PROBABILITY

- By using predicted displacement development and an advanced constitutive model for shotcrete, utilization of lining can be predicted
- Example: predicted range of displacements, adv. rate 4 m/d



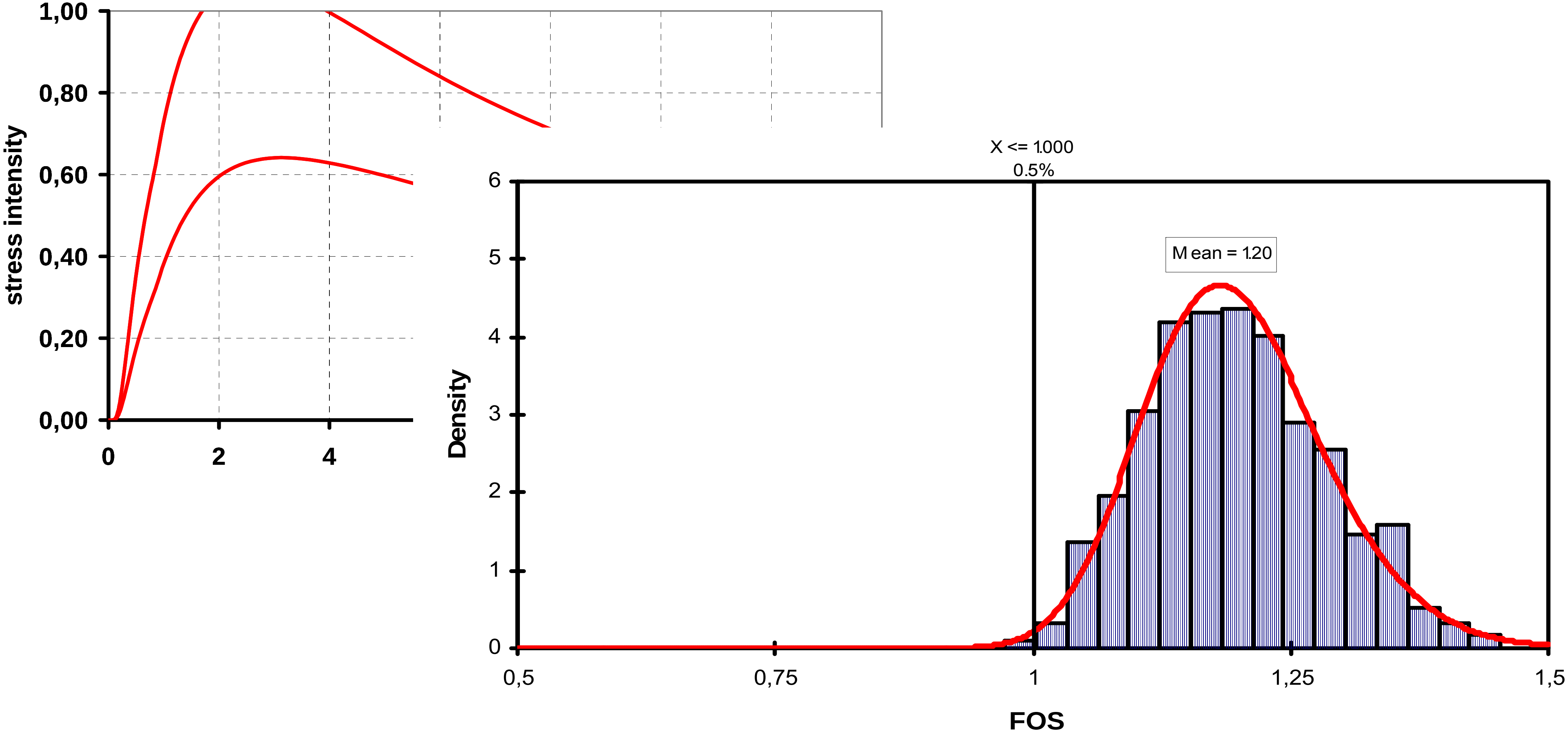
LINING UTILIZATION AND PROBABILITY OF FAILURE

- Steady progress rate 4 m/d

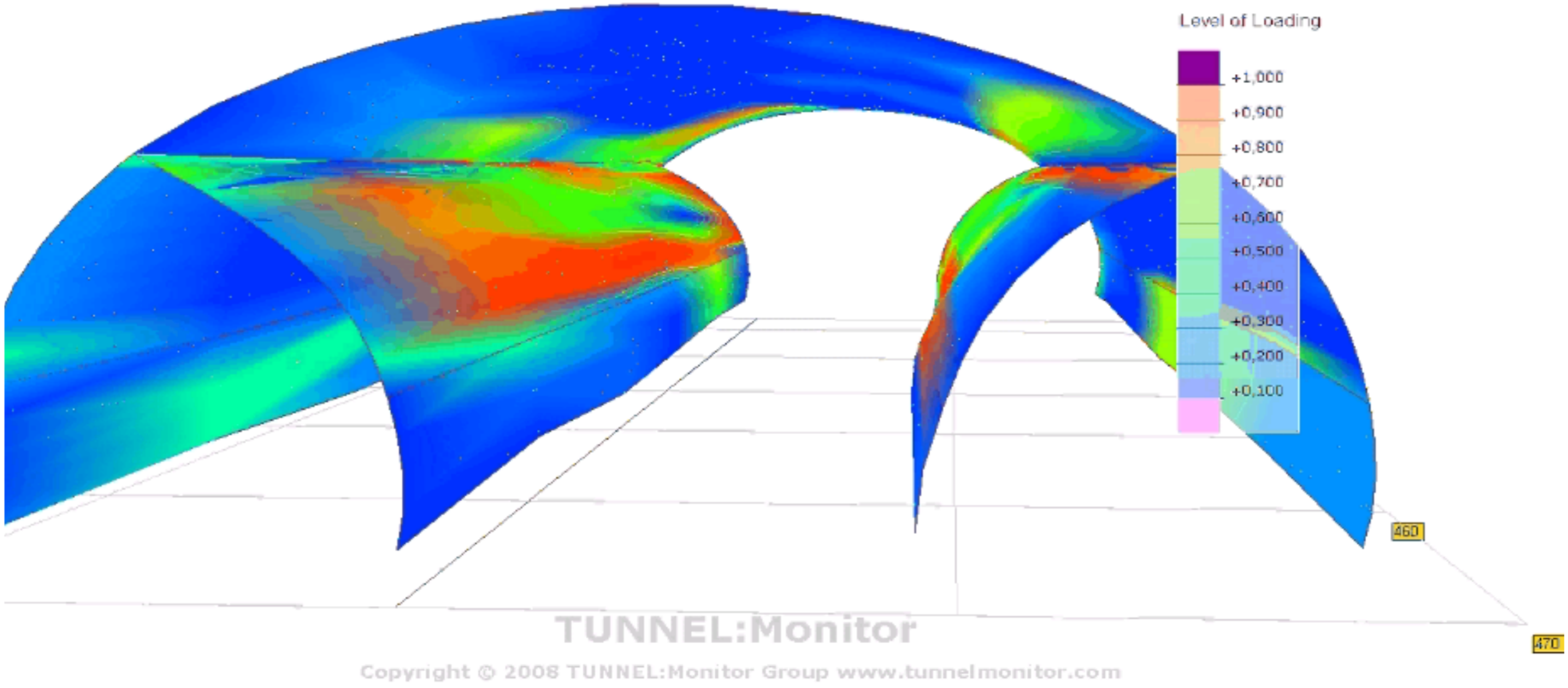


LINING UTILIZATION AND PROBABILITY OF FAILURE

- Steady progress rate 2 m/d



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

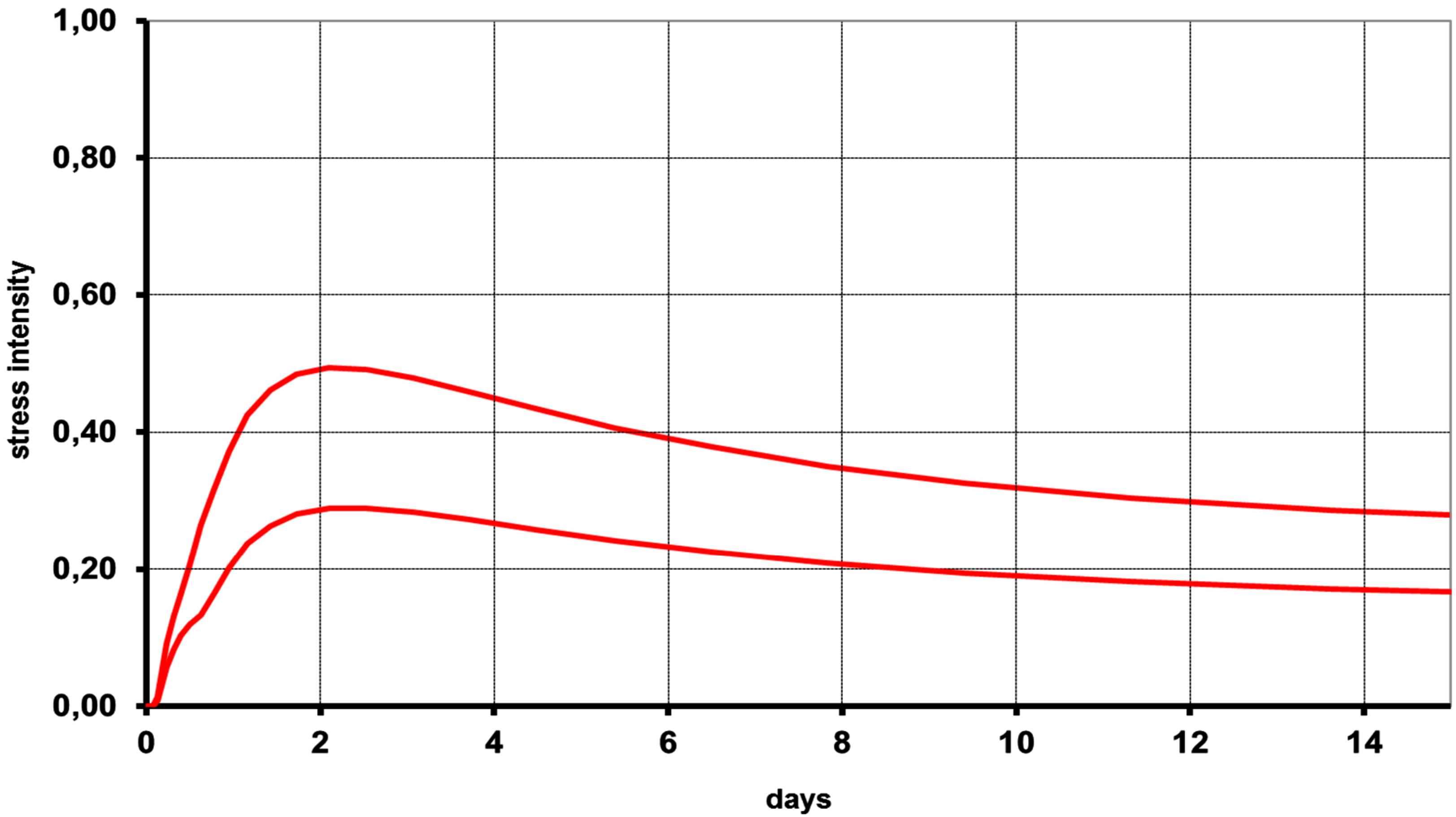


OPTIONAL: APPLICATION OF DUCTILE SUPPORT

- For maintaining higher advance rates without damage to the support, lining has to be modified to ductile type

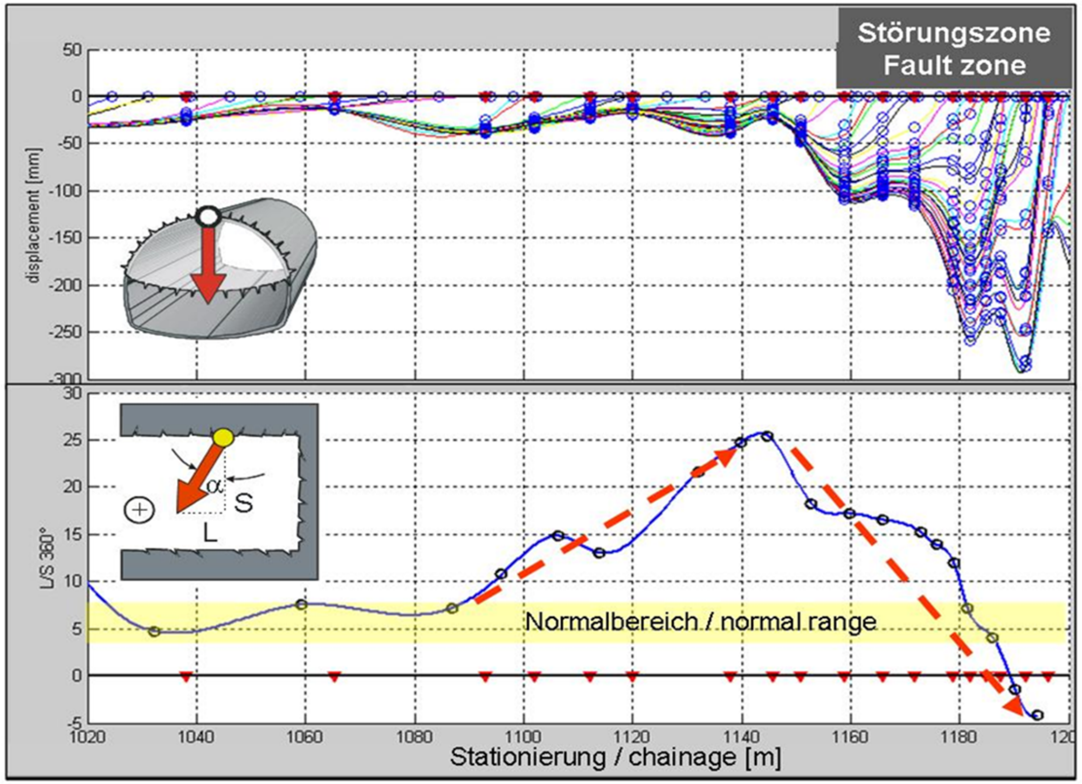
EFFECT OF DUCTILE LINING ON UTILIZATION

- Two rows of yielding elements control the stresses in the lining, with utilization rates of max. 30% to 50% for the expected displacement development range



EARLY WARNING OF CHANGING GROUND CONDITIONS

- Advanced evaluation of displacement monitoring data allows detecting fault zones well ahead of the face
- Timely adjustment of excavation and support reduces the probability of costly repairs



CONCLUSION

- Risk oriented design and construction requires understanding of potential behaviours and failure mechanisms
- Mitigation measures shall be targeted at reducing the probability of identified failure modes or reduction of the consequences
- Appropriate monitoring and evaluation system helps in identifying critical developments and significantly reduces the probability of experiencing „surprises“ during excavation
- To account for remaining uncertainties safety management system needs to be implemented during construcion
- State-of-the-art methods and tools are available!


Thank you for your attention
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