MINIMIZING RISK DURING TUNNEL CONSTRUCTION BY MONITORING

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INTRODUCTION

- Risk in engineering commonly is understood as the product of probability of an event and the consequences of such an event.

- 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.

- 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 do not allow precisely predicting the behaviour of the tunnel and the surrounding ground during the design.

- Thus a residual risk remains, which has to be dealt with during construction.
HAZARDS IN TUNNELLING

In tunnelling unfavourable events (hazards) 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.
UNPREDICTABLE ? UNAVOIDABLE ?

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OBSERVATIONAL APPROACH

- The inherent 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 establishment of a targeted monitoring program, appropriate site organization and a safety management plan.

- Focus of observation on verification of assumptions and identification of (predicted or unpredicted) hazards.

- To be able to detect deviations from the “normal behaviour” the expected behaviour and limits of acceptable behaviour need to be defined.
PURPOSE OF MONITORING

- Observe system behaviour and check if it is within the acceptable range
- Use data to verify assumptions made during design on ground behaviour
- Calibrate models
- Use results for fine tuning of excavation and support
- Use data for prediction of ground structure and quality ahead of the face
- Proof that prescribed limits are kept (for example surface settlements)
- Legal aspects
DISPLACEMENTS IN UNDERGROUND CONSTRUCTION

- Magnitude and characteristics of deformation depend on ground quality and structure, initial stress, tunnel size, construction sequence, and support.

- The monitoring programme must fulfill the following requirements:
  - Capture the expected behaviour
  - Monitoring intervals short enough to allow undertaking successful contingency actions
  - Processing and analysis of data sufficiently rapid in relation to possible evolution of the system.
MONITORING METHODS FOR TUNNELS

- A number of methods exist to measure displacements and strains above ground and in the tunnel

- Above ground (selection)
  - Levelling
  - Inclinometers, extensometers
  - Tiltmeters
  - Measurement of displacements by total station

- In tunnel (selection)
  - Measurement of displacements by total station
  - Extensometers
  - Strain meters
  - Measuring bolts
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TYPICAL INSTRUMENTATION FOR SELECTED SECTIONS

3D-displacement-targets

Extensometers

Measuring dowels

Strainmeters
Pressure cells
TYPICAL DEVELOPMENT OF DISPLACEMENTS

- Tunnel excavation causes a change in the boundary conditions and stresses (stress increase and relaxation)
- This naturally leads to displacements of the ground, usually a reduction in tunnel size
- Influence of stress rearrangement reaches ahead of the face and is generally completed a couple of diameters behind the face
- Highest displacement gradient usually at the face
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Sulem and Panet have developed an empirical relationship for the displacements behind the face in relation to face advance and time.

\[
C(x, t) = C_{x\infty} \cdot \left[ 1 - \left( \frac{X}{X + x} \right)^2 \right] \cdot \left[ 1 + m \cdot \left( 1 - \left( \frac{T}{T + t} \right)^{0.3} \right) \right]
\]

- \(C_{x,t}\) Displacement in relation to face advance and time
- \(C_{x\infty}\) Final time independent displacement
- \(X, T\) Shape parameters
- \(x, t\) Distance face-monitoring section, time since excavation
- \(m\) Proportion of time dependent displacements
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INFLUENCE OF FOLIATION ON DISPLACEMENT DEVELOPMENT

- When discontinuity strength is low, stress redistribution quite different for both cases
The formulation from Sulem and Panet has shown to represent „normal“ development of displacements.

Barlow and Sellner have further developed the method, now allowing for evaluation of displacements ahead of the face, as well as simulation of supports and sequential excavation.

Sellner has also extended the features allowing for the simulation of surface settlements and developed software (GeoFit®), which incorporates all the features.

Sellner then has developed software which allows considering face advance, time effects.
PREDICTION OF DISPLACEMENTS

- Basically two options exist:
  - Determination of function parameters by automatic fitting to measured values. A minimum of 3 readings (zero reading plus two consecutive readings) is required to obtain a fit. Fit can be improved, as more readings are available.
  - Estimating function parameters from previous experience and make forward prediction; Prediction can be improved, as more data are available.
- With an assumed excavation progress, "normal" development of displacements can be established and actual readings then compared to the predicted displacements.
- Effects of different supports can be assessed in advance.
Using fit function after a few readings and extrapolation of top heading displacements for assumed progress.
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COMPARE MEASURED TO PREDICTED

- Progress different from prediction, but predicted displacements adjusted to real sequence
FORWARD PREDICTION BY EXTRAPOLATION OF FUNCTION PARAMETERS
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EFFECT OF TOP HEADING INVERT

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COMPARISON PREDICTION - MEASURED
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SURFACE SETTLEMENTS

- In particular in built up areas, the surface settlements require special attention
  - Buildings and utilities have limited tolerance against deformation, in particular in case of different displacements at different locations (e.g. different settlements at the corners of buildings or along a utility line)
- Early detection of unfavourable development thus very important
- Basically same tools as for prediction of displacements in tunnels can be used
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ABNORMAL BEHAVIOUR – WHY ?

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SUDDEN SUBSIDENCE ON APRIL 15TH (FACE HAS PASSED FAULT)
DISCUSSION

- For controlling the system behaviour it is important to have a model (predicted displacements in quality and quantity) and compare the monitoring data to the model.

- In case of disagreement of monitored data and model, there is always a reason.

- Explaining the reason for unusual behaviour besides exploiting the data in the right way requires understanding the mechanical processes of the system.

- Using a mathematical description of the „normal“ displacement development is one of the options to easily detect abnormal behaviour.
PREDICTION OF GROUND QUALITY AHEAD

- Most costly events are associated to „unexpected“ changes in the ground quality

- Analysing displacement monitoring data in a non-traditional way, allows relatively reliably predicting such changes at practically 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 EVALUATION OF DISPLACEMENT TRENDS
CAUSE OF CHANGING TREND: FAULT ZONE AHEAD

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**COMBINATION OF TRENDS FOR SPATIAL ORIENTATION**

<table>
<thead>
<tr>
<th>Longitudinal Section</th>
<th>Geological Situation</th>
<th>Plan View</th>
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<tr>
<td></td>
<td>stiff</td>
<td>soft</td>
</tr>
<tr>
<td></td>
<td>stiff</td>
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</table>

- **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

<table>
<thead>
<tr>
<th>Ground Conditions Change</th>
<th>Transition to Softer Rock Unit</th>
<th>Transition to Stiffer Rock Unit</th>
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<tr>
<td>Basic Type</td>
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<tr>
<td>Ground Condition</td>
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<td></td>
</tr>
<tr>
<td>Vector Orientation</td>
<td></td>
<td></td>
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<tr>
<td>Left/Right</td>
<td>1.2.3</td>
<td></td>
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<tr>
<td>Displacement Ratio</td>
<td>1.2.3</td>
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**Legend:**
- ■: Significant positive correlation
- □: Significant negative correlation
- -: No significant correlation

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Using various trends as input, the type and spatial orientation of a change in the ground conditions can be evaluated.

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<td>✗</td>
<td>✗</td>
<td>✗</td>
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<td>✗</td>
<td>✗</td>
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<tr>
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<tr>
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<td>✗</td>
<td>✗</td>
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<td>✗</td>
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</tr>
</tbody>
</table>

**Evaluation components**

- **Component**: The term “Min. Correlation” will be set to 75 (standard) with every reset.
- **This sheet is protected; use the password “predictor” to unprotect.**
- **The columns “Q2T” are hidden.**
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.
- Continuous follow up of the lining utilization allows initiating mitigation measures in time, thus reducing the risk.
- Algorithms have been implemented in advanced monitoring evaluation software (e.g. Tunnel:Monitor).
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SHOTCRETE PROPERTIES
EXAMPLE OF UTILIZATION OF LINING

Diagram showing cracks and levels of load with a color scale for monitoring during tunnel construction.

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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!
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
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**ACTION AND REPORTING PLAN**

- Observations relevant for safety
  - Information of ENG
    - Discussion ENG and GE
      - Warning level?
        - Behaviour as expected
          - Continue as planned
        - Criteria attention level reached
          - GE: daily geotech.report meet with ENG and CO contact with IE, D
            - ENG: information CM
              - Measures acc. to recommendation of GE, D and IE
            - Regular geotechnical meeting
          - Criteria warning level 1 reached
            - GE: daily geotech.report meet with ENG and CO contact with IE, D, CHE
            - ENG: information CM, OT, CM, GE, IE, D, CHE
            - ENG, CO: initiate mitigation measures
              - CM: crisis management
            - Criteria warning level 2 reached
              - 3rd parties not affected
              - Criteria warning level 3 reached
                - 3rd parties affected
                - GE: inform and protect third parties
                  - Information CM, OT, CM, GE, IE, D, CHE
                - ENG, CO: initiate mitigation measures
                - PO: crisis management
            - Management of crisis by ENG until takeover by CM, resp. Owner
              - CM: calls special geotechnical meeting for fixing of further actions
            - Regular geotechnical meeting
              - optional
              - mandatory
WARNING AND ALARM 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
    - 5 m behind face: 20 mm
    - 20 m behind face: 30 mm
CASE HISTORY

Actual development of displacements

Expected development of displacements

Proclamation of warning level 2 due to unfavorable trend of displacements;
Initiation of mitigation measures

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DISPLACEMENT VECTORS CLEARLY INDICATE PROBLEM
MITIGATION MEASURES

- Additional bolting on a length of about 20m on the right 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

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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
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CONCLUSION

- Risk oriented construction requires sound preparation and 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 hazards.

- Appropriate monitoring and evaluation concept helps in identifying critical developments and significantly reduces the probability of experiencing „surprises“ during excavation, thus saving time and money.

- 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.

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