Prediction of Displacements in Tunnelling
Verschiebungsprognose für den Tunnelbau

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Abstract:
This paper proposes a new method to predict wall displacements, especially settlements and horizontal displacements, in tunnelling in squeezing rock. The proposed displacement calculation procedure is based on analytical functions which describe the displacement behaviour of the rock mass and support as a function of time and excavation advance. Information from the short term prediction of rock mass behaviour and knowledge from case histories provide the required calculation parameters. Any desired excavation concept and different types of support can be simulated and investigated. Highly developed mathematical tools such as artificial neural networks and curve fitting techniques are used for the calculation. The program was tested on site and results are promising. For a section of a railway tunnel characterised by heterogeneous geological conditions, the vertical displacements of the crown were predicted and compared with the monitoring results.

Kurzfassung:
Dieser Beitrag beschäftigt sich mit einer neuen Methode zur Vorhersage von Verschiebungen, im Besonderen Setzungen und Querverschiebungen, im Tunnelbau. Grundlage der Berechnung sind analytische Funktionen, die das zeitabhängige Verhalten des Gebirges und des Ausbaues sowie den Einfluß der fortschreitenden Ortsbrust beschreiben. Kurzzeitprognosen des Gebirgsverhaltens und Erkenntnisse von rückgerechneten Fallstudien liefern die notwendigen Parameter der analytischen Funktionen. Mit dieser Methode kann jedes beliebiges Vortriebs- und Stützmittelkonzept simuliert und beurteilt werden. Hochentwickelte mathematische Werkzeuge wie die Methoden der künstlichen Intelligenz und Kurvenanpassungs-Algorithmen werden dazu verwendet. Anhand eines Eisanbahntunnels mit schwierigen inhomogenen und heterogenen geologischen Gegebenheiten wird das Programm getestet. Der Vergleich der prognostizierten Firstsetzungen mit den gemessenen Werten zeigt eine sehr gute Übereinstimmung.

Introduction

When tunnelling through fault zones under high overburden large deformations are frequently observed, creating a variety of problems. One of them is the accurate estimation of the amount of overexcavation required. So far, methods for estimating displacements are not fully proven. In squeezing ground the lack of efficient displacement prediction may lead to reshaping or backfilling overexcavation with concrete in cases where the displacement estimation was too high. Modern tunnelling methods are based on monitoring and interpreting displacement measuring data as well as geological and geotechnical information. Systematic monitoring of absolute wall displacements to determine the appropriateness of support quantity and type to control tunnel stability is an integral part of the design of underground openings and an important feature of the NATM (1). The NATM considers the variations in local geological and geotechnical conditions and demands flexibility of support and excavation method. For safe and economical tunnelling under squeezing conditions a continuous adaptation of the support and excavation concept is required. Simple, quick and efficient tools are needed to predict rock mass behaviour and displacements.

Principles of Short term Prediction of Rock Mass Behaviour

In Austria, it is common practice that displacements are monitored by geodetic methods during tunnel excavations (2). This monitoring method provides valuable information about the deformation behaviour of the rock mass. It allows three-dimensional displacements to be determined, including the tunnels axial (longitudinal) displacements.

When tunnelling in major fault zones, it can be shown that the ratio of the longitudinal displacements to the settlements (L/S) varied significantly when rock masses with different stiffness or structure are encountered (3). When the excavation approaches a "stiffer" rock mass the vector orientation shows an increasing tendency to point in direction of excavation. On the other hand when excavation approaches a "weaker" rock mass the vector orientation shows an increasing tendency to point against direction of excavation.

A research project was initiated at the Technical University of Graz in order to systematically study the observed phenomena (4). The results indicated that when tunnelling in a rock mass with continuously increasing deformability, the amounts of the longitudinal and vertical displacements will increase, while the ratio (displacement vector orientation L/S) of those two components remains constant. Any deviation of the vector orientation from a "normal" orientation must be caused by a different stress situation around the tunnel.

Varying rock mass stiffness results in heterogeneous stress distributions around the excavation. This heterogeneous stress field strongly influences the rock masses natural tendency to self-stabilise. The rates of displacements in a heterogeneous rock mass have been observed to be highly variable. For example, one monitoring station may have displacements that cease within a few days, while at a neighbouring station displacements may continue for several days. The magnitudes of the final displacements are also highly variable, and can not be correlated to a specific response type.

It is obvious that prediction of displacement behaviour as well as final displacements, will become more accurate with increasing knowledge about the stress situation in the rock mass.

Principles of Prediction of Displacements in Tunnelling

Analytical methods allow one to determine the influence of geological and geotechnical parameters on displacements with a relatively low expenditure of time and costs. Useful methods have been applied for instance by Hoek (5) or Feder (6), but most are limited to two dimensional and time independent problems.

Guenot et al. (7) proposed a general analytical function for wall displacements during tunnelling. This function incorporates time-dependent behaviour of the rock mass as well as the effect of the advancing face. Barlow (8) expanded this function to consider sequential excavation, installation of support, and displacements occurring ahead of the face. The rock mass is described by four parameters: Two parameters describe the time dependent behaviour (comparable to creep) and the other two describe the response to the face advance (one parameter is proportional to the plastic radius around the tunnel, the other can be seen as an initial rate of displacement immediately after excavation). Support is simulated by damping the displacement function which requires two additional parameters. Sequential excavation is modelled by superimposing the displacement function for each face.

An exact physical dimension (in a conventional sense) cannot be assigned to the function's parameters. Rather, they can be seen and treated as descriptive properties of rock mass and support. They can be back calculated from case histories or numerical simulations, stored in data base systems and compared with other geological and geotechnical properties.

Using statistical methods, expert systems, and artificial neural networks it is possible to find correlations and dependencies between the function's parameters and the geological and geotechnical parameters. Those "rules" enable the determination of the function's parameters and consequently the displacement behaviour for a certain geological and geotechnical situation. The accuracy of this prediction method depends on quality and quantity of available information for both the specific problem and the case histories used for the knowledge base.

A procedure is currently under development which is based on these analytical displacement functions (9). To determine the function's parameters an expert system in combination with artificial neural networks is used. The expert system contains the knowledge of numerous site date, stored in the data base system DEST (10).

The calculation program, which is coded in MATLAB (The MathWorks Inc.), is prepared to consider several options, such as installation of supports of different quality and quantity at any desired time, simulation of sequential excavation and non steady tunnel advance, or calculation of displacements ahead of the face (see figure 1).

There are two possibilities for predicting displacements. The first, a very simple but accurate method is to predict final displacements after a few displacement readings at a given cross section. The rock mass behaviour is determined form previously excavated sections and from short term prediction as described above. This is done by fitting the analytical displacement function to the measured displacements. The obtained function's parameters represent the displacement behaviour of the observed section. Installation of additional support, of a temporary top heading invert or a change in excavation procedure can be done on time to meet displacement restrictions. This method is called the "Extrapolating Prediction Method" The accuracy of the prediction increases with the number of available displacement readings at the observed cross section.

The second method is used to predict final displacements and determine amount of overexcavation for sections to be excavated. The information required for the rock mass behaviour and support influence is gained from the data base which stores knowledge from back-calculated case histories and projects. Information describing the geological and geotechnical conditions for the specific section is gained at the face. Easy to obtain parameters such as overburden, joint parameters, RMR and weathering conditions are used as input parameters for the artificial neural network, which calculates the function's parameters and thus displacements. This method is called the "Pure Prediction Method".
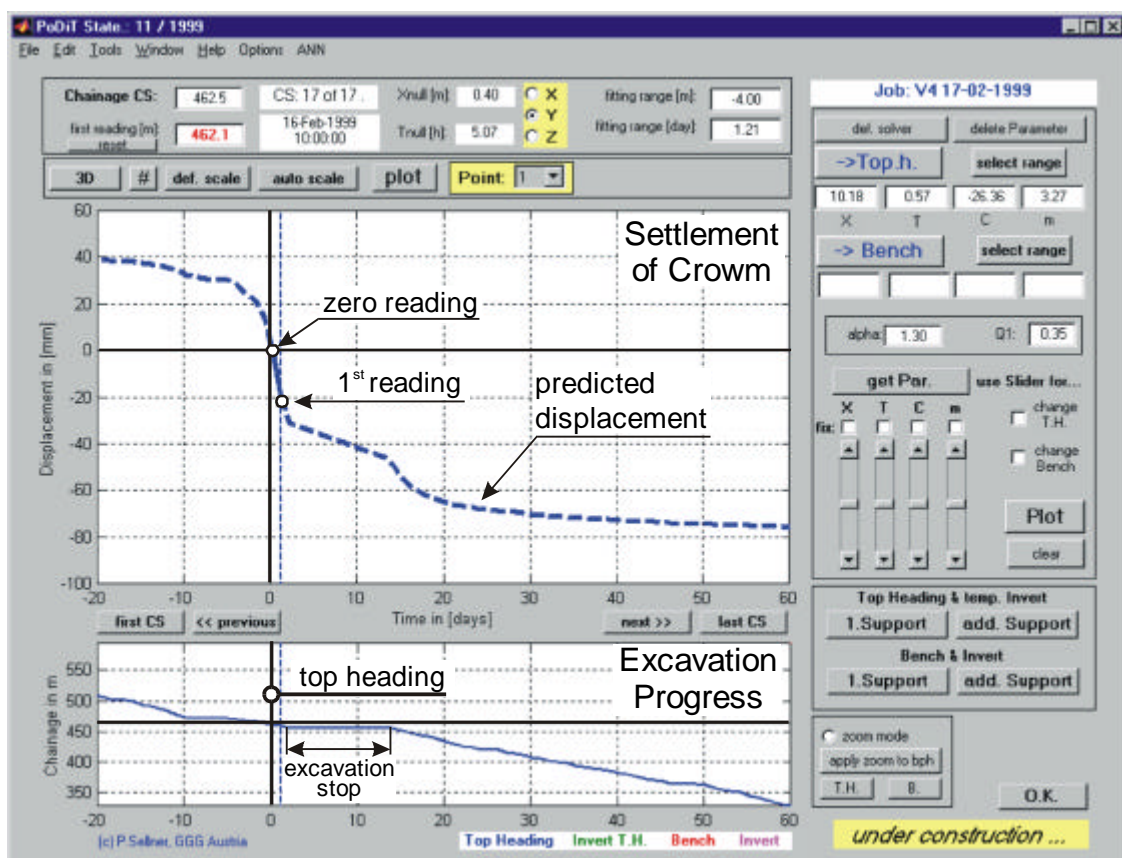

Fig. 1 **Control window for displacement prediction procedure.**
Bild 1: **Berechnungsprogramm für Verschiebungsprognose**

Application on site:
The following cases history ("Wolfsgruben" double-track railway tunnel) shows some of the practical applications of the methods described above. The tunnel, 1.5 km long, will increase the safety and capacity of the Arlberg railway line in Western Austria. The tunnel was excavated by drill and blast as well as with excavators and has a cross section of approximately 110 m². It was excavated using top heading and bench excavation method.
The following figures show examples from the first 500 m of the tunnel which are located in a tectonically influenced and partly disintegrated and fractured "weak" metamorphic rock consisting mainly of mica schists and phyllites. In this section the tunnel has a maximum overburden of about 40 m.

Prediction of rock mass behaviour:
In order to improve the displacement predictions, information about the stress situation around the tunnel is taken into account, which was gained from the interpretation of the displacement vector orientation on site.
Experience from tunnels constructed in weak rock showed that the average monitored angle between longitudinal displacement and settlement is approximately 10° against the direction of excavation, which can be considered "normal". As mentioned above, deviations from the "normal" are indicating a change in the stress rearrangement process and thus changing rock mass conditions ahead of the face.
Figure 2 shows the trend of the displacement vector orientation (L/S) of the left sidewall during the top heading excavation and the simplified geological situation (11). The advance is in decreasing chainage. From chainage 485 to 475 the vector orientation showed an increasing tendency against the direction of excavation, which indicated comparatively poor ground ahead of the face. The "weaker" rock mass was encountered at chainage 465. When the face entered the "weak" rock mass, the vector orientation tended to go back to "normal". With further advance the vector orientation again showed a significantly increasing tendency against the direction of the excavation. This indicated a stress concentration ahead of the face caused by two fault zones, which strikes obliquely to the axis and dip towards the face. After the face has passed the fault zones at chainage 435 the vector orientation tended to point in direction of the excavation, indicating "stiffer" rock mass ahead of the face. At chainage 419 an over break of approximately 50 m³ occurred at the right upper sidewall. The failure of the ground could possibly be explained by a competent rock pillar consisting of amphibolite at chainage 410, which accumulated stresses. The stress redistribution further ahead of the face lead to a relaxation in the vicinity of the face, which probably caused the overbreak.
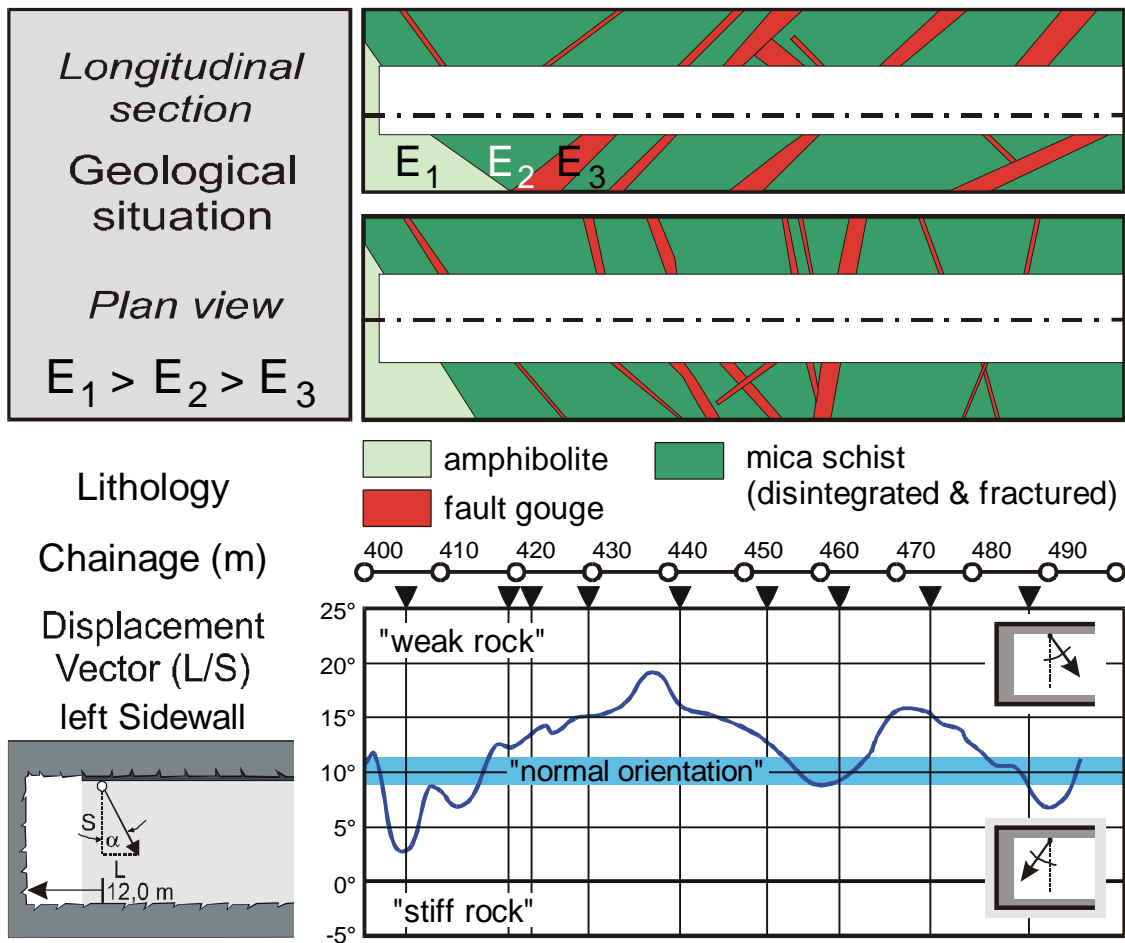
Fig. 2 Geological situation and trendline of displacement vector orientation
Bild 2 Geologische Situation und Trendlinie der Vektor Orientierung

Prediction of displacements:

During the construction of the "Wolfsgruben" tunnel, the displacement prediction procedure was tested on site. At this stage of development and data availability it was not possible to use and test the pure prediction method, because the required information database and the expert system was not yet established. Nevertheless, data from this project was used to test the procedure of predicting final displacements using the extrapolation method.

In figure 1 the control window of the calculation program is shown. The displacements are calculated with the monitoring data available at a certain time. The excavation advance for the extrapolation of the displacement function is assumed similar to that of the executed project, so that calculated displacements can be compared with the monitored displacements.

According to the geological and geotechnical information available at the respective stage of excavation final displacements are predicted and compared with the results of the geodetic survey. The overall error of predicted to final displacements is approximately 16 % using only the first reading after the zero measurement. Using three readings decreases the error to 13 %. In figure 3 the results of the prediction and the final settlements of the crown due to the top heading excavation are shown. The displacement prediction provides accurate results for most of the observed section.

Prediction of final Settlement of Crown
Wolfsgruben Tunnel
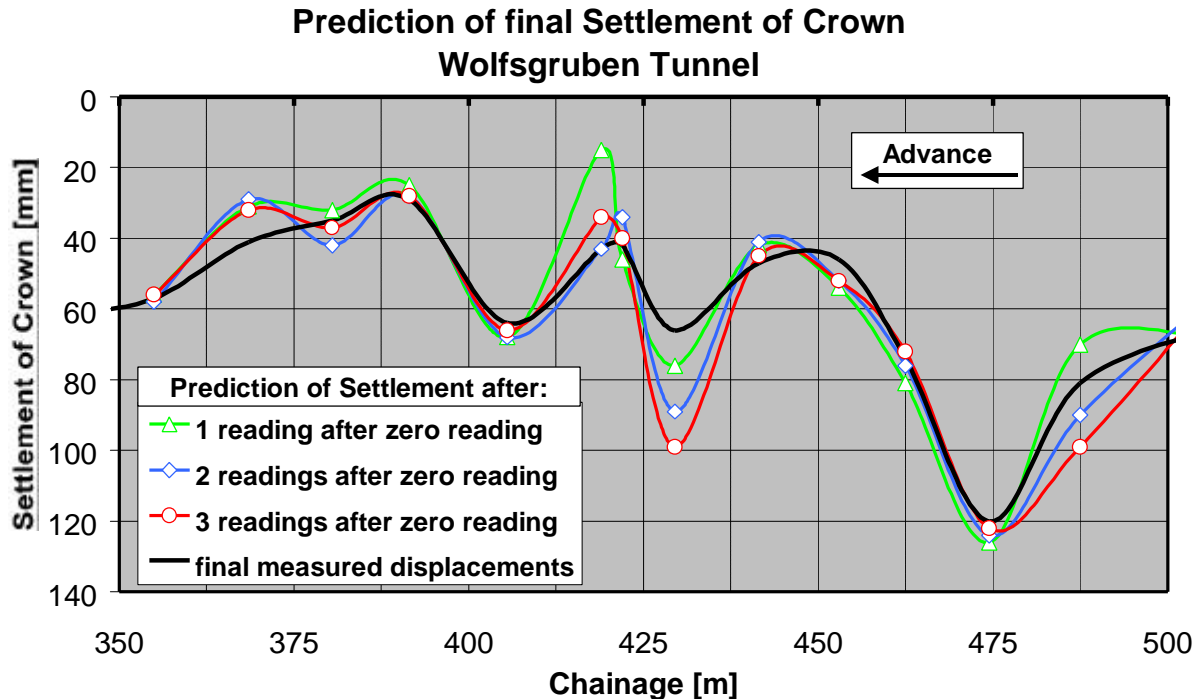
Fig. 3 Results of displacement forecast: Final displacements as well as the result of the prediction are displayed.
Bild 3 Ergebnis der Verschiebungsprognose: Dargestellt sind die gemessenen und die vorhergesagten Endverschiebungen.

Cross Section 430:
The worst result was obtained at chainage 430 m. The evaluation of the predicted settlements at cross section 430 m indicated an abnormal behaviour at this section. The predicted final crown settlement at cross section 430 m increases from 76 mm (one day after excavation) to 89 mm (two days after excavation) and further to 100 mm (three days after excavation). Ultimately 65 mm of settlement were observed at this section. Normally, the accuracy of the prediction's result should increase with the number of available displacement readings. However, for this section, the accuracy is decreasing. A closer investigation of this section was done to find reasons for this abnormal fact. As mentioned before, an overbreak occured on the 12th of March 1999 in the right sidewall and crown at chainage 419 m. Excavation stopped for a few days, and additional support was installed at the damaged section. The evaluation of displacement vector orientation of the crown does not clearly indicate this stability problem. Perhaps, the increase of predicted final displacements can be seen as an indicator of approaching worse conditions. Some days after the reconstruction of the overbreak the prediction provides an accurate result of 65 mm final settlement for cross section 430 m.

Section 405 m – 395m:
From chainage 405 m to 395 m the tunnel intersects amphibolite, which is stiffer and more competent in comparison to the previous section of partially disintegrated and intensively fractured mica schist, which is sometimes intersected by fault gouges. The geological longitudinal section and the trendline of the displacement vector orientation is shown in figure 4. Starting from chainage 435 m the vector orientation shows an increasing tendency in direction of excavation which indicates better conditions ahead of the face. The time depending deformation behaviour of the better quality rock mass will be less pronounced than in the last section and consequently displacements will decrease. This information was

used for the prediction of displacements within this section. For example, the procedure of prediction is shown for cross section 405 m:

First, the two parameters relating the time-dependent behaviour of rock mass were taken from the previously excavated and back-calculated section. The other two parameters, which describe the response to the face advance, were calculated by fitting the analytical function to the zero and first reading of the crown's settlement, keeping the time dependence constant. Then, the parameters describing the time depending behaviour were decreased to consider the "stiffer" and "more competent" conditions ahead of the face. Again, the function was fitted to the measured displacements using the modified time dependent parameters. The result of the displacement prediction incorporating short term prediction of rock mass behaviour is very accurate. One day after the excavation, the final settlements were predicted to 68 mm. The finally measured settlement was 64 mm.

Within a section of similar geological conditions the function's parameters – especially the parameters which control the time dependent behaviour – show little variability. This makes the displacement's prediction within this section straight forward. A change in rock mass conditions can be seen in time by evaluating displacement vector orientations and the function's parameters adapted adequately.
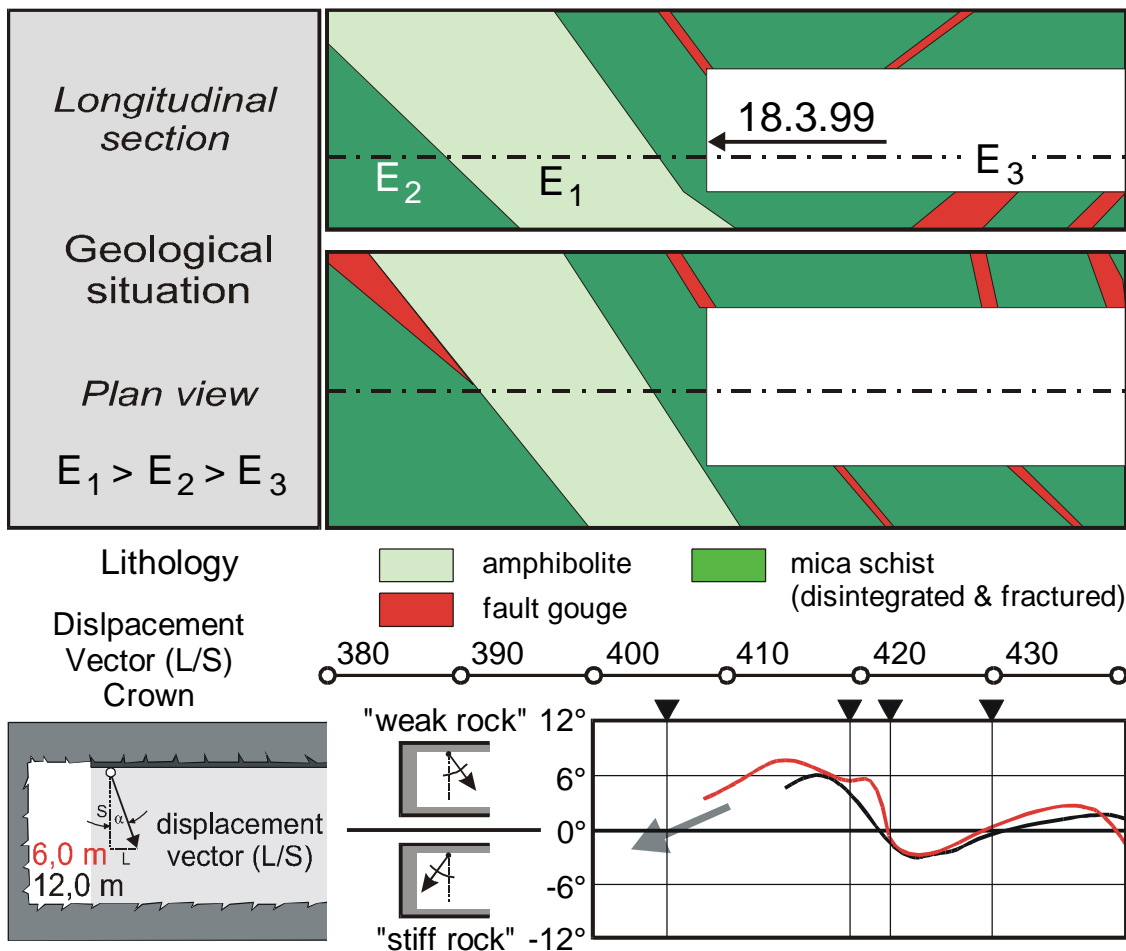
Fig. 4 Geological situation and trendline of displacement vector orientation
Bild 4 Geologische Situation und Trendlinie der Vektor-Orientierung

Conclusion

The proposed methodology offers two different prediction techniques: The first is based on back calculating displacement behavior from only few available measurements. Considering the observed behavior of already excavated sections and incorporating information of short term prediction of rock mass behaviour, it is possible to predict final displacement with a high precision. Installation of additional support or change in excavation procedure can be done on time to meet displacement restrictions. The second prediction technique uses the knowledge of case histories and provides reliable displacement determination before the excavation. Required overexcavation, support systems and excavation procedure can be fine tuned in time. The latter procedure has not been applied on site at this time, but successful tests have been accomplished and the accuracy is increasing by supplying more site data to the knowledge base. Both procedures show sufficiently accurate results.

Further research work and development is continuing at this time to install an expert system using a case history knowledge base to calculate the function's parameters and displacements preceding the excavation advance.

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