Tunnel convergence analyses in heterogeneous/anisotropic rock masses

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ABSTRACT: It is very difficult task to excavate a tunnel in poor and heterogeneous ground. Although with a good geological investigation, uncertainties due to the local rock mass structures will still remain. Especially for such conditions, a reliable prediction of the conditions ahead and outside the tunnel profile are of paramount importance for the choice of appropriate excavation and support methods. In this paper, we present the effects of the heterogeneity/anisotropy of the weakness zone on tunnel convergence. Three dimensional Finite Element simulations of different weakness zone properties, thickness, and orientation relative to the tunnel axis were carried out and the function parameters evaluated from the results. The results are compared to monitoring results from Alpine tunnels in heterogeneous/anisotropic rock. The good qualitative correlation between trends observed on site and numerical results gives hope that by a routine determination of the function parameters during excavation the prediction of rock mass conditions ahead of the tunnel face can be improved

1 INTRODUCTION

Displacements around tunnel are strongly influenced by small or large scale weakness zone such as heavily jointed and faulted zone, sometimes shear zones etc. Several case histories on large deformations and collapses due to these kinds of weakness zone show the importance of heterogeneity/anisotropy of the embedded weakness zones. If we can predict all these kinds of influencing factors during tunnel excavation, we can more be safe from the excavation induced hazards.

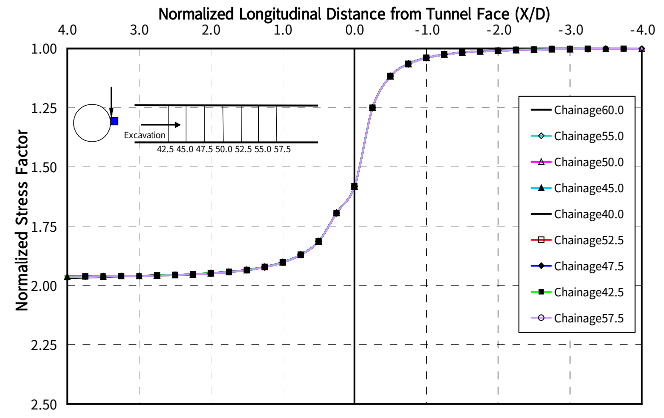
Henceforth, during the tunnel excavation a reliable monitoring and feed-back is very important for the determination of the proper support type and quantity, and for controlling the tunnel stability. Geodetic measurements of absolute displacement allow us to understand what happened ahead and outside of tunnel face in 3-dimensional monitoring space. These methods to a large extent have replaced relative displacement measurements in many countries, but still be used the conventional tape extensometers for measuring tunnel convergence in Korea. Comparing with the relative displacement measurement, the absolute monitoring results give us very useful information about the ahead or outside of tunnel face and several things etc. The evaluation of data gained from the excavation of tunnels constructed in Austria showed, that the ratio between radial and longitudinal displacement varied in a wide range. Matching the observed phenomena with the geological documentation, it was found that deviations of the ratio appeared when zones of different deformability were approached with the excavation (Schubert 1993). To verify the hypothesis, numerical 3-D simulations have been performed. The results showed that changing rock mass conditions ahead of the tunnel face clearly influence the displacement vector orientation (Schubert & Budil 1995, Steindorfer & Schubert 1997, Steindorfer 1998). To quantify the influence of weak zones on stresses and displacements, further research has been conducted (Grossauer 2001). Sellner (2000) developed software, which allows the short-term displacement prediction, namely GeoFit. Particularly, Kim (2003) suggest the relationship between convergence function parameter X, C and the rock mass quality of the ahead of tunnel face through several 3-D FE analyses, and verified by several Alpine tunnel case histories.

The function parameter X, C, T, m and the displacement vector orientations show some relationship between the modulus contrasts and the thickness of the weakness zones (Kim 2003). So, this paper suggests several qualitative clues for the effects of the heterogeneous/anisotropic nature of rock masses on the tunnel convergence results and the possibility of the prediction of the rock mass quality ahead of tunnel face during tunnel excavation using 3-D FE simulations.

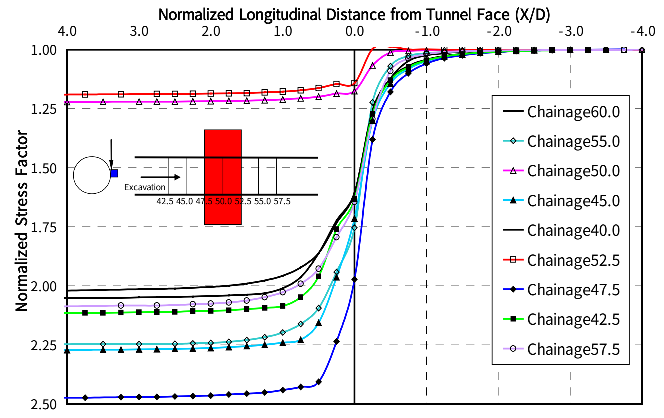
2 INFLUENCE OF WEAKNESS ZONES

2.1 *Stresses*

A weakness zone has a significant influence on the stresses and displacements during tunnel excavation. In the case of normal, namely without weakness zone (Fig. 1(a)), at all measuring points, similar stress concentrations are detected, but, in the case of the excavation through the weakness zone, near and around weakness zone, severely high or low stress concentrations are shown. In the weakness zone (Ch. 50, 52.5), very low stress concentrations are observed, on the other hand, near the weakness zone such as Ch. 45, 55, more higher stress concentrations are detected in Figure 1.



(a) without weakness zone



(b) with weakness zone

Figure 1. Stress concentrations of two cases; (a) without weakness zone, (b) with weakness zone (MC = 10, T_w =0.5D). MC; modulus contrasts, T_w; thickness of weakness zone, D; tunnel diameter

When the excavation approaches a weakness zone, stresses increase in the stiffer material. On the other hand, due to an arching effect in the weakness zone, stresses close to the stiffer boundaries decrease within the weakness zone. Figure 2 shows the stress and displacement changes in the vicinity of a weakness zone for different modulus contrasts. Variations of the embedded weakness zone widths and lead to similar results (Grossauer 2001).

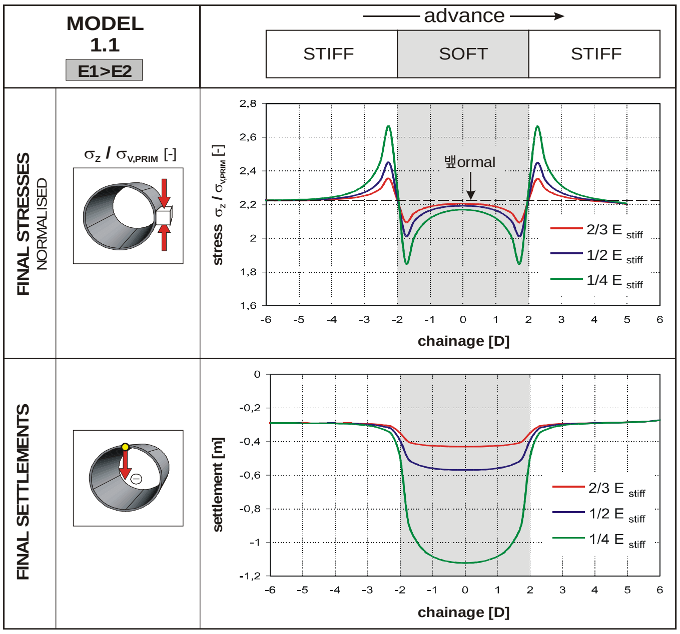


Figure 2. Stress distribution and final displacements when tunneling through a weakness zone (different modulus contrasts). Stresses are normalized to the primary stresses

2.2 *Displacements*

The changed spatial stress situation around a tunnel in the vicinity of a fault zone strongly influences the deformations of the rock mass. It could be shown, that the displacement vector orientation shows significant changes much earlier than radial displacements.

Figure 3 shows settlements and the trend of the displacement vector orientation for a tunnel in a tectonic melange in Austria. Pronounced changes in the displacement vector orientation can be observed well before the excavation actually reaches the stronger or weaker rock masses.

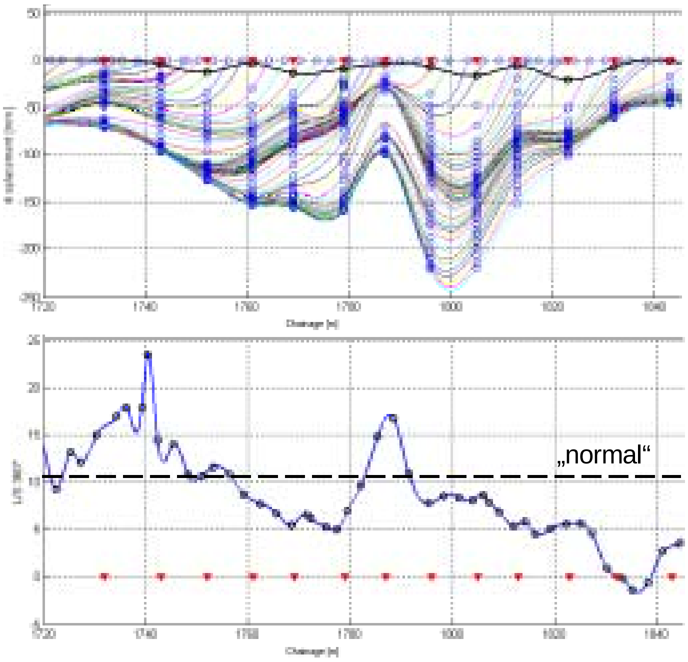


Figure 3. Settlement and displacement vector orientation trend for a side wall point at the tunnel Spital, Austria

3 NUMERICAL SIMULATIONS

3.1 *Finite element mesh*

In these numerical simulations, we mainly focus on the influence of the heterogeneity/anisotropy of the weakness zone due to tunnel excavation. Specially, the influences on the thickness, modulus contrasts and the orientations of the weakness zone are investigated. So, the support effects are neglected and purely excavation effects are analyzed in these parametric studies. The full face circular tunnel excavation is simulated by 2.5 m in each round length. The tunnel diameter is 10m, and the maximum overburden is about 50 m. Total 30 excavation steps are considered. In order to simplify the numerical model, pure elastic and gravity controlled models are investigated with non-linear elasto-plastic 3 dimensional FE code UTAH III.

Figure 4 shows the 3-D FE model which consisted of 10260 elements and 10912 nodal points.

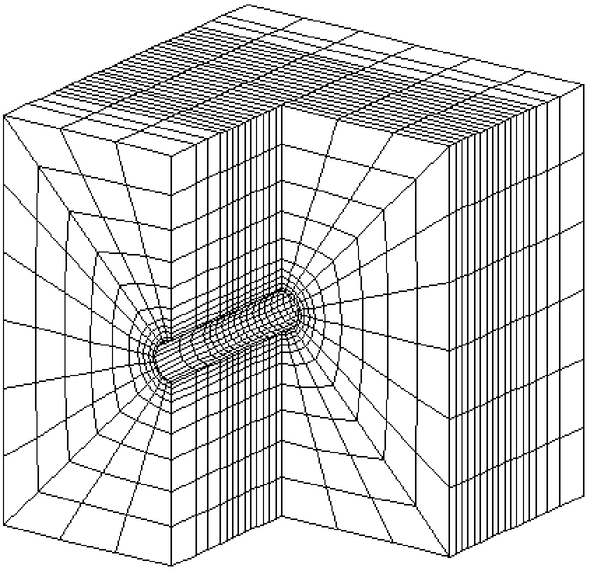


Figure 4. 3-D finite element model for the parametric study

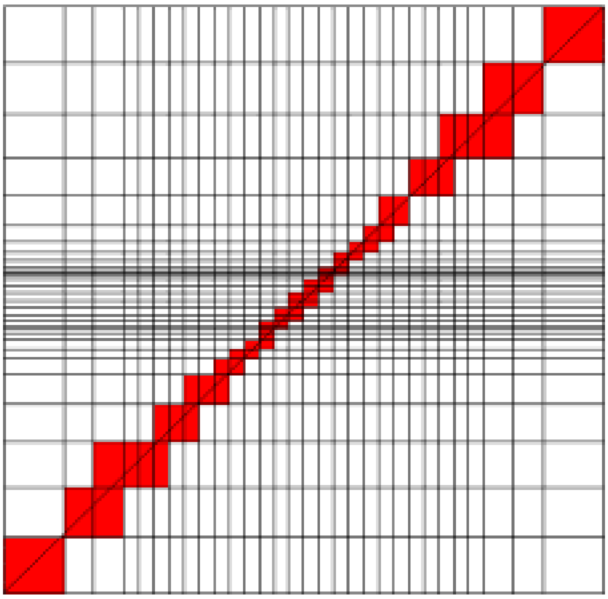


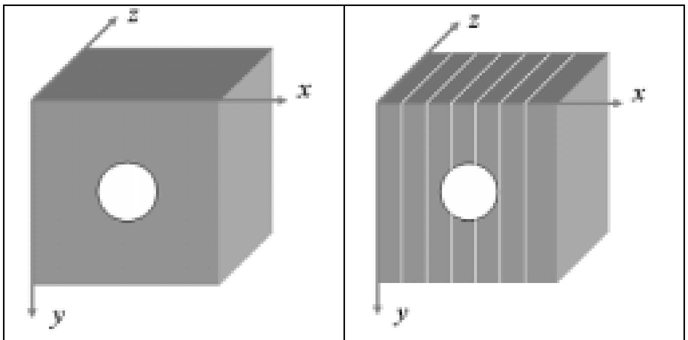
Figure 5. Weakness zone embedded model

3.2 *Weakness zone embedded model*

The FE code UTAH III has several preprocessors such as VOL4, PM etc. VOL4 program is the one of these pre-processors. VOL4 program can detect the arbitrary oriented joints or fault planes which can pass through the 3 dimensional space elements as shown in Figure 5. PM program also can calculate the overall modulus of the matrix which is consisted of the weakness plane and the intact rock masses.

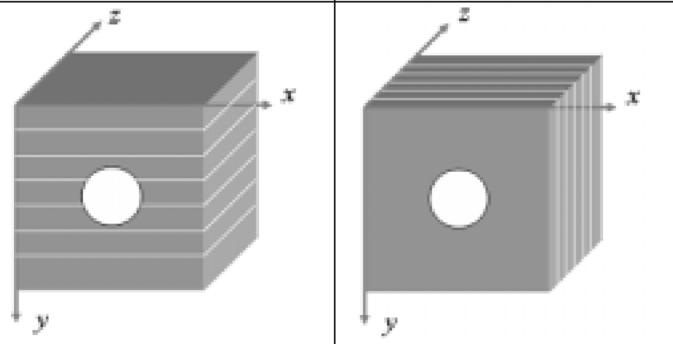
3.3 *Anisotropic model*

Simplified transversely isotropic models are investigated on the convergence function parameter X, C. Figure 6 shows 4 models. One isotropic model (Fig. 6(a)) and three transverse isotropic models (Fig. 6(b), (c), (d)) are considered. Rock masses properties are shown as Table 1. The Volume fraction means the ratio between total volume of weakness zone and intact rock. In this research, we assumed approximately 20% of the volume fraction. The modulus of the intact rock is ten times higher than the weakness zone.



(a) Isotropy

(b) Transverse isotropy plane perpendicular to x-xis



(c) Transverse isotropy plane perpendicular to y-axis

(d) Transverse isotropy plane perpendicular to z-axis

Figure 6. 3-D anisotropic model for RVE (Representative Volume Element)

Table 1. Rock masses properties for numerical analyses

	Intact rock mass	Weak/fractured zone	Volume. fraction (V_{weak}/V_{intact})
Young's modulus	1000 MPa	100 MPa	0.2
Shear modulus	400 MPa	40 MPa	

Table 2 shows the function parameter X, C value on 4 models. In isotropic case, the X value is about 5.40 and the C value is approximately -6.70 mm, but, the case of the transverse isotropic plane perpendicular to x-axis shows the highest value of X among these models. On the other hand, the case of the transverse isotropic plane perpendicular to z-axis shows the lowest value of X. In the case of C value, the isotropic case shows the lowest value, but, the case of the transverse isotropic plane perpendicular to y-axis indicates the highest value. Figure 7 indicates the normalized displacement history. The displacements are normalized by maximum settlements. The displacement history of the case of Y-anisotropy indicates very similar with the isotropic case. Although the case of X-anisotropy is more smoothly converged, the case of Z-anisotropy is more quickly converged than the isotropic case. It means that the value of X is very important to evaluate the influence of face advancing.

Table 2. Function parameter X, C value

	X		C	
	crown	side wall	crown	side wall
Isotropy	5.40	2.21	-6.70	-3.55
Transverse isotropy plane perpendicular to x-axis	7.24	2.42	-11.50	-7.57
Transverse isotropy plane perpendicular to y-axis	6.17	2.04	-16.19	-5.83
Transverse isotropy plane perpendicular to z-axis	4.35	1.27	-8.06	-4.09

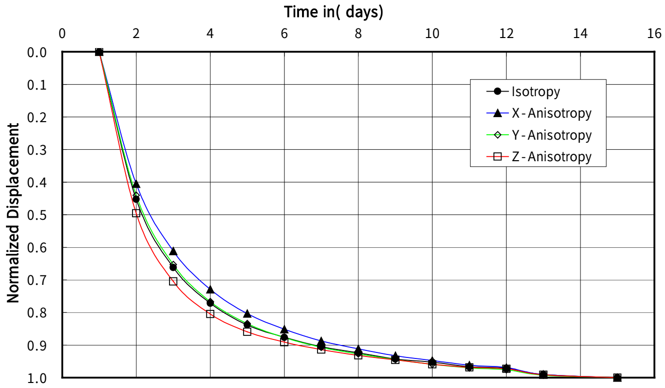


Figure 7. Normalized displacement history in each model

3.4 *Heterogeneous model*

When excavating in uniform rock mass and primary stress conditions, it can be assumed that the single displacement vector components have a certain relationship. With different deformability of the ground, the absolute displacement values change but the ratios between the single components do not vary substantially. Evaluations of data from tunnels constructed in poor rock show that the average angle between longitudinal displacements and settlements have a certain value against the direction of excavation. This vector orientation can be considered as 'normal'. Different boundary conditions, like changes in the rock mass structure or in the primary stress situation, influence the stress distribution around the cross section of the tunnel as well as ahead of the face, which leads to deviations of the vector orientation from 'normal'. 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 'weaker' rock mass the vector orientation shows an increasing tendency to point against the direction of excavation. Figure 8 indicates the concept of the differential vector orientation.

Figure 9 shows the displacement vector orientation tendency of the case, which the weakness zone thickness is 10 m, according to change the modulus contrasts. Similar pattern of vector orientation is observed in every modulus contrasts case (MC=2, MC=5, MC=10).

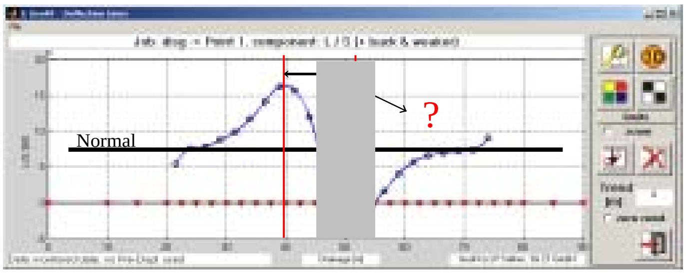


Figure 8. Normalized displacement history in each model

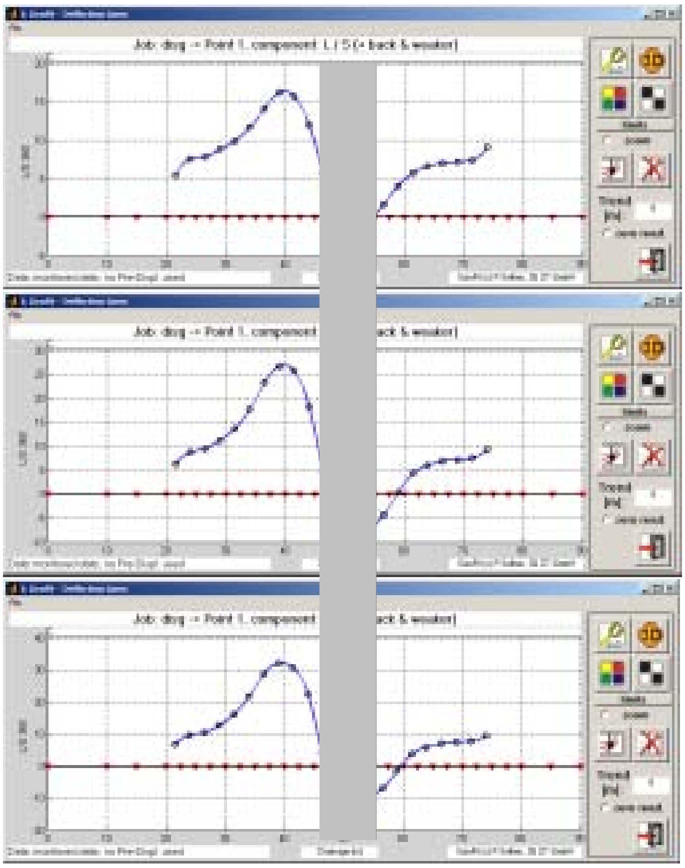


Figure 9. Displacement vector orientations with MC change

Before the weakness zone, the displacement vector orientation is increased to certain value, and then steeply decreased. The peak value indicates the influence of the weakness zone thickness and modulus contrasts etc. The concept of the differential vector orientation (D.V.O) means the difference value between the peak value and normal value which shows in the case of the intact rock mass. From Figure 10, we can see the tendency of the differential vector orientation variations according to the change of the modulus contrasts and thickness of the weakness zone. In brief, the weaker the modulus of the weakness zone, the higher the differential vector orientation, and the wider the thickness of the weakness zone, the higher the differential vector orientation.

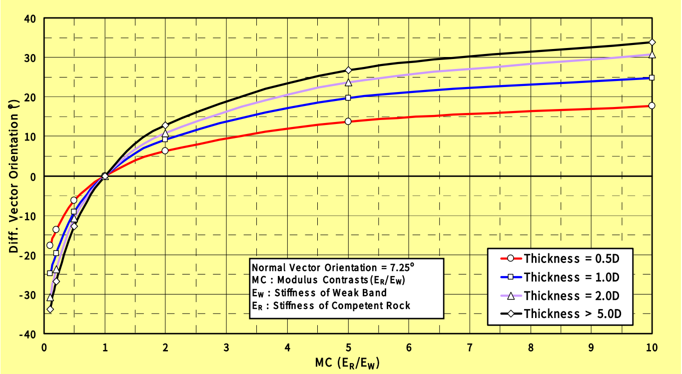


Figure 10. Differential vector orientation variations according to the change of the modulus contrasts and thickness of the weakness zone

Figure 11 shows the variations of the D.V.O according to the change of dip angle of the weakness zone. In this case, the plane of the weakness zone is perpendicular to the tunnel axis. The maximum D.V.O in tunnel crown measuring point is occurred in 60^{o} dip angle against the direction of the tunnel. On the other hand, the maximum D.V.O in tunnel shoulder measuring point is occurred in vertical case as shown in Figure 11.

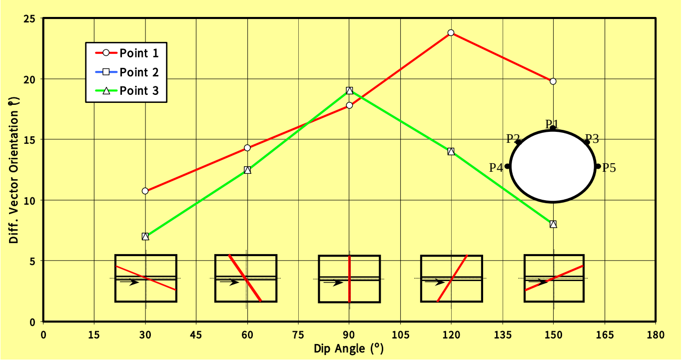


Figure 11. Differential vector orientation variations according to the change of dip angle of the weakness zone

Figure 12 shows a change of the value of a D.V.O by the variation of strike of the weakness zone. When the strike is 0 degrees, a D.V.O value becomes the maximum, and the minimum works when parallel to tunnel excavation direction as shown in Figure 12. Also, the results of measurement point of shoulder show the same trend.

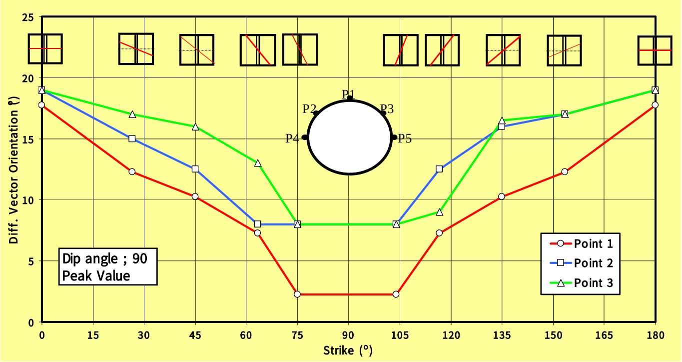


Figure 12. Differential vector orientation variations according to the change of strike of the weakness zone

When try to summarize the results, the strike and dip angle of the weakness zone are important for the D.V.O value.

4 FUNTION PARAMETER CALCULATIONS

4.1 *Back calculation*

Following the ideas on the influence of the changing stress field in a heterogeneous rock mass on the displacements, it is obvious that the trends of the function parameters X, T, C, and m should reflect the geotechnical situation, and thus could be used for prediction. The results of numerical models with elastic rock mass behaviour were imported into GeoFit® and the function parameters obtained by curve fitting (Kim 2003).

Figure 13 shows the back-calculated function parameters X and C for a fault zone width of one tunnel diameter and a modulus contrast of 2.0 between the two rock masses. It can be seen, that the parameter X significantly increases already 15 m ahead of the transition between stiff rock and weak rock, which is located at station 45 m.

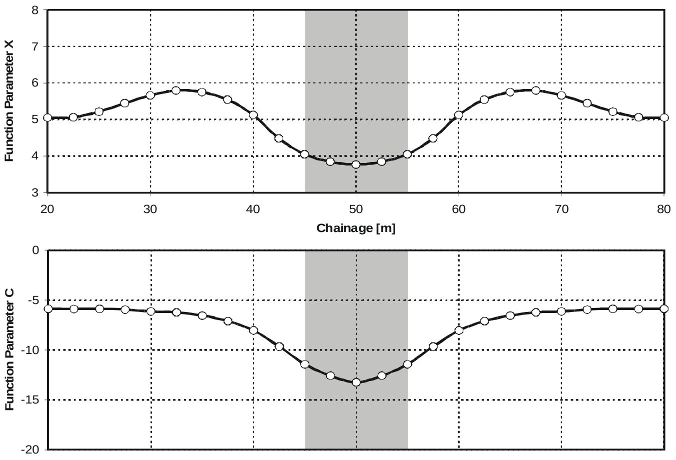


Figure 13. Back calculated function parameters X and C for a fault zone width of one tunnel diameter and a stiffness contrast of 2,0 between the two rock masses

Figure 14 shows the distribution of the function parameters X and C for lengths of the weak zone of 0.5, 1.0 and 2.0 tunnel diameters. Besides the increase of the parameter X well ahead of the weak zone, the results clearly show the influence of the fault zone length on the final displacements within the weak zone, which are reflected through the parameter C. With some experience in this kind of monitoring data evaluation, the combination of displacement vector orientation trends and distributions of function parameter trends can be used to predict quality and extension of weak zones ahead of the tunnel face.

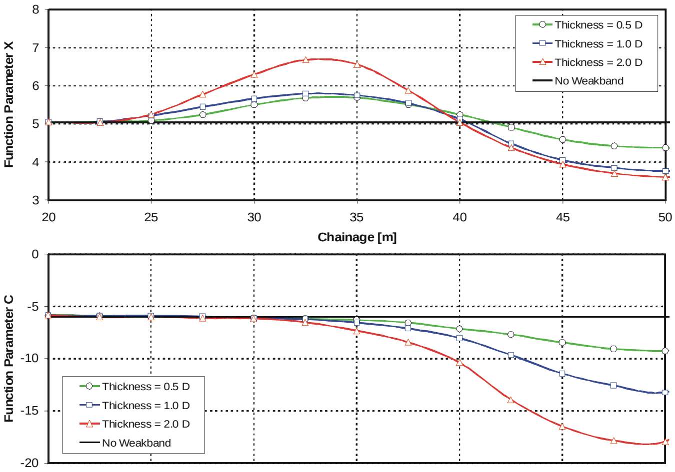


Figure 14. Distribution of the function parameters X and C for different fault zone widths

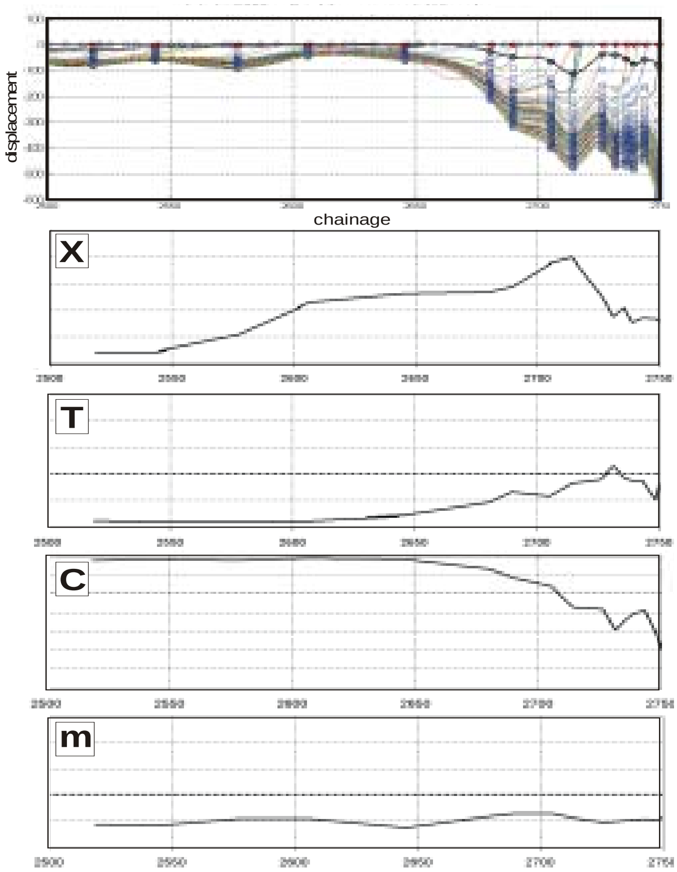


Figure 15.Vertical displacements of the crown point and the appropriate distribution of the function parameters X, T, C and m

4.2 *Case histories*

On several projects the program GeoFit® was used to predict displacements. Figure 15 shows the vertical displacements of the tunnel crown and the parameter sets for a tunnel in phyllites at the transition to a major fault zone. As in the numerical simulations a significant increase of the parameter X can be observed well before the excavation reaches the fault zone.

5 CONCLUSIONS

The 3D absolute monitoring technologies in combination with newly developed methods of data evaluation have improved the possibilities for the prediction ahead and outside of tunnel face. In particularly, in heterogeneous/anisotropic rock masses, the prediction of the vector orientation and function parameters plays an important role with respect to safety and economical aspects of a tunnel project. Software for the evaluation of displacement monitoring data is continuously improved and functions added. With the evaluation of a number of projects in different geological environments under various boundary conditions a knowledge base will be developed, eventually leading to a ‘smart’ data evaluation tool.

6 REFERENCES

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