DISPLACEMENTS IN THE EXPLORATORY TUNNEL AHEAD OF THE EXCAVATION FACE OF ŠENTVID TUNNEL

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Abstract

Fitting the displacement function to the measured displacements enables the assessment of the stabilization process of the observed cross section and the determination of its normal behaviour. The displacement function consists of three parts. Whilst the third part has been successfully applied for several times and thus proven to be very well defined, the first two parts were defined only on the basis of numerical simulations. To overcome this deficiency and to obtain the necessary coefficients of the pre-face part of the displacement function, the 3D displacement measurements ahead of the face due to tunneling should be performed. Such measurements were performed in the exploratory tunnel of the Šentvid tunnel during the excavation of the main tunnel. This paper presents the Šentvid tunnel project, the method of the 3D displacement measurements, the results of these measurements and their interpretation according to the geological structure of the site with an emphasis on items important for the coefficients of the displacement function.

Keywords

tunnel, exploratory tunnel, geodetic displacement measurements, pre-face displacements

1 INTRODUCTION

Since the ancient times, the construction of the tunnels and underground spaces has been a big challenge to engineers. This challenge is even greater when the underground spaces are constructed in faulted and heterogeneous rock mass of low strength and of high deformability. Although a lot of time and money has been spent recently in the design stage to establish a reliable and accurate geological model of the rock mass on the site of the future project, inconvenient geological surprises still occur. To minimize the risk of such situations during the construction of tunnels and other underground spaces according to NATM, the observational approach was introduced already by Rabcewicz [1] and has been later on widely accepted as its integral part [2,3]. Geological-geotechnical monitoring typically includes geological drafts of the excavation faces, results from pressure cells built in the primary lining, measurements of the forces in rock bolts, results from the extensometer measurements of the displacements of the surrounding rock mass and systematic monitoring of absolute primary lining displacements by geodetic methods.

Based on the interpretation of these results the quality and quantity of the rock mass support, the excavation sequence and the technology foreseen by the tunnel design are checked daily and adjusted when necessary. Monitoring enables the observation of the rock mass – support system response due to the face excavation advance and time dependent effects of the surrounding rock mass and shotcrete.

The interpretation of the 3D displacement measurements of the targets in primary lining has proven to be the most convenient method for daily monitoring of the tunnel behaviour [3]. The targets are installed on the circumference of the primary lining in measuring sections, which should be arranged at a distance approximately one equivalent diameter along the tunnel axis. The 3D positions of the targets are usually recorded once a day or more often if needed. The analysis of the measured displacement allows a reliable prediction of the rock mass conditions ahead of the face and around the tunnel tube [4].

The displacement history plots are the most common plots of the measured displacements and are used for the assessment of the stabilization process of each individual cross section. The displacement rate is highest immediately after the top heading excavation and the support installation, and it decreases with the further excavation advance (Fig. 1). As soon as the bench excavation face approaches the observed cross section, the displacement rate increases again and after the closure of the support ring (execution of the invert) it reduces to zero.

The expected behaviour of the cross section is shown in Fig. 1. Stresses induced by the excavation are regularly distributed between the support and the rock mass in the way that the support is not overstressed and thus damaged. The displacement history plot in Fig. 1 indicates the proper response of the rock mass – support system.

Contrary to the behaviour shown in Fig. 1 the displacement history plot in Fig. 2 reveals the inadequate support in the vicinity of the measuring section to carry the load transferred from the surrounding rock mass. The displacement rate did not decrease after the top heading excavation or after the closure of the support ring. Fig. 3 shows the failure of the primary lining in the area of this measuring section.

Although one can clearly see that the rock mass – support system had malfunctioned, the determination of the point where loads exceeded the capacity of the support is a difficult task. What would be the adequate

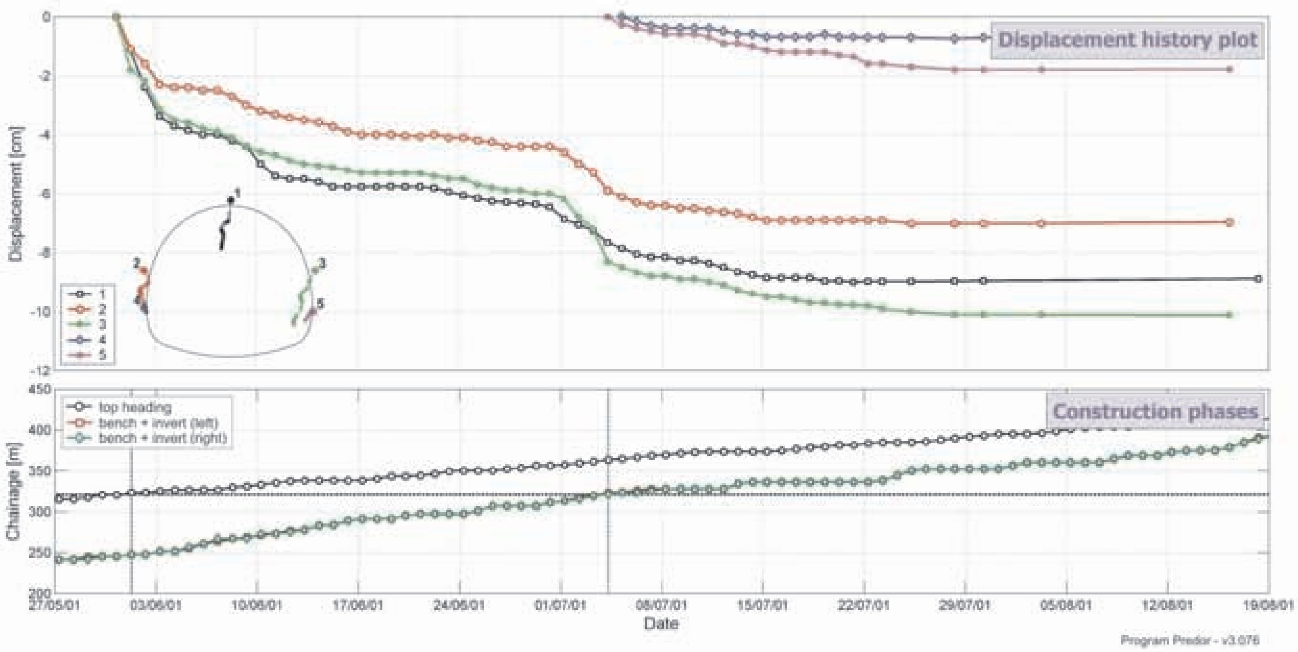

Figure 1. Regular behaviour of the cross section as shown on the displacement history plot.

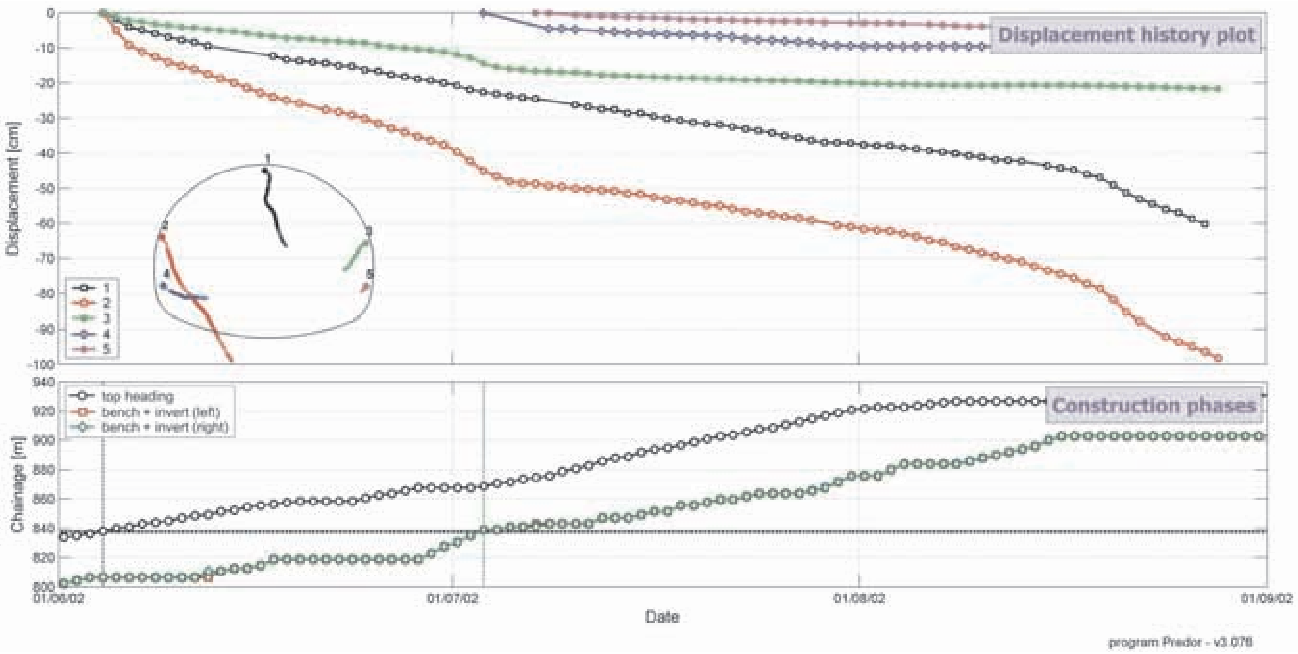

Figure 2. Displacement history plot of the points in vertical direction in the cross section with insufficient support measures to carry the pressure of the surrounding rock mass.

Figure 3. Failure of the primary lining in the parking by niche in the left tube of the Trojane tunnel at chainage km 82+295 (area of the measuring section from Fig. 2).

support measures to avoid excessive displacements and consequently the failure of the support?

There are several possibilities to answer this question. One of them is the 3D numerical analyses, which are not suitable for use on a day-to-day basis due to their inability to model complex geological structures, unreliable material parameters of the rock mass, lack of knowledge on the primary stress state and especially because they are time consuming and costly [5].

On the other hand, analytical methods with even more simplifications of the stress and rock mass conditions with limitations to two dimensional and time dependent problems do not provide the needed degree of reliability.

In the next chapter a description of a simple, but very accurate method will be given. This method is based on the fitting of the analytical function to measured displacements in order to determine the anticipated behaviour of the rock mass – support system.

2 THE DISPLACEMENT FUNCTION

2.1 BASICS OF THE DISPLACEMENT FUNCTION

The original proposal for the convergence equation was given by Guenot, Panet and Sulem [6]. This analytical function describes the displacements within a cross section of a circular tunnel with full face excavation without the installation of the support. These displacements are caused by face advance effect and time-dependent effects.

In order to overcome the limitations of the convergence equation Barlow extended the displacement function for more realistic description of the conditions during tunneling [7]. Barlow considered the support installation and the sequential excavation.

Further modifications of the displacement function were introduced by Sellner [8], which was implemented in the computer code GeoFit [9].

The displacement function as proposed by Barlow was used in this work and is expressed by the following three equations:

- the displacement that occurs ahead of the face - part 1:

$$C(x,t)=c_1(x)\cdot\left[C_{x\infty}+A\cdot c_2(t)\right] \qquad (1)$$

- the displacement that occurs between the excavation and the installation of support - part 2:

$$C(x,t)=\left[Q_1+Q_2\cdot C_1(x)-Q_k\cdot P_k^{+}(x)\right]\cdot\left[C_{x\infty}+A\cdot C_2(t)\right] \qquad (2)$$

- the displacement that occurs after the installation of support - part 3:

$$C(x,t)=\frac{\left[Q_1+Q_2\cdot C_1(x)+K\cdot C_s-Q_k\cdot P_k^{-}(x)\right]}{\left[1+K\cdot\left(C_{x\infty}+A\cdot C_2(t)\right)\right]}\cdot\left[C_{x\infty}+A\cdot C_2(t)\right] \qquad (3)$$

with

$c_1(x)$ = time independent function (loading function)

$c_2(t)$ = time dependent function

x = distance between observed cross section and excavation face

t = elapsed time between excavation and observation time

X = curve fitting parameter describing the shape of $C_1(x)$

T = curve fitting parameter describing the shape of $C_2(t)$

$C_{x\infty}$ = curve fitting parameter describing ultimate time independent displacement

A = curve fitting parameter describing ultimate time dependent displacement

Q_1 = proportion of the total stress change due to the tunnel excavation that occurs ahead of the face

C_{pf} = proportion of the total stress change due to the tunnel excavation that occurs after the excavation face passes the monitored cross section $(Q_1+Q_2=1)$

$Q_k\cdot P_k^{+}(x)$ and $Q_k\cdot P_k^{-}(x)$ = functions that distribute the effect of the support installation on the displacements ahead of and behind the face, respectively

C_s = displacement at the time of support installation

K = parameter of the support

The main objective of this work is related to the pre-face displacements described by Eq. 1, which includes the loading function ahead of the face (C_{pf}) defined as:

$$C_{pf}=\left[\frac{X}{X+\left(x_f-x\right)}\right]^{1.2} \qquad (4)$$

where

x_f = the length of the pre-face domain (influential area ahead of the excavation face)

2.2 ADVANTAGES OF THE DISPLACEMENT FUNCTION

The simplicity of the algorithm and consequently fast calculations are the major advantages of the use of the displacement function if compared to other methods described above. Unlike the analytical methods the displacement function takes account of time effects and 3D effects of the tunnel excavation. The use of the displacement function is much more time-effective than the use of numerical calculation and does not require a large amount of parameters, the determination of which needs a lot of costly and time-consuming laboratory tests. These advantages make the displacement function suitable for the use on a day-to-day basis on construction sites [9].

To fully exploit the displacement function's advantages, computer software for fitting the function to the measured displacements is required. For this purpose the computer code Predor has been developed [10].

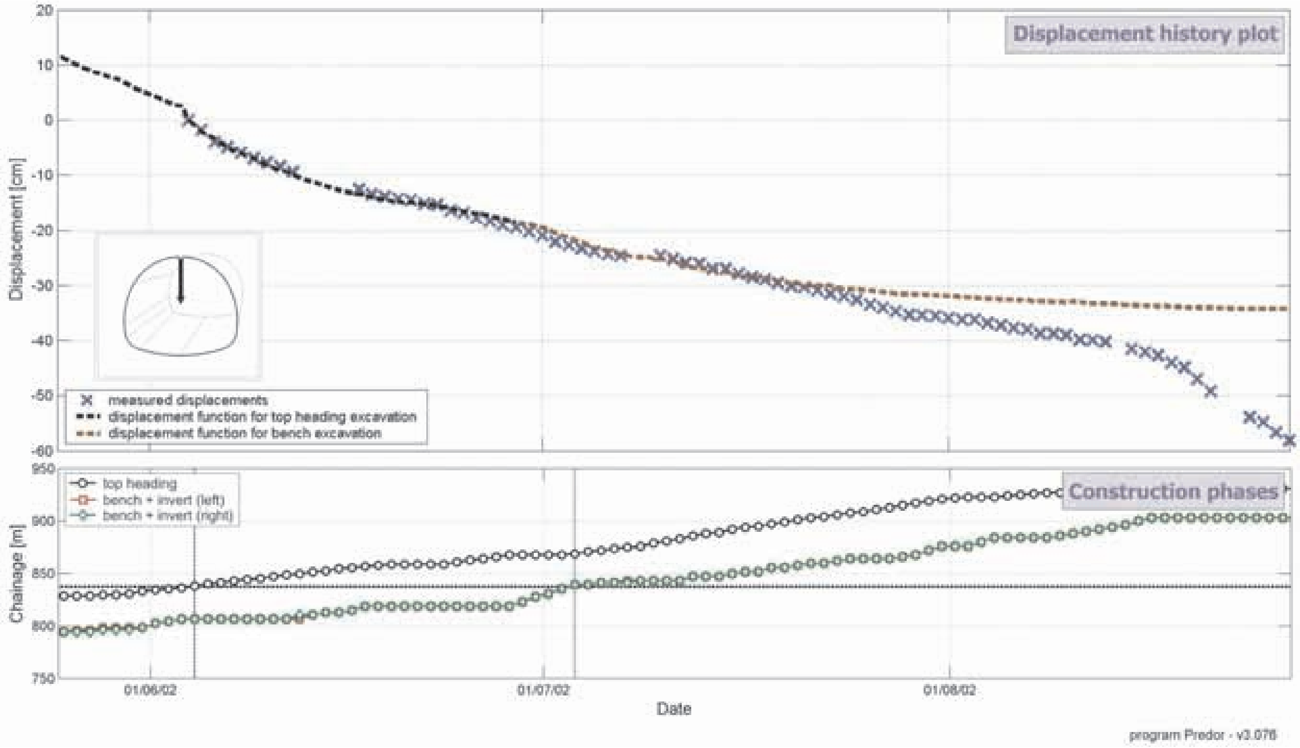

Figure 4. Displacement history plot of the vertical displacement of crown point with fitted displacement function for top heading and bench excavation.

For the case described in Fig. 2 the fitted displacement function to the measured displacements is shown in Fig. 4. The divergence of the theoretical curve and measured displacements in this case indicated the support failure in the vicinity of the measuring section (Fig. 3). According to the fitted displacement curve the failure of the cross section occurred soon after the ring closure at approximately 30 cm of vertical displacement of the crown point. At this point additional support measures should have been undertaken to avoid further disintegration of the rock mass – support system.

2.3 LIMITATIONS OF THE DISPLACEMENT FUNCTION

While part 3 of the displacement function (after the excavation face passed the observed cross section - Eq. 3) is very well defined by fitting the curve to the measured displacements, the first two parts (ahead of the face (part 1) and between the excavation and the support installation (part 2)) are determined on the basis of numerical simulations and rely on the parameters that depend on the rock mass behaviour ahead of the tunnel face:

Q_1 = proportion of the total stress change due to the tunnel excavation that occurs ahead of the face and

x_f = parameter presenting the magnitude of the pre-face domain.

The magnitude of both parameters and the shape of first two parts of the displacement function could be verified or accurately determined only by measuring the displacements within the rock mass ahead of the tunnel face. Obviously, this cannot be done in terms of ordinary geodetic methods.

In case of low overburden and provided that monitoring of the displacements is established in the tunnel as well as on the surface along and perpendicular to the tunnel axis, the amount of the displacements that occurred before the first measurement in the observed cross section can be estimated from the difference between the tunnel and the surface settlements.

Extensive monitoring of the surface displacements was established above the eastern part of the Trojane tunnel that passes the Trojane village at shallow depth. The Trojane tunnel was constructed in heavily faulted and densely foliated rock mass of carboniferous age. The comparison of the measured displacements in the tunnel tube and above it revealed that less than 50% of the final displacement measured on the surface was only measured in the tunnel tube [11]. The rest of displacement occurred before the first measurement of the measuring cross section was performed. From the relation between the surface displacement and the distance to the approaching top heading excavation face the magnitude of the pre-face domain can also be estimated.

More reliable information on the rock mass behaviour ahead of the face and magnitude of the pre-face domain was given by the interpretation of the measurements of the horizontal inclinometer that was installed in the length of 40 m in the crown of the left tube of the Trojane tunnel under the Trojane village ([12], [13]). The crown settlements measured by the horizontal inclinometer are shown in Fig. 5 together with influence lines.

At the chainage km 80+293 a geodetic measuring cross section (marked in Fig. 5) was installed. The settlement measured by the horizontal inclinometer at the given chainage was 17.5 cm and the measured spatial displacement of the crown point in the geodetic cross section was 4.9 cm, which is less than 30 % of the final settlement. All three components of the displacement vector are drawn in Fig. 6.

The magnitude of the pre-face domain is approximately 1 - 1.5 equivalent tunnel diameter (10 - 15 m in the case of the Trojane tunnel) ahead of the face as one can observe from Fig. 5.

The advantages of measuring displacements ahead of the face with the horizontal inclinometer are the accuracy of measurements, minimum disturbance of the rock mass and the position of the inclinometer, which allows the direct comparison with the geodetically measured settlement of the crown point. The major disadvantage is the inability of measuring the 3D displacement. Only the settlement of the crown is obtained. The longitudinal component of pre-displacement might be additionally measured using deformeters, but no reports on such measurements can be presently found in literature.

3D displacements ahead of the tunnel face can be easily obtained by geodetic monitoring, when a small diameter tunnel existed within the alignment of the future tunnel with considerably larger cross section.

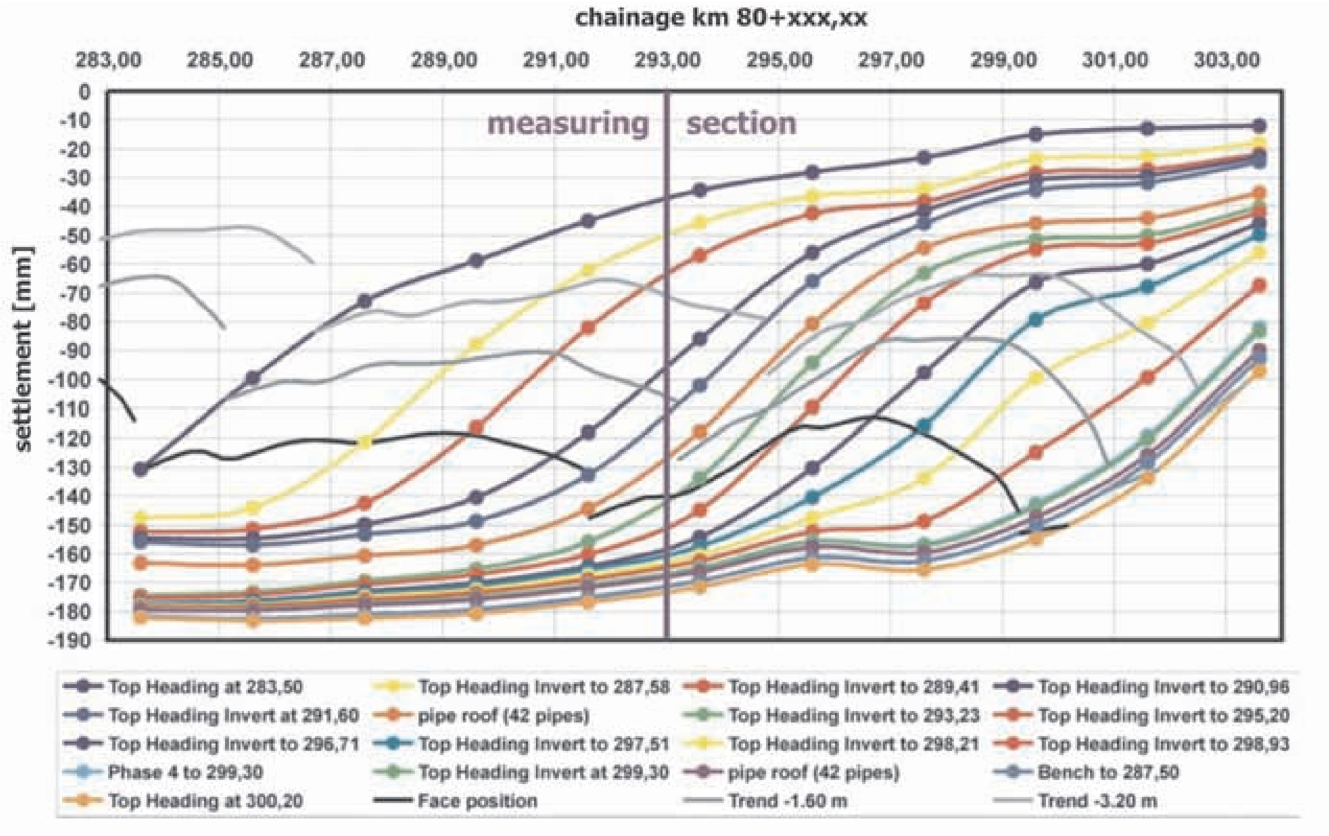

Figure 5. The influence lines of the settlements, measured by the horizontal inclinometer in the crown of the left tube of the Trojane tunnel (unpublished report by Button and Volkmann).

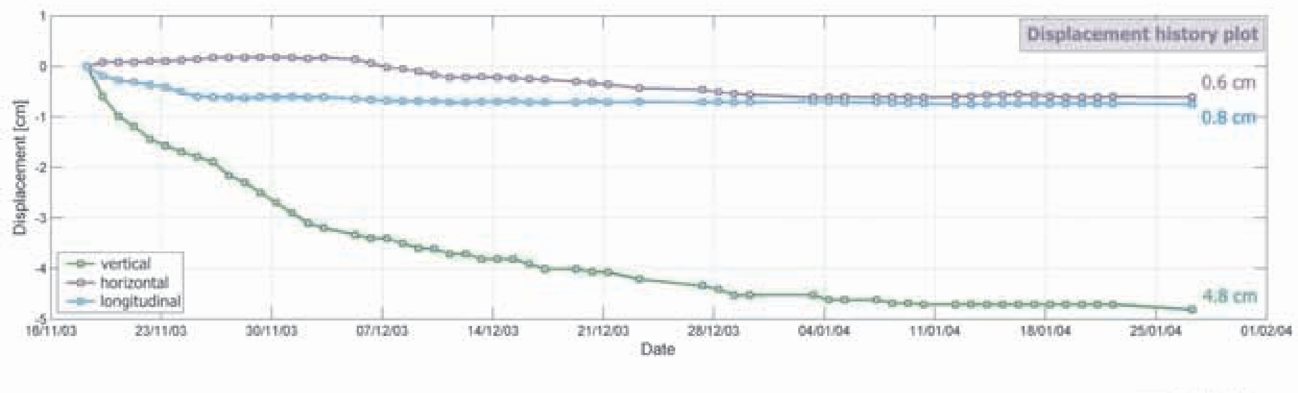

Figure 6. Displacement history plot of all three components of the crown point displacement vector (left tube of the Trojane tunnel, measuring cross section at the chainage km 80+293).

3 3D GEODETIC DISPLACEMENT MEASUREMENTS AHAED OF THE MAIN TUNNEL FACE

In the eight-month period between September 2005 and April 2006 the 3D displacement measurements were performed in the exploratory tunnel of the Šentvid motorway tunnel ahead of the main tunnel excavation face.

3.1 THE ŠENTVID TUNNEL

The Šentvid tunnel system is the missing link of the Slovenian A2 Karavanke-Ljubljana motorway to the Ljubljana ring motorway (Fig. 7).

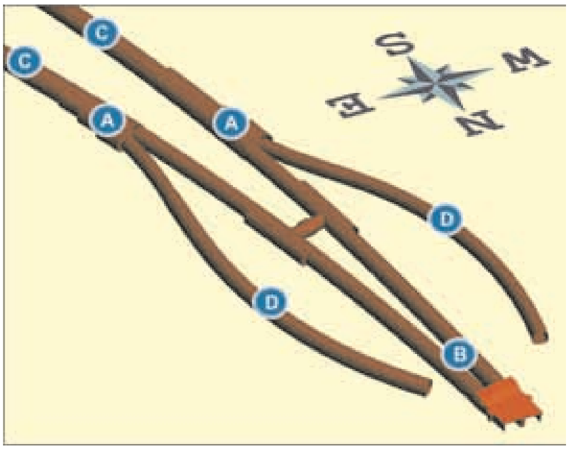

Figure 8. The scheme of the Šentvid tunnel [14].

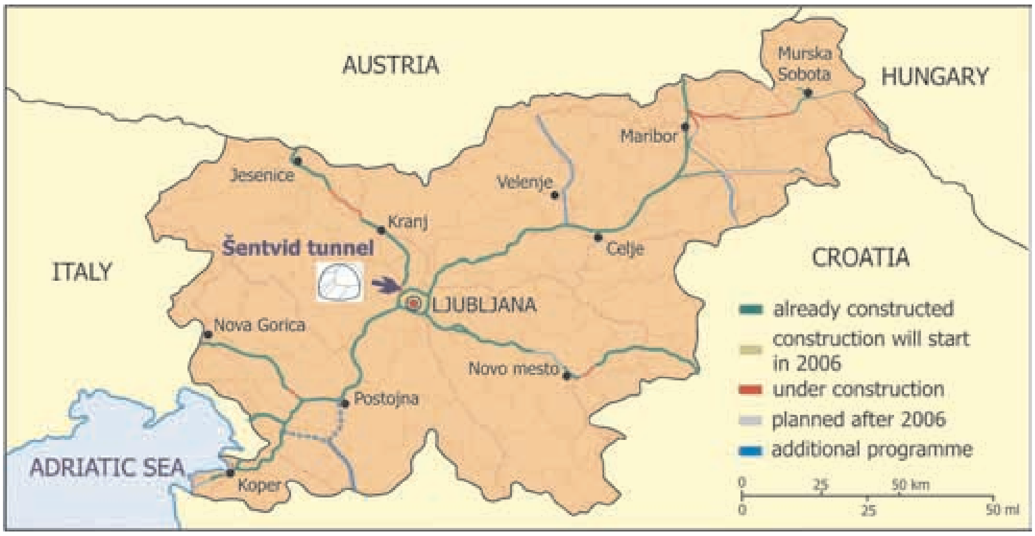

Figure 7. Slovenian road map.

An approximately 1100 m long motorway tunnel is designed as a double tube tunnel with two large merging caverns with maximum excavation cross section of approximately 330 square meters and the length of 60 m (label A in Fig. 8). The Šentvid tunnel consists of twin two lane tunnels from northern portal up to the merging caverns (label B) and twin three lane tunnels from southern portal to the merging caverns (label C). Two ramp tunnels (label D) will connect the Celovška street to the main motorway tunnel. The tunnel system is currently under construction. All underground structures are constructed following the principles of NATM. Maximum overburden reaches 115 m.

The Šentvid tunnel alignment passes through densely foliated clastic sedimentary rocks of carboniferous age, mainly sandstones, siltstones and clayey slates. The region has undergone intense tectonic deformations, presumably during several deformation phases. Due to intensive tectonics the rock is folded, fault zones are up to several meters thick and consist mainly of gouge clay. The rock mass itself is very heterogeneous and anisotropic (Fig. 9).

The quantity of water that percolates from the surface into the tunnel tube is small. Water appears mainly in fault zones. Together with deformations that occur due to tunneling this water causes the increase of the water content along the foliation and consequently the decrease of rock suction, which affects mechanical properties of the rock mass and worsens the tunneling conditions in the vicinity of fault zones.

Tunneling conditions for the Šentvid tunnel system were estimated in the range from fair to very poor [15].

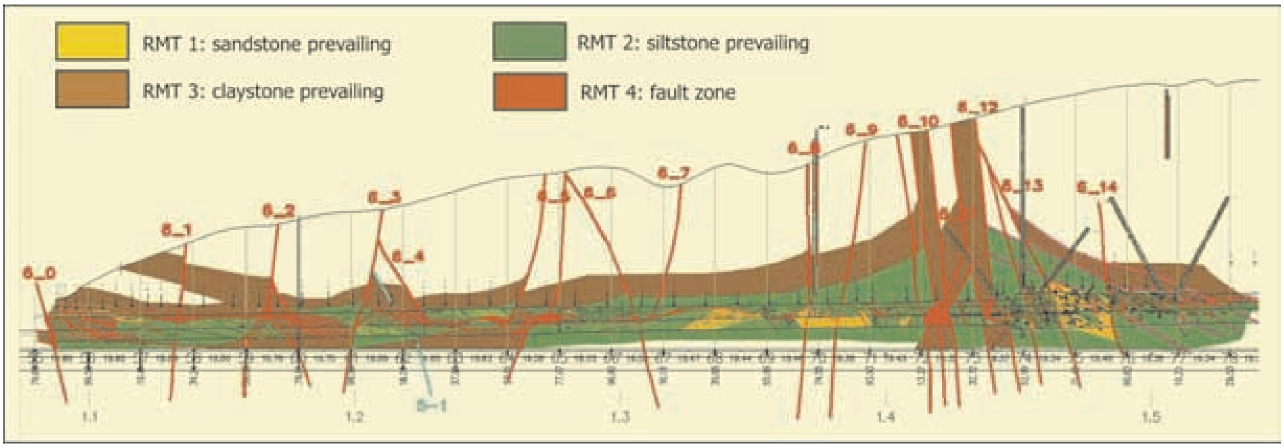

Figure 9. Geological cross section of the Šentvid hill – left tube, northern part (ELEA iC).

Figure 10. Ground plan and cross section of the Šentvid exploratory tunnel.

To determine the most favorable position of the caverns in terms of geological and geotechnical criteria the exploration gallery in the axis of the main tunnel was constructed in the final stage of the design. The length of the exploration gallery was approximately 655 m with a cross section of 13 m^2 (Fig. 10). Due to a small cross section the primary lining was executed as a micro fiber reinforced shotcrete with steel arches and wire mesh in the crown. No rock bolts were installed.

The exploratory tunnel allowed the establishment of a reliable geological model and enabled the in-situ geotechnical testing (core drilling, geophysical surveys, extensometers). The geodetic measurements of the 3D displacements during the exploratory tunnel construction improved the knowledge of the rock mass behaviour and its response to the tunnel excavation.

Beside all the information that contributed to the successful execution of the main tunnel, the exploration gallery enabled the observations of the rock mass – support system behaviour ahead of the face of the main tunnel during the execution of the main tunnel.

3.2 PERFORMANCE OF GEODETIC MEASUREMENTS

Continuous measurements of the primary lining were performed in both tubes of the exploratory tunnel. When the left tube of the main tunnel was approaching the intersection of the cross-passage and left tube of the exploratory tunnel (chainage km 1.3+97), the geodetic measurements of the targets were performed once a day in cross-passage, perpendicular to the main tunnel axis. These results improved the knowledge on the rock mass behaviour perpendicular to the tunnel axis.

The monitored sections are marked with a blue dotted line in Fig. 10. The lengths of the monitored sections and the number of the measuring profiles are given in Table 1.

Table 1. Chainages, lengths and number of measuring profilein monitored tunnel sections.

	chainage	section length [m]	measuring profiles
right tube	km 1.2+57 - km 1.3+32	75	37
cross-passage	km 0+20 - km 0+40	20	9
left tube	km 1.3+97 - km 1.5+44	147	72

The geodetic prisms were installed in the primary lining of the exploratory tunnel every two meters in the crown and every six meters on both side walls and ground along the tunnel axis. The 3D positions of the targets in the lining of the exploratory tunnel in front of the main tunnel face were recorded every hour by precise electronic tachymeter LEICA TCRP 1201R300.

3.3 RESULTS OF 3D DISPLACEMENT MEASUREMENTS

The magnitude of the measured displacements was in range from a few millimeters to almost 35 cm. The maximum observed displacements in each direction are given in Table 2.

Figure 11a. Electronic tachymeter and geodetic prisms installed in the primary lining and on the bottom of the exploration gallery.

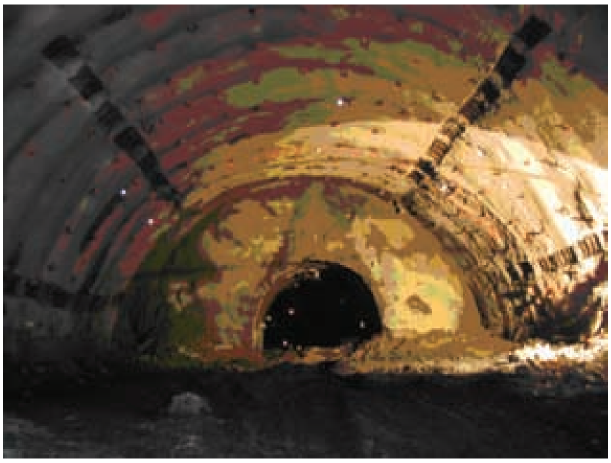

Figure 11b. Position of the exploratory tunnel on the double lane tunnel top heading face.

Table 2. Maximum displacements in each direction for different points in the exploratory tunnel due to the excavation of the main tunnel.

	vertical		lateral		longitudinal	
	[cm]	dir.	[cm]	dir.	[cm]	dir.
crown	18.7	↓	6.4	←	29.3	↙
left side wall	26.5	↓	16.9	→	21.1	↙
right side wall	20.4	↓	17.1	←	21.0	↙
bottom	34.6	↑	11.3	←	6.4	↗

3.3.1 General behaviour

General behaviour of rock mass – support system that was measured in the exploratory tunnel in front of the main tunnel face is shown in Fig. 12 together with the prevailing geological scheme in monitored sections (sub-horizontal foliation in cross section with slight inclination towards left side of the tunnel and steeply inclined foliation into the excavation direction in longitudinal cross section, i.e. dip angle of the foliation is approximately 55° with relative dip direction with respect to the tunnel axis of 25° to the left).

The distinctive bilinear deformation pattern can be observed in Fig. 12 (evident in longitudinal section and cross section). The displacement vectors in cross section of the exploratory tunnel followed the direction of the rock mass foliation towards the left sidewall of the tunnel when the excavation face was far away from the observed cross section. In this first deformation phase the additional rock mass pressure onto the primary lining was small and the sliding mechanism along the foliation dominated over the radial deformation due to rock mass pressure. For this reason the left sidewall point tended vertically down and not in the radial direction. Similar explanation can be given for the longitudinal section.

As the tunnel face approached the observed cross section, the displacements due to the rock mass pressure became significantly larger than the sliding displacements along the foliation and consequently the displacement vectors changed their orientation.

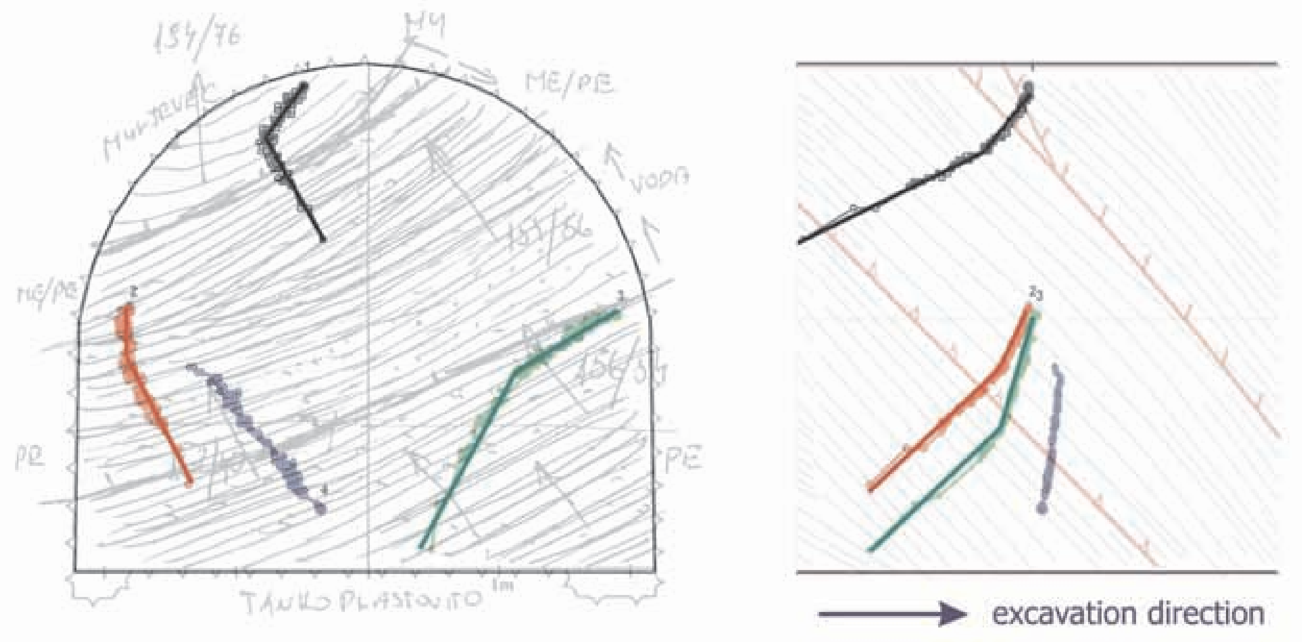

Figure 12. Bilinear displacement vectors in cross section and in longitudinal section in the left tube at chainage km 1.4+56.

The deformation mechanism changed from sliding along the foliation in the first phase to the buckling of the foliation in the second phase when the influence of the excavation face to the monitored cross section was intensified. On the basis of several monitored cross sections with similar deformation patterns we can conclude that the rock mass – support system behaviour well ahead of the face is mainly governed by the orientation of the rock mass discontinuities.

The displacement vector orientation change occurred suddenly and a turn point can be located on the plots of displacement vectors (Fig. 12). This turn point happened at a certain distance between the monitored section and the approaching face of the top heading.

If the percentage of the final measured displacement is plotted against the distance from the top heading excavation face the displacement-distance curve is obtained (Fig. 13). This curve is also bilinear and can be simply divided in two parts. The turn point for monitored cross section between both parts occurred 5.5 m ahead of the two lane tunnel excavation face and at 45 % of the final displacement for the presented measuring cross section.

The analysis of other cross sections indicates that the turn point occurs at about one half of an equivalent tunnel diameter in front of top heading face at 40-60% of final displacement. Between the measuring section and the approaching face of the top heading at the moment when the diagram in Fig. 13 exhibits the turn point there is the area of large displacements. The area further away from the tunnel face in the excavation direction can be referred to as the area of small displacements.

Observed structural damage of the primary lining coincided well with the measured displacements. In the area of small displacements only micro cracks were noticed while in the section closer to the tunnel face up to 25 cm wide cracks were registered (Fig. 14). These large cracks were formed mainly due to large longitudinal displacements. As it can be seen from displacement vectors in longitudinal section in Fig. 12, the longitudinal displacements in the first phase were much smaller than the vertical, but were greatly increased in the second phase.

In some cross sections no vertical displacements were observed in the second deformation phase, sometimes even heaving was registered.

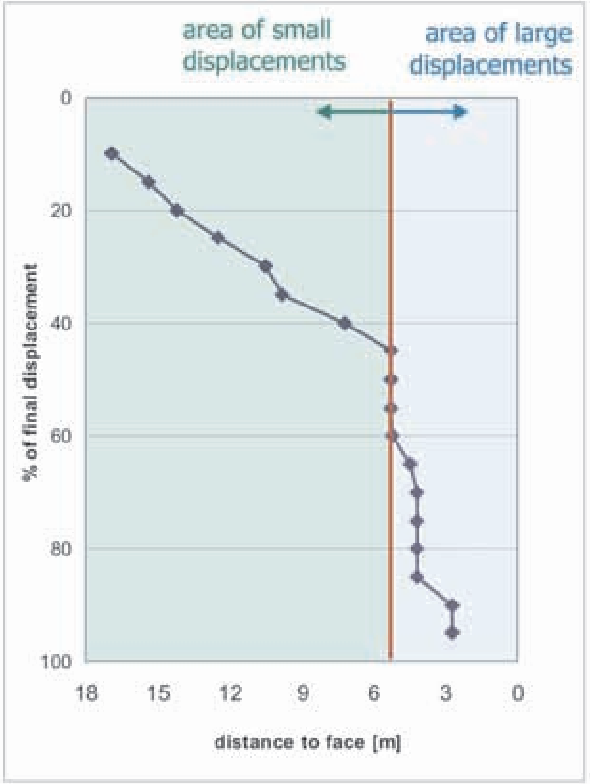

Figure 13. Relative vertical displacement of the crown point in exploratory gallery vs. distance to the top heading excavation face.

Figure 14. Large crack in primary lining of the exploration gallery due to large longitudinal displacements.

3.3.2 area of small displacements ahead of the main tunnel top heading face

The beginning of the area of small displacements at the far end from the main tunnel face was determined at a 3 mm displacement of a particular measuring point to eliminate the measurement error (the inaccuracy of determining the position of measuring points was less than 2 millimeters [16]).

In Fig. 15 the distances from the excavation face to the measuring points at which the measured vertical displacements of a bottom and crown point reached 3 mm and 1 cm, respectively, are plotted along the monitored section of the left tube of the exploratory tunnel. It can be observed that the bottom points moved prior to the crown points. A rather stiff primary lining where the crown point was installed on one hand and no invert at the bottom of the exploratory tunnel on the other can explain such behaviour.

Area of recognizable displacements as observed on bottom points reached the length of about 18 – 25 m (2 - 2.5 equivalent tunnel diameters) for a 3 mm displacement and 10 – 20 m (1 – 2 diameters) for a 1 cm displacement in front of the face of the two lane tunnel. Due to a larger excavation cross section in the cavern with simultaneous transition into the fault zone, the uplift of the bottom was registered at larger distances from the top heading face from the chainage km 1.4+95 on. The maximum distance to the excavation face, where the measured vertical displacement of the bottom point exceeded 3 mm, reached 42 m.

Similar behaviour was observed for the crown points, only the distances to the face were considerably smaller (10 – 20 m for a 3 mm displacement and 5 – 12 m for a 1 cm displacement in front of the two lane tunnel).

3.3.3 comparison of the displacements in the exploratory tunnel measured during the exploratory tunnel construction with the displacements measured during the main tunnel construction

As described above in chapter 3.3.1, the rock mass behaviour in the exploratory tunnel ahead of the face during the main tunnel construction is mainly governed by the orientation of the foliation. Similar dependence can also be observed at the displacements measured during the exploratory tunnel construction. Fig. 16

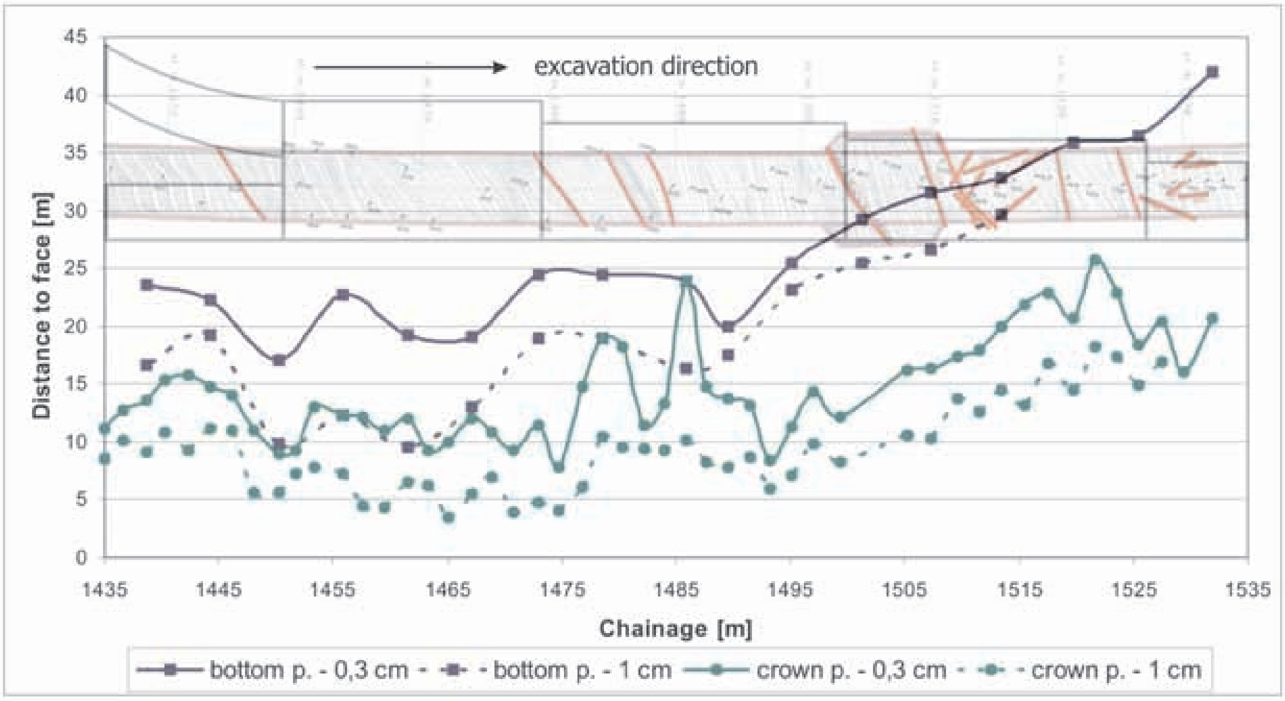

Figure 15. Distance of measuring points to the top heading face when the vertical displacement of the bottom and crown point reached 3 mm and 1 cm, respectively, plotted along the left tube of the exploratory tunnel. The scheme of the merging cavern is not in scale.

shows different behaviour of the exploratory tunnel due to two different construction activities (construction of the exploratory tunnel and construction of the main tunnel) and consequently two different load cases.

When the exploratory tunnel was under construction, the stress change rate due to the excavation was the highest in the area of the excavation face. As the excavation continued, the stress change rate around the same cross section was reduced. Consequently, the displacement rates were high during the initial phase and were close to zero later on. The displacement vector of the crown point tended perpendicularly to the foliation during the initial phase (in the area of large displacements – a blue line marked with letter L in Fig. 16) and parallel to the foliation in the second deformation phase (the area of small displacements – a purple line marked with letter S). Bilinear displacement pattern can only be seen to a limited extent because the absolute values of the measured displacements are small. This phenomenon became more evident from the displacement measurements ahead of the main tunnel excavation face, since the measured displacements were considerably larger in this case due to larger cross section of the main tunnel compared to the exploration gallery. Moreover in the latter case the entire displacement history was measured.

The behaviour ahead of the main tunnel excavation face was just the opposite of the behaviour, observed during the excavation of the exploratory tunnel. The directions of displacement vectors in both cases coincided well when the displacement rates are small (letter S in Fig. 16) and were similar in the area of large displacement rates (letter L in Fig.16). The hypothesis is proposed that the displacements parallel to the foliation dominate when stress change rates are small, while radial displacements govern the behaviour when stress change rates are high.

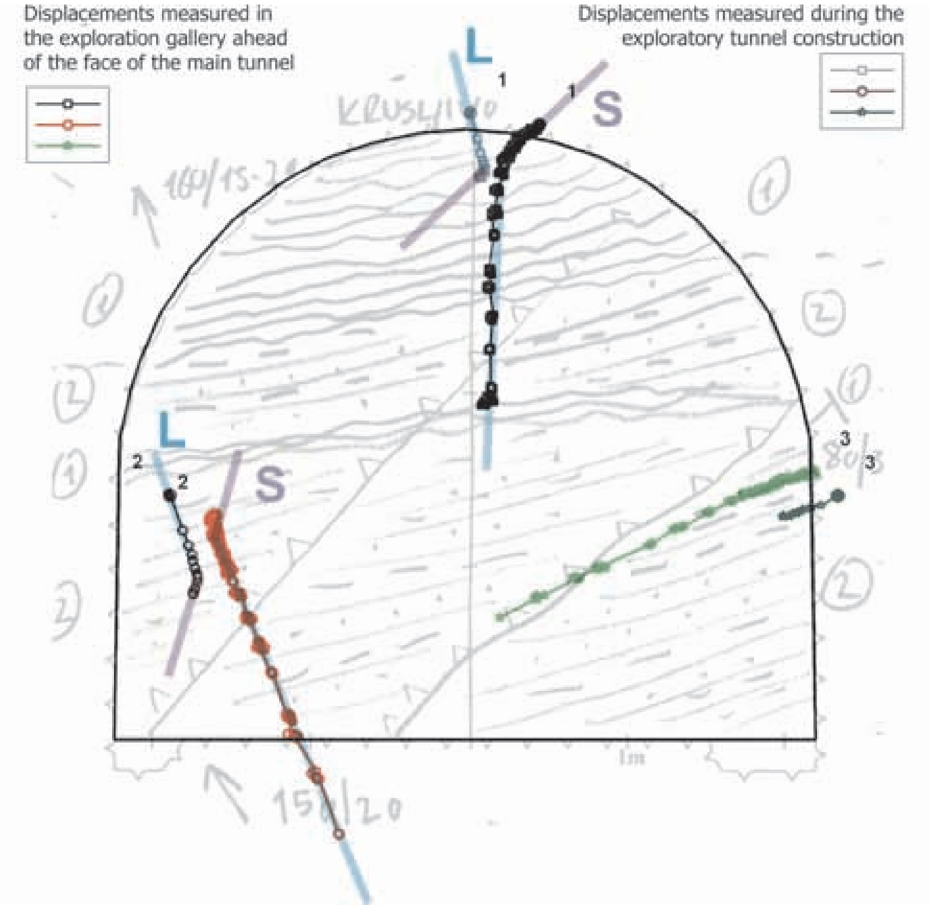

Figure 16. Comparison of the displacements during the execution of the exploration gallery and the displacements measured during the main tunnel construction in the left tube at the chainage km 1.5+17 – cross section together with a face log.

3.3.4 comparison of the displacements ahead of the face and the displacements within the main tunnel due to the main tunnel construction

The comparison of the measured displacements ahead of the face of the main tunnel with the displacements of the main tunnel at the same chainages along the tunnel axis allows the estimation of the portion of the pre-face displacements in total measured displacements and the influence of the orientation of foliation on the orientation of the displacement vectors.

The displacement vectors of the exploration gallery and of the main tunnel, caused by the execution of the main tunnel, are plotted in Fig. 17. Similar displacement patterns as described in the previous chapter can be seen. The displacement rates of the monitored cross section were largest some meters ahead (measured on the lining of the exploration gallery) and behind the top heading excavation face (measured on the lining of the main tunnel). Hence, the crown and left sidewall point's displacement vectors tended perpendicularly to the rock mass foliation. The orientation of the displacement vectors changed when the excavation face was far enough from the observed cross section (ahead or behind the face) and the rate of displacements diminished.

The magnitudes of the vertical and horizontal displacements of both sidewall points in the exploratory tunnel were approximately the same as the displacements of the sidewall points in the primary lining of the double lane tunnel. The vertical displacement of the crown point was in the exploration gallery than the vertical displacement of the crown point target in the main tunnel and reached about 35% of total measured displacement (marked with a red square in Fig. 18 for the cross section shown). Total measured displacement refers to the sum of displacements measured ahead of and behind the face of the main tunnel. The displacements caused by the exploration gallery execution are neglected. It should be also noted that the targets, where displacements were summed and compared, were not installed at the same places in the observed cross section, as can be seen in Fig. 17. The influence of these simplifications on the assessment of the pre-face portion of total displacements will be studied by numerical analyses. Preliminary numerical study by Jemec showed that the presence of the exploration gallery had limited effect on the behaviour of the main tunnel [17].

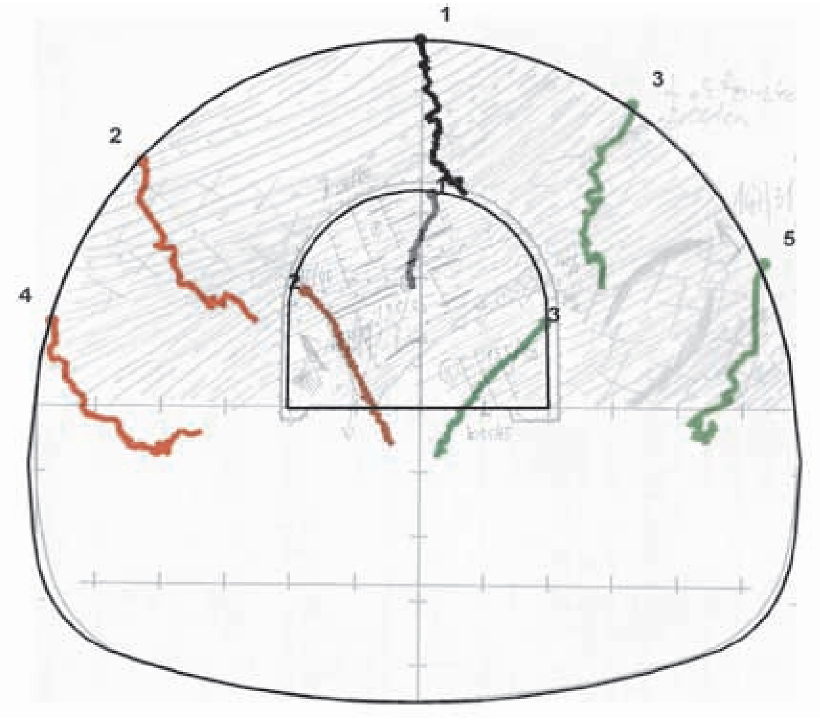

Figure 17. Comparison of the displacements ahead of the face and the displacements after the excavation of the main tunnel at chainage km 1.4+44 in the left tube of the Šentvid tunnel – displacement vectors in cross section with face log.

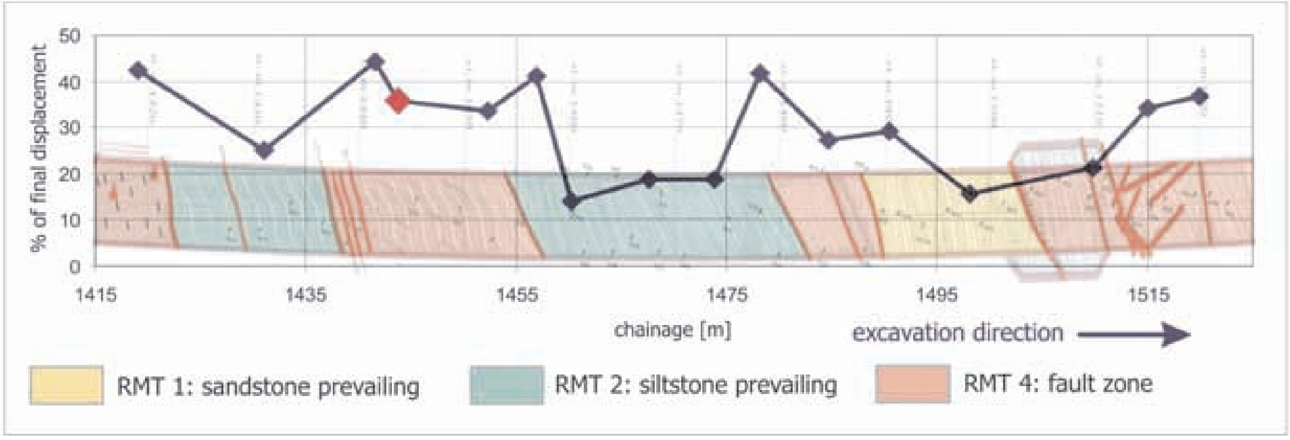

Figure 18. The portion of the vertical displacements that occurred ahead of the face for the crown point in the exploratory tunnel and for a point in the main tunnel that is situated above the exploration gallery.

In the monitored section of the left tube of the Šentvid tunnel the measured displacements ahead of the face amounted 15% to 45% of the total measured displacements in the same cross section (Fig. 18). A lower portion of the pre-face displacements was observed in stiffer and non-folded rock mass or folded to smaller extent (regions of green and yellow colour in Fig. 18), whilst in more deformable or intensively folded rock mass (regions of red colour) the percentage of the pre-face displacements was considerably higher.

The stated percentage does not take into account the displacement that occurred between the excavation and the first measurement of the newly installed measuring

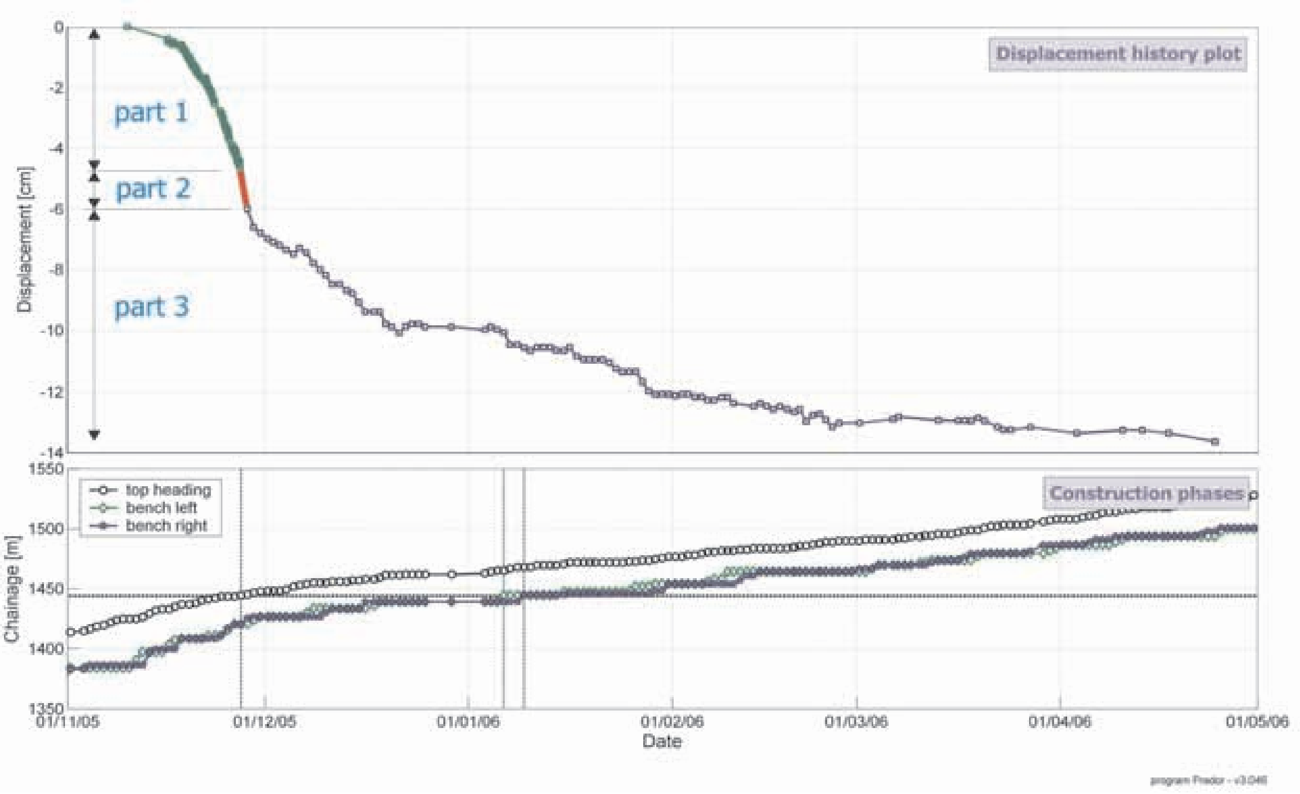

Figure 19. The complete displacement history plot of the crown point in the cross section at the chainage km 1.4+44.

section (part 2). The displacement rates in this phase are the highest because of the unsupported rock mass immediately after the excavation and low stiffness of the installed support before the shotcrete hardens. On the basis of the displacement's tangent slope close to the excavation face (some days before and after the excavation of a certain cross section) and time delay between the excavation and the first measurement, we can anticipate the course and the magnitude of the second part of the displacement function's curve (Fig. 19). The estimated portion of the displacements in part 2 is in the range from 10% – 25% of the total displacements.

From the presented cases we can deduce that 25% - 70% of displacement occurs before the first measurement of the observed cross section, depending mainly on the stiffness of the surrounding rock mass, construction sequence and the time delay of the first measurement.

4 CONCLUSION

Back analyses and interpretation of measured displacements ahead of the excavation face of the main tunnel and perpendicular to its axis and the comparison with the displacements measured during the exploratory tunnel construction as well as the main tunnel construction allow comprehensive interpretation of the rock mass – support response due to the tunnel excavation.

A large amount of data was obtained on approximately 250 m long section of the exploratory tunnel of the Šentvid tunnel system. The analyses of these data can provide the knowledge on deformation mechanisms of the rock mass – support system ahead of the tunnel face, which is essential in case of tunnel construction at low overburden under populated area. According to the presented cases one can conclude that the behaviour of the rock mass – support system strongly depends on the foliation orientation if the tunnel is constructed in foliated rock mass of low strength and stiffness like the Šentvid tunnel.

The magnitude of the displacements of the exploratory tunnel primary lining due to the main tunnel construction and its portion in all the measured displacements is strongly correlated to the stiffness of the rock mass. The comparison of the displacements ahead of the face with the displacements after the excavation of the main tunnel indicates that 15-45% of the measured displacements occur ahead of the face (less displacement in stiff rock mass that was not folded and more in worse geological – geotechnical conditions). On the basis of the measured displacements in different rock mass types we can assume the strong dependence of the portion of the stress state alternation ahead of the face (parameter Q_1) on the stiffness of the rock mass.

The geological structure ahead of the face and the size of the tunnel affect the influence area ahead of the face due to the excavation face advance or what is called pre-face domain. The analysis of the measured displacements shows that the small displacement domain can be observed approximately 2 equivalent diameters of the tube ahead of the face and the majority of the displacements occur within a half of an equivalent tube diameter from the face. The value for the parameter x_f cannot be deduced from the measured data at present time. Detailed analyses including fitting displacement function to the measured displacements ahead of the face as well as the displacements of the excavated area will define the recommended value for x_f.

The fitting of the displacement function to the displacements measured ahead of the face allows a judgment on the suitability of the first part of the proposed displacement function and possible modifications of its shape to demonstrate the observed bilinear response of the primary lining in the foliated rock mass.

To establish a reliable model for the rock mass behaviour prediction ahead of the face measured displacements will serve as an input to extensive 3D numerical simulations to confirm the suitability of the model.

If the proposed model proves to be reliable and accurate, it will be a fast and powerful tool for the prediction of the overall rock mass – support system behaviour. Such tool can contribute to better understanding of the ground behaviour around tunnels with low overburden under populated area [5]. For a given geological structure and known rock mass behaviour on some sections at the same site the displacements of further sections to be excavated can be calculated and therefore sufficient support measures can be designed to comply with the displacement tolerance in the tunnel as well as on the surface.

The knowledge on the rock mass behaviour ahead of the face can also serve for the optimization of the support, installed ahead of the face.

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