MINED TUNNEL MONITORING AS A PART OF OBSERVATIONAL APPROACH – A CASE STUDY

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Abstract

The observational method is widely used in tunnelling works. For a successful implementation of observational method in tunnelling, an efficient monitoring, data evaluation and interpretation on site is of prime importance. Reviewing the common practice on sites in Singapore, it could be said that, there is a potential for improvement in the data collection and interpretation techniques employed for mined tunnelling works in Singapore. Although there are several advanced tools available in the market for data handling, evaluation and interpretation; there is a scope for development of simple and easy to use tools, to properly handle the spatial displacement measurements. With the adoption of Eurocode 7 in Singapore, it is further more important to evaluate the mined tunnel movements, continuously update the geotechnical model & adjust the excavation/support system to suit the actual ground conditions.

This paper presents simple implementation of absolute tunnel displacements visualisation in the ubiquitous spreadsheet software (eg. Microsoft Excel). A practical procedure for predicting and comparing displacement behind the face in relation to face advance and time is presented with a case study of mined tunnel in shallow overburden condition. The case study considers a mined tunnel which is in overburden ranging from 6m to 8m under a road with significant traffic as well as major utilities and services. The design included temporary excavation support using staggered piperoof, sprayed concrete with lattice girder and wire mesh. Observations & insights provided by spatial visualization of the tunnel displacements are presented.

Keywords: Mined tunnel, Observational approach, Monitoring, EC7

1. Introduction

The Eurocode 7 [1] specifies that when prediction of geotechnical behaviour is difficult, it can be appropriate to apply the approach known as “the Observational method”, in which the design is reviewed during construction. However, the following requirements shall be met before construction is started:

- Acceptable limits of behaviour shall be established
- The range of possible behaviour shall be assessed to demonstrate that this range is within the acceptable limits
- A plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully
- The response time of the instruments and the procedure for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system
- A plan of contingency actions shall be devised which may be adopted in the monitoring reveals behaviour outside the acceptable limits.

Further the Eurocode 7 specifies that during construction, the monitoring shall be carried out as planned and the results of the monitoring shall be assessed at appropriate stages.

In order to assess the actual behaviour during construction at an early stage and for the procedure for analysing the results to be sufficiently rapid, the monitoring method and data evaluation/interpretation play a very important role. This paper, using a case study, presents a simple tool to compare displacement behind the face in relation to face advance and predict ground movements ahead of face.

2. State of Practice in Singapore

Tunnelling induced ground movement measurements and lining displacement measurements have developed during the last few decades. The information, especially from instruments installed on tunnel lining, can be evaluated in many different ways. This section summarizes different monitoring instruments that are being used for interpretation of ground behaviour in Singapore.

2.1 Lining Displacement Monitoring

Lining displacement monitoring using convergence monitoring bolts on shotcrete lining are commonly used in Singapore. It allows to measure relative displacement of lining during the progress of tunnel excavation. However, it has been documented that 3D prism readings for convergence are more useful than the convergence measurements using tape extensometer [2], [3]. 3D prism readings allows to measure the transient displacement in space which allows better evaluation of the influence of stiffness of the geotechnical unit being excavated.

2.2 Inclinometers

Inclinometers installed from the surface are often used to monitor the horizontal movement caused due to the excavation of the tunnel. Inclinometers have also proved to measure the ahead of face displacements efficiently and total displacement path could be determined based on inclinometers installed on either side of the mined tunnel [4].

2.3 Extensometer measurements

Extensometer are also commonly used in Singapore to measure the subsurface ground movements. They are commonly used to determine the depth of the influence zone of excavation activity and to verify the assumed failure mode.

2.4 Strain Measurements

Strain measurements in the shotcrete lining are seldom used in Singapore. Strain measurements in shotcrete lining are used to back calculate the stresses and the utilisation factor of shotcrete lining as the tunnel excavation progresses. Although there are numerical models developed to estimate the stresses in the shotcrete lining based on above routine measured displacement data (discussed above), they are seldom used in Singapore.

3. Project Description

The case study presented in this paper is a part of Singapore cable tunnel project. A 30m long mined tunnel is constructed to connect 400 kV substation with the rest of the cable tunnel infrastructure. The proposed tunnel is a horse-shoe shaped, 6m wide and 7m in height. The mined tunnel excavation would be primarily in SVI to SIV Jurong formation. Overburden above the tunnel crown consists of Fill, silty gravelly sand, brick woods and organic matters. Thickness of fill/Kallang formation ranges from 2m to 5m. Geological profile along the tunnel is shown in Figure 1.

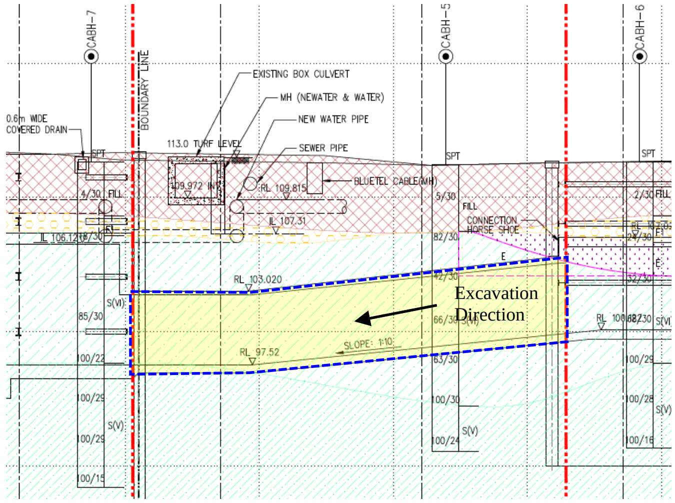

Figure 1: Mined tunnel – Geological profile along tunnel

The proposed excavation scheme involved heading excavation of 4.2m height and bench excavation of around 3m at the smallest cross section. 114mm dia, 12m long grouted Pipe roofs are installed at the crown to form ahead-of-face support (indicated as shaded region in Figure 2). Typical round length for excavation of heading as well as bench was 1.2m with invert closure within 2.4 to 3.6m from the face. Pipe roofs are installed every five rounds forming ~6m overlap of pipe roofs. Details of the design philosophy and sequencing are not discussed in this paper for the sake of brevity.

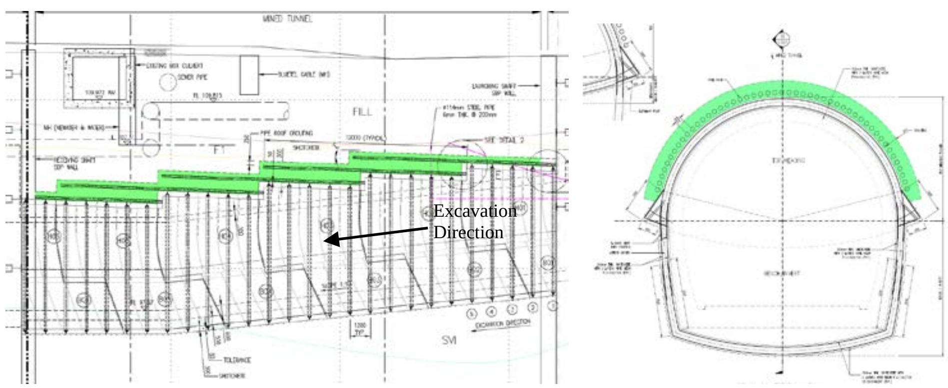

Figure 2: Longitudinal profile and cross section of mined tunnel

The proposed excavation scheme was designed in order to minimize ground movements and cause least settlements to the utilities above the mined tunnel crown. The risk of unforeseen soil profile, overestimated geotechnical design parameters and water drawdown might cause the predicted settlement being exceeded. Therefore, continuous assessment of soil consolidation during excavation and a comprehensive monitoring scheme was deemed essential and hence proposed. Apart from surface and subsurface instruments (which includes ground settlement markers, extensometers, inclinometers, Piezo meter, utility markers etc), a series of 3D prisms were proposed to be installed on the shotcrete lining as shown in Figure 3. 3D prism monitoring array was installed at every alternate lattice girder location (i.e every 2.4m) along the mined tunnel. The rest of the paper would discuss on the interpretation of the readings from these 3D prism instruments.

Figure 3: Location of 3D prisms in the mined tunnel

4. Evaluation and Interpretation Methods

4.1 Displacement histories (displacement vs time)

Displacement history is the most commonly used method in Singapore for plotting the displacement data against time with reference to Alert Level (AL) and Predetermined Level (PDL) or Work Suspension Level (WSL). PDL or WSL are determined based on what is considered as an acceptable behaviour for the given ground condition while considering its impact on the surface structure and subsurface utilities. The interpretation of such time histories is very simple for a homogenous ground condition and a continuous advance of tunnel. However in complex geological conditions, the evaluation of displacement histories is not sufficient to allow a timely reaction to the changing ground conditions. The value of information provided by displacement histories is limited, as the face advance plays a major role in the displacement development.

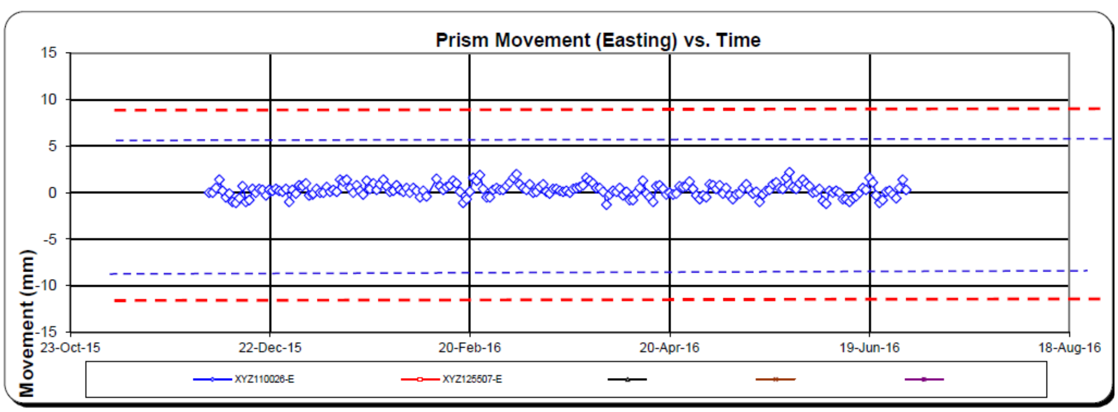

Figure 4: Typical example of displacement history plot

Figure 4 presents a typical displacement history plot. From the plot it could be inferred that the movement of the prism is within AL. However, it does not give any idea of the spatial distribution of the movement nor anisotropic behaviour of the ground.

4.2 Deflection Curves & Displacement vectors

A custom-built spreadsheet macro was prepared for this case study project to visualize the displacement vectors at each monitoring array and deflection curve along the tunnel alignment at any point in time based on the latest raw data obtained from the instrumentation and monitoring contractor (IMC). Figure 5 shows the monitored displacement characteristic of the mined tunnel as vector plot in a plane perpendicular to the tunnel axis. The displacement plot in this figure is for the lattice girder location “S3-5” (which could be selected from the option button on left side. List indicates the location of all monitoring array locations). The displacement pattern can be described as almost symmetrical in the cross section with slightly increased displacement on the right side. In a homogenous, isotropic ground, the crown prism movement is expected to be vertically down however the movement is towards left side which could indicate a possibility of singularities near the face. In case there was any fault / singularities on the right side of the tunnel face, the readings on the right side (instrument P3 and P5) would register larger movements. In this manner, features outside the excavation area (faults, slickensides etc), change in stress situation and kinematics could be predicted based on these displacement vector plots [3].

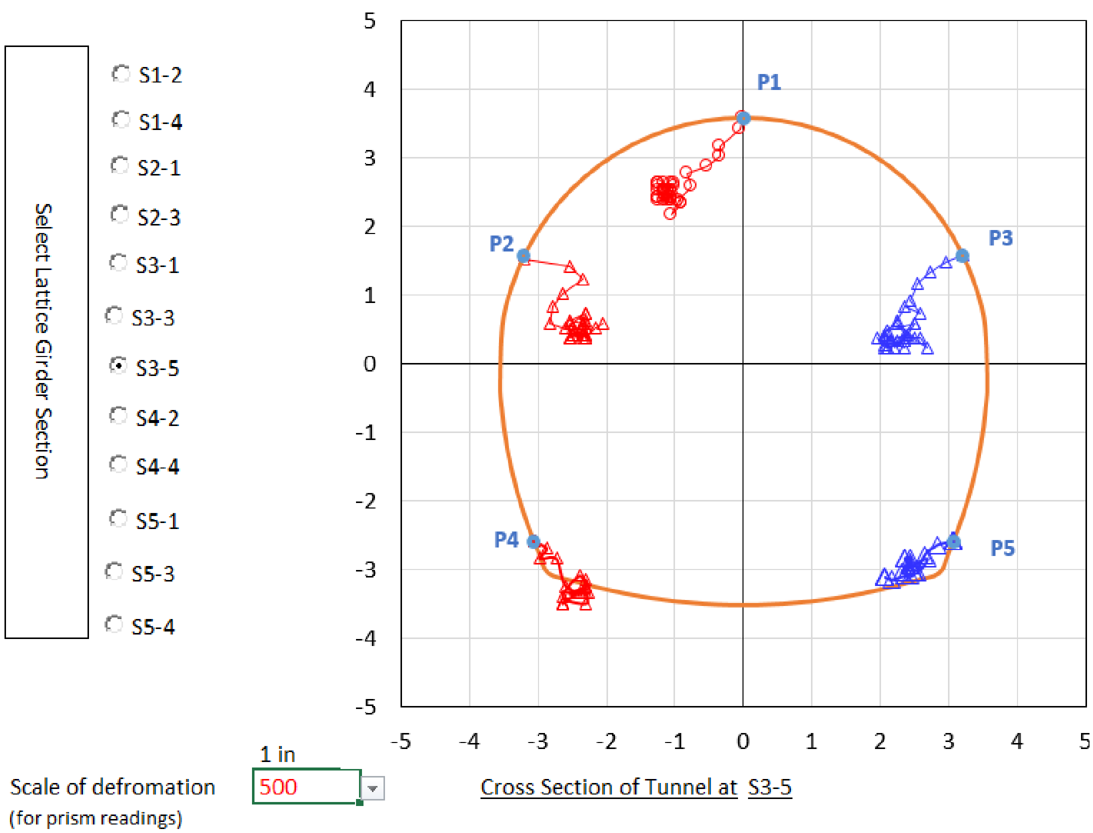

Figure 5: Custom built spreadsheet VB script to visualize displacement vector

4.3 Longitudinal displacements

Figure 6 shows the monitored displacements vectors in a plane parallel to the tunnel axis. The plot in longitudinal direction shows displacement vectors tending against the excavation direction.

Influence of foliation on the longitudinal settlements is shown in Figure 7. Using the knowledge about the influence of the anisotropy orientation on the displacement development, the geological structure encountered on site can be used to predict the expected spatial displacement vector orientation. Any significant deviation from this “normal” behaviour will thus reflect an abnormal behaviour. In case the reason for the abnormality does not originate from a failed support system, the type of deviation can be used to predict changes in the ground condition ahead of the tunnel.

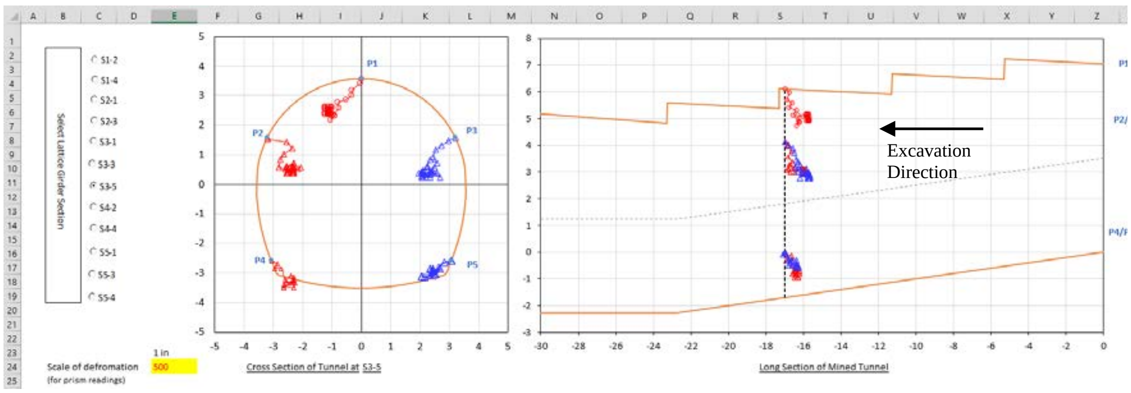

Figure 6: Custom built spreadsheet VB script to visualize 3D prism movements

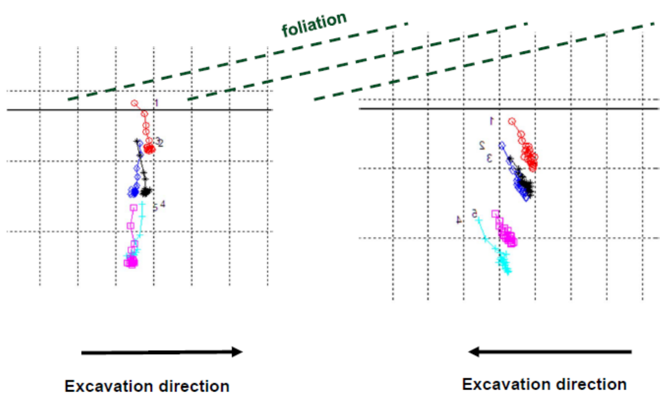

Figure 7: Influence of foliation on the longitudinal displacements (Schubert, 2015)

Figure 8 presents the deflection curve of the crown prism at the end of excavation. The crown displacement is seen to be decreasing as the tunnel progressed. This was probably because the tunnel excavation moved to better ground as the excavation progressed. While maximum crown displacement was around 5mm in this case, the maximum ground surface settlement was around 25mm.

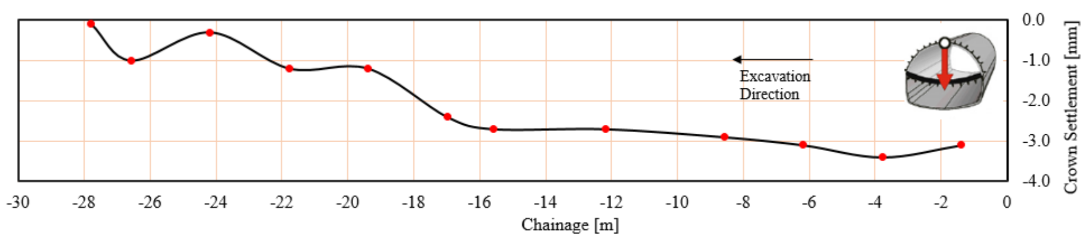

Figure 8: Deflection curve based on crown point movement (output from spreadsheet)

It is worth indicating that excavation ground behaviour is difficult to be judged based on usual surface settlement markers only as the surface settlement markers are influenced by other nearby and subsurface structures. Figure 9 shows the surface settlement profile at different stages of tunnel excavation. Surface settlement markers are strongly influenced by the ERSS/ Temporary works for the launching and receiving shaft hence the maximum crown movement near the launching shaft (as shown in Figure 8) is not reflected in the ground settlement marker.

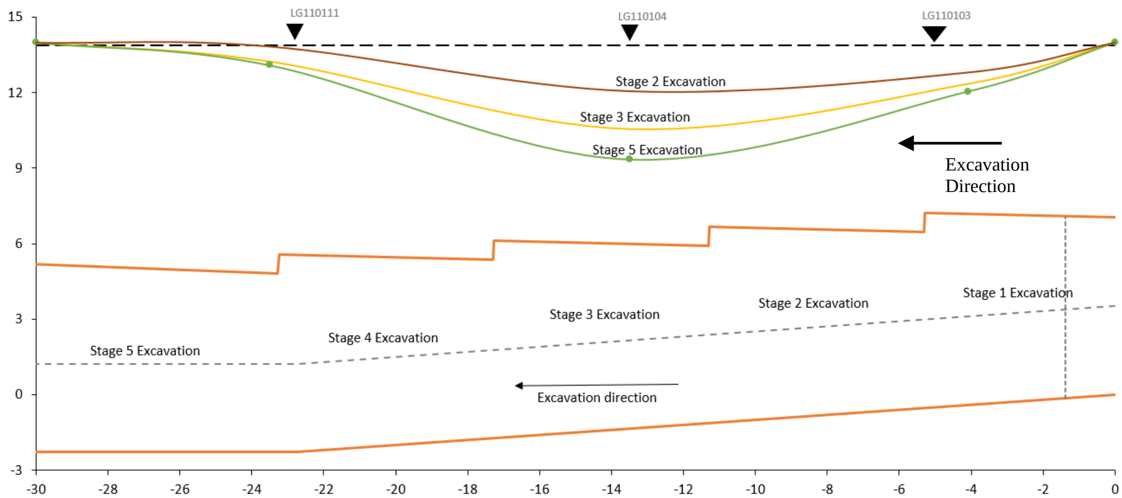

Figure 9: Ground settlements at different stages of excavation

4.4 Advanced Evaluation of Displacement Monitoring Data

In complex geological conditions, to be able to observe the influence of geological features outside of the tunnel profile, trends of displacements and trends of ratios of different displacement components can be used. In this way, the geotechnical conditions ahead of the face and outside the visible area in the tunnel can be predicted.

Figure 10 presents the L/S plot (ratio of longitudinal displacements and settlements, expressed as an angle in degrees) along the tunnel alignment. This plot reflects the deviation of the displacement vector from the vertical direction in a vertical plane parallel to the tunnel axis. When relatively soft ground is ahead of face, there is a change of displacement vector against the direction of excavation. If relatively stiff ground is ahead of face, there is a change of displacement vector towards the direction of excavation [5]. At Chainage 4m, the tunnel face transited from Kallang formation to Jurong formation hence a sudden change in trend is observed. The "abnormal" displacement characteristics around Chainage 24m to 26m could be attributed to the canal above the mined tunnel crown. Piles supporting the canal were exposed during the excavation during this stretch.

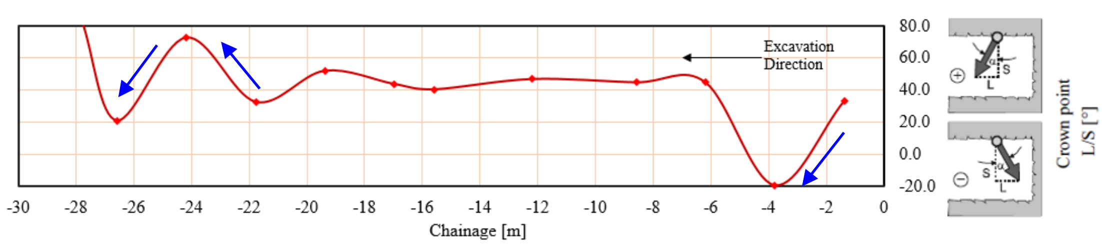

Figure 10: Development of settlement and displacement (L/S) vector orientation

Figure 11 presents the development of settlement and displacement (H/S) vector orientation expressed as an angle in degrees. This reflects the deviation of displacement vector from vertical direction in a vertical plane perpendicular to the tunnel axis. Till about Chainage 10m, the vector orientation was tending towards right side of the excavation. For the rest of the alignment, the vector orientation was tending towards left side. In general, the trend didn't suggest any faults / singularities on either side of the excavation face and could be considered fairly homogenous. The "abnormal" displacement characteristics around Chainage 24m to 26m is noticed again in H/S trend indicating the stiffness changes due to presence of canal piles.

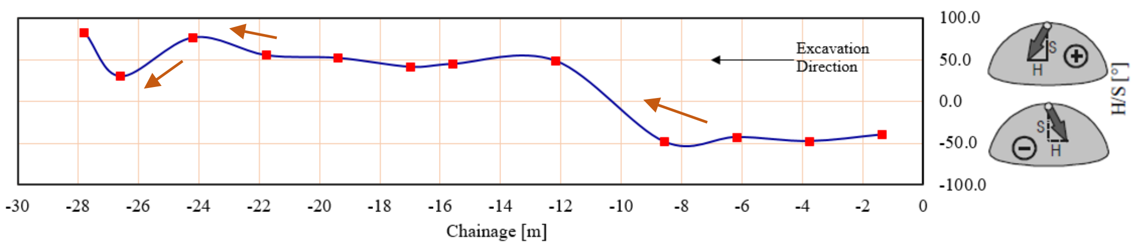

Figure 11: Development of settlement and displacement (H/S) vector orientation

Based on case study and past research by Grossauer et al [6], overview of the interpretation tools for different objectives presented in this paper can be summarized in Table 1 as below. While displacement history is most suitable for assessment of general stability, it fails to understand rest of the ground behaviour. Other interpretation methods presented in this paper tend to give better understanding for the other objectives as summarized in Table 1.

Table 1: Overview of evaluation objective & interpretation tools

	Assessment of stability	Prediction of final displacement	Stress redistribution	Detection of stiffness changes	Prediction of geological condition.
Displacement history	**Most Suitable**	Limited use	Not Suitable	Limited use	Not Suitable
Deflection curves	Limited use	Limited use	**Most Suitable**	Limited use	Limited use
Cross section vectors	Not Suitable	Not Suitable	Not Suitable	**Most Suitable**	Not Suitable
Longitudinal section vectors	Not Suitable	Not Suitable	Not Suitable	Limited use	**Most Suitable**
Trends of displacements	Not Suitable	Not Suitable	**Most Suitable**	**Most Suitable**	**Most Suitable**

4.5 Prediction of displacement based on advance rates

With the above data analysis methods, it is also possible to predict the anticipated ground movements due to change in advance rates. Guenot et al. [7] and Sulem et al. [7] proposed a method based on analytical functions that describe displacements in a plane perpendicular to the tunnel axis as a function of time and the advancing face. The displacement behaviour of the ground and support basically is represented by four function parameters. Two parameters (T, m) are used to simulate time dependency and another two parameters (X, $C_{x\infty}$) the face advance effect. These parameters can be back-calculated using curve fitting techniques. This procedure allows to predict displacements for any time and point of the tunnel wall as well as the ground surface considering different construction stages and supports. The general form of function can be represented as:

$$C(x,t) = C_1(x) * [C_{x\infty} + A * C_2(t)]$$

where: $C_1(x)$ is advance dependent component and $C_2(t)$ is time dependent component, $C_{x\infty}$ is final time independent displacement and A is final time dependent displacement. Further $C_1(x)$, $C_2(t)$ can be represented as:

$$C_1(x) = \left[1 - \left(\frac{X}{X + x}\right)^2\right]$$

$$C_2(t) = \left[1 - \left(\frac{T}{t + T}\right)^{0.3}\right]$$

Where: X and T are shape parameters, x is distance between face and observed section and t is elapsed time between excavation and observation. Fourth function parameter is represented as A/ $C_{x\infty}$. The back calculated function parameters (X, T, $C_{x\infty}$, m) represent the displacement behaviour of the observed section and the displacements can be calculated for any desired excavation advance. These models give a quick engineering assessment to decide about the change in round lengths (if required). This was not implemented in this case-study however is briefly explained here as the above plots will aid in determining the four parameters.

5. Conclusion

Monitoring methods along with latest interpretation methods has improved short term prediction in tunnelling. The information, which can be extracted from displacement monitoring data, is enormous. This insight plays a crucial role in difficult geotechnical conditions or in sensitive environments. In order to meet the requirements of a Eurocode 7 compliant "observational method" design, dedicated design preparation work prior to construction and organized monitoring system is required. In addition, professionally trained tunnelling engineers are required on site to identify, interpret and react to the changing patterns of ground improvement.

In most of the projects, once the design is carried out by Qualified Person for Design (QPD) and approved by relevant authorities and checkers, the involvement of QPD during execution stage is limited. The amount of time spent by QPD during project execution is very less comparative to the time spent by Qualified Person for Supervision (QPS). Hence the supervision team needs to understand the meaning of different convergence behaviour. This kind of simple visualization could be a useful tool for such process. In addition, with such tools, it is possible to study, normalize and compare case histories of various sites. This can be used to further improve monitoring and interpretation techniques.

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