Monitoring and Control in Tunnel Construction

AITES/ITA WG2-Research

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1 >> Introduction and Scope

Instrumentation and monitoring are an essential part of current tunnelling practice. For safe and economical tunnelling in sensitive construction environments a continuous adaptation of excavation and support design is required so that input parameters can be revised when the predictions deviate from measured values. In addition, systematic monitoring results can provide valuable information pertaining to imminent collapse, thus, making it possible to control the tunnel stability by providing proper countermeasures.

Over the decades monitoring techniques have been considerably improved. For example, determination of absolute displacements during tunnel excavation by geodetic methods is to a large extent replacing measurements of relative displacement. The resulting increase in the amount of information available has necessitated the development of data visualization techniques for proper interpretation and immediate feedback. Information Technology (IT) has also become an integral part of instrumentation and monitoring for data collection, visualization, and evaluation.

The purpose of this document is to give guidance to tunnel engineers in the basic concepts of instrumentation and monitoring for control of tunnelling activities. It has been developed as part of the ITA approach to encourage knowledge transfer within Member Nations, and facilitate the dissemination of technical knowledge towards stakeholders at an international level that may be involved in a tunnelling project.

As such this recommendation is not meant to serve as a text book, and does not present detailed descriptions of monitoring technologies. It is rather aimed at providing relevant information on key principles and methodologies that may assist stakeholders in their approach to a tunnelling project and encourage them to seek proper specialized advice as and when appropriate.

The document is based on a compilation of a number of publications concerning tunnelling works from various countries and organizations, such as Hudson (1995), ICE (1996), Kastner et al. (2003), Tunnel Lining Design Guide (2004), Conventional Tunnelling (2005), Leca and New (2006), and KTA (2007).

The recommendation focuses on the contribution of monitoring to the successful completion of a tunnelling project, through real time usage of monitoring information as part of the construction process. It should be read in conjunction with the ITA publication Guidelines for Tunnelling Risk Assessment by Eskesen et al. (2004), as this approach can be viewed as one way of mitigating risks involved in tunnel construction.

A special emphasis is given to the use of absolute displacement measurements by geodetic methods for use in tunnelling control. It should be noted that this recommendation does not address the specific aspects related to monitoring of TBM parameters.

2 >> Instrumentation and Monitoring

2.1 OBJECTIVES

The main objectives of instrumentation and monitoring are to (i) obtain information on ground response to tunnelling; (ii) provide construction control; (iii) verify design parameters and models; (iv) measure performance of the lining during and after construction; (v) monitor impact on the surrounding environments such as ground settlement and groundwater regime. Of the aforementioned purposes of instrumentation and monitoring, the main purpose lies in the optimization of the design and execution of safe tunnelling works. Additional important objectives may include to (i) give warning of any safety-critical trends; (ii) to predict future trends in monitored parameters and other parameters not yet being monitored; (iii) to make predictions on the performance and management of the completed tunnels.

The required degree of effort and expense employed for instrumentation and monitoring depends on the nature of design, perceived hazards and level of risk. For example, obviously the need for instrumentation and monitoring during tunnelling operation is small for well-established design in well-known ground conditions. In high-risk environments, however, such as shallow tunnels with variable ground conditions, or where significant ground movements are expected, the benefits of instrumentation and monitoring are even more important.

Instrumentation and monitoring should therefore be viewed as an integral part of the risk management process as indicated by the ITA Risk Management Guidelines prepared by Working Group 2 Research published in 2004 (Eskesen et al. 2004).

In view of this, monitoring is done at the surface as well as for the tunnel structure including the surrounding ground as shown in Figure 1 (ITA-CET 2009).

Figure 2 shows a systematic simplified flow chart for instrumentation and monitoring during tunnel construction.

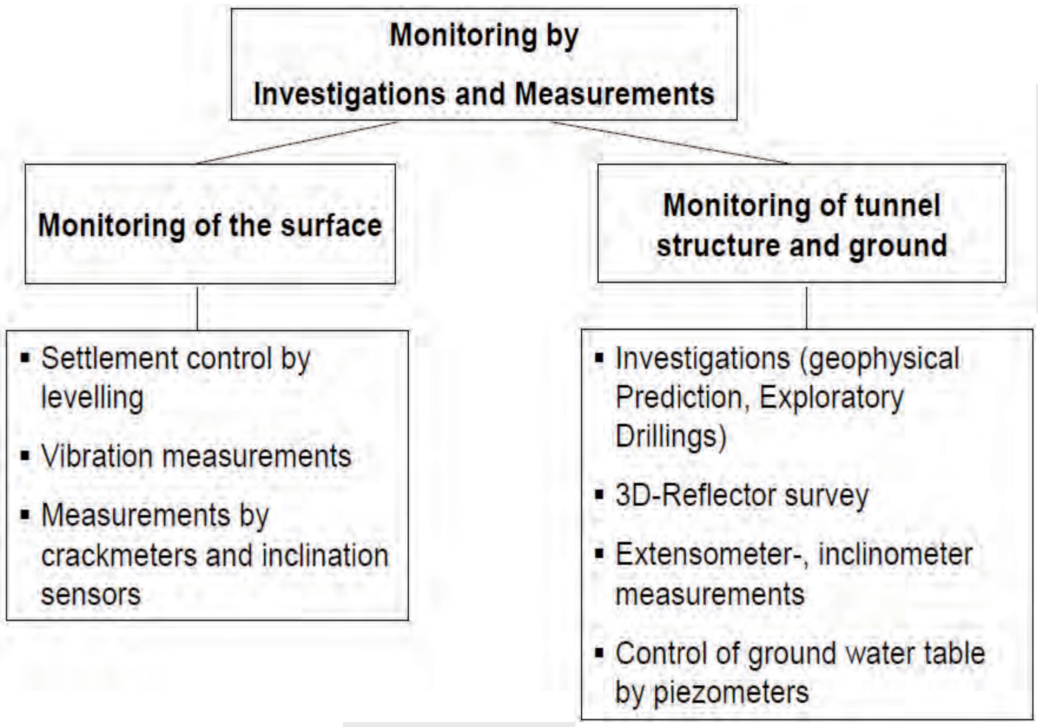

Figure 1. General concept of monitoring (Felix Amberg 2009)

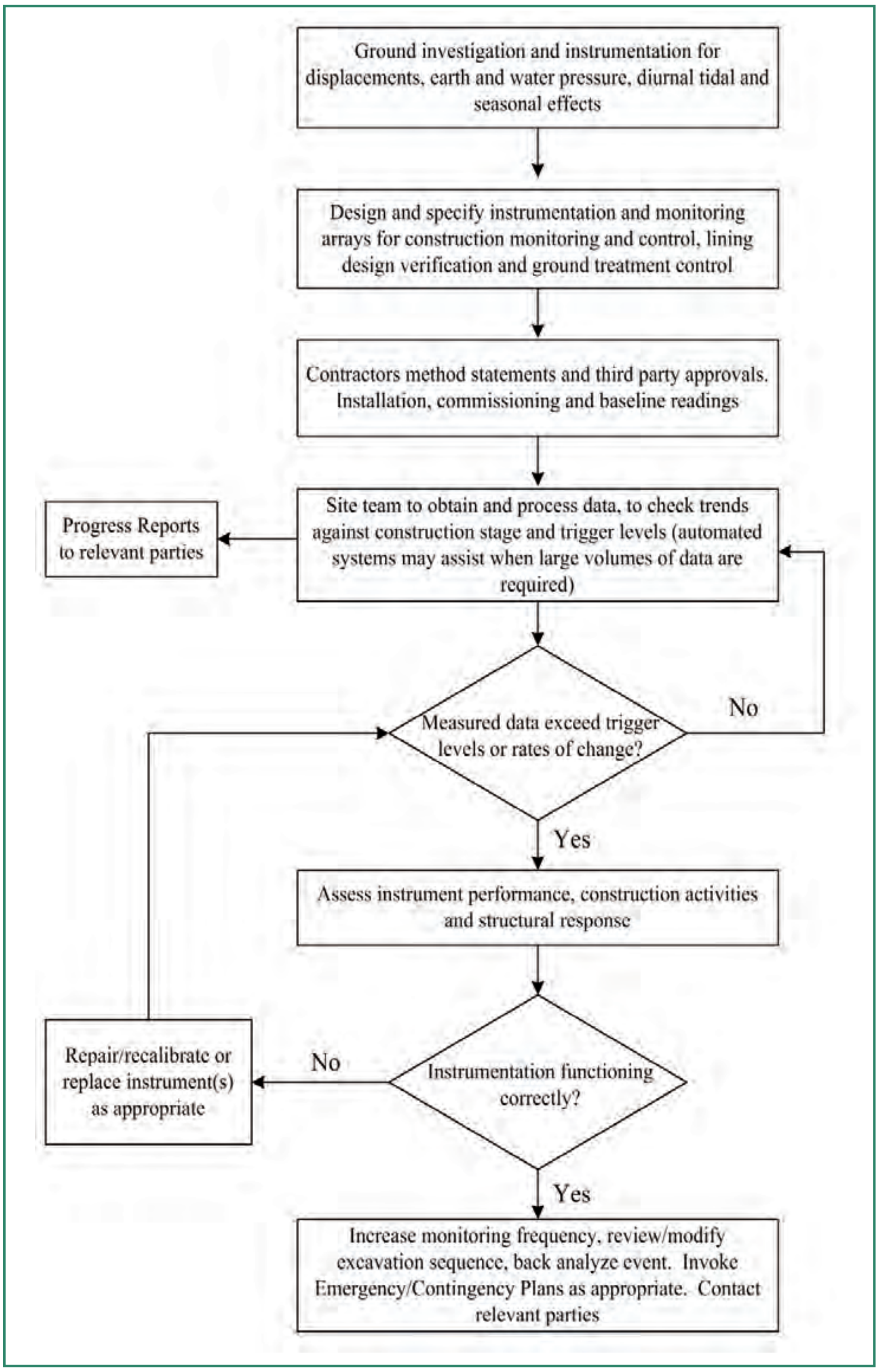

Figure 2. Monitoring of the construction process (Tunnel Lining Design Guide, 2004)

2.2 INSTRUMENTATION PLANNING

When planning a monitoring program some sound principles have to be followed in order to obtain useful results for practical purposes with a minimum of expenditure. The layout and spacing of instrumentation arrays should be selected with due consideration of the site specific conditions as they will depend on factors such as the stratigraphy, level of detail (volume of data) and degree of redundancy required. Some redundancy in instruments and instrumented points is always desirable as a way of insuring against unreliability of readings or instrument failure and helping identify effects and causes.

An instrumentation program should be planned to obtain the following information (Tunnel Lining Design Guide 2004):

- **Greenfield ground response:** earth and water pressures, displacement, and strains;
- **Ground-structure interaction:** relative structural displacements, structural tensile and compressive strains and earth pressures;
- **Ground-lining interaction:** lining strength and stiffness, relative displacement (distortion), tensile and compressive stresses and strains in the lining and earth pressures acting on the lining;
- **Ground conditions:** borehole instrumentation to assess ambient earth and pore pressure conditions, groundwater regime and chemistry, face logging for geological conditions, forward probing, groundwater inflow rates, external changes in earth and water pressure
- **Monitoring of control and mitigation measures:** (such as compensation grouting or ground freezing): temperature, earth and water pressures, grout-take and pressures, displacements and strains;
- **Monitoring environmental effects and working environment:** ground displacements, noise and vibration, air quality'

In general, instrumented sections can be categorized based on their objectives.

- Standard instrumented sections: These sections are to evaluate general tunnelling performance in routine tunnel sections based on convergence measurements. There may be in general more standard sections than fully-instrumented sections against which they are calibrated.
- Fully-instrumented sections: Both convergences and stresses in the lining are measured in these sections. Geotechnically uniform and representative locations should be chosen for these sections so that the monitored parameters can be used for calibration of the assumed design parameters.
- Singularity monitoring sections: Sections with singular geometries (tunnel portals, intersections, nearby buildings sensitive to settlement) or geological singularities (shear faults, transition zones, weathered zones, etc.) should also be monitored.
- Monitoring sections for new construction method verification: Instrumentation and monitoring should also be planned to verify the efficiency of any new construction methods adopted.

There are several factors to be considered when designing an instrumentation programme as described by Dunnicliff (1993).

- Ground evaluations: The ground should be fully understood in terms of stratigraphy, strength and stiffness, in-situ stress, compressibility and permeability of the ground, and anticipated magnitude of changes.
- Greenfield check': Instrumentation and monitoring should be planned to monitor the 'greenfield response' that will help identify the degree of interaction with adjacent structures, if any, in areas of the project, and the natural variations that occur before construction.
- Instrumentation limitations: There are certain requirements by which all types of field instrumentation should be evaluated in terms of range, sensitivity, repeatability, accuracy, and survivability. Critical areas where additional 'local' instrumentation may be required should also be identified.
- Responsibility: In contract documentation, responsibilities for installation and commissioning, calibration, provision of baseline data within the chosen contractual framework and responsibilities for ongoing maintenance, monitoring, interpretation and reporting should be clearly defined.
- Methodology: It should be ensured that trained installation and monitoring personnel are available, and that all relevant data during site calibration are recorded.
- Frequency of readings: The frequency at which instrument readings are taken should be based on type of project, instrument type, available instrumentation personnel, location, and time. The range of change of the condition that is being monitored may vary over time, dictating a change in the established frequency at which readings are taken.
- Data management: Acceptable trigger levels and associated courses of action, the method of data collection, interpretation and presentation should be established. Data collection should be flexible to respond to unexpected changes with an increase in reading frequency at specific instruments or arrays. The data should be presented in a readily digestive form. There should be a clear hierarchy for passing the data and interpretations to the correct responsible people.
- Real-time monitoring: Real-time monitoring using automatic data acquisition systems may be used on the basis of the anticipated rate of change of the parameters being measured and the requirement for a rapid response.
- Tunnelling data: In-tunnel logging data such as geological mapping results should be included as part of monitoring data.

2.3 INSTRUMENTS SELECTION

Generally the physical parameters monitored include as shown in Figure 3: (i) strains; (ii) relative displacements; (iii) absolute displacements; (iv) changes in curvature (in the tunnel lining); (v) stresses in the lining and in the rock mass; (vi) rock or earth pressures on the tunnel lining, forces in rock anchors; and (vii) piezometric levels. Typical measurement items for conventional tunnelling and TBM tunnelling are summarized in Table 1.

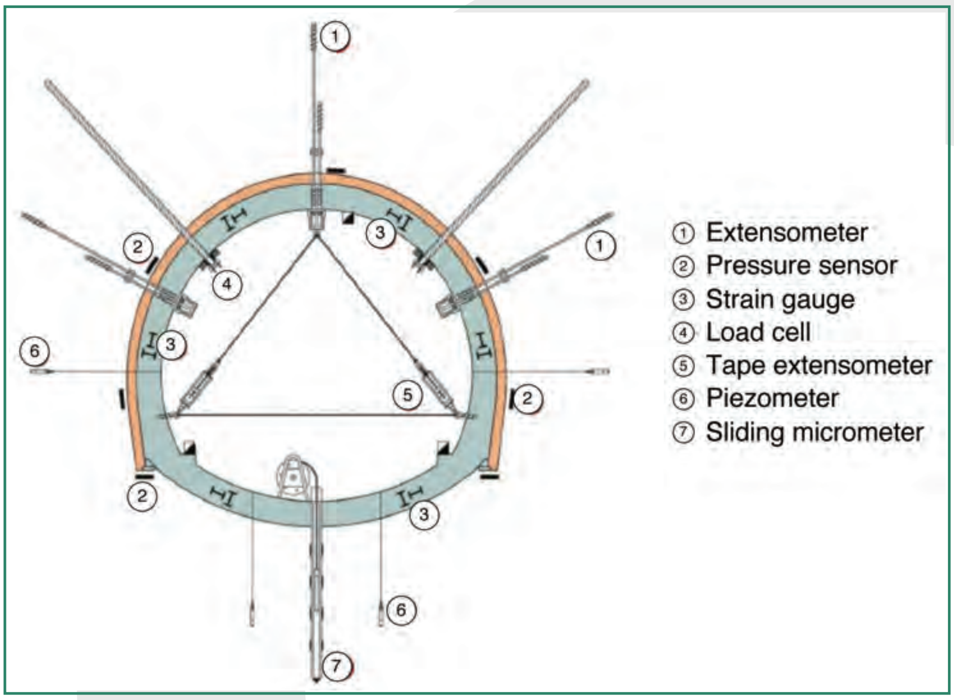

Figure 3. Typical layout of instrumentation (after ITA-CET 2009)

Table 1. Leading parameters to be monitored in four tunnel configurations (modified AFTES 2005)

	Conventional Method (low overburden in urban areas	Closed-face TBM (urban areas)	Operational tunnel in creeping ground
0. VISUAL INSPECTION (face & sidewall)	●	❍	●
1. GEOMETRICAL PARAMETERS			
Face extrusion (horizontal displacdement)	●		
Surface settlement	●	●	
Surface rotation	❍	❍	
Extrusion of the ground ahead of tunnel face (extrusion-meter)	■		
Displacement in borehole (extensometer, inclinometer)	❍	❍	×
Convergence at sidewall	●		●
Crack monitoring	❍		●
Deformation of permanent lining	×	×	●
2. MECHANICAL PARAMETERS			
Force (arch base, anchoring rod, rock bolt, etc.)	●		×
Stress in ground			❍
Stress in support /lining	❍	×	❍
3. HYDRAULIC PARAMETERS			
Pumped out water rate	❍		❍
Surface rainfall	×		×
Piezometric levels in ground	●	●	●
Temperature of leakage			×
4. OTHER PARAMETERS			
Tunnel air temperature		❍	×
Tunnel air pressure		×	
Tunnel hygrometry	×	×	❍
Date and time	●	●	●
Vibration from blasting	●		

Notes
× Usually secondary parameter
❍ Frequently important parameter
● Essentiel parameter, always monitored
■ Essentiel parameter, always monitored when advance full face with pre-confinement

Typical instrumentation equipments used for routine instrumentation are listed in Table 2 for initial guidance. Instruments should be selected with due consideration of quoted ranges, accuracies and precisions pertinent to site specific conditions. These instruments should be calibrated before they are put into use.

2.4 FREQUENCY OF READINGS

The frequency of readings can vary according to the monitoring phases as follows:

Table 2. Types of instrumentation equipment (modified Tunnel Lining Design Guide, 2004)

Objective	Instrumentation	Range	Resolution	Accuracy
Extrusion of ground ahead of face	Increx probe	0.1 mm	0.01 mm	±0.003 mm/m
	Sliding micrometer	1 m	0.01 mm	0.002 mm/m
	Sliding deformeter	1 m	0.01 mm	0.02 mm/m
Relative vertical movement	Precise leveling pins installed on structures, settlement points, geodetic surveying targets in structures or tunnel linings	any	0.1 mm	0.5~1.0 mm
	Precise liquid level settlement gauges with LVDTs installed in surface structures	100 mm	0.01~0.02 mm	±0.25 mm
	Borehole magnet extensometer	any	±0.1 mm	±1~5 mm
	Borehole rod or invar tape extensometers	100 mm	0.01 mm	±0.01~0.05 mm
	Satellite geodesy	any	to ±50 mm	to ±1 mm
Lateral displacement	Surface horizontal invar wire extensometers	0.01%	0.001~0.005%	0.01~0.05 mm
Change in inclination	Borehole electrolevels; Electrolevel beams on structures and in tunnels; 'tilt meters'	50 mm/m (to 175 mm/m)	0.05 mm/m (to 0.3 mm/m)	to 0.1 mm/m
	Horizontal borehole deflectometer	±50 mm	±0.02 mm	±0.1 mm
	Borehole inclinometer probes	±53° from vertical	0.04 mm/m	±5 mm/25 m
Change in earth pressure	'Push-in' total pressure cells	up to 1 MPa	up to 0.1% FS	up to 1.0% FS
Change in water pressure	Standpipe piezometers	any	±10 mm	±10-20 mm
	Pneumatic piezometer (pore pressures are balanced by applied pneumatic pressures); Electronic (vibrating-wire type) piezometric sensors	0-20 bar	0.01 bar	0.5% FS ± 0.02 bar
Crack or joint movement	Telltales	±20 mm	0.5 mm	±1 mm
	Calliper pins/micrometer, or mechanical strain gauges	up to 150 mm	0.02 mm	±0.02 mm
	Vibrating wire jointmeters	up to 100 mm	up to 0.02% FS	up to 0.15% FS
Strain in structural member or lining	Vibrating wire strain gauges	up to 3000 $\mu\varepsilon$	0.5~1.0 $\mu\varepsilon$	±1~4 $\mu\varepsilon$
	Fibre optics	to 10,000 $\mu\varepsilon$ (1% strain)	5 $\mu\varepsilon$	20 $\mu\varepsilon$
Tunnel lining diametrical distortion	Tape extensometers across fixed chords	up to 30 mm	0.001~0.05 mm	±0.003~0.5 mm
	3D geodetic optical leveling ('retro' or 'bioflex') targets, leveling diodes or prisms	any	0.1~1.0 mm	0.5~2.0 mm
	Strain gauged borehole extensometers installed from within tunnel	100 mm (3000 $\mu\varepsilon$)	0.01 mm (0.5 $\mu\varepsilon$)	±0.01~0.05 mm (±1~10 $\mu\varepsilon$)
	Convergence system	±50 mm	0.01 mm	±0.05 mm
Lining stress	Total pressure (or 'stress') cells	2-20 MPa	0.025~0.25% FS	0.1%~2.0% FS
Lining leakage	Flow meter	any	1 litre/min	2 litre/min
Vibration	Triaxial vibration monitor/seismograph	250 mm/sec	0.01-0.1 mm/sec	3% at 15 Hz

2.4.1 Instrument installation phase: it is important to record the sign of the measurements, to check the numbering of the instrumented points and data channels, and to detect any anomalous behavior.

2.4.2 Initial reading phase: This phase is to have values for the "baseline readings', to gradually improve measurement accuracy, and to validate design assumptions as early as possible.

2.4.3 Routine monitoring phase: In this phase, the reading frequency must be chosen with due consideration of the rate of change in the measured quantity and monitoring stage, i.e., active monitoring and close-out monitoring. It should also be periodically reviewed in the light of observed results. In addition, time synchronization of various data acquisition systems and consideration of seasonal variation of reading are also important.

3.1 DATA PRESENTATION

Most types of data are best presented in graphical form as graphical presentation facilitates the interpretation of relationships and trends in the data. Readings are compared over time and with other instrument readings as well as with construction activities and changing environmental conditions. Observed trends should be compared with predicted trends to make an assessment of overall performance. It is important to ensure that adequate resources are provided to ensure timely interpretation and response to real-time data. This can be done using advanced visualization techniques available to date. The use of geographical information system (GIS) has gained popularity for data storage and visualization of monitoring data.

3.2 DATA EVALUATION

Several factors should be considered when evaluating instrumentation data such as instrument drift, cross sensitivity, calibration, and environmental factors. Instrument drift is the change in instrument readings over time when other factors remain constant. Making repetitive readings helps to detect and account for drift errors.
In order for an instrumentation program to be successful, recorded data should be understood fully and used in controlling the tunnelling project. A clear understanding of the purpose of the program is essential for an understanding of the data obtained. Data evaluation must be completed in the shortest possible time. Predicted behavior at a design stage may be used as a reference point from which all interpretations of the data are made. The original designer's involvement is highly recommended so that key design assumptions can be examined. Improvement of the original design can be made by feedback of the results of data evaluation during construction. There should be a well established communication line between the designer, contractor, owner, and the supervisors in interpreting and evaluating monitoring data.

The following information should also be considered when interpreting monitoring data:
• advance of the tunnel face, bench or other data relating to the progress of the works;
• changes in geology encountered;
• rainfall and piezometric data;
• temperature changes when there is no systematic detection system;
• deformation predicted from design analyses.
• change or replacement of monitoring equipment during construction

3.3 TRIGGER VALUES

Measurements must be part of the Risk Management process, and used as a possible warning mechanism enabling preventive measures to be introduced in an acceptable time. It is normal practice to establish 'trigger values' for key indicator parameters (such as displacement, strain or pressure), which determine appropriate actions in response to these values being exceeded. For example in UK, usually two trigger values are used as defined in the Tunnel Lining Design Guide (2004). These trigger values are usually determined at a design stage.

3.3.1 Warning/amber: A pre-determined value or rate of change of a key indicator parameter that is considered to indicate a potential problem, but not of sufficient severity to require cessation of the works. Exceeding this trigger level will generally require a check on instrument function, visual inspection of the structure being monitored, increase in monitoring frequency, review of the design and modification of the construction process.

3.3.2 Action/red: This level may equate to displacement, strain, or pressure above which an unacceptable damage is expected to occur to the tunnel or nearby structures. If this value is exceeded, an immediate check on instrument function and visual inspection of the structure being monitored will be required, as well as the initiation of a pre-determined response, which may include temporary cessation of work, back analysis of the event and modification of the design and construction process.

Monitoring records should always be examined by an expert on a regular basis in order to detect any unexpected trends and take necessary measures in a timely fashion. The selection of appropriate trigger values will depend on the particular requirements of the project and the governing 'failure mechanism(s)' assessed by the designers. Even if serious anomalies are not indicated, it is always worth comparing predictions with observed values in order to understand the behavior of the structure and ground.

When setting up trigger values, the following have to be specified:
• procedures for passing on information
• allocation of responsibilities between the owner, supervisor, designer, and contractor
• time allowed for each person to pass on information or make a decision;
• remedial actions for dealing with foreseeable situations.

4 >> Control of Tunnelling Works Using In-Tunnel Monitoring Data

4.1 CONVERGENCE MEASUREMENTS

4.1.1- General

The monitoring of convergence is carried out with the help of pins or target plates mounted onto the tunnel wall immediately after excavation. To determine convergences, the readings between individual pins of the same cross section should be plotted over time. Whereas the traditional method consisted in measuring the distance between pins with invar wire or steep tape devices, more recent advances have made optical methods standard practice. They consist of installing reflective targets on the walls and measuring the absolute displacements of those targets. One of the benefits of the optical method is that the monitoring system does not impair the tunnel construction process; this monitoring system is dealt with in Section 4.2.

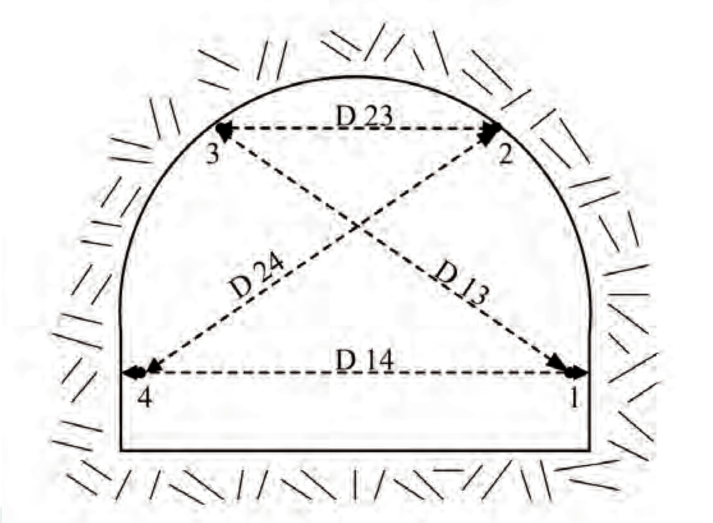

Figure 4. Pins to measure the convergences in a tunnel (Hudson 1995)

Tunnel convergences can be used in controlling tunnelling as in a mathematical sense they are integrated quantities representing major local effects. Stresses, strains, and curvatures, on the other hand, are differential quantities, the magnitude of which is significantly influenced by local effects. Displacement measurements should be observed at several successive points so that their distribution over a sufficient area can be obtained.

4.1.2- Decision making in tunnelling based on relative convergence measurements between two pins.

The convergence can be defined

$$C(t) = D_o - D(t) \quad (1)$$

Where ***C(t)*** is the convergence at time t between any two opposite points in a tunnel cross section, i.e., points 1 and 3, 2 and 4, etc. in Figure 4. D_o is the initial measurement of the distance between the two points, and ***D(t)*** is the measurement at time ***t*** of the distance between the two points. The convergence is considered positive if the distance between the two points has decreased and negative if it has increased.

The convergence of a tunnel may be attributed to the effect of face advance and the time-dependent behavior of the rock mass. To carry out a complete analysis of the convergence in the simple case of full-face excavation, the three typical graphs shown in Figure 5 should be plotted (Hudson 1995); (i) the distance *x* between the convergence station and the face of excavation versus time t; (ii) the convergence *C* versus *t*; and (iii) *C* versus *x*. Whereas the effect of the face advance decreases rapidly with *x*, the slope of the convergence curve is much steeper to the face as shown in Figure 5(b). It is therefore important to take the first measurement as close as possible to the excavation face, although this may be difficult or impractical, for example, when the shield tunnelling method is used. When the excavation face has advanced to a distance two to three times the tunnel diameter from the convergence monitoring station, the convergence is controlled by the rheological behavior of the ground mass and the stiffness of the support.

The distance of face influence may be evaluated using the *C-t* plot after an interruption of the excavation.

For example, during the interruption of tunnel advance as in Figure 5(a) for the two periods $t_2 - t_3$ and $t_6 - t_5$, no convergence should be recorded if the face is far ahead of the convergence station. If the convergence continues to develop, the time-dependent ground mass properties such as creep or instability must be involved. When face advance is resumed, a discontinuity in the slope of the curve *C-t* plot shown in Figure 5(b) appears if the face is close enough to the convergence station as for time t_3. However, when the face is far ahead of the convergence station, this discontinuity does not appear as for time t_6. The convergence versus face distance plot shown in Figure 5(c) can also be used to evaluate the face influence.

When a multi drift excavation is used, the analysis is more complex because it is necessary to consider the effect of the different sequences of excavation. When interpreting the convergence curves, care should be exercised by the site engineer to make a sound judgment concerning the sequence of excavation and the efficiency of the various techniques of supports, e.g., steel arches, rock bolting and shotcrete.

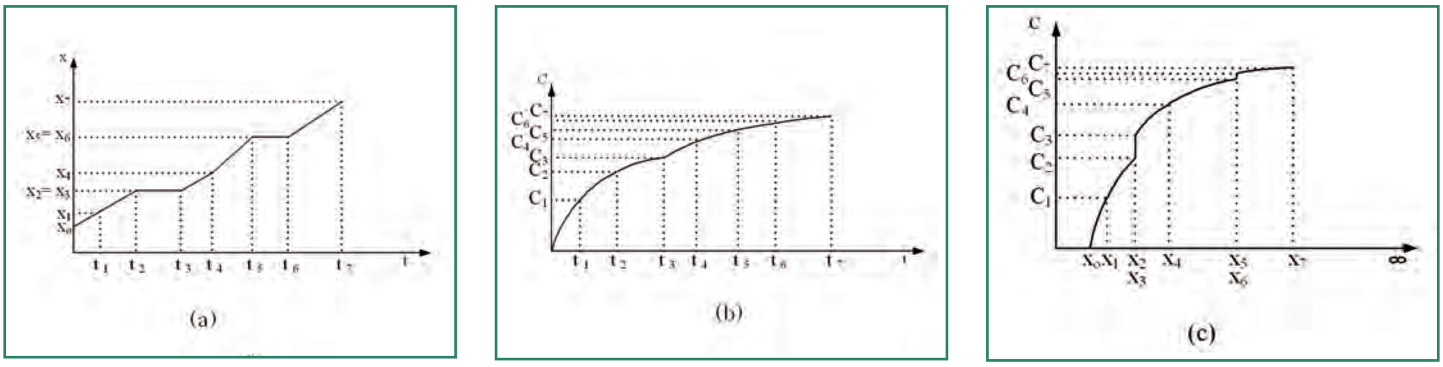

Figure 5. Graphs for the analysis of distance versus time, convergence versus time and convergence versus distance (Hudson 1995)

4.2 ABSOLUTE DISPLACEMENT MONITORING

4.2.1 General

Over the decades, displacement monitoring techniques have considerably improved. Absolute displacement monitoring during tunnel excavation using optical instruments in particular has made it possible to better understand the meaning of measured displacement quantities. For example, the optical 3D-convergence measurement method has become available and has been used in a number of tunnelling site (ITA-CET 2009). Advantages of the optical 3D convergence measurement are summarized in Figure 6.

In addition, there has been a great deal of advances in data processing and evaluating techniques for measured absolute displacements during tunnelling (Austrian Society of Geomechanics 2005). These techniques are becoming more common practice as they allow a better understanding of geomechanical processes during tunnel excavation which eventually allows optimum tunnel construction through an enhanced ability to predict ground conditions ahead of the tunnel face.

This section presents recent advances in data processing and evaluation techniques using absolute displacement monitoring results, introduced in the document Conventional Tunnelling (2005) published by the Austrian Society for Geomechanics Division "Tunnelling", Working Group "Conventional Tunnelling".

Measuring results are absolute
Accuracy 1-2 mm
Information about deformation of the tunnel walls surface
Information about the cavity deformation of the tunnel walls surface
Lower accuracy is compensated by absolute measuring results

Figure 6. Illustration of optical 3D convergence measurement (ITA-CET 2009)

4.2.2 Data processing for absolute displacement monitoring data

Displacement history plot

A displacement history diagram for any particular measuring point as shown in Figure 7 in conjunction with construction phases (top heading, bench, invert, etc.) allows for correlations between construction activities and displacements so that the stability of a given tunnel excavation can be assessed. For a constant face advance rate the displacement rate over time should decrease for the excavation to be stable, whereas any acceleration of the displacement rate can be considered unstable, unless it can be correlated to ongoing construction activities in the vicinity of the monitored tunnel section such as bench and invert excavation, or shaping activities. Signs of creep deformation can be shown in Figure 8.

Deflection curve

A deflection curve for a given displacement component can be constructed by connecting displacement values at measuring points along the tunnel axis. A series of deflection curves are normally plotted for a specified time span as shown in Figure 9. Construction phases (top heading, bench, invert, etc.) should also be included to allow for correlations to be made between the construction activities and the deflection curves. The deflection curves can be used to identify the following information i) longitudinal extent of tunnel deformation behavior; ii) change in rock mass stiffness; and iii) pre-displacement prior to measurement. An increase in the area between two successive deflection curves indicates the presence of a weak zone or a major discontinuity ahead of the tunnel face

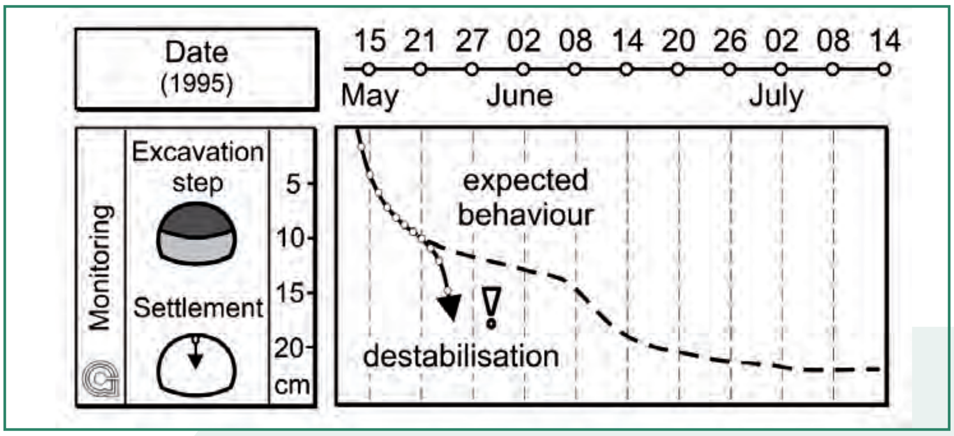

Figure 7. Typical displacement history plot (Austrian Society of Geomechanics 2005)

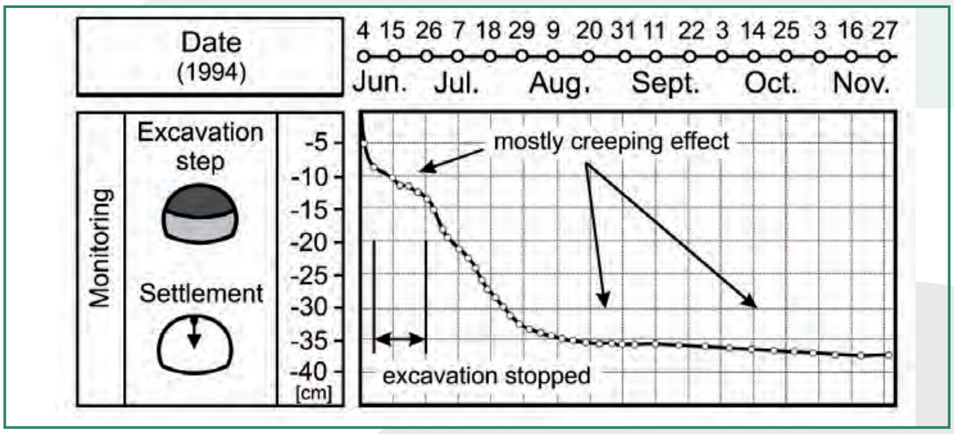

Figure 8. Displacement history plot showing signs of creep in the rock mass (Austrian Society of Geomechanics 2005)

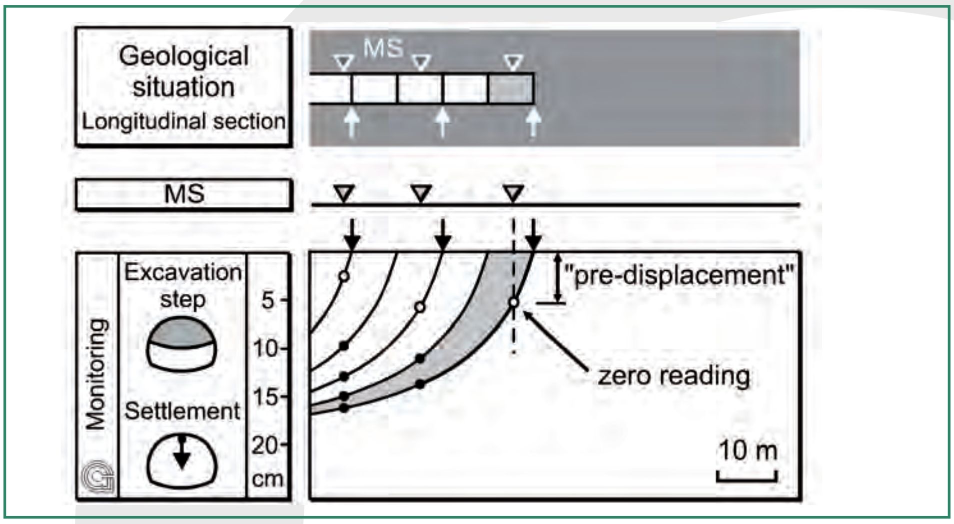

Figure 9. Typical deflection curve for tunnelling in homogeneous rock mass (Austrian Society of Geomechanics 2005

Trend line

Trend lines are constructed by connecting points at a constant distance behind the face from the deflection curves (Figure 10), providing an overview of the displacement development along the tunnel axis for a given excavation component.

The presence a weak zone or a major discontinuity ahead of the face tends to increase the displacement over several readings.

Displacement Differences between Two Measurement Points

Differences in displacements between two monitoring points within a tunnel section can be used as a criterion for evaluating the tunnelling performance. The displacement differences frequently used are as follows:

- S_{Crown} - $S_{Sidewall}$
- S_{Crown} - $S_{Surface}$
- $S_{leftSidewall}$ - $S_{rightSidewall}$
- $H_{leftSidewall}$ - $H_{rightSidewall}$

Where S_{Crown} is the crow settlement, $S_{Sidewall}$ is the sidewall settlement, $S_{Surface}$ is the surface settlement, $S_{leftSidewall}$ is the left sidewall settlement, $S_{lrightSidewall}$ is the right sidewall settlement, $H_{leftSidewall}$ is the left sidewall horizontal displacement, $H_{lrightSidewall}$ is the right sidewall horizontal displacement.

For shallow tunnels, the index (S_{Crown} - $S_{Sidewall}$) together with ($H_{leftSidewall}$ - $H_{rightSidewall}$) provides information on tunnel lining distortion while the index (S_{Crown} - $S_{Surface}$) can be used to identify loosening of the ground above the tunnel.

The difference in displacements between two measuring points can be used to detect weak zones or faults outside the excavation area (Figure 11). In homogeneous ground, the difference in settlements between two points should typically remain constant. When excavation approaches a fault zone across the tunnel axis at an acute angle, the difference in settlement between the crown and the sidewall will change.

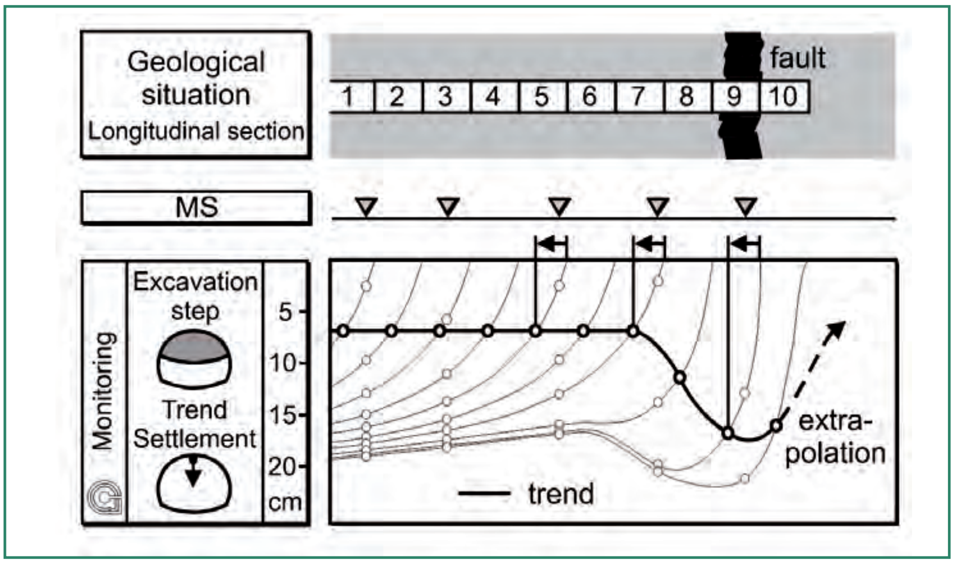

Figure 10. Typical trend line plot for tunnelling with a major fault zone (Austrian Society of Geomechanics 2005)

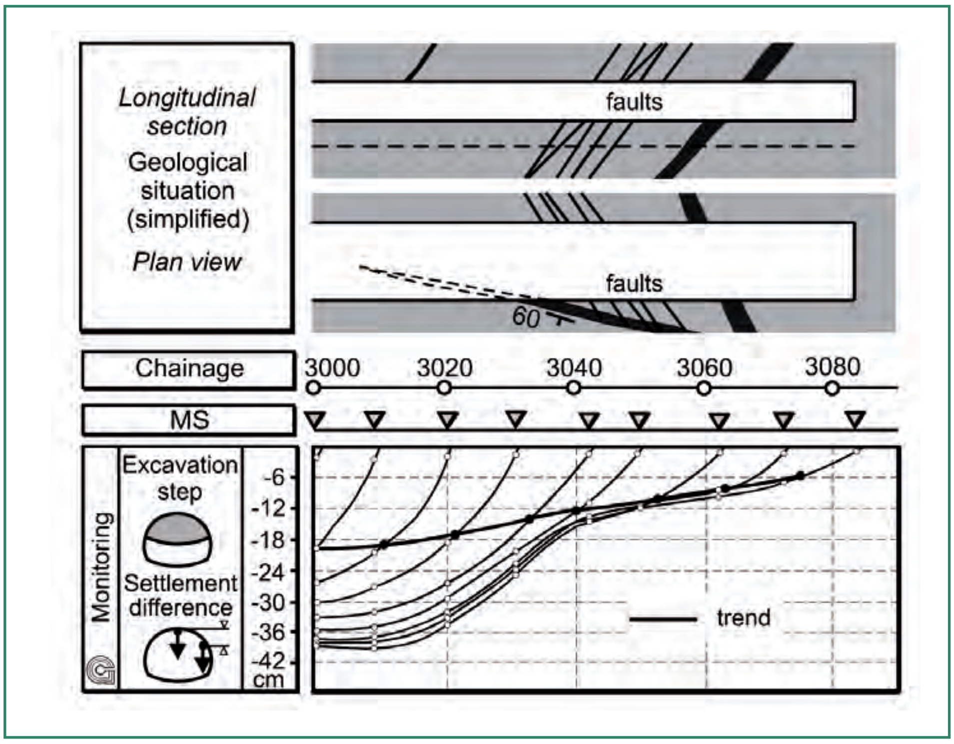

Figure 11. A plot for S_{Crown} - $S_{Sidewall}$ for tunnelling condition with faults (Austrian Society of Geomechanics 2005)

Displacement Vector Plots in Cross Section
The absolute displacement monitoring results can be used to draw displacement vector plots for a given tunnel cross section. The displacement vector orientations in a cross section provide information on the rock mass structure and deformation phenomena in the region adjacent to the tunnel. For example, tunnelling in a homogenous ground results in a symmetric displacement vector plot with respect to the tunnel center-line as shown in Figure 12. When a steeply dipping fault zone is present adjacent to the tunnel, the displacement tends to increase and the vector orientations tend to change as shown in Figure 13, due to the overstressing of the ground between the tunnel sidewall and the fault. This pattern can be used to gain an understanding of the deformation phenomena which, in turn, allows one to adjust the support characteristics in the areas including layout, spacing and orientation of rock bolts when used (Schubert et al. 1993).

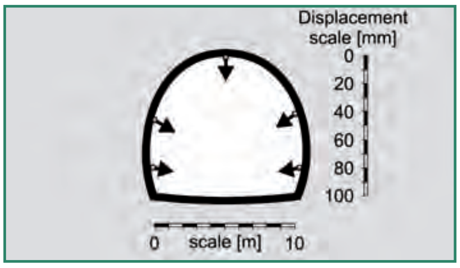

Figure 12. Typical displacement vector orientation in cross section for tunnelling condition in homogeneous rock mass ((Austrian Society of Geomechanics 2005)

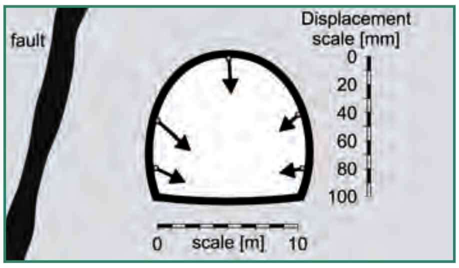

Figure 13. Typical displacement vector orientation in cross section for tunnelling with a steeply dipping discontinuity near the left sidewall (Austrian Society of Geomechanics 2005)

4.3 EXTRUSION MEASUREMENT

4.3.1 General
The measurement is typically carried out in an extrusion station, which is meant to identify the extent and condition of the de-stressed zone ahead of the tunnel face (core) by determining its longitudinal deformation and (if the core is accessible from the face) its radial deformation. An accurate measurement of the extent of the distressed core is of paramount importance because it gives forewarning of excessive deformation well in advance with respect to the convergence, which is only the resulting aspect of ground deformation (Figure 14). As shown in Figure 15, the station consists of an incremental extensometer (Figure 15), which is 2-3 diameters long, is typically installed in the center of the tunnel face and is parallel to the tunnel axis; its collar is quipped with a target for topographic measurements. All extensometers consist of fixed rings separated by plastic pipes, which are cemented in a borehole; the measurement is taken by inserting a probe in the plastic pipe, which measures the distance between the rings. If the tunnel face does not advance in more than one week, then 8 additional targets are typically mounted at the face. Finally, when the core is accessible from the surface, multi-point extensometers are used to determine the radial deformation ahead of the tunnel face, pre-convergence.

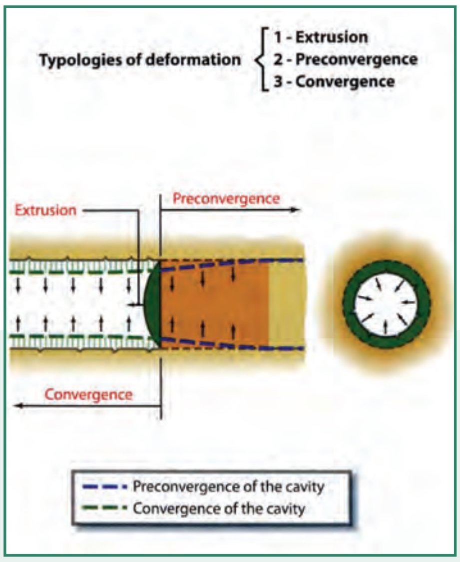

Figure 14. Three deformation components around the tunnel (Lunardi 2008).

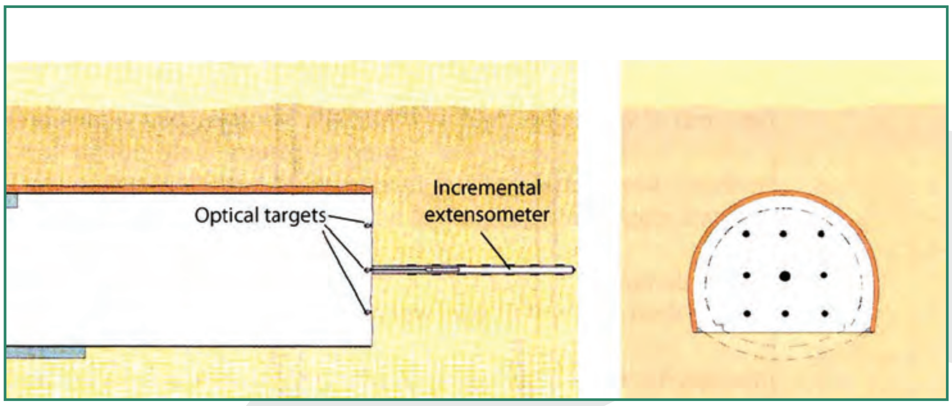

Figure 15. Extrusion station (Lunardi 2008).

4.3.2 Data processing for extrusion monitoring data
Once the zero reading is taken right after installation, face advance causes the extension of the plastic pipe between the rings. By measuring the change in distance between the rings (with respect to the zero reading), the cumulative extrusion may be easily calculated. For points close to the tunnel face, cumulative displacements may be obtained using an additional forward extensometer installed ahead of the tunnel face (figure 16).

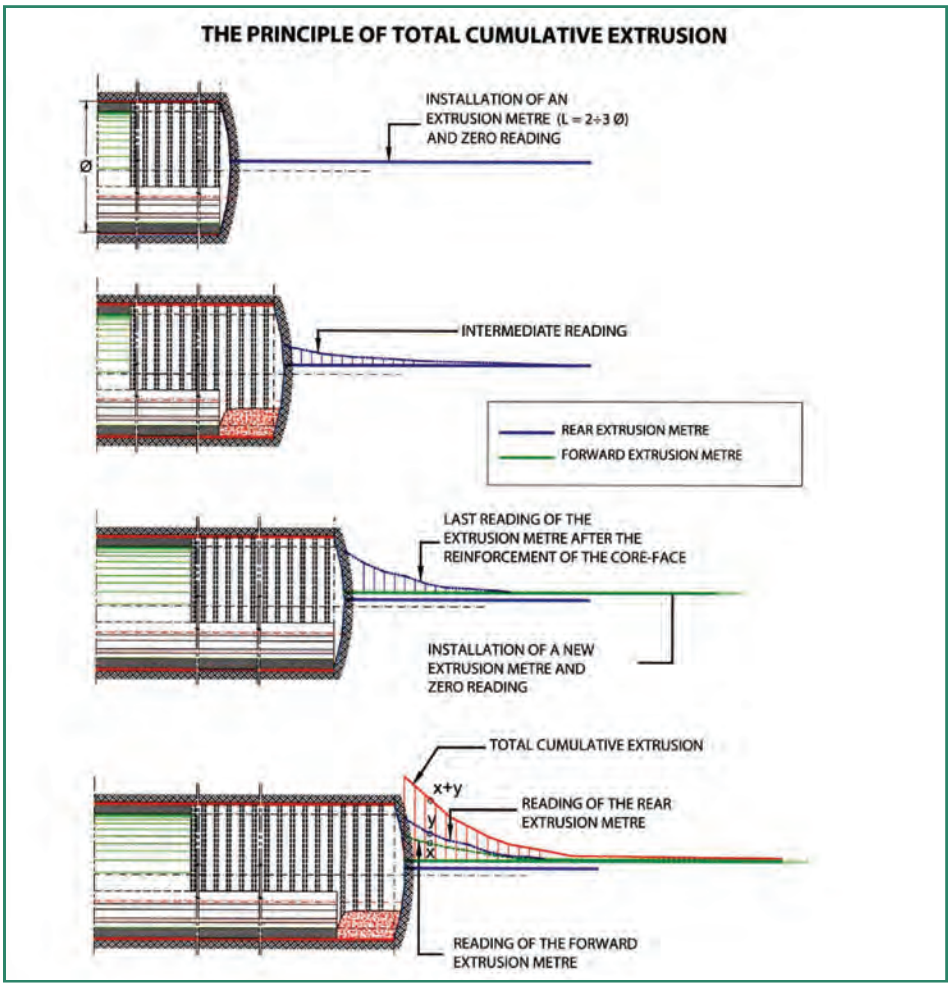

Figure 16. Measurement of total cumulative extrusion (Lunardi 2008).

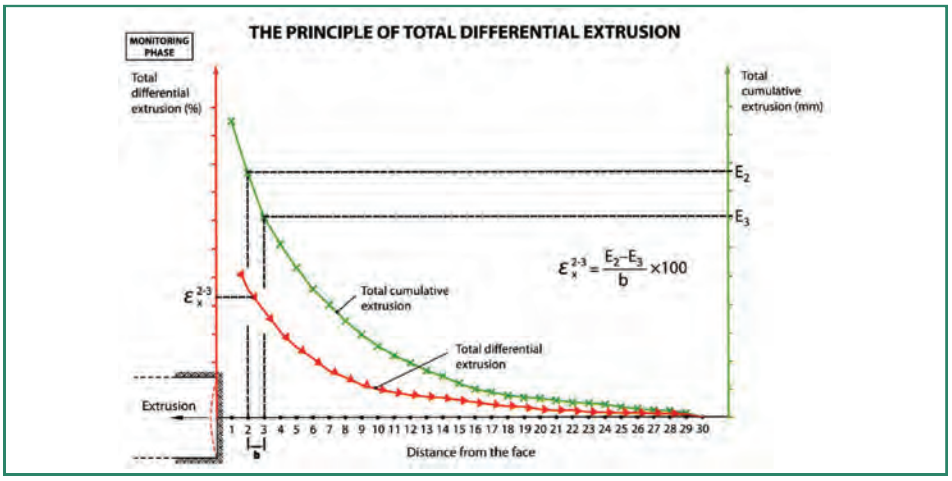

Figure 17. Calculation of differential extrusion (Lunardi 2008).

In addition to the total cumulative extrusion, the total differential extrusion can be calculated (Figure 17) as the total extrusion difference between two adjacent rings divided by the distance between two adjacent rings. When these measured strains are compared with the strains predicted at the design stage, one may determine whether the ground is in an elastic, plastic, or even residual condition, which allows some evaluation to be made of the extent of yielding ahead of the tunnel face, safety of the core and face, and need for additional pre-confinement measures.

When cumulative and differential extrusions are plotted against time, their velocity and acceleration may be appreciated. As for other monitoring devices, acceleration can be used as an indicator of failure potential. Typically, negligible extrusion indicates that the face is stable; significant extrusion with negative acceleration indicates that the face is stable only in the short term, and significant extrusion with positive acceleration indicates that the face will be unstable:
supporting/preconfinement measures must in such situation be changed/added to revert to stable face conditions during construction. Additionally, the radius of influence of face can be calculated.

The radial deformation ahead of the tunnel face (pre-convergence) may be obtained directly from extensometer readings if the tunnel is accessible from the surface. Otherwise, the extrusion measurement may be used to this effect as follows (Figure 18) together with chars developed for typically observed face deformation profiles (Lunardi 2008).

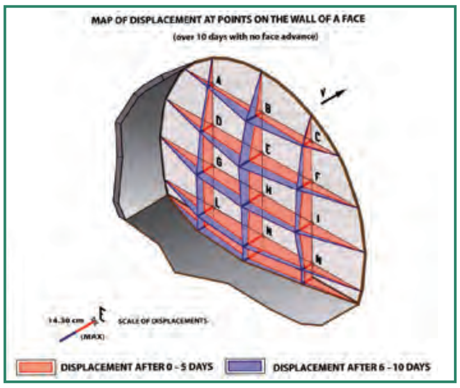

Figure 18. Measurement of the shape of the tunnel face (Lunardi 2008)

5 >> Control of Ground Movement and Impact on Adjacent Structures

5.1 GENERAL

Shallow tunnelling in soft ground inevitably induces surface settlements. These settlements may cause damage to buildings and services located within the settlement trough, and therefore the control of ground movement is of uttermost importance, especially in urban tunnelling situations.

Surface and subsurface movements are usually monitored using electronic autolevel stations and/or precise leveling stations. Geodetic surveying equipments, displacement measuring transducers and tape extensometers are used to monitor horizontal surface movements. Subsurface settlements are measured using instruments, magnetic ring extensometers for vertical movements and inclinometers for horizontal movements, normally installed in boreholes from the surface. Electrolevels in boreholes installed either from the ground or from shafts and tunnels provide an effective means of measuring subsurface ground movements. For structures likely to be affected by tunnelling, the movements should be monitored for surveillance using leveling points, or sometimes more sophisticated instrumentation such as electrolevels. Usually, as a minimum, routine leveling is required.

5.2 GROUND SURFACE MOVEMENT MONITORING

5.2.1 Objectives

There are two objectives for the ground surface movement monitoring; 1) to identify the settlement influence zone, and 2) to manage any risks of damage to adjacent structures. When planning a ground movement monitoring programme, the following should be considered (Tunnel Lining Design Guide 2004).

- Maximum anticipated settlement and horizontal displacement at defined points, for example tunnel centerline, sensitive buildings, etc.;
- The procedure for monitoring actual settlements;
- The method for recording and reporting measured data;
- Trigger levels at which specified action shall be taken, for example begin compensation grouting.

5.2.2 Layout of monitoring arrays

Either simple centerline levels at regular spacing or grid-type levels may be adopted depending on anticipated settlements as well as the degree of sensitivity of the surface and subsurface structures to settlements. A typical layout of ground movement monitoring for a transverse section is shown in Figure 19.

As tunnelling-induced surface settlements start to occur ahead of the tunnel face arrival, the ground movement monitoring programme must be such that the longitudinal extent of settlement zone can be identified (Figure 20).

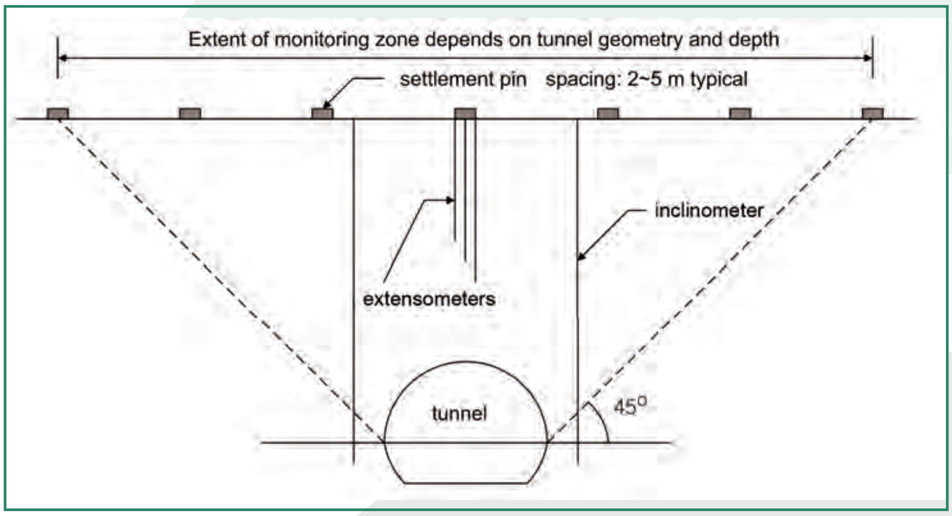

Figure 19. Typical transverse layout of ground movement monitoring arrays

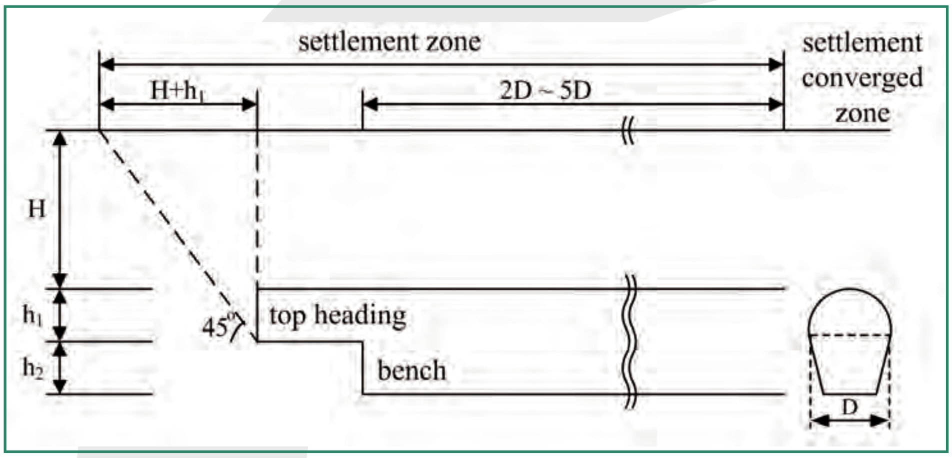

Figure 20. Typical longitudinal layout of ground movement monitoring arrays

5.2.3 Data processing
Data processing can be manual, or automated to a highly sophisticated standard, which may also include computerized recording, analysis and representation of results.
The procedure should include the following (Tunnel Lining Design Guide 2004).
• Recorded levels for a period of time before the tunnel face passes a monitoring point, for example three readings at weekly intervals to identify any natural ground movement;
• Recorded levels at a specified distance in front of the tunnel face as it reaches a monitoring point. This will record the development of the settlement trough (or potentially heave) ahead of the tunnel face and provide early information on how the settlement is developing compared with the anticipated behavior;
• Recorded levels at regular time intervals as the tunnel face passes a monitoring point, depending on the construction rate of advance and potential impact on local traffic conditions when transportation means may be affected.

Based on the rate of settlement, predictions on whether the settlements will eventually exceed prescribed trigger levels can be made, and necessary action can be taken before the settlements exceed trigger values.

5.3 SETTLEMENT RISKS AND CONTROL

When tunnelling in urban environment, settlements should be controlled to reduce risks associated with the tunnelling woks. The following in-tunnel protective measures should be adopted when settlement and/or convergence measurements exceed trigger values:
• dividing the face into small surface areas
• reducing the length of face advance
• shotcreting and/or supporting the face immediately after exposure
• increasing the shotcrete thickness and/or rock bolts reinforcement
• adopting measures to enhance load carrying capacity ahead of the face

5.4 MANAGEMENT OF THIRD PARTY IMPACT

5.4.1 General
The management of third-party impact is important where instrumentation and monitoring is required. When determining the layout of the instrumentation and monitoring arrays for tunnels in developed areas, it is recommended that, where possible, instrumentation be installed to assess greenfield behavior if such a location is available. This will provide useful indirect data on the performance of the tunnelling process and will facilitate an assessment of the degree of ground-structure interaction in other areas.
Monitoring of significant existing defects, noted during pre-contract condition surveys in services and structures within the anticipated area of influence of tunnelling induced movement, is also required. Pre-construction condition surveys, agreed to by all parties, are essential before work commences onsite. A descriptive scheme that is commonly adopted for describing damage to building is that proposed by Burland et al. (1996).

5.4.2 Building and utility damage assessment
Risk of damage to buildings due to tunnelling-induced ground movement can be assessed in a phased manner as described in the Tunnel Lining Design Guide (2004), based on the approach proposed by Burland and Wroth (1974). Measured data along the route of a given tunnelling site can be used to evaluate the risk of damage to buildings in the remaining area of the site.

Due to a larger number of buildings involved in urban tunnelling, a staged process of assessing risk of damage is usually adopted, such as a preliminary assessment, second stage assessment, and detailed assessment.
• Preliminary assessment: Buildings experiencing a maximum rotation of 1/500 and a settlement of less then 10 mm can be assumed to have negligible risk. Contours of greenfield ground surface settlement along the route of the tunnel under consideration can be used.
• Second-stage assessment: In this stage, the approach by Burland and Worth (1974) is adopted, in which a building is represented by a simple beam assuming foundations of the building follow the greenfield ground displacements. The limiting strain approach by Burland et al (1977) can also be used.

5.4.3 Vibrations
Other principal environmental effects include noise, dust and vibration. Pre-construction surveys will be required to establish existing ambient conditions in terms of noise and vibration. Ground borne vibration, which may also affect a building as re-radiated noise, can be a major constraint and has been an area of considerable recent study. Vibrations may arise both during construction and during operation of the completed tunnel and consideration may have to be given to mitigation of this effect during the preliminary selection of tunnelling method.

The likelihood of damage to a structure from ground vibrations depends not only on the magnitude of the peak particle velocity at the structure, but also on the type, condition and age of the structure. For example, historical masonry structures, particularly those with fine architectural finishes, are more sensitive to vibrations than modern reinforced concrete frame structures. Guidance on the threshold or critical peak particle velocities for different types of structures and different types of soil is presented in Table 3.

Table 3. Peak particle velocity damage thresholds in mm/s for different structures and soils (Kastner et al. 2003)

	Loose/soft soil	Medium soil	Dense soil
Historical buildings	2.5	5	10
Current construction	5	10	20
Reinforced construction	15	30	50

6 >> Concluding Remark

This recommendation has been prepared as part of the new approach developed by Working Group 2 of the ITA, which aims at consolidating updated information on key aspects of tunnelling principles and practices that may assist stakeholders in their approach to tunnel projects. In this respect, WG2 would welcome comments from users, as to the contribution of this approach to serving Member Nations needs and facilitating the dissemination of tunnelling knowledge at an international level.

The document is based on a compilation of a number of publications concerning tunnelling works from various countries and organizations. Although it focuses on monitoring and control of conventional tunnelling, major principles and techniques covered in this document apply to TBM tunnelling. Only specific areas such as TBM parameters monitoring has been kept outside the scope of this document.

Monitoring provides an economic means for reducing the risk of tunnel construction and constitutes an essential component of modern tunnel engineering. As such, the use of monitoring for tunnelling control can be viewed as part of the risk management approach applied to tunnel projects. This involves: an effective and well-managed monitoring program established before construction commences; continuous data acquisition and immediate feedback; and reliable prediction of the expected ground response to tunneling and back analysis.

The introduction of modern means of data storage and processing may contribute to the efficiency of the monitoring and control approach. Further developments should be required in this respect to achieve a comprehensive assessment of the benefits provided by their practical implementation in tunnel projects.

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