Chapter 5

Monitoring

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5.1 INTRODUCTION

Over the past decade, geotechnical instrumentation has undergone a significant evolution as a result of new technological developments deriving from microelectronics sensors, digital telemetry and interrelated computing devices (IoT applications).

Many types of transducers, dataloggers and supervisory control systems are available from different manufacturers over the world, and e-market development has contributed to reduce prices and time of delivering.

In the following chapters, up-to-date instrument types and data-acquisition & transmission technologies are shortly described in order to provide a complete picture of tunnel monitoring state of the art for practical use.

5.2 MEASUREMENT, TECHNOLOGIES AND TYPE OF INSTRUMENTS

5.2.1 Displacement and rotation

Displacement and rotation monitoring in tunnels has a long tradition. Methods have changed over the decades, allowing the extraction of more information from the measured data.

Displacement measurements inside the tunnel and on the ground surface are normally performed with topographic methods, with the aid of different instruments and technologies according to the quantities/surface to be monitored and the accuracy required for the analysis.

Typically, in the execution of a tunnel the following displacements are checked:

- The deformations of the tunnel cavity in terms of convergence, face extrusion and subsidence.
- The surface deformations of the ground and structures above the tunnel.

Tunnel rotation measurements are performed with electronic sensors of various types and accuracies, which use analog, digital or mixed technologies.

Typically, in the execution of a tunnel the following rotations are checked:

- The rotation of the final lining in the long-term monitoring of the tunnel.
- The rotation of pre-existing structures above the tunnel.

5.2.1.1 3D topographical methods

The topographical approach for tunnel monitoring consists of the systematic comparison of an initial X, Y, and Z measure with the following ones for a certain period of time.

Internal monitoring is carried out on the tunnel cavity in two successive and non-contiguous phases, immediately after temporary lining and on the final tunnel's lining.

Both phases have the purpose of following the movement of the cavity, but the first phase involves monitoring in terms of worker/structural safety and checking the occurrence of the project deformation hypotheses. The second phase normally has a long-term control function of the stability of the tunnel.

5.2.1.1.1 TOTAL STATION (MANUAL MEASURING)

Total stations are used in tunnel construction and monitoring to measure the movements of the tunnel surface – convergence – during and after the construction before and after the installation of preliminary/temporary and final lining.

They can also be used in conjunction with extrusion measurement as well as to measure the movements at the tunnel entrance.

Manual measurements by total stations shall be performed by specialized technicians according to the standards procedures for a geodetic survey and by using dedicated software for data reduction.

To perform measurements, total station shall be placed, at the stated frequency of measurements, on suitable tripos or on pillars to be built in order to enable a secure and repeatable positioning of the device. Reference points will be prisms or targets to be fixed to tunnel walls or on the temporary or final lining. Prisms and targets are normally installed in an array of 5 or 7: at tunnel crown, at side and at invert. They shall be protected from construction activities as well as from dust and water.

Total stations provide for distance – measured by an infrared ray–and angles – by means of optical encoder – of prisms/targets with respect to the georeferenced Station.

A typical range of measurements are:

- *Distance*: up to 1,000+ m.
- *Angle*: 360°.

Final measurement accuracy depends on the type of total station, reference constellation accuracy, prisms and/or target distances, dimensions and specifications as well as on the environmental conditions. Using a top model Total Station (angle accuracy: 0.15 mgon, distance accuracy: 0.6 mm + 1 ppm) a final accuracy of ±5 mm up to ±1 mm on *X*-*Y*-*Z* differential displacement can be reached.

Modern total station provides for data acquisition, storage and pre-processing unit embedded into the device. Data are downloaded to PC by means of standard connection protocol, such as Blue Tooth, Serial Interface, Memory cards, etc.

5.2.1.1.2 TOTAL STATION (AUTOMATIC MEASURING)

Automatic total stations – ATS – enable to perform automatically the geodetic measurement which is performed manually by operators.

These devices are similar to those of the manual ones but are provided with electric actuators – motors – which move the optical device – LCD or equivalent sensor – to detect the reference prisms which reflect the measuring ray.

The main advantage of these types of equipment is that they enable to perform high frequency – almost “continuous” – monitoring, due to the absence of operators and the possibility to transmit data to remote users by means of wireless connections.

Their working principle is based on the use of the initial – reference – coordinates to re-position the measuring ray at the known positions during each sequent measuring cycle. If the prisms move, the ray doesn’t detect them in their original positions, thus the device starts searching for them by moving the optical ray in circles with increasing diameters until the prism is detected. When detected, the new position – in terms of the coordinates *X*, *Y*, and *Z* – is assumed and the difference with the reference position is made in order to obtain the global one, providing for the "monitoring" of the measured phenomenon.

Modern total stations allow reflector-less measurements taken without the aid of prisms or targets when, for different reasons, it's not possible to install them, such as on-road platforms, on prestigious buildings, etc.

Accuracy is less than the one by using prisms. This approach requires special procedures at the time of the initial measurement, in order to identify and assume reliable reference points which must be stable and detectable during the monitoring lifetime.

The maximum reading frequency with automatic total stations depends on the number of prisms, the number of measures for each prism, their rate of movements and on the environmental conditions. Reference frequency value for ten prisms is about one reading every ten minutes.

As per manual ones, automatic total stations provide for distance and angles.

A typical range of measurements are:

- *Distance*: up to 1,000+ m.
- *Angle*: 360°.

Final measurement accuracy is similar to manual measurement but using ATS a greater number of readings are available for further data analysis (i.e. filtering and smoothing). For monitoring purposes, the total stations shall be powered by the mainline or by solar panels and backup batteries. Stations shall be protected from environmental and meteorological adverse conditions by a suitable cabinet with or without glass windows, or with a cap of such dimensions as to prevent rain/snow from wetting the instrument (Figure 5.1).

5.2.1.2 Optical levels

The digital optical levels are used for the monitoring of vertical movement (settlement, heave, and subsidence–1D monitoring) both inside the tunnel and on the surface. They

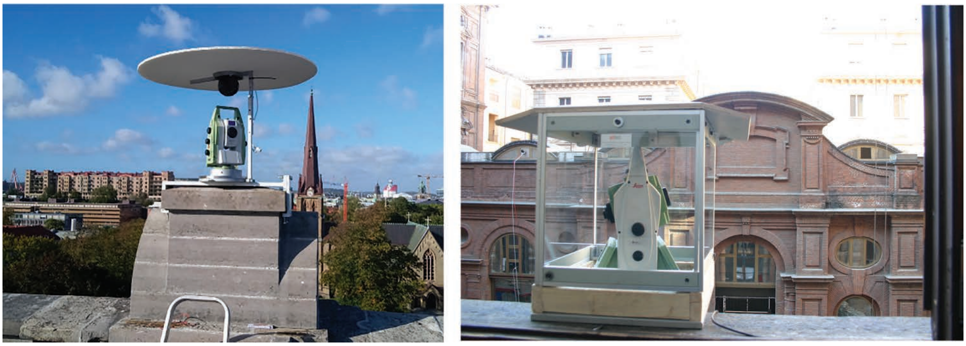


Figure 5.1 Example of ATS installed in a fixed and protected monitoring location. (Courtesy of Leica Geosystems AG.)

Figure 5.2 Example of digital optical level. (Courtesy of Leica Geosystems AG.)

perform high-accuracy electronic measurements on leveling staff and pins installed on tunnel surfaces or buildings and structures involved in the construction of the tunnel.

The measurements are typically electronic with the help of staff with an invar metered bar or barcode. For optimal performances, typical measurement distance must be <30 m (Figure 5.2).

A typical range of measurements are:

- *Distance*: up to 25/30 m.
- *Angle*: 360°.
- *Typical accuracy*: 0.3 mm/km.

5.2.1.3 Laser scanner

Laser scanner technology in tunnels is used both in the excavation phase and in the long-term monitoring phase. During the excavation, laser scanner enables to compare the project sections with actual ones, allowing the automatic calculation of the over-excavation and under-excavation surfaces, as well as the calculation of the convergences and deformations of the cavity in a distributed and non-punctual way as per a geodetic survey. On long-term monitoring with the laser scanner, deformations on the surfaces as well as cracks on the final coating can be identified.

The laser scanner creates a bubble points cloud derived from distance and angle measurements with a variable relief grid defined by the user technician. It can detect up to 2 million points per second with an accuracy ranging between 1.5 and 4 mm for distance measurement and from 8″ to 20″ for angle measurement. Typical measuring distance between two adjacent measuring station points in tunnels application is about 30 m (Figure 5.3).

Figure 5.3 Application example of the laser scanner in tunnel construction. (Courtesy of Leica Geosystems AG.)

A typical range of measurements are:

- *Distance*: up to 30 m.
- *Angle*: 360°.

5.2.1.4 GPS/GNSS

Global Navigation Satellite System (GNSS) monitoring is used for surface monitoring of the tunnel appurtenances. It can be used for monitoring buildings, landslides, and infrastructures and for the control of automatic total station reference positions. It is particularly useful when the geomorphology of the area to be monitored is unstable and wide not allowing for a classic approach with total stations, or when points to be monitored are few and far from each other. A survey of single points based on satellite measurements provides for absolute movements with high accuracy.

Typical configuration of GNSS monitoring involves the installation of one or more "master" receivers installed in stable areas, from the object of the survey – even kilometers – and the installation of "rover" receivers on the points to be monitored. Alternatively, to lower costs, permanent stations in the area can be used instead of the master-receivers configuration.

The technology is suitable for both manual and automatic monitoring. For manual monitoring, dual-frequency instruments are required, whilst for the automatic one, single-frequency instruments can be used which allows for lower costs for medium/long-term monitoring (Figure 5.4).

A typical range of measurements are:

- *Distance*: up to 10/15 km.
- *Angle*: 360°.
- *Accuracy*: typically 5 mm in plan, 10 mm in height.

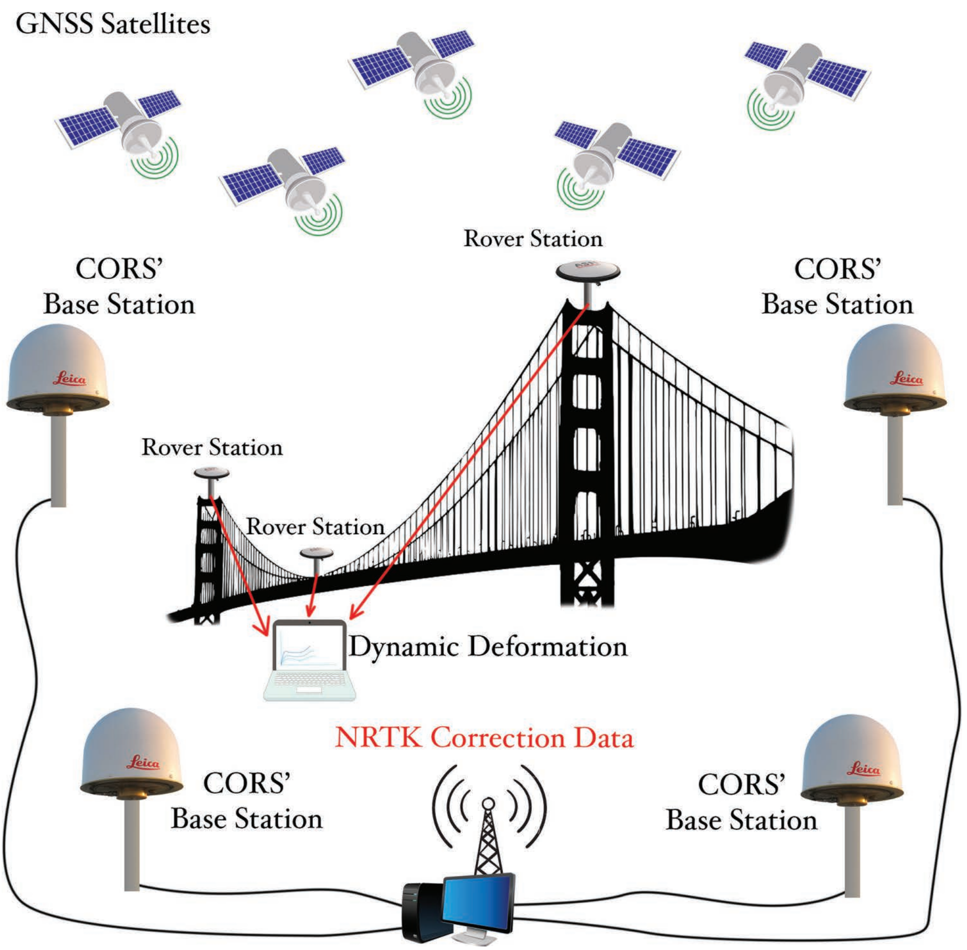
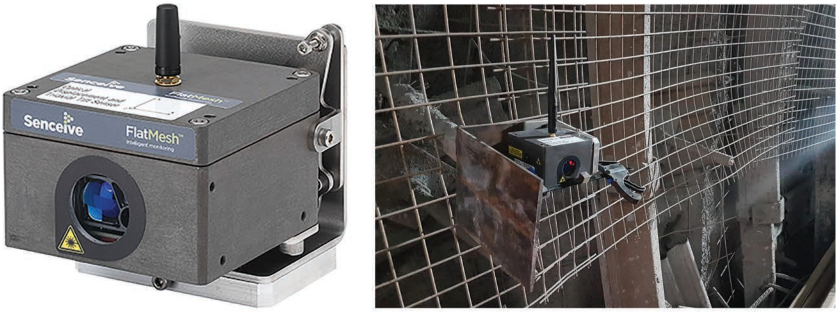


Figure 5.4 Layout of a GNSS monitoring system. (Courtesy of Leica Geosystems AG.)

5.2.1.5 Laser distometers

Laser distometer (or laser distance meter) is an optical displacement sensor based on measuring the transit time of laser pulses between the sensor and the object to be measured. Typical applications of laser distometer are the automatic and continuous monitoring of the relative displacement (convergence) of a single line in tunnel or shaft sections, where the topographical method by robotic total stations is not usable or too expensive. Available range is normally about 100–150m with accuracy up to ±0.5mm. Measurements are generally taken automatically. Some recent type of sensors includes a triaxial accelerometer for accurate integrated biaxial tilt monitoring and wireless transmission. Generally, laser distometers are able to measure distance on a natural surface (mirrorless measurements) but, especially in an underground environment, it is recommended to use a light color plastic target for reliable and accurate measurements (Figure 5.5).



(a) (b)

Figure 5.5 Type of wireless laser distometer and application example in tunnel construction. (Courtesy of Senceive Ltd.)

5.2.1.6 Hydrostatic levelling system

Hydrostatic levelling system (HLS) is an electro-hydraulic instrument for monitoring differential vertical displacements (settlement or heave) between several measuring points and a reference point. The system consists of a fluid-filled tube which hydraulically connects the measuring points to a reference reservoir. The elevation difference between each measuring point and reference tank induces a change in fluid level with hydrostatic head change which are measured by level meter, load or pressure cells. HLS gives high accurate settlement measurement (up to ±0.1 mm depending on the total range) and is suitable for long-term automatic monitoring but it is quite sensitive to temperature change and requires almost horizontal installation of the hydraulic circuit avoiding "U" configuration (Figure 5.6).

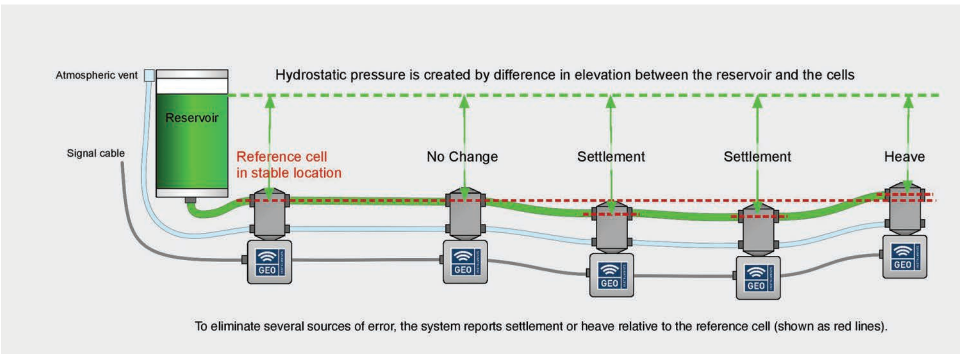


Figure 5.6 HLS functioning layout. (Courtesy of Geo-Instruments.)

5.2.1.7 In-SAR methods

SAR interferometry, or In-SAR (Synthetic Aperture Radar), is a technique used to control the displacement of slopes, and anthropogenic structures and, in general, to control the deformations of the Earth's surface.

The main interferometric methods are as follows: Satellite SAR interferometry (Sinsar) and Terrestrial SAR interferometry (Tinsar). In both cases, the acquisition takes place by means of a transmitting and receiving antenna system that moves along a given trajectory: an orbit in the case of satellites, a track in the case of terrestrial instruments.

The analysis takes place by comparing the phase of electromagnetic signals emitted in the microwave field and reflected by objects (points) on the ground. Such points may be those naturally present in the relief area and having an adequate backscatter value of the radar signal, or specially installed artificial reflectors (e.g. corner reflectors).

By combining the multiple radar images obtained, it is, therefore, possible to estimate the displacement of the various points in time.

5.2.1.7.1 TERRESTRIAL INTERFEROMETRY

Terrestrial SAR interferometry involves the use of a sensor consisting of two antennas (transmitter and receiver) positioned on a platform installed in front of the object to be monitored. The sensor, moving on rails on the support platform, emits a signal that is reflected by the target and regained by the sensor itself. The captured images consist of a matrix of pixels whose size and quantity are related to the measuring distance and instrumental characteristics.

By comparing the phases measured for the same point at different times, it is possible to measure the displacement of that point. Capturing a large number of images, a time series of displacement for each pixel of the image is determined (Figure 5.7).

(a) (b)

Figure 5.7 Type of terrestrial interferometer. (Courtesy of NHAZCA S.r.l.)

5.2.1.7.2 SATELLITE INTERFEROMETRY

Satellite interferometry SAR is an interferometric technique that involves the use of images acquired by sensors installed on special satellites. The satellites, passing on a punch, acquire a signal whose phase is dependent on the distance from that point at that time. If the point moves (for example due to a landslide), a phase corresponding to the new distance will be measured at a subsequent passage of the satellite and, consequently, the variation between the two phases measured will be determined.

The fields of application can be different and include the control of gravitational phenomena of slope (especially slow-motion phenomena), deformations related to subsidence, tectonic movements and volcanic activity and the control of human movements.

The SAR Satellite interferometry allows not only real-time monitoring of the various movements on the ground but also allows to perform a historical analysis through the use of the images acquired by the satellites in previous years (Figure 5.8).

5.2.1.8 Inclinometers

Inclinometers are instruments that measure the horizontal (and sometimes vertical) displacements of the ground (landslide, road embankments, excavations area) or structures (piles or retaining walls), thus allowing to assess the deformative state. They are widely used in many geotechnical problems.

The deformative state can be detected either by measurements conducted inside inclinometric tubes, by means of removable or fixed probes, or by using inclinometric chains (recent and increasingly widespread) to be inserted either inside inclinometric tubes or directly into boreholes. Inclinometers can also be installed both vertically and horizontally depending on whether the horizontal or the vertical is to be measured. Regardless of the type of acquisition system used and the measured component, the inclinometric system is comparative. Therefore, all measurements after the initial one (called zero measure and taken as a reference) will be related to it and will be plotted on "Shift-Time" graphs both local (of each single point) and cumulative (profile of the casing).

5.2.1.8.1 VERTICAL AND HORIZONTAL INCLINOMETER (MANUAL MEASURES)

The inclinometric tubes can be plastic (ABS or PVC) or aluminum made and have four grooves called "keyways", orthogonal to each other, inside which the measuring probes slides.

Manual inclinometric measurements are carried out by means of a special removable probe equipped with a biaxial sensor (servoaccelerometric or MEMS) which is lowered into the access tube to the bottom and then raised slowly to the surface taking readings at steps equal to the probe length. The probe consists of a body containing the sensor and is equipped with two pairs of wheels. A metered cable – marker distance equal to the wheel distance "the step" – is connected to the probe to lower and relieve the probe as well as to power sensors and transmit signals.

The recorded data are then processed and reported on specific reports that show the trend of movement/deformation vs depth at each measuring time (Figure 5.9).

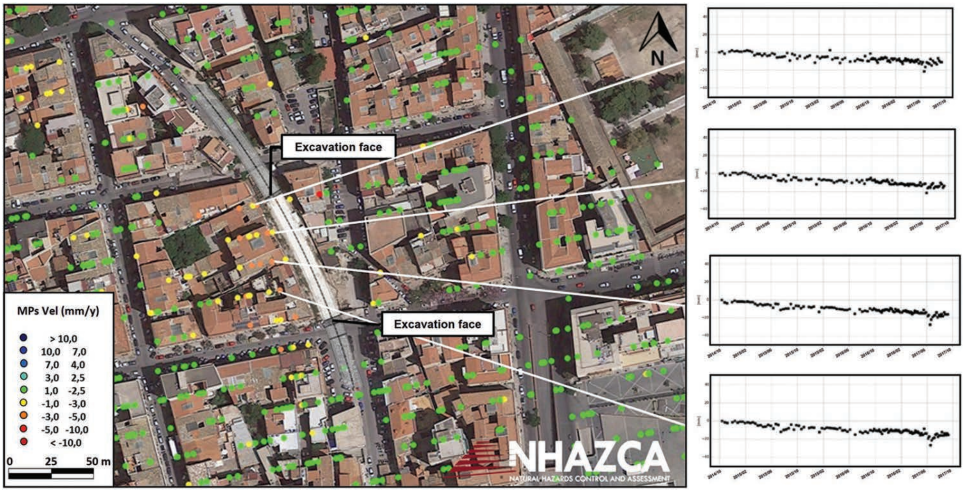


Figure 5.8 Example of settlement monitoring by satellite Interferometry.

Figure 5.9 Type of removable digital system for manual measures of inclinometers. (Courtesy of Encardio rite Ltd.)

5.2.1.8.2 VERTICAL AND HORIZONTAL INCLINOMETER (AUTOMATIC MEASURES)

Automatic inclinometric measurements are carried out by means of a chain consisting of a series of probes/sensors connected to each other and inserted into a previously arranged inclinometer tube or, depending on the different types, directly inside a borehole.

In tunnels, a series of sensors (currently mainly MEMS type), can be placed not only vertically or horizontally but can be installed on the walls to measure the convergence.

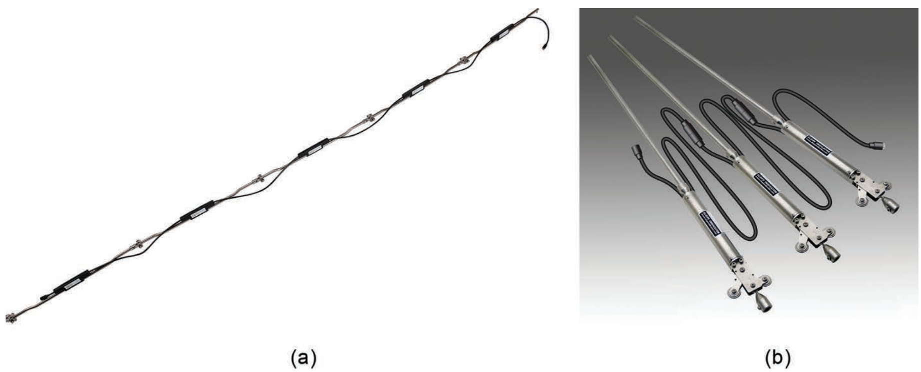


Figure 5.10 Type of automatic inclinometers. (Courtesy of DGSI.)

Special types of inclinometric probes are equipped with additional sensors, such as temperature sensors, magnetic compasses or piezometric sensors for controlling the groundwater level.

Data are acquired by specific dataloggers and transmitted – even in real time – to dedicated servers and can be made available through dedicated web platforms.

Automatic inclinometric measurements allow a series of benefits, such as the possibility of setting the measuring frequency as a function of the monitoring phases, avoiding the need for technicians to travel and reach the monitoring site, and increasing the possibility to correlate measurements to boundary or site conditions, to trigger alert/alarm signals. These benefits compensate for the initial higher cost (Figure 5.10).

5.2.1.8.3 SURFACE INCLINOMETERS (OR TILTMETERS)

Wall inclinometers are used to measure the tilt of civil works and rock masses. They make it possible to record the angular variations of the structures. The measurement can be at a point (using inclinometers or inclinometric plates) or on a portion of the structure/rock (using bar inclinometers).

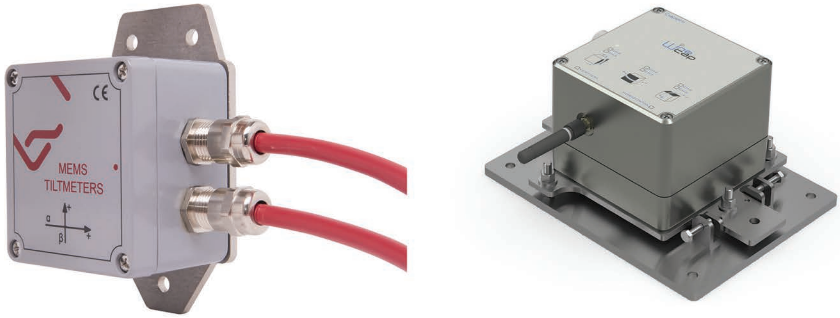
These sensors can be both servoaccelerometric or MEMS type, biaxial or, sometimes, monoaxial. The measurement can be carried out either manually, by means of a measuring unit, or remotely, by connecting the tiltmeter to a dedicated datalogger.

In some cases, when the installation point is easily accessible, it is possible to use removable tiltmeters in conjunction with reference plates to be fixed on the structure/rock. The tiltmeter is positioned on the plates in repeatable positions and the tilt value is recorded.

Inclinometers measurements are referred to the zero reading after the baseline period (Figure 5.11).

5.2.1.9 Surface extensometers

Surface extensometers are instruments finalized to measure linear displacement between two reference points on a structure or ground surface. A typical example of application is the distance monitoring between the edges of a fracture.



(a) (b)

Figure 5.11 Type of surface inclinometers/tiltmeter (cabled and wireless). (Courtesy of Pizzi Instruments S.r.l. and Capetti Elettronica S.r.l.)

(a) (b)

Figure 5.12 Type of surface extensometer and example of installation on a rock slope above a tunnel under construction for stability monitoring. (Courtesy of Gestecno S.r.l. and GD Test S.r.l.)

5.2.1.9.1 WIRE EXTENSOMETERS

Wire extensometers are normally used in those applications where large displacements (up to some meters) may occur between two reference points whose distance can reach a few tens of meters. The instrument is generally composed of a rotary displacement gauge (rotary potentiometer or encoder) and a stainless-steel wire that is tensioned by a rotary spring and runs between the gauge and an opposing anchor. The high flexibility of the wire makes the instrument particularly suitable for installations where the two anchor points can dislocate or rotate in case of large displacements (Figure 5.12).

5.2.1.9.2 CRACKMETERS

Crackmeters (or jointmeters) consist of rigid linear displacement gauges with a small measurement base (generally from 10 to 100 mm) and high accuracy (from ±0.01 to ±1 mm). Crackmeters can be mechanical – to be measured by means of a dial gauge – or electrical type – with different kinds of displacement transducers (potentiometric, electromagnetic, vibrating wire) suitable for automatic data acquisition. Special mounting devices allow for displacement measurement along three normal directions (3D crackmeters) (Figure 5.13).

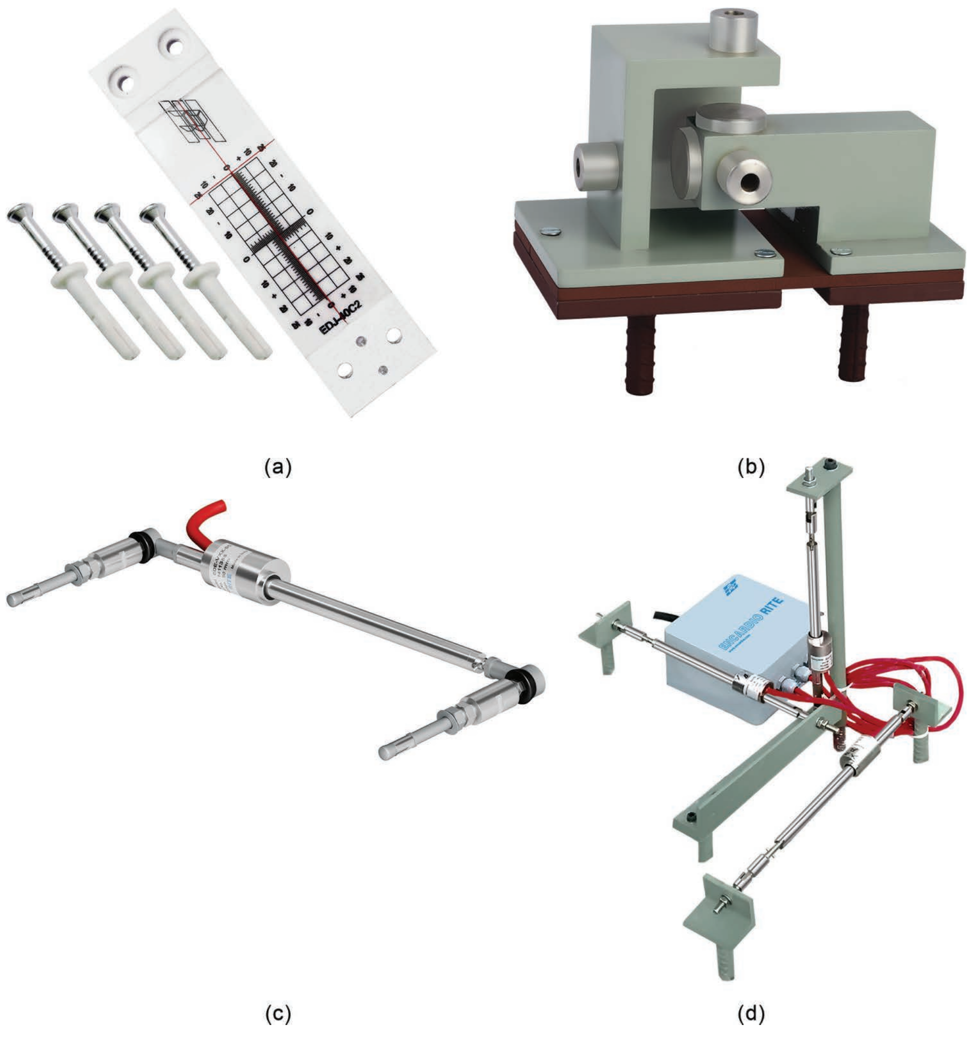


Figure 5.13 Different types of mechanical and electrical crackmeters. (Courtesy of Encardio Rite Ltd.)

5.2.1.10 Borehole extensometers

Borehole extensometers are used for monitoring linear displacement along the line of a hole drilled in soil and rock medium in any direction from the surface or underground. Borehole extensometers are available with manual or automatic reading.

5.2.1.10.1 MULTI-POINT EXTENSOMETERS

The measuring principle of Multi-Point Borehole Extensometers (MPBX), consists of monitoring the displacements between different downhole anchors (generally from 1 to 6–7) and a reference head placed on the surface. The rigid connection between downhole anchors and reference head is provided by fiberglass or stainless (or invar) steel rods which slide inside plastic sleeves. Measurement is taken at the reference head manually by dial gauge or automatically by displacement transducers. In case of very large displacements, extensometers with rotary displacement transducers on the reference head are also used. Anchor points are normally solidarized to borehole walls by grouting. In case of boreholes in fractured rock or upward oriented and difficult to grout, special hydraulic, mechanical or groutable packers are suggested (Figure 5.14).

5.2.1.10.2 INCREMENTAL EXTENSOMETER

Incremental extensometer is a borehole extensometer in which the measurement of the linear displacement along the borehole is obtained as the sum of the local displacements read between two following measuring marks – normally with an interspace of 1 m. Two types of measuring probes are generally used: magnetic, with displacement transducers which require magnetic rings fixed outside an inclinometer casing and offer a larger range – up to ±100 mm – and accuracy up to ±0.02 mm; mechanical with high precision measuring referenced couplings along the special tube and a digital displacement transducer. The *mechanical* probe offers a smaller range (up to ±10 mm) – but higher accuracy (up to ±0.001 mm). 3D measurements are also available

(a) (b) (c)

Figure 5.14 Type of a rod MPBX (a) and example of an application in a tunnel with wireless automatic datalogger (b and c). (Courtesy of Encardio Rite Ltd. and GD Test S.r.l.)

Figure 5.15 Example of incremental extensometer measurements in tunneling. (Courtesy of GD Test S.r.l.)

in sub-vertical boreholes by incremental extensometers adding inclinometer measurements to the extensometer. Magnetic type also allows to have automatic monitoring by means of in-place extensometer (or extenso-inclinometer) columns. Due to its modular characteristic, a particular application of the magnetic incremental extensometer is the so-called "extrusometer" for measuring horizontal deformation of the excavation face and core during tunnel construction (Figure 5.15).

5.2.2 Strain

In geotechnical monitoring, strain represents a very common and important parameter from which other physical quantities, such as force and pressure, are normally derived. In tunnel monitoring, strain is directly measured on the preliminary and final lining.

5.2.2.1 Electrical strain gauges

Two types of electrical strain gauges (also called strain gages) are normally used in geotechnical monitoring: *resistive type* based on the change of electrical resistance of a metallic foil due to the strain change of the support and *vibrating wire type* based on the change of vibration frequency due to the change of the length/tension off a metallic wire stretched between two reference anchors. Vibrating wire types are widely used in tunnel monitoring due to their cheapness, high reliability and long-life characteristics. Typical model available on the market is the weldable type to be fixed by spot or arc welder directly on metallic support (reinforcing bars, steel lining or tubes, etc.) or embedment type to be directly included in the concrete casting. Almost all the vibrating wire sensors have an embedded thermistor for compensating strain variations due to temperature oscillations (Figure 5.16).

5.2.2.2 Fiber optic strain gauges

Fiber optic sensors for strain measurements have been used for the last 30 years with a good confidence in their performances. The greatest advantages of the fiber optic are

(a) (b) (c)

Figure 5.16 Different types of vibrating wire strain gauges: arc weldable, spot weldable and embedded. (Courtesy of GD Test S.r.l.)

that they are immune to electromagnetic fields and radio frequency, provide for a large number of "measuring points" being able to be very long – kilometers – and can be located several kilometers far from the interrogator.

Fiber optic using Fiber Bragg Gratings have a great multiplexing potential. This feature allows the measurement of different parameters along a fiber using a single cable and single channel of the interrogator. Currently, it's possible to connect strain and deformation gauges, temperature sensors, tilt meters and accelerometers. Typically, up to 25 probes can be placed on a single fiber line, depending on both types of sensors and readout unit model.

Because of their length, FBG (Fiber Bragg Gratings) can be used as a replacement for conventional strain gauges and installed on the surface or embedded. With adequate packaging, they can also be adopted as long-gauge sensors with a basis length from 10 cm to 2 m. The measurement frequencies of these sensors can be up to 1 kHz and they are becoming more and more useful for monitoring infrastructures like tunnels (Figure 5.17).

5.2.3 Force

In Tunnel, monitoring forces are measured in order to monitor the behavior of temporary or permanent elements to ensure the tunnel stability and safety.

Such elements are ribs, bolts, anchors, and supporting and retaining structures.

Most of the applications are related to the measurement of Normal forces exchanged between two elements or within the same element. In practical applications, forces are not perfectly "normal" but have a transverse component. This is due to the imperfections of the elements, to the uneven installation or to unexpected and unpredicted behavior of the rock/soil or to the excavation effect. It is therefore mandatory to select the load cells with appropriate metrological and geometrical properties, as well as to design their mounting frames in order to minimize the transverse components effect as well as to adopt the most suitable installation procedures to ensure reliable measurements.

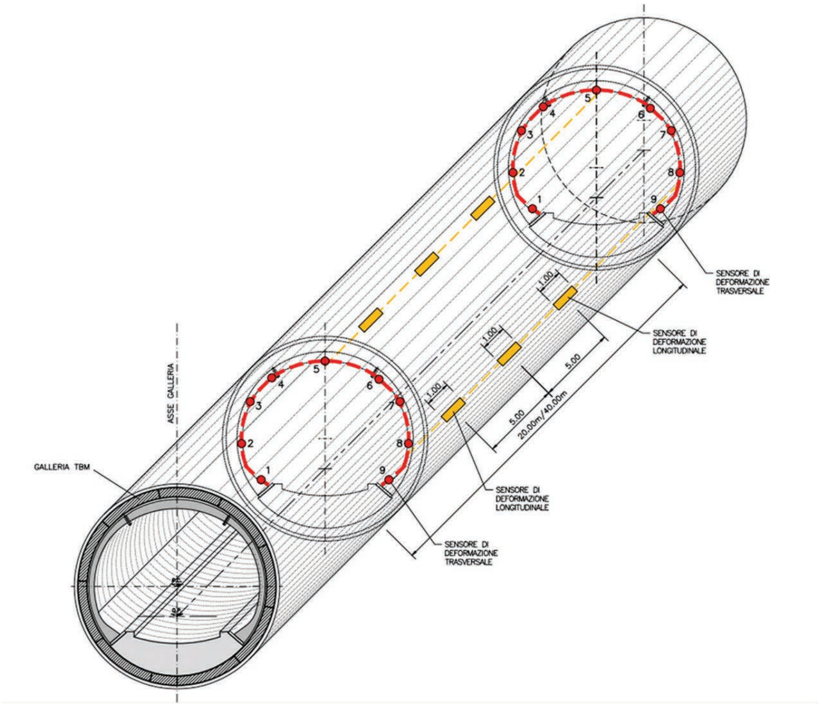


Figure 5.17 Type of optical strain gauge and example in tunneling application for convergence/section deformation and long-base longitudinal deformation sensors. (Courtesy of Smartec.)

5.2.3.1 Load cells

Load cells are field instruments for monitoring normal forces. Their measuring principle can be either electric or hydraulic. A special type of load cells can be used to measure shear forces on structures or caused by the interaction of structures with the surrounding soil.

Load cells for measuring normal forces are subject to measuring errors due to the eccentricity of the load. This effect is enhanced in hydraulic cells.

The available range is normally about 100 kN up to 15 MN or even more for a specific application such as pile testing. Typical accuracy is ±0.5% f.s.

Measurements can be taken manually or automatically.

Manual measurement of electric or hydraulic load cells with an electric pressure transducer is taken by means of a readout unit. Hydraulic cells with a pneumatic measuring system are read by a specific external device which applies fluid pressure to the pneumatic valve up to the equilibrium with the fluid inside the cell.

Load cell readings are subject to temperature effects. To take into consideration thermal effects it is advisable to o use cells with a built-in thermistor or to measure the temperature at the cell surface. Automatic measurements can be taken by wired or wireless dataloggers (Figure 5.18).

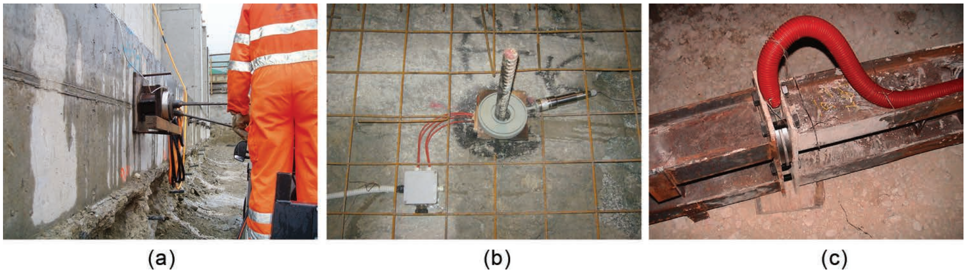


Figure 5.18 Example of different types of load cells and their application. (Courtesy of GD Test srl and Gestecno S.r.l.)

5.2.4 Stress

Stress measurement is applied in tunnel monitoring to determine the surrounding soil/rock mass stress state to evaluate their residual capacity as well as to assess the structural behavior of the reinforcing structures such as ribs, lining, and steel reinforcement.

Actually, *strain* is measured when strain meters or strain gauges are used. From strain, stress is calculated by knowing the mechanical properties of the material/structures (i.e. elasticity modulus). From Stresses, forces can be derived knowing the geometry – area – of the considered structures.

When Total Pressure Cells – also known as Total Stress Cells – are used, the normal stress acting on the surface of the cells is measured. In presence of pore water or joint water pressure, the total stresses measured by the cells include the water pressure.

5.2.4.1 Total pressure cells

Total pressure cells are field instrument for stress change measurement. They consist of a pressure pad, a pressure tubing and a pressure measuring device.

The pressure pad consists of two steel plates, welded together along their perimeter, where the intervening cavity is filled with a liquid. The cavity is connected to the inner chamber of the pressure measuring device via a liquid-filled pressure tubing. The measuring principle of load cells can be either electric or hydraulic.

Total pressure cells are stationary instruments which are embedded in a medium.

The target of the measurement is the change of the total normal stress of the medium acting onto the flat side of the pad.

A special type of pressure cells is the so-called “Flat Jacks” which is an active instrument to apply stresses to the surrounding soil (i.e. rock) to determine the in-place stress state.

The available range is normally about 50 kPa up to 50 MPa, with typical accuracy up to ±0.1% f.s. Measurement of the total stresses is highly influenced by the installation procedure, i.e. the interface between the cell and the surrounding materials: soil, rock, and structures.

(a) (b) (c)

Figure 5.19 Example of different types of pressure cells and their application.

Manual measurement of electric or hydraulic pressure cells with an electric pressure transducer is taken by means of a readout unit. Hydraulic cells with a pneumatic measuring system are read by a specific external device which applies fluid pressure to the pneumatic valve up to the equilibrium with the fluid inside the cell.

Load cell readings are subject to temperature effects. To take into consideration thermal effects it is advisable to use cells with a built-in thermistor or to measure the temperature at the cell surface. Automatic measurements can be taken by cabled or wireless dataloggers (Figure 5.19).

5.2.4.2 Stress meters

Stress Meters are field instruments for stress change measurement in boreholes.

A Stress Meter consists of a rigid cylinder equipped with sensors to measure its deformation caused by surrounding rock pressure change.

Stress meters are stationary instruments which are embedded in a medium and need to be firmly in contact with the media in order to provide reliable results.

Contact between the instrument and the media can be either mechanic – a pre-load which presses it against the borehole wall – or by grouting.

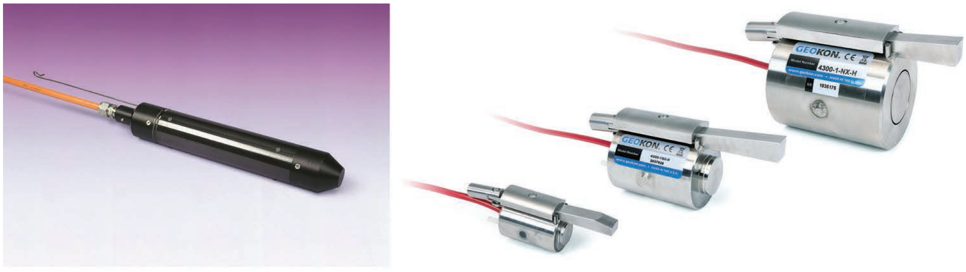
When a mechanic pre-load is applied it has to be considered that, due to the creep of the media material, the contact pressure will change – decrease – and contact can be lost.

If the instrument is grouted, the mechanical as well as rheological properties of the grout have to be considered in order to minimize the re-distribution of the stresses due to different mechanical properties of media and instrument.

The available range is normally about 20 up to 100 MPa, with typical accuracy of up to ±0.3% f.s. Measurement of the total stresses is highly influenced by the ratio between the instrument and media elasticity modulus, therefore it is mandatory to select the instrument according to the media properties.

Measurements can be taken manually or automatically.

Manual measurement is taken by means of an electric readout unit to be connected to the instrument. Automatic measurements can be taken by cabled or wireless dataloggers (Figure 5.20).



(a) (b)

Figure 5.20 Example of vibrating wire borehole stress meters. (Courtesy of GEOKON LLC.)

5.2.5 Water pressure and flow

The main physical parameters which characterize the water effect in underground constructions and have to be monitored during tunnel excavation are groundwater pressure (water level or pore pressure) and the amount of groundwater inflowing into tunnels. Physic-chemical groundwater properties represent additional parameters that are often monitored in order to deepen the hydrogeological knowledge of the aquifer.

5.2.5.1 Piezometers

The family of "piezometers" include all the instruments dedicated to monitor groundwater level/pressure in soil and rock joints. The following types are commonly used:

- Open standpipe piezometers and Casagrande piezometers.
- Electrical piezometers (water level transducer and pore-pressure gauges).

5.2.5.1.1 OPEN STANDPIPE PIEZOMETERS AND CASAGRANDE PIEZOMETERS

Open standpipe piezometers are used to monitor groundwater level in a vertical downward borehole and consist of an access tube with a perforated – or slotted – section and a blind section. Casagrande piezometers have porous cells and an access tube. The perforated section and the cells are sealed off in the boreholes in order to ensure the measurement of the groundwater level at the required depth without any influence of the water pressure at other elevations. Perforated sections and cells are normally surrounded in the borehole by permeable medium (sand) and sealed by bentonite or cement-bentonite plug. Open standpipe piezometers are used in permeable rock mass/soil while Casagrande piezometers are used in medium-low permeable soils. Water level indicators (dipmeters) or water level transducers are used for manual/automatic measurements. Casagrande filters are normally in high-density polyethylene or porous ceramic (with porosity from 40 to 70 µm) with one or two connection plastic tubes. Pair of tubes allow to clean the filter by inlet-outlet water flushing (Figure 5.21).

Figure 5.21 Example of standpipe and Casagrande filter and water level manual indicator. (Courtesy of Gestecno srl and Encardio Rite Ltd.)

5.2.5.1.2 ELECTRICAL PIEZOMETERS

Electrical piezometers consist of pressure transducers which allow to measure automatically pore water pressure in saturated soil and water joint pressure in the fractured rock mass, as well as groundwater level in open standpipe piezometers. The main difference between water level and pore water pressure transducers is the presence and type of porous. Pore pressure transducers are normally equipped with plastic, bronze or sintered steel porous filters. Filters are classified as LAE – Low Air-Entry type with a pore size of about 20–80 µm – suitable for medium to high permeability soil or HAE – High Air-Entry, HAE type with a pore size of about 0.25–3.0 µm – suitable for low permeability soil or even for negative pore pressure. Both LAE and HAE filters require previous full water saturation before installation.

Two types of electrical sensors are commonly used in tunnelling:

- Vibrating Wire Piezometers (VWP).
- Electrical Resistive Piezometers (ERP) or strain gages piezometers.

VWP provide excellent long term accuracy, reading stability and high reliability. The limit of VWP consists of the low-frequency data logging available, due to the vibrating wire technology.

ERP are suitable for high frequency and high accuracy data acquisition (dynamic monitoring) but in short-middle-term applications.

5.2.5.2 Flowmeters

Two type of water flow measurement are normally used in tunneling:

- Local water leakage from single boreholes.
- Total water flow at tunnel sections or at tunnel portals.

Local water leakage is normally monitored by means of mechanical or electrical flowmeter installed at the head of drainage boreholes at the excavation front face or along the tunnel profile. Different types of electrical flowmeters are available with different measuring ranges. The most commonly used are magnetic devices which have no moving parts and are compatible with liquids that include contaminants (solid or liquid); ultrasonic flowmeter has the advantage to be applied externally to the pipes without sectioning them.

Global water flow rate in tunnel is generally measured in monitoring sections of open channels using Venturi/Parshal flumes or weirs with pressure transducer, ultrasonic/radar or mechanical water level sensor. When flumes or weirs cannot be used, water speed transducers (ultrasonic or laser) are also used.

5.2.6 Temperature

Temperature measurements in tunneling are monitored for the following purposes:

- Detecting and recording temperature values of the environment (rock-mass, groundwater, tunnel environment) for hydrogeological, geothermal and safety knowledge.
- Evaluating temperature changes vs. time for analysis of structure behavior (stress-strain variation, time setting of the fresh concrete, etc.).
- Detecting and recording temperature changes in order to compensate thermal effects on sensitive transducers.

5.2.6.1 Electrical thermometers

Three types of electrical thermometers are normally used:

- NTC (Negative Temperature Coefficient) thermistors. NTC are the smallest and cheapest sensors, often embedded by manufactures inside transducers (ex. Vibrating wire sensors).
- RTD (Resistive Temperature Detectors) sensors (usually made with platinum wires, so-called PT-100 or PT-1000 devices) which are the most used for external and rock-mass temperature measurements.
- Vibrating Wire temperature sensors which offer the typical features of VW sensors: very good long term stability, frequency output suitable for long-distance data transmission.

5.2.6.2 Fiber optics distributed strain/temperature sensors

Brillouin scattering sensors show an interesting potential for distributed strain and temperature monitoring. Systems able to measure strain or temperature variation over a length exceeding 50 km with spatial resolution down to 1m, are now demonstrating

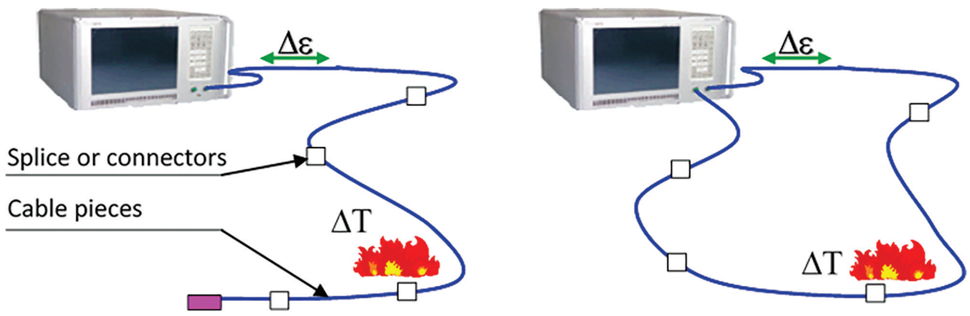


Figure 5.22 Schemes of fiber optic distributed strain/temperature sensor: (a) open configuration; (b) loop configuration. (Courtesy of Smartec.)

their usefulness in applications like tunnels. Where damage location forecast in large structures represents a challenge, distributed techniques offer the capability of monitoring the whole length of the tunnel using a single fiber optic sensor. Typical needs in tunnel monitoring include detection and localization of cracks in concrete lining, monitoring horizontal and vertical deformations, convergence monitoring, joint movements and localization of water ingress points. All those events are unpredictable in their location. It is therefore unpractical to address those using traditional point sensor installed at some predefined locations. A permanent and autonomous monitoring system able to cover the whole length of the tunnel presents real operational and safety advantages (Figure 5.22).

5.2.7 Velocity and acceleration

Vibration monitoring in tunnels is carried out in compliance with the UNI 9614: 2017 technical standard which provides for the measurement of the particle peak velocity (PPV) using triaxial accelerometers (or velocimeters)

For a correct evaluation of the disturbance linked to vibratory phenomena it is necessary to take into account the following factors:

- Mechanism of excitation and transmission.
- Duration of the phenomenon.
- Deterministic or random nature of the phenomenon.
- Spectral distribution of energy.

5.2.7.1 Vibrometer system

In tunnel monitoring, vibration analysis is typically performed in correlation to blasting activities; in addition to this, it may be necessary to evaluate the vibratory impact of tunnel excavation activities on structures or buildings adjacent to the excavation areas.

(a) (b)

Figure 5.23 Example of vibration measuring devices. (Courtesy of Instantel Inc. and Sol-Geo S.r.l.)

Tunnel monitoring can include a first phase (design of the blasting scheme) with the execution of a test field in which several measuring stations are installed in order to determine not only the extent of the induced vibratory phenomenon but also the attenuation of the energy correlated to the distance from the source point.

Once the muzzle geometry has been optimized, the vibration monitoring in the excavation phase is then performed by installing triaxial accelerometers (or velocimeters) with one axis facing the mine blasting area. The ideal positions for the correct evaluation of the vibratory impact are:

- Left wall.
- Cover key.
- Right wall.

The measured values as the maximum values of PPV must be related to the spectral content in frequency. The relationship between speed value and frequency peak is used for the evaluation of the impact through the schedules of the reference technical standard (Figure 5.23).

5.2.8 Data acquisition and transmission system

Most modern monitoring systems are based on advanced data acquisition and communication devices. This leads to an optimization of systems performances enabling more suitable and reliable management.

Logging frequency can be adapted to the scope of the monitoring process and easily modified during the system lifespan to follow the evolution of the system and boundary and/or environmental conditions. Alert and alarm thresholds can be set to trigger warning signals; instruments calibration factors can be uploaded in order to convert electrical signals into physical / engineering units; data can be transferred from the site to a data collection center by wired or wireless systems, enabling a larger number of users to be updated on the system status and to log-in for *on demand* data collection and evaluation; information can easily spread to all the involved parties and, if necessary, to the population in *real time*.

5.2.8.1 Dataloggers

Datalogger is a device which is performing the following tasks:

- Power the electric instruments. It can be configured in order to provide appropriate power – voltage and current – to the instruments;
- Read the signals generated by the instruments.
- Convert the analog signals into digital signals.
- Store readings in non-volatile memory.
- Make readings available for remote communication.

Other functions which can be set in a datalogger are:

- Conversion of the signals into physical or engineering units by using calibration coefficients for each single instrument.
- Setting threshold values for each single instrument or for group of instruments. Thresholds can be either single or multiple values to set different levels of attention (i.e.: warning, alert, alarm).
- Generation of output in case of anomalous/uneven values.
- Generation of output in case of non-authorized access to the unit, power failure, environmental conditions out of range.

Selection of data logger shall be part of the system design and shall be based on specific project requirements. Basic features to consider are:

- Number and type of instruments to be connected.
- Possibility to modify the number and type of instruments to collect (flexibility and limits of the unit).
- Power supply: main line, batteries, solar panels.
- Autonomy in case of loss of main power supply.
- Reading frequency according to number and type of connected instruments.
- Manual Data Retrieval: by connecting a laptop to a serial port or by Bluetooth, USB Key, flash memory, dedicated interface unit.
- Environmental conditions: temperature range; humidity range; degree of protection for enclosure against water and dust (IP degree); acceptable shock/vibrations level.
- Electrical insulation and protection for connected instruments (to be designed according to actual site conditions and system layout).

5.2.8.2 Telemetry

Telemetry – the possibility to transfer the signals collected by the Data Logger to a remote device – is nowadays mainly based on two solutions:

- Wired connection.
- Wireless connection.

Wired connection requires to set up a physical connection between the data logger and the remote device (or devices). It has to be considered in the design of the monitoring system, in terms of feasibility and reliability.

Wired connection can be either an electric cable or a fiber optic cable.

Electric cables are easier to use at the site, can be easily modified in length and can be repaired by unqualified personnel. The main limit is the distance between the data logger and the device. This distance depends on the standard of the digital signal (RS232, RS485, Modbus, etc…) and on the electrical properties of the cable (conductors' section, insulations, etc.)

When cables are installed in an open area, electrical cables are subject to other critical phenomena which can interfere with the correct transmission of the data such as lightning and electromagnetic interferences due to the presence of power cables, antennas, electric generators, earthing nets, etc.

Fiber optic cables can transmit signals at a longer distance (kilometers) without loss of signal; can transmit a larger number of data at a very high-speed rate and do not suffer from electromagnetic interference and lightning. From the operative point of view, they require skilled people and specific equipment to install, connect, repair and check. Cables cannot be bent with too small radii and are, in general, more fragile.

Wireless connection is more and more available due to the technology development and to the affordable costs which sometimes are lower than wired solutions.

They are based on "radio" transmission between the data logger installed at site and the point where signals have to be collected and managed.

Solutions can be based on different types of radio transmission systems such as UHF/VHF, GSM, WNS, and Bluetooth, and can be configured as a Point-to-Point connection or a Network with a number of remote stations, one or more concentrators collecting data from remote stations and a System Control Unit. Communication between remote stations and the concentrator can be one-way, from site to concentrator to collect data only or bi-directional among all the stations and the concentrator in order to enable a complete dialog between Center and periphery.

Remote stations can even act as repeaters for long-range transmission or when obstacles can hide some of the stations (for tunnel monitoring when signals have to be transmitted over long distance and when the layout of the tunnel is not linear).

The selection of the transmission system has to consider possible site restrictions on the use of specific radio frequencies as well as the layout of the network (Figure 5.24).

Figure 5.24 Typical TBM "control room" for monitoring data analysis. (Courtesy of Geodata Engineering SpA.)

5.3 TBM PERFORMANCE MONITORING

5.3.1 Performance parameters (all TBMs type)

5.3.1.1 Drilling Length [DL: m/cycle]

DL represents the progressive progress of the TBM (distance mined) within the "stroke" (cycle length).

5.3.1.2 Penetration Rate [PR1: mm/min; PR2: mm/rev.]

Distance mined/mining time. Penetration rate can be expressed as the instant TBM advancing length per minute or the TBM advancing length per cutter head revolution.

In hard rock tunneling, PR is a function of the thrust (cutterhead thrust or unit thrust per disc cutter: kN/cutter) and rock mass characteristics (UCS, fracturing factor, …).

5.3.1.3 Advance Rate [m/h]

Distance mined/mining time. Advance Rate is the total advancing length for unit time:

1. meter per shift (or ring per shift in case of shielded TBMs with segmental lining);
2. meter (ring) per day/week/month (working days or calendar days).

The actual Advance Rate – calculated for the entire tunnel construction – represents the effective TBM tunneling performance giving a simple but clear picture of the difficulties during construction (Figure 5.25).

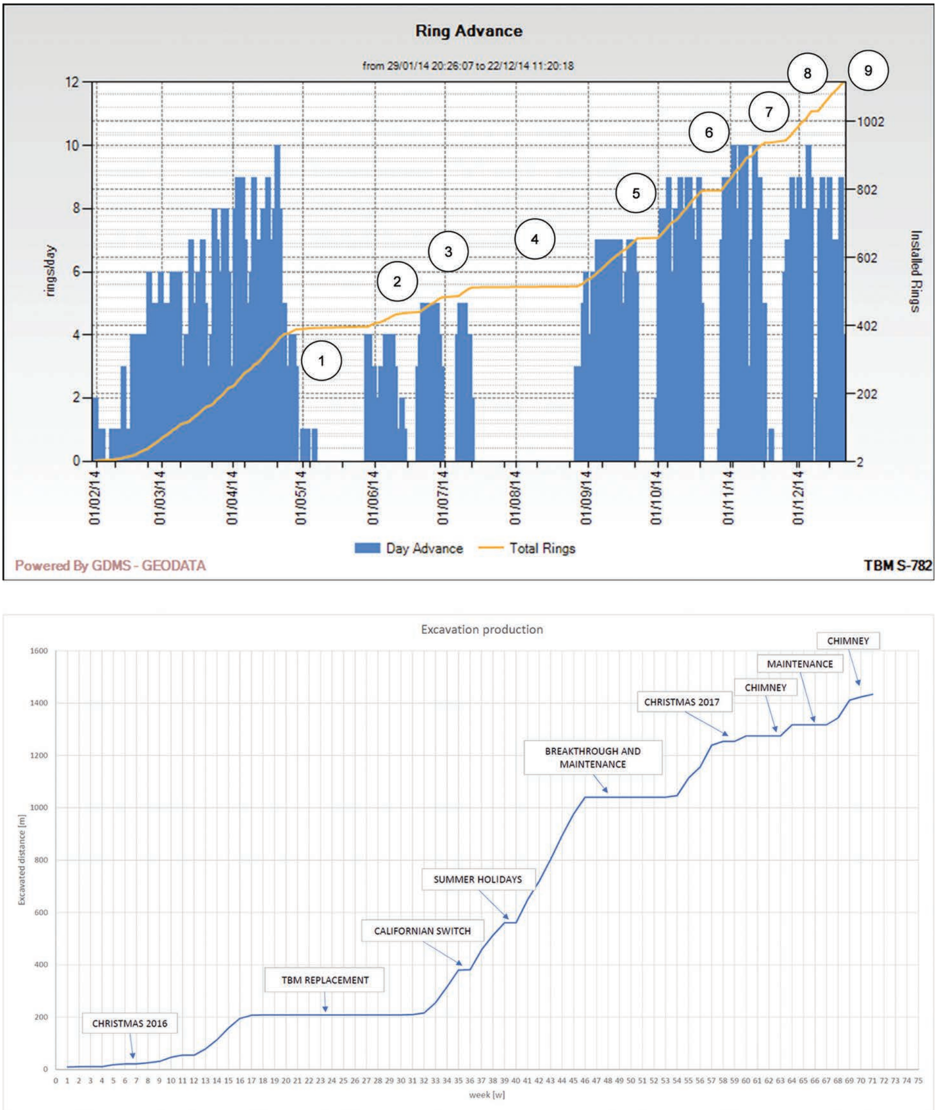


Figure 5.25 TBM's actual daily advance records (installed rings) and main TBM's stop reasons. (Courtesy of Geodata Engineering SpA.)

5.3.1.4 Cutterhead rotational direction and speed [clockwise/anticlockwise RPM: rev/min]

Number of cutterhead revolution for unit time (normally the measurement unit is rotation per minute). Cutterhead rotation speed (V_{RPM}) is inverse proportional to the cutter head diameter to limit the rolling velocity of the peripheral cutters. For hard

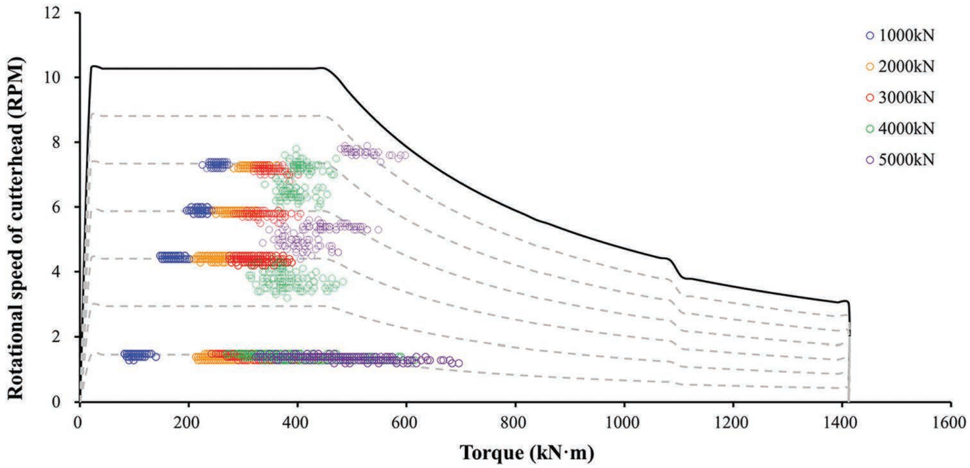


Figure 5.26 TBM's cutter head drive capacity is expressed by the relationship between torque and rotation speed (Kim, 2020).

rock TBMs, V_{RPM} depends on the disc cutters maximum rotation speed (V_L: rev/min) and the machine diameter (D_{TBM}: m) (Figure 5.26).

$$V_{RPM} = V_L / (D_{TBM} * p).$$

5.3.1.5 Cutter head torque [T: kNm]

For the open TBM type, normally used for excavation in good rock mass condition, the Uniaxial Compressive Strength (UCS) of the rock is the main factor affecting the torque (T).

T can be calculated by the formula $T = N_c * F_r * D/4 * f_L$. Where: N_c = number of cutters [Adim.]; D = excavation diameter [m]; F_r = rolling force on cutter [KN]; f_L = friction loses empirical constant [Adim] (normally $f_{L} = 1.2$).

For shielded TBMs T calculation should be considered also considered the friction forces acting on the cutterhead face and circular surface. $T = (\pi * D^3/12) * K_0 * n_i *$ Gamma $* H * (1 - n_u)$. Where D = excavation diameter; K_0 Coefficient of lateral earth pressure [Adim.]; n_i = coefficient of friction; H = Overburden height [m]; Gamma = rock mass unit weight [kN/m^3]; n_u = opening ratio of the cutter head (Figure 5.27).

For counterpressure type TBMs several factors are responsible for the resistance torque applied on the cutter head during tunneling ground characteristics and behavior, TBM cutter frame, lubricants and additives, and many others.

Conventionally, the torque equipped for cutterhead of counterpressure type TBMs can be determined in terms of the diameter of shield machine as:

$T = \alpha D^3$, where D = TBM diameter; α = Empirical coefficient (normally $\alpha = 25$ EPB TBMs:

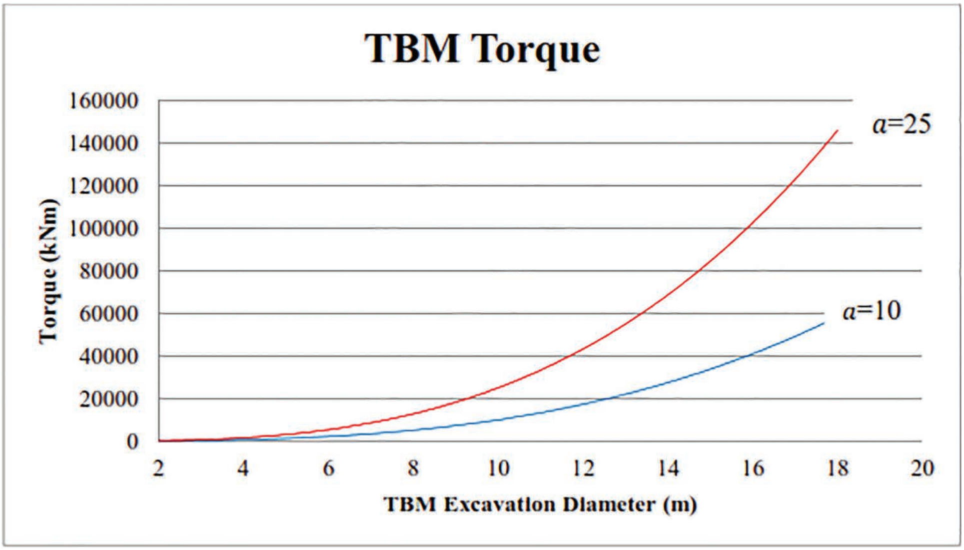


Figure 5.27 The empirical relationship between TBM's cutter head torque and TBM's diameter (Zhou & Zhai, 2018).

Note that the reported formula can be used also for rough T calculation of Open or shielded TBMs adopting $\alpha = 10$.

5.3.1.6 *Cutter head thrust [F: kN]*

For open type TBMs thrust (F) is simply the normal force applied to the cutters: $T = N_c * F_r * f_L$.

For shielded TBMs and counterpressure type TBMs $F = \text{Sum}\ (F_{1-6})$, where F_{1-6} are the thrusts required to overcome:

- F_1 = friction (adhesion) shield – ground.
- F_2 = chamber pressure (only for counterpressure TBMs type).
- F_3 = drive force caused by directional changes.
- F_4 = friction segmental lining – TBMs tail seals.
- F_5 = hauling force of back-up.
- F_6 = penetration of cutting tools into the ground.

F can be obtain measuring the pressure on TBMs thrust cylinders (Figure 5.28).

5.3.1.7 *Cutterhead power [P: kW]*

TBM's absorbed cutterhead power (P) can be calculated as $P = T * V_{RPM}$ [RPM] $* k$

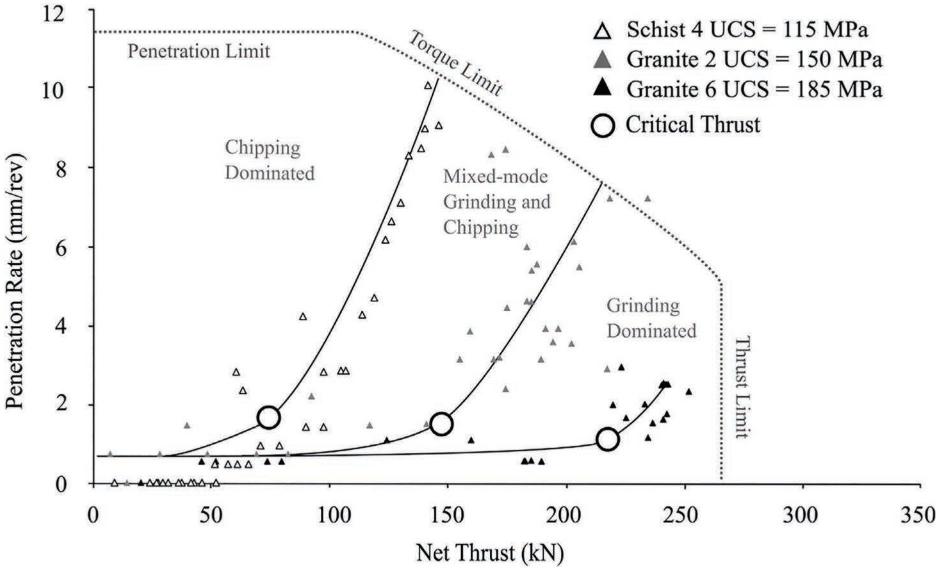


Figure 5.28 Curves cutter head thrust: penetration deriving from laboratory tests for some lithologies (Villeneuve, 2017).

Where T = cutterhead requested torque kNm; V_{RPM} [RPM] = cutterhead rotation speed; $k = 2\pi \times 100/60$ = conversion factor.

P varies mainly with TBM's diameter: it can range from 1.5 MW for a 4 m TBM's diameter up to 8.0 MW for a 10 m to overcome 16.8 MW for "Martina" Herrenknecht EPB TBM (Dexc = 15.62 m) that excavated 2.5 × 2.0 km Bologna – Firenze Motorway Sparvo Tunnel in 2011–2013.

5.3.2 TBM position

Tunnel construction using a TBM entails precise machine positioning and guidance in the underground space; the current practice relies on Laser Guidance Systems which project a laser point onto a target board fixed in the machine.

A Control Station (CS) is transferred from the surface to a tunnel point behind the TBM back up, then a Laser Station (LS), located immediately behind the machine, carried out the coordinates from the CS and shot a video and a prism target to determine the absolute spatial coordinates of the TBM (Figure 5.29).

The positioning data, tracked continuously during TBM advancement, are sent to the TBM control cabin where they are displayed on a screen showing the theoretical and actual tunnel axis spatial position.

The typical TBM positioning data are (a) altimetric and planimetric actual axis position (x, y, z); (b) vertical and horizontal actual axis inclination (degrees); (c) machine rotation (degrees) (Figures 5.30 and 5.31).

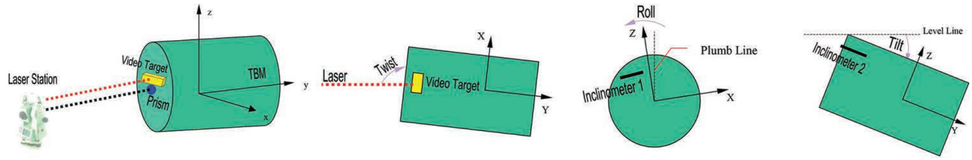


Figure 5.29 Example of working principles of TBM guidance system (Lee, 2007).

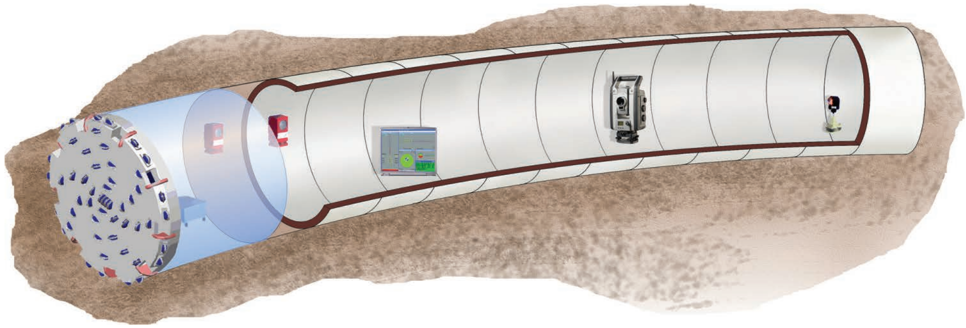


Figure 5.30 Overview of TBM position monitoring system. (Courtesy of TACS Gmbh.)

Figure 5.31 Example of screw display showing tunnel axis spatial position. (Courtesy of TACS Gmbh.)

5.3.3 Tunnel face stability and support action control (EPB/SPB TBMs type)

To ensure the stability of the excavation face and the containment of subsidence, it is essential that the values of (a) pressure in the excavation chamber, (b) density of material in the excavation chamber, and (c) volume of material extracted per excavation cycle, are always included within the minimum and maximum values expected in the project. To ensure this, continuous control of the following parameters is essential (Figures 5.32 and 5.33).

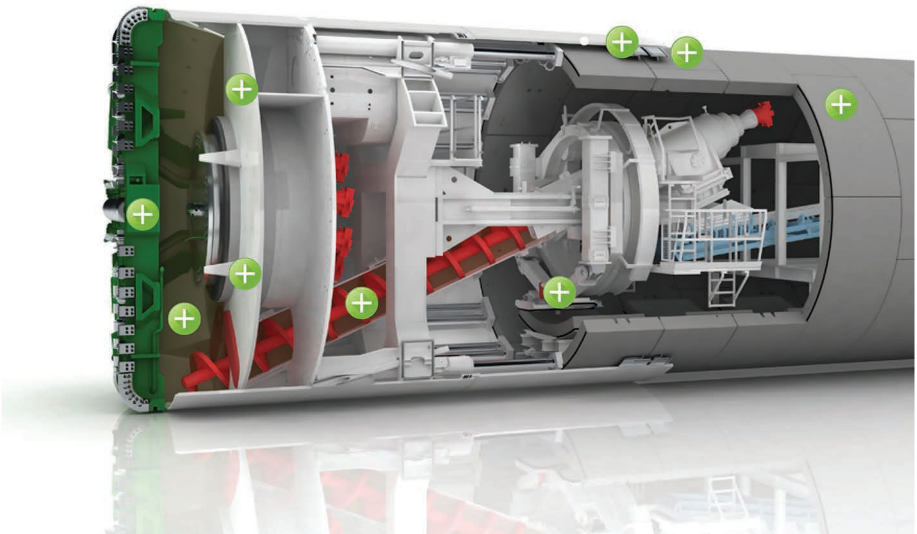


Figure 5.32 The main parameter to be controlled during EPB TBM tunnelling.

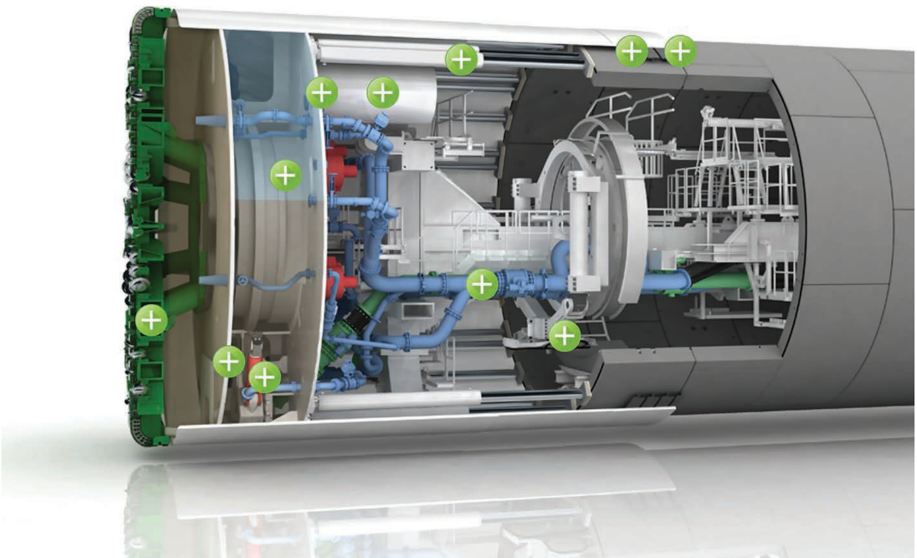


Figure 5.33 The main parameter to be controlled during SPB TBM tunnelling.

5.3.3.1 Excavated ground volume per advancing cycle [m³/m]

The excavated ground volume per unit tunnel length is one of the most important parameters to be controlled during TBM tunneling, particularly in shallow overburden and/or urban conditions.

Various measurement methods can be adopted mainly depending on the TBM type: the oldest and most coarse (all TBMs except SPB) consists of counting the muck cars/wagons filled with the excavated materials for each tunneling cycle.

More accurate measurement of the excavated ground volume has been possible using a scanner that can detect the shape of the muck transported by a conveyor belt that is moving at a constant speed

$$\frac{\text{Actual Excavated Volume AEV } (\text{m}^3 \times \text{ TBM advancing cycle})}{\text{Theoretical Excavated Volume TEV } (\text{m}^3 \times \text{TBM advancing cycle} : \text{TEV} = S \times L \times F)}$$

Where: S = Excavation section [m^3]; L = Advancing cycle length [m]; F = Bulking factor (ratio or percentage of the volume change of excavated material to the volume of the original in situ volume before excavation).

The possibility to compare in real time theoretical with actual unit ground excavated volume reduces the risk of over-excavation, excessive settlements or chimney and related consequences to nearby structures.

5.3.3.2 Excavated ground weight per advancing cycle [kN/m]

An efficient method to measure the excavated ground weight is through a scale(s) mounted on the TBM primary conveyor belt.

A typical conveyor belt scale weighing system has a weight bridge structure supported on load cells, an electronic integrator, and a belt speed sensor. The load cells measure the material weight and send a signal to the integrator that receives also signal from the belt speed sensor. With these data, the integrator calculates the rate of material transferred along the belt (weight × speed = rate) (Figure 5.34).

In SPB TBMs the quantity of the extracted material is calculated by measuring the in-flow and out-flow discharge and material densities. To do it, it is necessary to install the relevant pipelines measuring systems for density (i.e. through a nuclear density gauge) and flows (flowmeters) (Figure 5.35).

5.3.3.3 Pressure in the excavation chamber (EPB TBMs) [bar]

The measure of the pressure at various levels in the excavation chamber allows us to verify the effective counterpressure acting against the tunnel face (Figure 5.36).

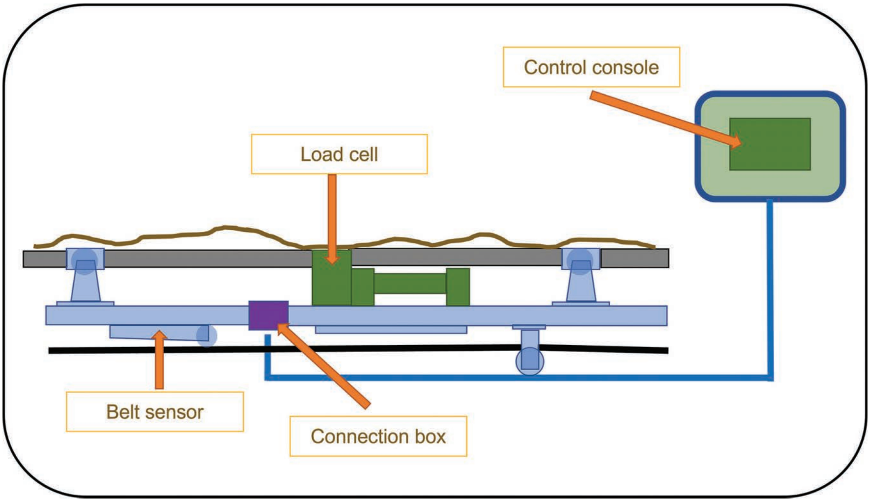


Figure 5.34 The principal components of a weighting belt conveyor system. (From https://www.coalhandlingplants.com/belt-weigher-or-belt-scale.)

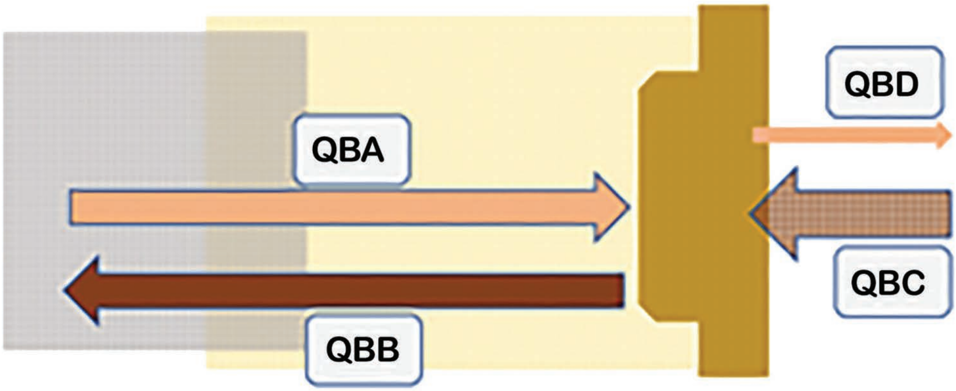


Figure 5.35 The equilibrium equation in SPB TBM tunneling.

5.3.3.4 *(Apparent) density of the material in the excavation chamber (EPB TBMs) [kN/m³]*

The measure of the pressure at various levels in the excavation chamber allows also to verify the characteristics of the material, mainly the apparent density: an indication of the consistency of the material in the excavation chamber (Figure 5.37).

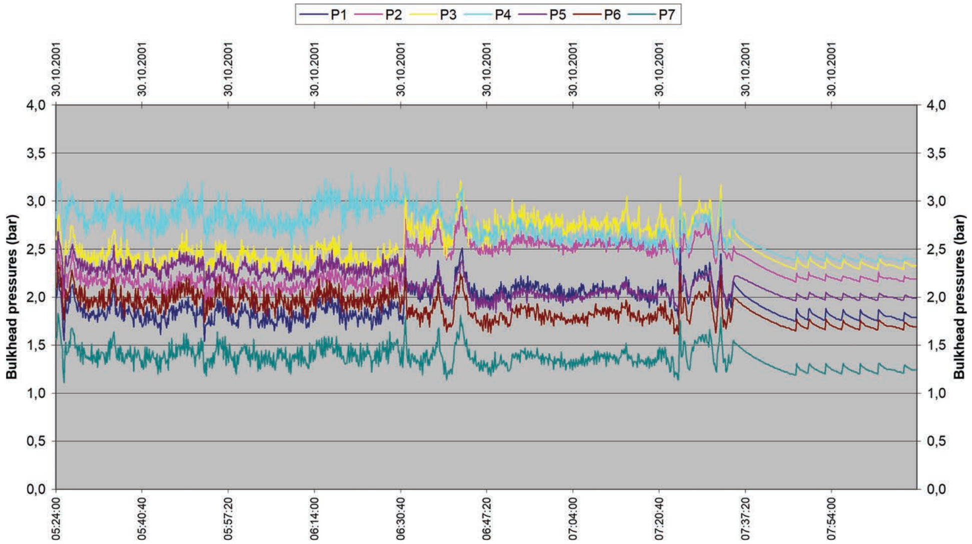


Figure 5.36 Pressure measured in pressure sensors positioned at different levels in the excavation chamber versus time. (Courtesy of Geodata Engineering SpA.)

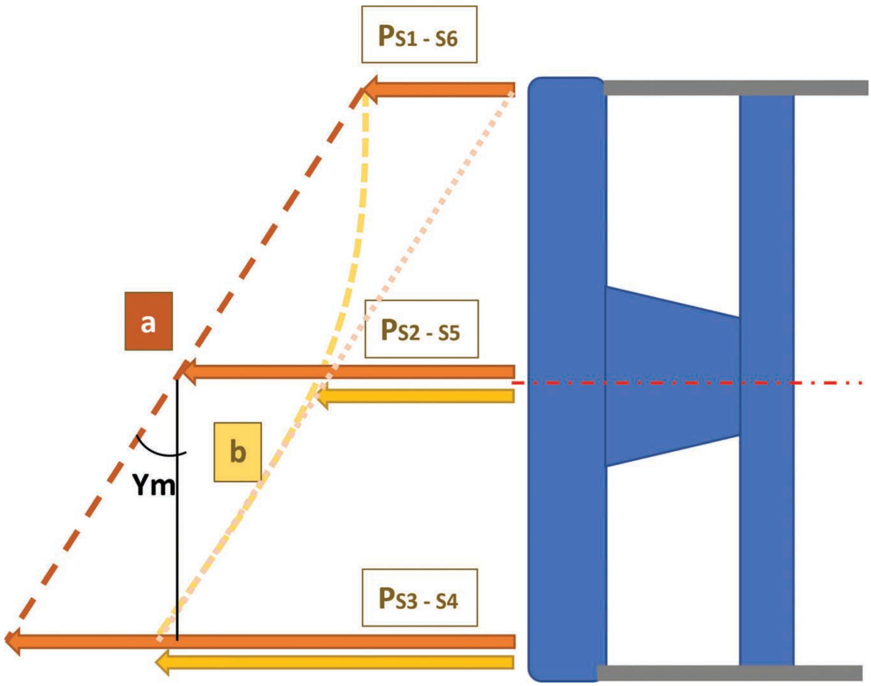


Figure 5.37 Apparent density derived from pressure sensors positioned at different levels in the excavation chamber. Curve a: straight line indicates homogeneous material in the excavation chamber. Curve b: curved line with gradient reduced in the upper part of the chamber indicates possibly denoting the presence of air/foam ($\gamma \approx 0$ kN/m^3) + water ($\gamma \approx 10$ kN/m^3) mixed with the ground (usually in the range $\gamma \approx 13$–15 kN/m^3).

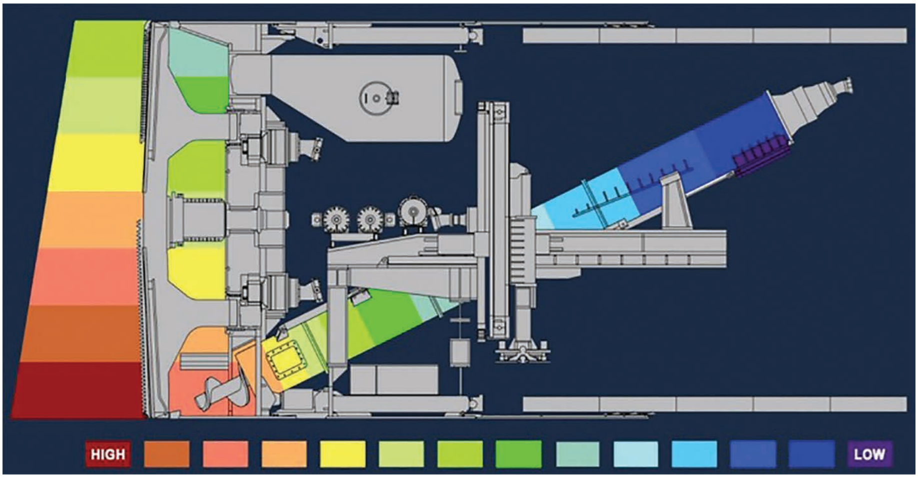


Figure 5.38 The typical (ideal) pressure distribution in excavation chamber and screw conveyor of EPB TBM (Lovat, 2012).

5.3.3.5 Pressure in the screw conveyor (EPB TBMs) [bar]

The screw conveyor must guarantee the discharge with a homogeneous variation of the pressure of the material from the excavation chamber (high pressure) to the primary belt conveyor (atmospheric pressure). The pressure measure in various crew conveyor positions allow to verify anomalies (excavated material density, presence of boulders, water, …) (Figure 5.38).

5.3.3.6 Screw conveyor rotation speed (EPB TBMs) [rev./min]

During EPB TBM tunnelling, advancing speed (penetration) and screw conveyor rotation speed must guarantee the equilibrium between excavated (plus injected) materials and discharged (on the primary conveyor belt) materials; screw conveyor rotation speed measurement is fundamental to achieve this result (Figure 5.39).

5.3.3.7 Screw conveyor torque (EPB TBMs) [rev./min]

Muck discharge from the pressurized excavation chamber to the TBM's belt conveyor (atmospheric pressure) is controlled by the combination of screw conveyor rotation speed and screw conveyor back-gate opening.

Monitoring the screw conveyor torque gives useful information for evaluating the screw stresses and the transported material frictional characteristics.

5.3.3.8 Air pressure in the air bubble (SPB TBMs) [bar]

The air pressure in the air bubble regulates the pressure transmitted by the grout to the ground in the face, thus controlling the stability of the ground.

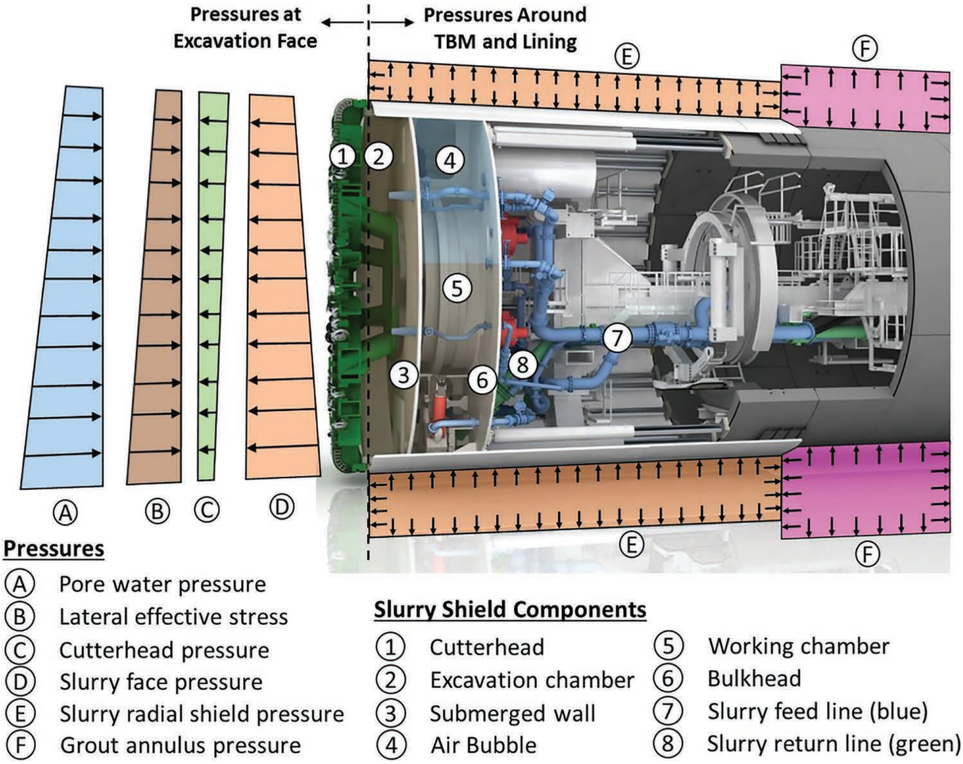


Figure 5.39 Main SPB components and pressures acting during tunnelling (Mohammed, 2017).

5.3.3.9 Height of slurry in the excavation chamber (SPB TBMs) [m]

Height of slurry in the excavation chamber should be monitored to verify the fulfillment of the chamber. Slurry level can be obtained by the measurement of the pressure variation in the excavation chamber considering that the slurry unit weight [kN/m^3] is a constant parameter, at least for a short time period.

5.3.4 Construction data (all TBMs type)

The construction data represents all the constructive information that can be collected, during tunnelling. The construction data will be acquired daily for each shift of work.

5.3.4.1 Shift Report (SR: Adim.)

Shift Report is prepared by the TBM Shift Engineer every shift must include: Shift time; Mining time; and downtime

Shift time [ST: h]
TBM tunneling is usually performed 7/7 24 h/day; that normally means three shifts (8 hours each one) per day.

Mining time [MT: h]
It is the "production time" corresponding with TBM excavation/advancement. Mining time can be expressed in hours or in % respect time (total project, monthly, weekly, daily, shift).

Down time [DT: h]
Downtime is the "no TBM excavation time"; it should be subdivided at least in the following:

a. *Support installation* (rock bolting, steel ribs, shotcrete, segmental lining,......).
b. *Tunnelling equipment ordinary maintenance*/advancement (TBM, including cutting tools, backup, transport system, ventilation system, services, others,).
c. *Unexpected ground condition* (water inrush, running ground, squeezing ground, rock burst,…).
d. *Tunnelling equipment failure* (TBM, backup, mucking system, transport system, ventilation system, services, other,).
e. Others (i.e.: in advance tunnelling investigation, grouting, drainage; accident, strike,.... To be specified case by case) (Figure 5.40).

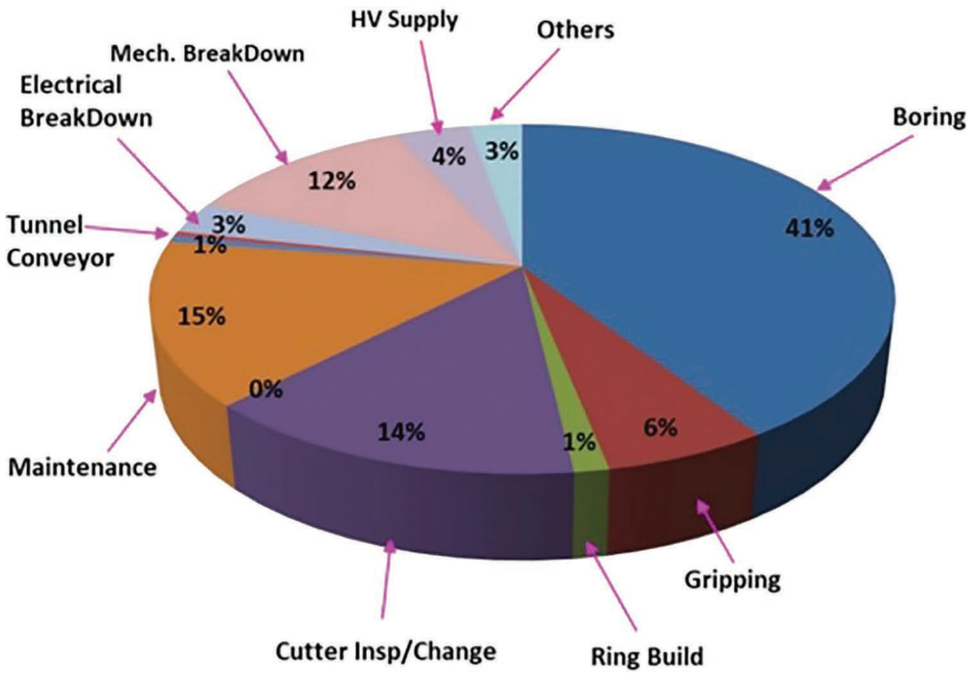


Figure 5.40 Example of an open TBM utility pie chart (Brox, 2020).

5.3.4.2 Production data

The main production data should include at least: (a) tunnel progress [m] (b) support type and amount (rock bolts, steel ribs, shotcrete, segmental lining rings, …) [Adim.]; (c) other tunnel intervention type and amount (ground consolidation, drainages, secondary back-filling, …).

5.3.4.3 Utilization [U: %]

Percentage of Mining Time with respect to Shift Time (U = TBM mining time Shift Time × 100).

On a shift basis, 100% < U < 0; on a whole project basis, normally 35% < U < 50%.

Utilization depends on:

a. Underground condition (terrain to be excavated characteristics, water table position, presence of dangerous/explosive gases, environmental temperature,...).
b. Equipment type/characteristics.
c. Commitment to maintenance.
d. Contractor capabilities.
e. Project conditions interferences, alignment, service site characteristics: dimensions, geometry, constraints (i.e. environmental limits for muck deposit/transport, noise, pollution,…).

5.3.4.4 Specific Energy [SE: MJ/m^3]

The specific energy (SE) is defined as the amount of energy required to excavate a unit volume of rock; SE is a function of many parameters such as rock mass behavior, machine properties and project parameters.

According to various authors, SE has a good correlation with (a) the mechanical properties of the rock mass; (b) the uniaxial compressive strength; (c) brittleness of rock mass; (d) rock mass excavability.

5.3.5 Other monitoring data

5.3.5.1 Volumes and pressure of materials injected during excavation (all TBMs type) [m^3; bar]

Various materials are used during TBM tunneling, such as water, bentonite, foam, polymers, other chemical additives, fillers, and grease. They can be injected through the cutterhead (all TBMs), in the excavation chamber (counterpressure TBMs during excavation and/or during TBMs stops), and in the screw conveyor (EPB TBMs), behind the segmental lining (shielded TBMs), behind the TBM's shield. Having their characteristics, measure volume and pressure of the injected materials is of paramount importance to facilitate and control the excavation.

5.3.5.2 Ground conditioning parameters: concentration, FIR, FER (EPB TBMs) [bar]

For EPB TBMs the main purposes of the conditioning agents are (a) to guarantee control of the pressure of the front support; (b) to facilitate the formation of a "plug" inside the screw conveyor; (c) to minimize the torque of the cutting head and the wear of the tools. Usual elements to provide adequate ground treatment in the excavation chamber are bentonite, foams, polymers, and fillers. When it is used foam as a conditioning agent, the usual control parameters are:

- Concentration (CF)
- Foam Injection Ratio (FIR = 100 * V_f/V_s), typ. 30%–60%
- Foam Expansion Ratio (FER = V_f/V_F), typ. 10–30

5.3.5.3 Slurry characteristics (SPB TBMs)

The knowledge of the slurry during tunneling is of paramount importance for excavation control: the main slurry parameters to be checked are (a) Marsh viscosity; (b) yield value; (c) density; (d) Ph.

5.3.5.4 Air pressure and volume losses in the hyperbaric chamber (counterpressyre TBMs) [bar, m^3/h];

The interventions in the excavation chamber (for cutting tools change, ordinary maintenance, remove obstacles, or any other reason) often have to take place under hyperbaric conditions; in these cases, it is necessary to guarantee the requested counterpressure at the tunnel excavation face with air. Continuous real-time monitoring of the air pressure and air volume losses is requested.

AUTHORSHIP CONTRIBUTION STATEMENT

The chapter was developed as follows. A. Morino: chapter coordination and Sections 5.1, 5.2.1.5, 5.2.1.6, 5.2.1.9, 5.2.1.10, 5.2.2, 5.2.5, 5.2.6; A. Balestrieri: Sections 5.2.1, 5.2.1.1, 5.2.1.2, 5.1.2.3, 5.1.2.4, 5.2.7; G. Carrieri: Section 5.3; M. Martino: Sections 5.2.1.7, 5.2.1.8, G. Pezzetti: Sections 5.2.3, 5.2.4. All the authors contributed to the chapter review. The editing was managed by A. Morino and G. Pezzetti.

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