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MONITORING AND MODELLING GROUND DEFORMATIONS DURING TUNNELLING

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Abstract

Monitoring of ground deformations in tunnelling is a principal means for selecting the appropriate excavation and support methods among those foreseen in the design, for ensuring safety during tunnel construction (including personnel safety inside the tunnel and safety of structures located at ground surface) and, finally, for ensuring construction quality management according to ISO 9000. This paper briefly describes the types of ground deformation measurements often used in tunnelling, the difficulties in obtaining ground measurements and their subsequent evaluation, and the application of these measurements (a) in modeling tunnel excavation and support and (b) in establishing early warning systems against incipient ground collapses or damage to structures at ground surface.

Examples of ground deformation monitoring and their application in tunnel design and construction are illustrated via cases from the Jubilee Line Extension of the London Underground, from Lines 2 and 3 of the Athens Metro and from a nine-kilometer long mountain tunnel in Greece. In the first two examples, ground deformation monitoring aimed to ensure that structures at ground surface would not be harmed by the tunnelling operations. In the third case, the objective was the optimization of the temporary support requirements as well as early warning against potential collapses.

1. Introduction

The need to upgrade and further develop transportation infrastructure (high-speed railway, highway and urban transit lines) has lead to the on-going construction of large-diameter, long tunnels under difficult conditions. Such conditions usually arise from a combination of adverse ground and groundwater regimes, very high overburden pressures or, in the case of urban tunnels, the existence of sensitive structures within the zone of influence of the tunnel. Typical examples of such tunnels are the high-speed railway Alpine base tunnels in Switzerland, at present in the early stages of construction (the 57 km Gotthard and the 43 km Lotschberg) as well as several large Metro tunnelling projects recently completed (e.g. in London and Athens). Difficult tunnels also include several highway and railway mountain tunnels at present under construction in Greece, due to the very difficult ground conditions caused by the intense tectonisation and heterogeneity of the geology in Greece.

Until quite recently, tunnel excavation and temporary support was based solely on the experience of the Contractor and support methods were based on analogies from the mining industry (steel sets and timber lagging). The engineer was mainly involved with the design of the final lining (concrete arch) using assumed loads, often based on the classical recommendations by Terzaghi (1946), as shown in Fig. 1.

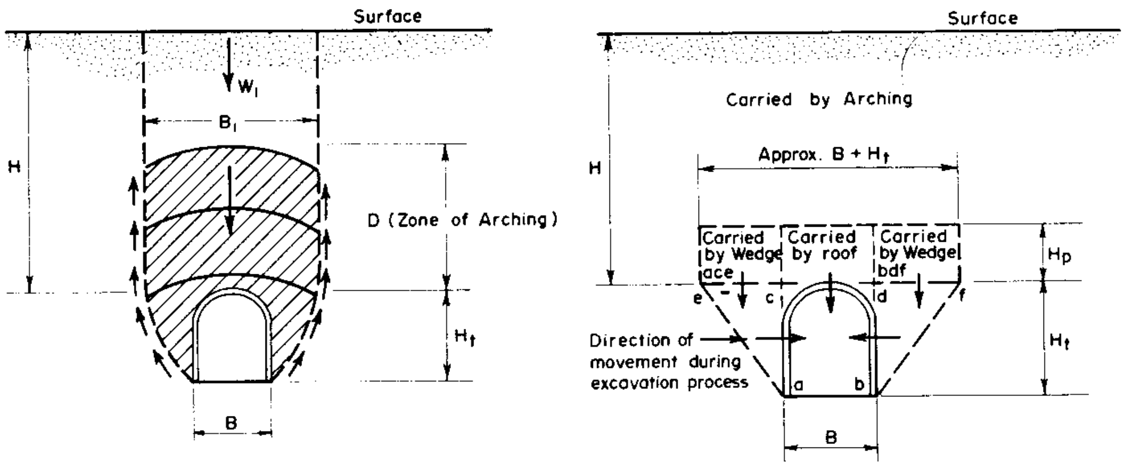


Fig. 1 : Terzaghi's recommendations for the loading on tunnel linings :
pv = Ht , ph = Ka pv (after Terzaghi, 1946).

This attitude was probably adequate for short tunnels with low ground covers and small diameters in favourable ground conditions. In the last three decades, however, as tunnel lengths, sizes and depths of overburden increased rapidly, design and construction techniques have developed dramatically, mainly as a result of the technological advances in tunnel excavation (e.g. large-scale mechanical excavation using Tunnel Boring Machines) and rockmass support techniques (sprayed concrete liners, rock-bolting, etc) as well as a gradually increased concern about safety and economics in underground structures. The application of these modern design and construction techniques has benefited significantly from field measurements of ground deformations both around the tunnel and at the ground surface.

The present paper briefly describes the types of ground deformation measurements often used in tunnelling, the difficulties in obtaining these measurements and their subsequent evaluation, and the application of ground measurements in modeling tunnel excavation and support and in establishing early warning systems against incipient ground collapses or damage to structures at ground surface. Examples of ground deformation monitoring and their application in design and construction are illustrated using examples from the Jubilee Line Extension of the London Underground, from Lines 2 and 3 of the Athens Metro and from a nine-kilometer long railway mountain tunnel in Greece.

2. Ground deformation measurements

The objectives of ground deformation monitoring are different in mountain and urban tunnels. In mountain tunnels, the main objective of deformation measurements during construction is to ensure that ground pressures are adequately controlled, i.e., there exists an adequate margin of safety against collapse, including roof collapse, bottom heave, failure of the excavation face, yielding of the support system, etc. Adequate control of ground pressures ensures a safe and economical structure, well adapted to the inherent heterogeneity of ground conditions. This procedure is compatible with modern tunnel design methods which include a range of excavation and support systems to cover the anticipated spectrum of conditions along the tunnel, with selection of the applicable system in each case relying on the encountered geology at the tunnel face, experience on tunnel behaviour at previously excavated sections under similar conditions and, on accurate deformation measurements, i.e., by applying the so-called "observational method". This method of construction can ensure adequate safety and, at the same time, an economical construction. On the contrary, in urban tunnels, the main objective of ground deformation monitoring is to limit ground displacements to values sufficiently low to prevent damage to structures and utilities at ground surface. Thus, the fundamental difference in deformation monitoring stems from the fact that in mountain tunnels the objective is to guard against an ultimate limit state (i.e., collapse) while in urban tunnels the objective is to guard against serviceability limit states (i.e., crack initiation) for structures and utilities at ground surface. As a result of these differences in objectives, design philosophies, and construction techniques, the types and required accuracy of the measured ground deformations vary between the two classes of tunnels, as follows :

- In mountain tunnels, considerable ground deformations are deliberately permitted (and often provoked) in order to reduce the initially very large "geostatic" loads on the temporary support by increasing ground de-confinement. Such reduction of ground loads on the tunnel support can be appreciable and, thus, extremely beneficial provided that excessive "loosening" of the rockmass is prevented (such "loosening" can cause roof failures and an eventual increase of the ground loads). De-confinement is achieved by controlled inward ground deformation at the excavation face (face-take), controlled delay in the completion of the temporary support measures (by increasing the distance from the face where the tunnel invert is closed), a relatively flexible temporary support system (e.g. long passive rock-bolts and thin sprayed concrete liners) and, finally, by installing the permanent lining at a later time when evolution of the long-term (creep) ground deformations has practically stopped. In extreme cases of strongly squeezing ground conditions, sliding supports may be installed to permit tunnel wall convergencies of several tens of centimeters. In all these cases, control of ground deformations depends strongly on efficient and timely deformation measurements. However, due to the large ground deformations (several centimeters and even several tens of centimeters), the required level of precision of these measurements needs not be excessive; typically, accuracy of the order of one centimeter is sufficient in mountain tunnel applications.
- In urban tunnels, the main objective is limiting ground deformations around the tunnel and thus causing the minimum possible movement and disturbance at ground surface and the structures founded there. This is achieved by (a) limiting inward ground deformation at the excavation face (face-take), e.g. by face pre-reinforcement using fiber-glass nails, stiff steel beams (fore-poles), cement- or jet-grouting techniques, (b) by installing a stiff temporary lining, usually including invert closure, as early as possible and (c) by installing the final lining as quickly as possible, especially when tunnel wall convergencies continue to evolve with time. The above "stiff" construction methods tend to reduce ground de-confinement and thus the ground loads on the tunnel lining are a significant fraction of the initial "geostatic" loads. Such loads often are not a problem, since urban tunnels are usually shallow and thus the initial "geostatic" loads are much smaller than those in deep mountain tunnels. Due to the small ground deformations induced by tunnelling (usually less than 10mm at ground surface and occasionally less than 5mm), measurement precision and the early installation of the measuring devices is of utmost importance.

Regardless of the type of the tunnelling project, ground deformations measurements are used in feed-back loops as part of the integrated design-construction-performance monitoring procedure shown in Fig. 2. The smallest loop is the most common application of deformation measurements and is used to adapt construction practices to the in-situ conditions, due to the inherent ground variability. In more rare cases, where deformation measurements indicate significant and persistent deviations from the design provisions, the largest loops are used to modify the design (sub-surface model) or even to prescribe additional geotechnical investigations aiming to re-evaluate ground conditions and possibly re-design the tunnel.

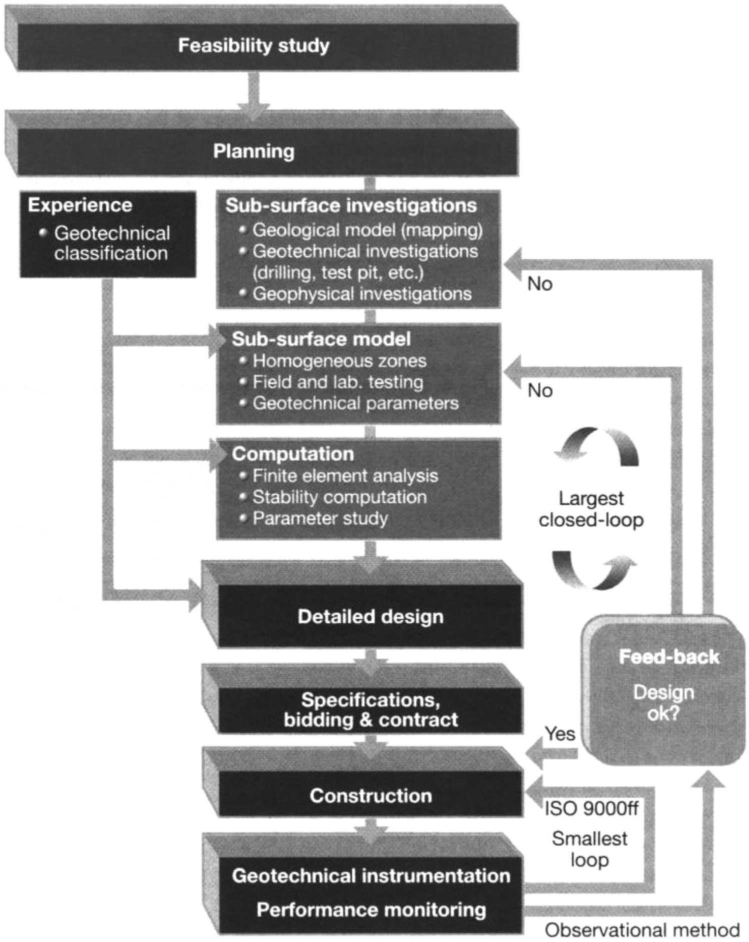


Fig. 2 : Deformation monitoring as part of the integrated design-construction-performance monitoring sequence. The smallest loop is used to adapt construction to the in-situ conditions. The largest loops are used to modify the design (sub-surface model) or even to require additional geotechnical investigations.

3. Instruments for deformation measurements

Deformation monitoring in tunnelling projects is performed with instruments installed or operated either from the ground surface or from within the tunnel. Instruments installed from the ground surface can be put in place prior to tunnel excavation in the area of interest. In this way, their proper functioning can be checked and several zero-load measurements can be obtained thus verifying their level of accuracy (by the fluctuation of the zero-load measurements). On the contrary, instruments installed from within the tunnel are necessarily put in place as the tunnel advances and thus an appreciable portion of the actual ground deformation is not recorded, as it has occurred prior to the installation of the instrument. Typically, the majority of ground deformation takes place close to the tunnel face (from about one tunnel diameter ahead of the face up to about 1.5 diameters behind the face). Thus, monitoring instruments placed on the tunnel wall (e.g. optical reflector targets) or installed in the ground from the tunnel wall (e.g. borehole rod extensometers) should be installed as early as possible. Unfortunately, the minimum distance of instrument installation from the tunnel face is 2-4 metres due to the unavoidable interference with the construction of the temporary support (e.g. sprayed concrete, steel sets, etc). At this distance, 60-80% of the immediate deformation has already occurred, thus reducing the usefulness of these measurements to long-term deformation monitoring (e.g. creep deformations), for monitoring the effect of benching (in multi-stage excavations) and for monitoring the effect of driving an adjacent tunnel (e.g. in twin tunnel projects). An exception to this unavoidable deficiency are ground deformations along the tunnel axis measured with sliding micrometers installed from the tunnel face, thus rendering extremely useful measurements for predictions of excavation conditions ahead of the tunnel face (these measurements are influenced mainly from the ground conditions ahead of the tunnel face and thus are useful in assessing tunnel behaviour in the upcoming excavation stages).

Deformation monitoring in tunnelling usually includes some of the following measurements :

(i) Convergence of the tunnel wall, and usually crest settlement and spring-line closure.
(ii) Deformations at ground surface, including settlements and tilts of surface structures.
(iii) Deformations in the ground, around the tunnel or deep below the ground surface.

Tunnel deformations can be monitored with geodetic or geotechnical methods. Geodetic measurements provide absolute coordinates of the target locations in time, while geotechnical measurements usually provide relative displacements of the target locations with respect to an initial condition (at the time when the initial measurement is recorded). Geotechnical measurements can provide absolute coordinates of the target locations in time, if the initial positions of the targets are obtained using geodetic means. Depending on the tunnelling application, deformation measurements can be recorded, processed and evaluated in real-time using digital recording and telecommunication systems, or can be recorded manually and processed later in batch mode. Real-time processing of ground deformations offers the possibility of rapid response to upcoming situations but requires advanced technology and an appreciably higher cost. Thus, real-time monitoring is limited to cases where rapid response is absolutely necessary, i.e., mainly in urban tunnels near sensitive structures. Such cases include not only the typical situations where risk minimization is critical, but also innovative construction procedures for actively controlling ground deformations, such as compensation grouting, as discussed below in the Case Study regarding the Jubilee Line Extension of the London Underground. Accurate monitoring of ground deformations in real-time is essential for the application and control of these methods, as the injected amount of grout and, generally, the grouting programme are governed by these measurements.

The following sections summarize the types of devices typically used for measuring ground deformations in tunnelling.

3.1 Measurements of tunnel wall convergence

Tunnel wall convergence (closure) between reference points (hooks) bolted on the tunnel walls is usually measured with standard metal tape extensometers. For distances up to about 10-15 metres, the accuracy of such measurements is typically ± 0.2 mm. The method is easy to use and maintain but it only offers the magnitude of the deformation along the line of measurement. Because of this disadvantage, in most present-day tunnelling applications, deformations of the tunnel walls are obtained in three dimensions, by routine geodetic surveying using total stations with integrated distance measurement. In such applications, optical reflector targets are installed at regular distances along the tunnel axis (e.g. at sections every 15-20m) and, on each section, at selected locations of the tunnel wall (e.g. five reflectors per section : at the crest, at 45 degrees and at the spring-line). As tunnels are usually long, the fixed (stable) reference positions are typically located outside the tunnel, often at distances exceeding one kilometer and usually out of sight from inside the tunnel. Thus, measurements of the targets inside the tunnel are obtained by placing the total station at pre-defined rugged stations[1] (bolted on the tunnel wall) and successively moving the instrument forward (towards the tunnel excavation face) while measuring the coordinates of the visible targets from each station. The theoretical accuracy of these measurements over a distance of about 100m) is about 2-3mm for lengths and ± 5 arcsec

[1] which occasionally continue to move, even at large distances from the tunnel excavation face due to long-term (creep) ground deformations.

(2.5mm) for angles. For long tunnels, the accuracy of the measurements is usually reduced by unclean atmosphere and due to the multiple positions of the instrument (especially if these positions are not stable due to creep deformations of the tunnel).

A recent development in measuring the geometry of tunnel walls in cross section (and thus assessing the deformation in the interval between two measurement epochs) are the Tunnel Profile Scanners (profilometers). In addition to measuring tunnel wall convergencies in time, profilometers are also employed for a variety of other purposes like comparing the actually excavated tunnel cross section with the design requirement and for measuring the volume of shotcrete placed on the excavated rock surface (by measuring the profile before and after shotcreting). Tunnel profilometers are fully digitized photogrammetric measuring devices. A typical such system (DIBIT tunnel scanner; Grafinger, 1997) shown in Fig. 3 consists of two CCD cameras which are mounted on a portable frame. The cameras produce stereoscopic digital images of the tunnel surface. The position of the camera frame is automatically determined by a total station with automatic target recognition placed up to a maximum distance of 100 metres. For this purpose, three reflector targets are permanently mounted on the frame. Digital images are automatically stored in a laptop computer and can be processed to provide the 3-D coordinates of the surveyed tunnel wall surface with an accuracy of ± 5 mm for each coordinate. Although the accuracy of this method is low compared to routine geodetic surveying, the advantage of recording a very large number of points on the tunnel wall outweighs the low accuracy in many applications.

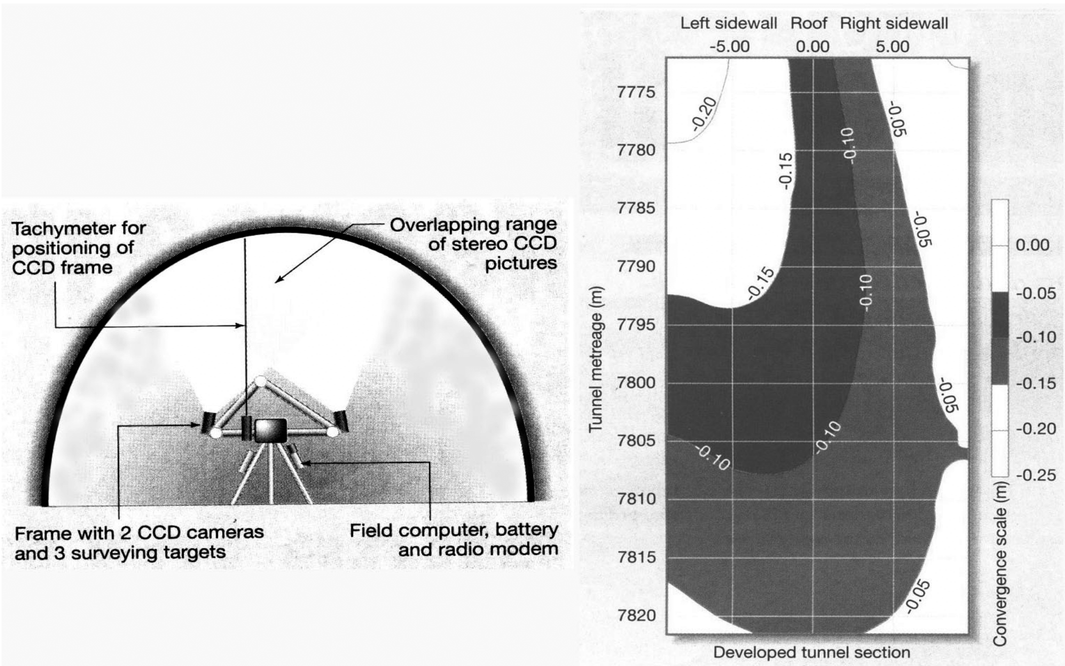


Fig. 3 : Typical features of the DIBIT tunnel profilometer (left) and typical plot of the measured wall convergence as contours on the developed tunnel wall area (Tunnels and Tunnelling, April 2001) .

3.2 Measurements of deformations in the ground

These measurements record the deformation of target positions in the ground, either around the tunnel or deep below the ground surface. They are often used to calculate strains or control the deformation of characteristic points in the ground (e.g. below the foundation of buildings, below utility lines, etc). Such measurements are performed with geotechnical instruments including single- or multi-point borehole rod extensometers, magnetic extensometers, sliding micrometers, inclinometers, probe deflectometers (often called sliding curvometers) and deep settlement plates. These instruments can be installed either from the ground surface (before the tunnel face reaches the area of the instrument) or from inside the tunnel (radially from the tunnel wall or along the tunnel axis ahead of the excavation face).

Fig. 4 shows a typical application of a three-point rod extensometer installed from the tunnel wall, to measure the relative deformation of the three outward ends of the rods (anchored in the ground) with respect to the tunnel wall. The inward end of the rods moves with respect to the tunnel wall (i.e., with respect to the base plate of the instrument) and this movement is measured either manually (with a depth micrometer) or electronically (with a linear displacement transducer - LVDT). The precision of the measurement is of the order of 0.01 mm, sufficient to calculate strains in the ground. These measurements can be used to assess the extent of the zone of influence around a tunnel, or the deformation of building foundations and other critical elements buried below the ground surface. If the position of the base plate of the instrument is recorded with geodetic means, the absolute magnitude of the displacement (along the line of the measurement) of the outward points of the rod can also be assessed.

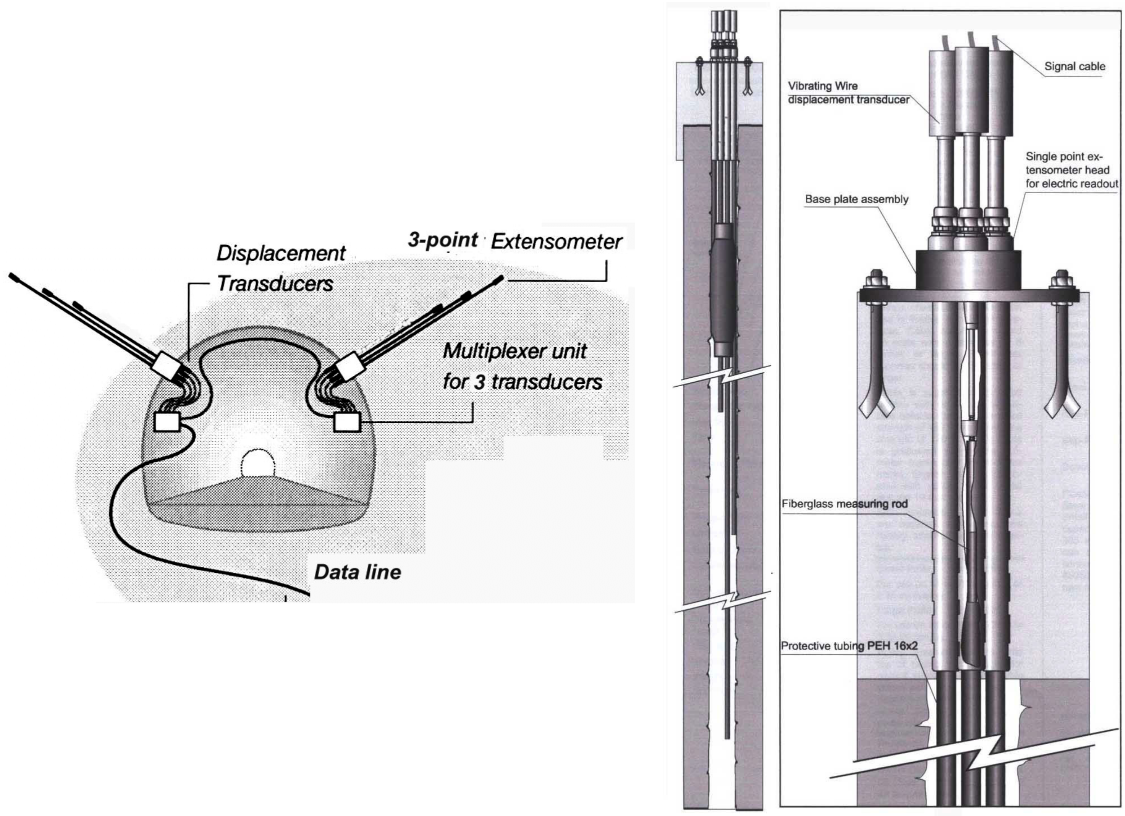
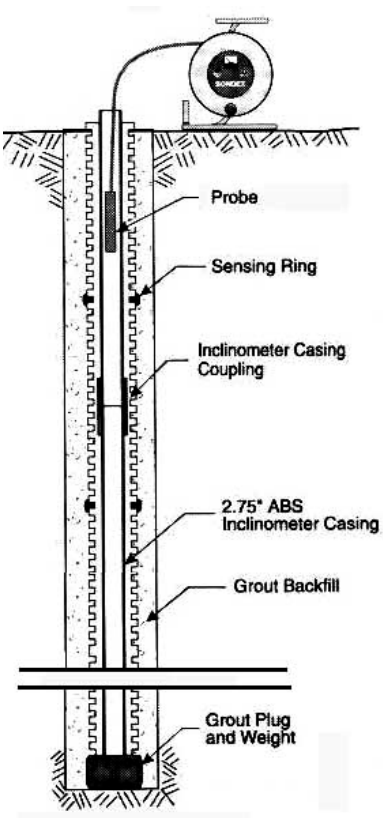


Fig. 4. Left : Three-point rod extensometers installed in boreholes drilled from the tunnel wall. Right : Detail of the measuring head of the instrument, using electronic displacement transducers for automatic recording of the measurements.

Fig. 5 shows two types of instruments for measuring the vertical settlement of a series of locations in the ground. The Magnetic Extensometer consists of a probe (a survey tape with a steel mass at the end) spooled on a tape reel with built-in light and buzzer, and a number of magnets positioned along the length of an access pipe. The access pipe with the magnets is inserted in a near-vertical borehole and is coupled with the surrounding ground by grouting the annulus between the pipe and the borehole wall. As the pipe is flexible and can stretch or compress, the magnets can move up or down following the movement of the adjacent ground. Readings are obtained by lowering the probe to the bottom of the access pipe and drawing it up to find the depth of each magnet (as the buzzer and light are activated when the probe enters the magnetic field). The precision of the instrument is of the order of ±5 mm, mainly due to the uncertainty in assessing the exact position when the probe enters the magnetic field. If the bottom of the access pipe is not in stable ground, the depths of the magnets can be referenced to the top of the pipe which can be optically surveyed before readings are taken. The instrument can provide the settlement of all measuring locations (magnets) and the strain between adjacent magnet locations.

The Sliding Micrometer shown on right side of Fig. 5, also includes an extensometer casing equipped with metallic measuring marks at one-metre intervals along the casing. The casing is inserted in a borehole and fixed in place by grouting. The measuring probe is a high-precision one-metre long instrument with spherically shaped heads at both ends, fitting exactly on the conically shaped measuring marks of the casing. Both the measuring marks and the probe heads are provided with recesses which enable the probe to slide along the casing from one measuring mark to the next (sliding position). By rotating the probe by 45 degrees and pulling it upwards, the two heads of the probe lock on two adjacent measuring marks of the casing and the probe is tensioned between them (measuring position). A linear displacement transducer (LVDT) inside the probe measures the tension and the signal is transmitted to a digital readout unit for processing. The accuracy of the measurements is of the order of 0.01 mm. A variance of the Sliding Micrometer is the Fixed re-Installable Micrometer (FIM) shown in Fig. 5 (right); this instrument can remain attached between two measuring marks of the casing and provide continuous measurements of the strain between these two locations.



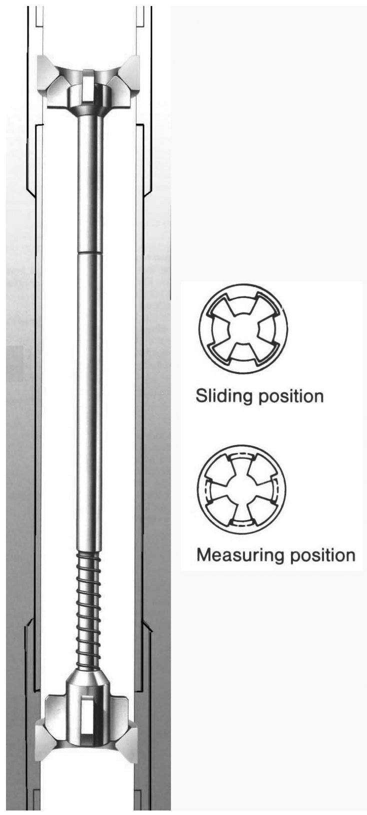


Fig. 5 : Left : Magnetic extensometer and Right : Fixed re-Installable Micrometer (FIM) of the Sliding Micrometer class, for in-depth vertical settlement measurements.

The inclinometer probe shown in Fig. 6 can measure the tilt of a casing pre-installed in a borehole (and grouted in place) or firmly attached on near-vertical structural elements (e.g. walls of buildings). The internal face of the casing bears four longitudinal grooves (at quarter circle locations) which force the probe to slide (on two-pairs of spring-loaded wheels) along a specific orientation of the casing, thus measuring the tilt along this orientation from bottom to top. After the end of he measurement, the probe can be re-inserted in the perpendicular orientation of the casing and measure the tilt along this line as well, thus permitting to measure the tilt along two perpendicular directions. Inclination measurements are typically taken at half-metre intervals from the bottom to the top of the casing. Integration of the tilt along the length of the casing can provide the horizontal deflection of the casing (with respect to a previous measurement). As the tilt integration process requires a point with known deflection, the bottom of the casing is usually assumed to be stable and deflections are referenced to the casing base point. If the base point is suspected to move, the top of the casing can be used as reference, provided that its displacement is independently measured by a geodetic method.

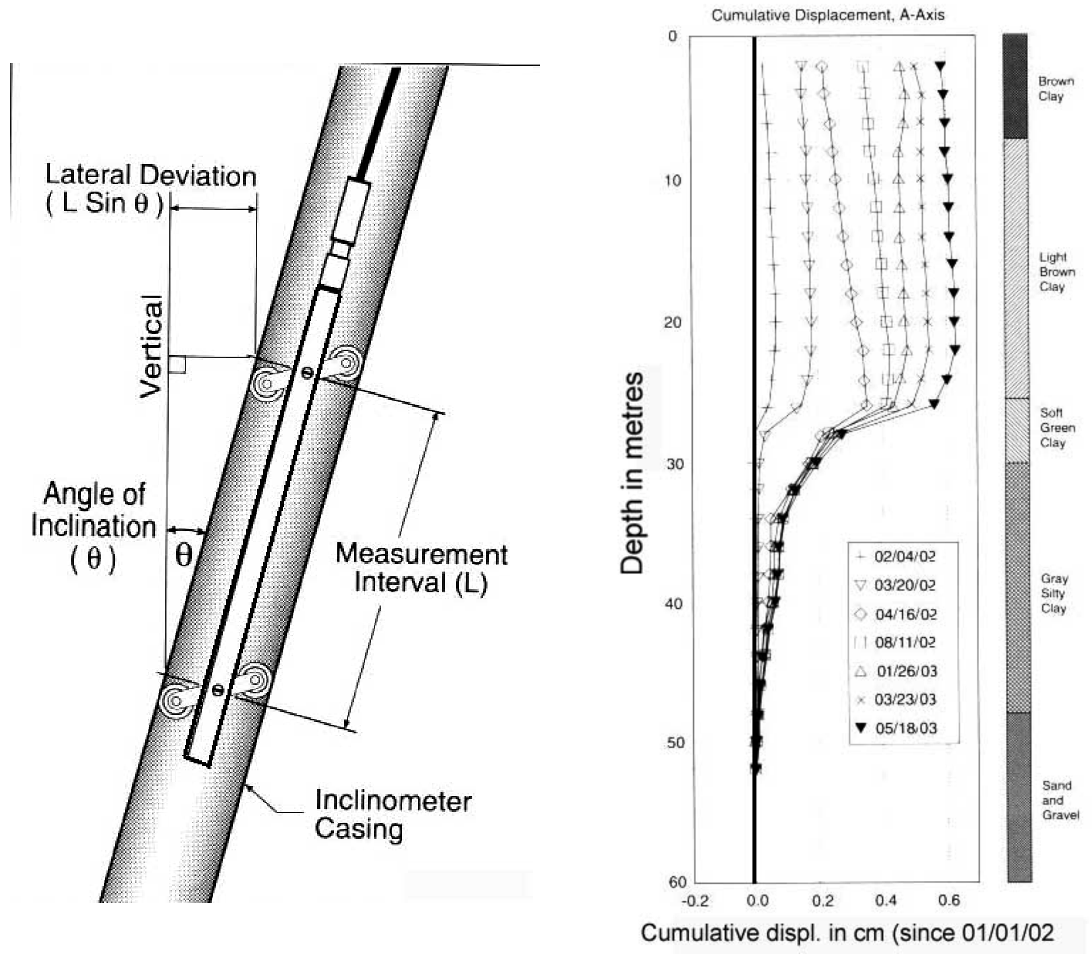


Fig. 6 : Left : Inclinometer probe and Right : typical horizontal displacement profile obtained by an inclinometer.

Inclinometers are typically used to measure deflections of casings installed in boreholes of near vertical orientation. Measurement of borehole deviation in any orientation can be performed by the sliding curvometer and the chain deflectometer shown in Fig. 7. The Sliding Curvometer is a biaxial tilt-meter which can slide on three pairs of spring-loaded wheels along a specially grooved casing installed in a borehole having any orientation. The probe is made of two 1m-long rods connected to each other with an electronic joint which includes a biaxial tilt sensor, a signal conditioner and amplifier and a temperature sensor. The Chain Deflectometer is a multi-element sliding curvometer which is installed in a borehole and remains there for a relatively long period of time, continuously monitoring the deflections normal to the axis of the borehole at the positions of the joints of the chain. The base length of each rod is 1m or 2m and thus deflections can be monitored simultaneously (and in real time) along long boreholes. Typical applications include monitoring the deflection in the ground above the crest of tunnels and below the foundation of buildings.

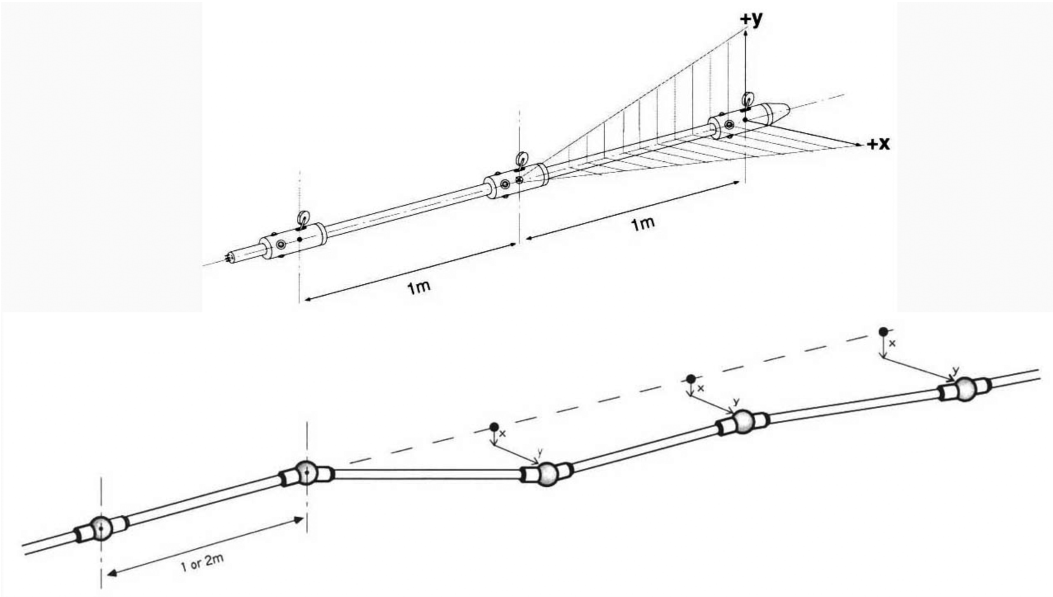


Fig. 7 : Top : Sliding curvometer and bottom : Chain deflectometer, for measuring deflections of boreholes in any orientation.

The sliding curvometer can also be used to control alignment deviations of boreholes such as long anchor drill-holes, exploration boreholes in the face of advancing tunnels and drill-holes in tunnelling applications including round freezing. Experience has shown that horizontal and inclined drill-holes are particularly prone to deviation; the degree of deviation depends on the quality of the drilling equipment, the experience of the crew, the length of the drill-hole and, of course, the ground conditions. Fig. 8 shows the deviation of a 56m long exploration borehole which was drilled in the face of an advancing tunnel. Fig. 8 shows that the borehole runs like a corkscrew with maximum deviation from linearity equal to 0.18m downwards and 0.20m to the left.

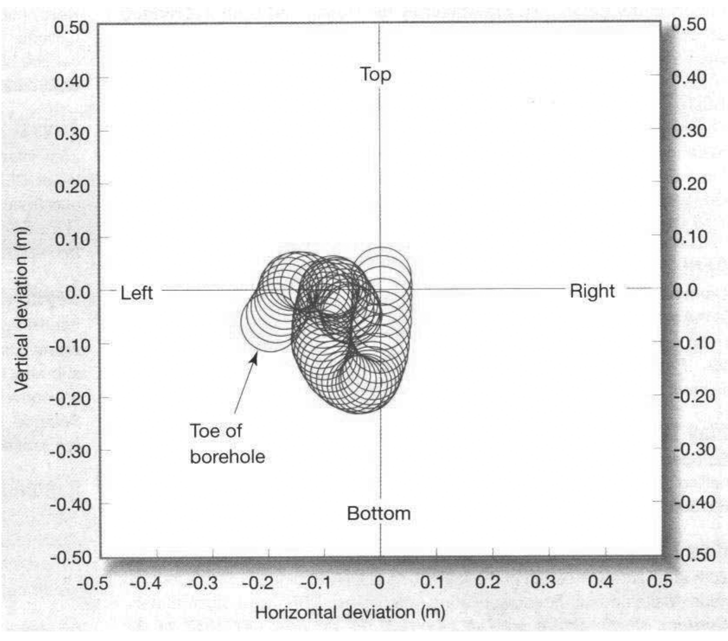


Fig. 8 : Application of the curve deflectometer in measuring the deviation of borehole alignment

3.3 Measurements of deformations at ground surface

Measurement of deformations at ground surface are crucial in urban tunnelling projects where damage to surface structures and utilities should be prevented. These measurements typically include settlements (and heaves) of structures as well as tilting. Such measurements are performed with surveying instruments (Precise Geodetic Leveling and Geodetic Façade Monitoring using total stations), or with geotechnical instruments like Electronic Liquid Level Gauges, Electrolytic Tilt Sensors (electro-levels) surface clinometers/tiltmeters, precise taping, and crack-meters.

Precise levelling and façade monitoring are the most common methods for monitoring displacements at ground surface. The accuracy of these measurements is typically ±0.2mm (over about 100m lengths) for precise leveling and ±5 arcsec (0.025mm per metre) for angles and 1mm + 0.2mm/100m for distances in the case of façade monitoring with total stations. Façade monitoring can be automated and measurements can be obtained and transmitted in practically real-time.

Inside buildings and in areas with limited visibility for the application of the above geodetic measurements, geotechnical measurements can be performed using the following precision instruments :

1. Electronic Liquid Level gauges, for the measurement of settlements at several locations. The method consists of installing a number of liquid filled pots, hydraulically connected to a reference pot located in a stable area. The elevation of the liquid in the reference pot is maintained constant by means of a mini-pump, reservoir and an overflow unit. LVDT float sensors monitor the height of the liquid in each pot. When settlement or heave occurs, the sensor detects the apparent change in the height of the liquid and transmits the signal to a data logger for continuous monitoring and real-time processing. The accuracy of the system is typically ±0.3mm.
2. Electrolytic tilt sensors are precision bubble levels that are electrically sensed as a resistance bridge. The bridge circuit outputs a voltage that is proportional to the tilt of the sensor. The sensors are usually attached on metal beams, one to three metres long, with their ends mounted on the structural elements to be monitored. Chains of such tilt sensors are often installed in sequence in the horizontal direction to monitor differential settlements along long walls or beams. The precision of the instrument is typically ± 1 arcsec (0.005mm per metre).
3. Surface clinometers (tiltmeters), precise taping using invar tape between fixed anchor points and various types of crack-meters are also used in measuring deformations at ground surface.

Although ground deformations are the principal and most direct means of monitoring tunnel response, the following quantities are also monitored in some tunnels :

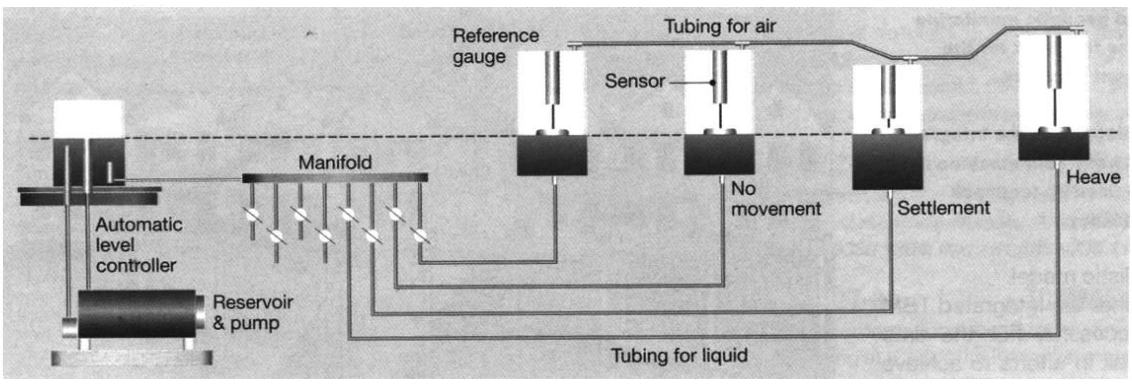


Fig. 9 : Electronic Liquid level gauge for measurement of settlements in several locations (after Tunnels and Tunnelling, May 2001)

1. Pore water pressures. As tunnel excavation alters the groundwater regime by causing seepage towards the tunnel, measurement of groundwater table draw-down is often used in assessing the environmental impact of tunnels. Such measurements are also used in assessing the hydraulic loads on the final lining in the case of watertight lining systems. Pore water pressure measurements are performed with various types of hydraulic piezometers.
2. Ground pressures acting on the tunnel lining. Although in principle useful in assessing the actual ground loads on the lining, these measurements difficult and usually unreliable mainly because the installation of the probes strongly influences the in-situ stresses to be measured.

4. Use of deformation monitoring in tunnel construction

Ground deformation monitoring is extremely useful in tunnelling projects (probably much more than in other geotechnical projects) for the following reasons :

1. Tunnels are linear structures and thus experience from the behaviour of already excavated tunnel sections can be used for reliable assessments of the anticipated ground response and tunnel behaviour in the following excavation steps, in conjunction with ground quality observations at the excavation face (and occasionally ahead of the face). As ground deformations are the principal means of assessing tunnel behaviour, ground deformations are commonly used in such extrapolations of the anticipated ground response (and thus in decisions related to the applicable excavation and support methods). Specifically, tunnel designs following the principles of the so-called New Austrian Tunnelling Method (NATM) rely heavily on the "observational method" which is based on ground deformation monitoring. Such designs include several typical excavation and temporary support systems (typical sections), each applicable in a specific range of anticipated ground conditions, while the whole set covers the complete spectrum of the anticipated conditions along the tunnel. The numerical analyses performed for each typical excavation and support section predict ground deformations at key locations around the tunnel (e.g. wall convergence at the crest and spring-line) and ahead of the excavation face (along the tunnel axis). During tunnel excavation, ground deformations are monitored and the measured values in the immediately previous excavation steps are used for the selection of the appropriate typical section to be used in the next excavation step, by matching predicted and observed deformations. This procedure is more reliable than a selection based solely on ground quality observations at the exposed tunnel face (e.g. rockmass classifications) since these last observations are indicative of ground quality at the tunnel face only, while ground deformations compound the engineering effects of ground quality in a wider zone around the tunnel and ahead of it, which actually influences tunnel behaviour.
2. Reliable assessment of ground parameters (e.g. deformability and strength parameters) for use in the design is usually based on back-analyses of already excavated tunnel sections. Such analyses use the observed ground and tunnel behaviour (i.e., mainly measurements of ground deformations inside and around the tunnel) as a criterion for the acceptance of the ground parameters input in the design (by matching observed and predicted deformations). Such correlations usually are much more reliable than direct assessment of the ground parameters for the following reasons :
    a. Due to the natural heterogeneity of the ground, local measurement of ground parameters on selected samples is rarely representative of the in-situ conditions. Furthermore, such sampling is influenced by disturbance and operator bias (i.e., tested samples are usually better or worse than the average quality since specimen preparation on average samples is more difficult and sometimes impossible). Finally, the required size of a representative sample often exceeds the usual testing capabilities in most laboratories (especially in fractured rockmasses).
    b. Field tests for the determination of ground parameters avoid some of the above deficiencies but have a very high cost and thus their reliability is greatly diminished by

the small number of available test data (compared to the usual tunnel lengths and the types and qualities of ground formations encountered). Furthermore, the interpretation of field tests usually involves appreciable uncertainty since the initial in-situ stresses are usually unknown and (in some cases) the installation of the measuring probes modifies significantly the ground parameter to be measured by the test (e.g. measurements of in-situ stress levels).

3. Safety during tunnel excavation relies heavily on ground deformation monitoring, as early warning of incipient failures is often based on the rapid collection and evaluation of ground deformation measurements. As such failures usually evolve in a relatively short period (a few hours to a few days) automation in the collection and processing of monitoring data is necessary. Similarly, control of damage to structures located at ground surface also relies heavily on deformation monitoring of these structures. In these cases, the evolution of ground surface deformations due to tunnelling needs to be correlated with accepted thresholds of damage levels.
4. The design of the final lining of tunnels is governed by the loads exerted from the surrounding ground. The magnitude of these loads cannot be accurately assessed before tunnel excavation. Such assessment is usually performed after the excavation of the tunnel and the installation of the temporary support and is usually based on a combination of the observed ground quality, the height of overburden and the measured ground deformations (during and after tunnel excavation).

The usefulness of deformation monitoring in tunnelling projects is illustrated in three cases : the Jubilee Line Extension of the London Underground, the construction of Lines 2&3 of the Athens Metro and the construction of a mountain tunnel in Greece under difficult ground conditions.

4.1 Jubilee Line Extension of the London Underground

The Jubilee Line Extension (JLE) of the London Underground is certainly one of the most carefully monitored tunnelling projects in terms of deformation measurements at ground surface, due to the passage of the tunnels below many historical monuments of London. A detailed account of the deformation monitoring, including methods employed, difficulties and achieved results, is given by Burland et al (2001). That document forms the basis of the present brief account of some characteristic ground deformation monitoring schemes.

A significant portion of the JLE tunnels were excavated in the stiff overconsolidated London Clay. The example discussed in this paper is related to ground deformation monitoring for the protection of the Big Ben Clock Tower at Westminster, located between Green Park and Waterloo Station (Contract 102 of the JLE project), as shown in Fig. 10. Tunnel excavation in this area was performed in the London Clay and included two single track tunnels (4.5m in diameter) excavated with EPB tunnel boring machines and enlargement of these tunnels to 7m in diameter for the Westminster Station platforms, as well as the excavation of the Westminster Station deep cut (cut and cover method of construction).

Due to the sensitivity of the Big Ben Clock Tower to settlements caused by tunnelling, active settlement control was used, by applying compensation grouting techniques to “lift” the structure in a carefully controlled fashion, thus compensating for the settlements caused by tunnelling. Compensation grouting was also used in several other locations along the project, but the Big Ben Clock Tower was probably the most spectacular application of the method. The method consists of injecting cement grout in the ground through pre-drilled horizontal boreholes constructed in a fan from a vertical shaft. The location of grout injection along each borehole is controlled by a number of a number of no-return valves (tube-a-manchette system) along the tube used for grouting and packers attached on the grouting stem. As the tube is cleaned after each grouting episode, repetitions of the grouting process are possible at various times. Grout injected into the ground effectively “lifts” the ground and any structures above it thus compensating for previously occurred settlements. As London Clay is also prone to consolidation settlements, i.e., long-term settlements caused by the gradual dissipation of the excess pore water pressures developed in the ground during tunnelling, the heave induced by compensation grouting should account not only for the immediate settlements but also for future anticipated consolidation settlements.

In compensation grouting, ground deformation monitoring was essential, as it was used not only to observe settlements induced by tunnelling but also to control compensation grouting activities, thus preventing damage to structures by excessive heave. Fig. 11 shows the results of monitoring the tilt of the Big Ben Clock Tower (in millimeters of horizontal movement at the top of the 55m high tower) during the period of tunnelling and subsequent consolidation of the London Clay illustrating the effect of compensation grouting in reducing these settlements. The tilt of the monument was monitored with an optical plumb suspended from the top of the Clock Tower, 55 metres above the ground. The movement of the base of the plumb was sensed on a digitizing tablet (placed just below the plumb) and the measurements were processed in real-time, thus permitting to rapidly adapt compensation grouting operations.

Fig. 11 shows that the tilt of the Tower was maintained within the 15-25mm range during tunnel construction by successive compensation grouting episodes. Following construction, the tilt increased with time (within the next three years) due to consolidation and reached about 36mm, corresponding to a tilt of 36 / 55000 = 0.065% = 1 / 1528, which is still very low.

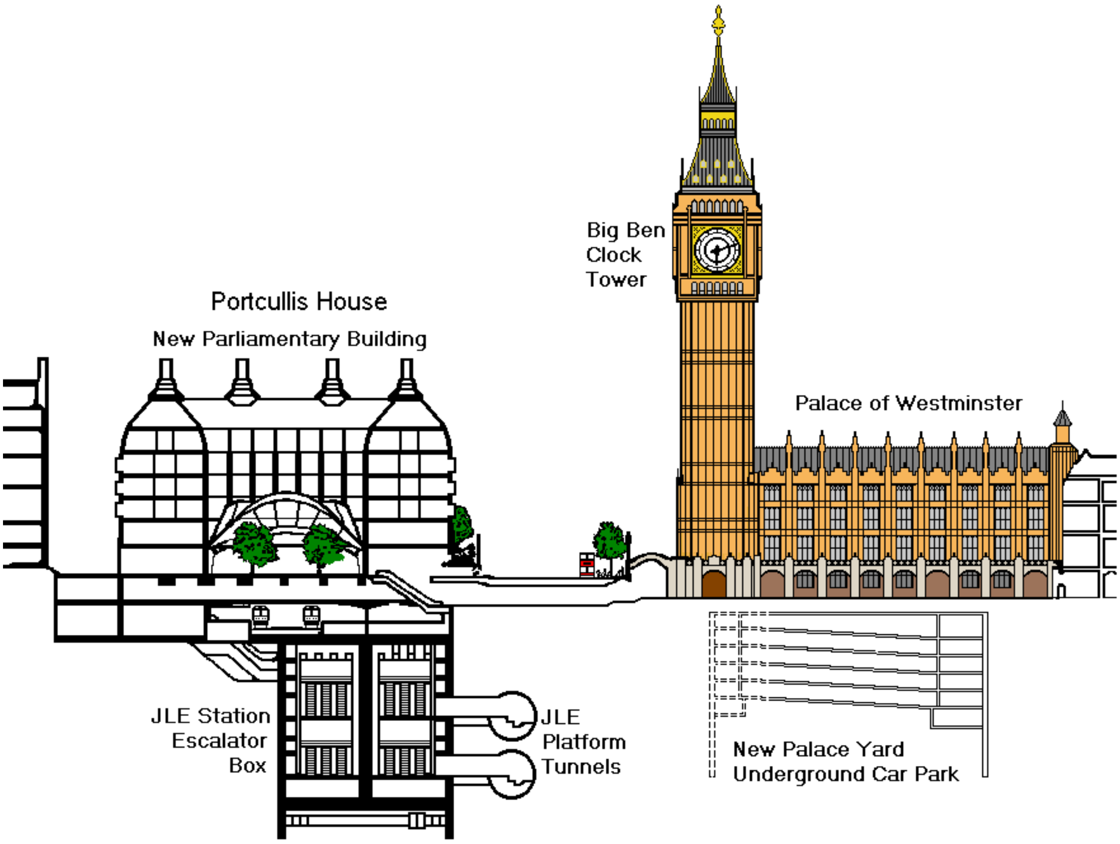


Fig. 10 : Cross section of the platform tunnels and the underground Westminster Station next to the Big Ben Clock Tower (after Burland et al, 2001).

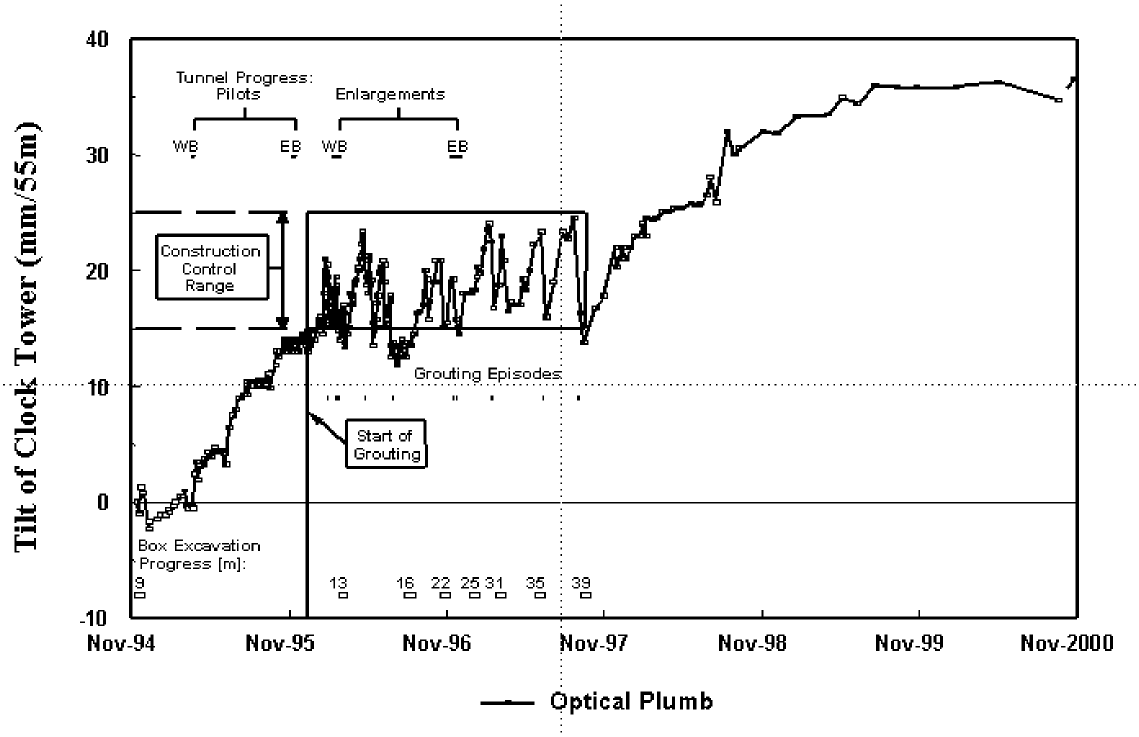


Fig. 11 : Monitoring of the tilt of the Big Ben Clock Tower (in millimeters of horizontal movement at the top of the 55m high tower) during the period of tunnelling and subsequent consolidation of the London Clay (after Burland et al, 2001*)*.

4.2 Lines 2 and 3 of the Athens Metro

Tunnelling for the Athens Metro was performed mostly in the Athens Schist formation, a thick sequence of flysch-type sediments consisting of calcareous sandstones, siltstones, phyllites, shales and (occasionally) limestones and marls. The 19km long and 9.5m in diameter double-track tunnels were mostly excavated by two open-face Tunnel Boring Machines (TBM), while underground stations were excavated either using conventional mining techniques (often called NATM) or as deep cuts from ground surface (cut and cover technique). Ground deformation monitoring was an integral part of the tunnel excavation process and was used for decision-making in undertaking ground pre-treatment prior to TBM tunnelling. Fig. 12 shows one method of ground pre-treatment (tube-a-manchette cement grouting) used in conjunction with TBM tunnelling (more details are given by Mihalis and Kavvadas, 1999).

Details of the ground deformation monitoring techniques are given by Kavvadas (1998) and Kavvadas (1999). Fig. 13 shows typical measurements of ground surface settlements along the 110m-long Omonia underground station cavern (16.5m wide and 13.5m high) located in the very center of the city. Ground surface settlements were measured by 3D-optical methods at monitoring points installed at street level (pavement, sidewalks and building columns). The relatively large settlements measured in the east side of the station (50-60mm) were attributed to the existence of ancient wells reaching the depth of the tunnel (about 15m at the crest).

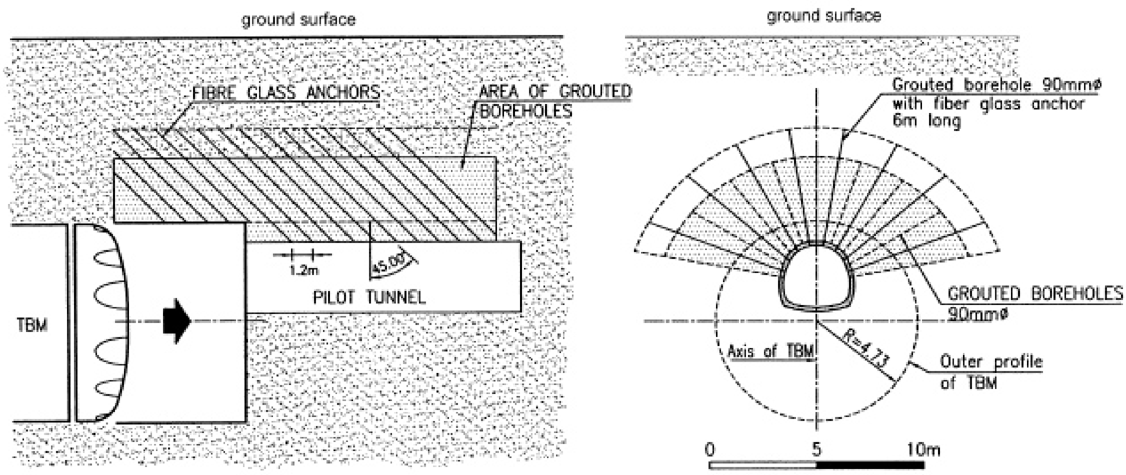


Fig. 12 : Ground pre-treatment with Tube-a-Manchette grouting from a pilot tunnel ahead of the tunnel face in the Athens Metro. Such ground improvement proved to be very effective in drastically reducing ground settlements and was used extensively in the Syntagma-Acropolis interstation where the tunnel passed below buildings of the Old City (Plaka) (after Kavvadas, 1999).

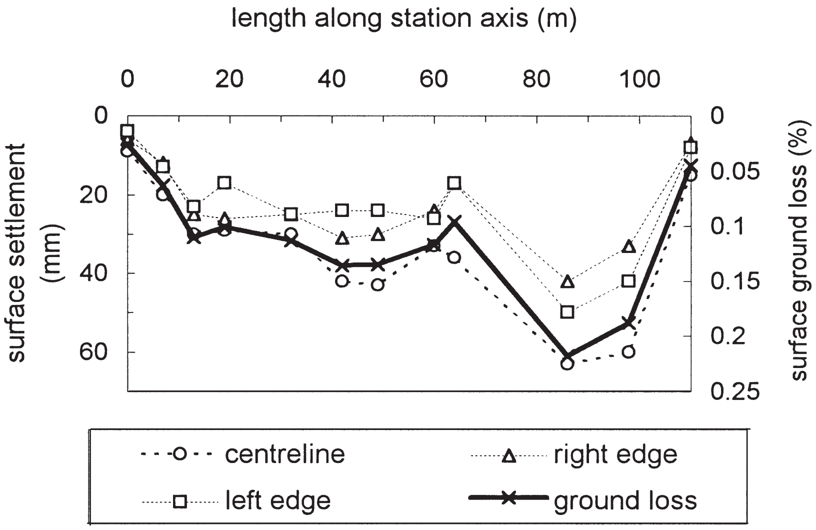


Fig. 13 : Measured ground surface settlements and ground loss factors along Omonia Station (after Kavvadas, 1998).

Fig. 14 plots the statistical data of ground surface settlements due to TBM tunnelling in the Athens Metro (52 measurements), indicating that ground surface settlements were usually below 20 mm (in 82% of the measurements). Actually, the real frequency of low settlements was even higher because the measurement database is biased towards high settlements (because ground surface monitoring was more intense in areas where large settlements were expected).

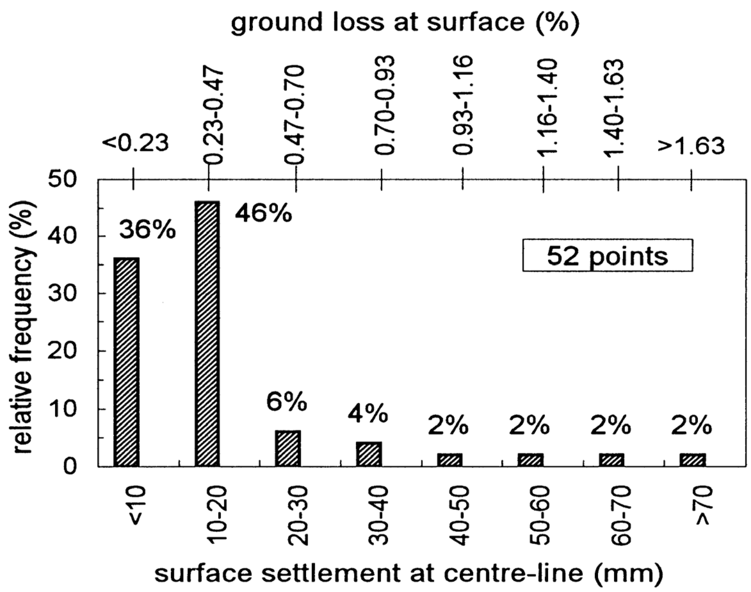


Fig. 14 : Statistical data of ground surface settlements due to TBM tunnelling in the Athens Metro Lines 2 & 3 (after Kavvadas, 1999).

5.3 Mountain tunnel in Greece under difficult ground conditions

The previous examples illustrated cases where ground deformations caused by tunnelling were of the order of millimetres. In mountain tunnels under large ground overburden, tunnel wall convergencies can be much larger and in cases of unfavourable ground conditions can exceed several tens of centimetres. This example describes the case of a long transportation tunnel in Greece crossing a mountain with a maximum overburden of about 600m. The tunnel consists of two tubes (about 8.5m wide and 9.5m high each) running in parallel at a distance of about 25m. The central part of the mountain consists of peridotites and limestones while the north and south slopes (each about 1800m along the tunnel) consist of stiff Pliocene clays and marls with an overburden up to 180m. Tunnel excavation is performed with conventional mining techniques in three stages (top-heading, bench and invert closure) while temporary support consists of sprayed concrete, passive rock-bolts and steel sets. Face pre-reinforcement using heavy forepoling and fibre-glass nailing is used when face is unstable either due to the high overburden or due to the existence of running ground (cohesionless soils, water ingress for the face, etc). Ground deformation control included 3D-optical measurements at five reflector benchmarks installed on the tunnel wall at each cross-section using standard surveying instruments (total stations). These measurements aimed to ensure that ground pressures on the temporary lining are adequately controlled, i.e., there exists an adequate margin of safety against collapse (roof collapse, bottom heave, failure of the excavation face, yielding of the support system, etc). In this way, ground deformation measurements contribute significantly to adjusting the temporary support system thus achieving a safe and economic structure.

Although ground deformations were usually adequately controlled, with measured tunnel wall closure in the range of 5-20 cm, occasionally ground deformations exceeded these values and, most importantly, did not stabilise even after constructing the closed tunnel invert. Such long-term ground displacements are indicative of creep in the surrounding rockmass, which cause a gradual increase of the loads on the temporary support and may eventually lead to structural collapse if the strength of the support elements is exceeded. One such case is illustrate in Fig. 15 which plots the vertical displacement (settlement) of the target locations at a specific section of the tunnel, which eventually collapsed. Tunnel excavation included the top-heading only. Temporary support was installed immediately after excavation and consisted of 6-9 metre long passive rock bolts, steel sets HEB-140 at 1.0m spacing and a 25cm thick fibre-reinforced shotcrete shell (including the invert).

Three targets were installed at the top heading of the control section shortly after excavation : one at the tunnel crest and one at each of the side-walls (right and left). All three targets measured very similar settlements indicating that the whole tunnel settled practically uniformly. The settlements within two months from excavation and construction of the temporary support (end of Jan. 2002) reached about 300 mm and appeared to stabilise. The abrupt increase in settlement observed in the beginning of February 2002 was due to failure of the shotcrete invert of the tunnel (invert of the top heading). The invert was demolished and repaired while an additional 150 mm of settlements accumulated. At the end of March 2002, the repaired invert failed again and settlements gradually increased despite the attempts to stabilise the section by reinforcing the shotcrete shell and by installing longer rockbolts. Eventually, at the end of May 2002, the tunnel collapsed along a section about 100 metres long, when the settlement had exceeded about 700 mm.

This example indicates that tunnel wall deformations can be used in assessing the condition of the rockmass around the tunnel and the evolution of the loads on the temporary support, although in some cases, conditions are so adverse that contingency measures do not succeed to avoid the eventual collapse. However, even in this extreme case, the rapid and accelerating increase of tunnel wall deformation prior to the eventual collapse of the tunnel (i.e., in the second half of May 2002) served to ensure safety of personnel and equipment.

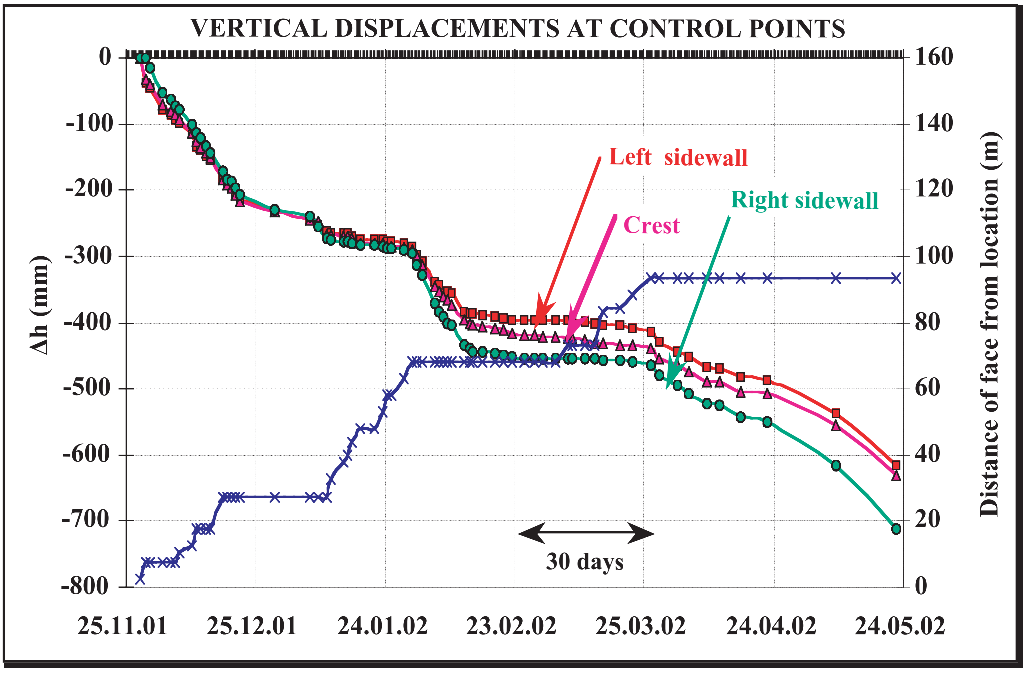


Fig. 15 : Monitoring of wall deformation (settlement) in a mountain tunnel. The abrupt increase of settlement after a period of apparent stabilisation indicates failure of the tunnel invert. After two consecutive such failures and repairs, the tunnel failed completely as shown by the abrupt increase of settlement at the end of May 2002.

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