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Deformation monitoring during construction of subway tunnels in soft ground

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ABSTRACT: Monitoring the deformations of subway tunnels in soft ground is a principal means for selecting the appropriate excavation and support methods in the design. In this paper, briefly describes the basic deformation monitoring requirements, analyzes the tunnel deformation monitoring accuracy difference between mountain area and urban area, discusses the measurements of deformations at ground surface, measurements of deformations on the ground and measurements in the tunnel, especially gives an example of vertical convergence monitoring, introduces the data processing method and the quality evaluating method based on the measured data. Mainly explores the technique of tunnels' crown settlement monitoring, convergence monitoring and the Automatic Deformation Monitoring methods. It is put forward that the monitoring job during the construction of subway tunnels can be done with both traditional and modern surveying instruments and the job will be significant to the same kinds of projects.

1 INSTRUCTIONS

Determining shape and position changes occurred in engineering is one of an application area of geodetic surveys. Temporary and permanent deformations occur in engineering structures such as dams, bridges, tunnels, viaducts and towers due to natural and artificial forces. Causes of these deformations are usually physical properties of ground, weight of structure, active external forces etc. (Clough 1960). The need to upgrade and further develop transportation infrastructure 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. It is imperative to provide accurate and frequent monitoring of tunnel linings to detect any movements that could pose a safety hazard.

Deformation monitoring in tunneling usually includes some of the following measurements (Dunnicliff 1993):

1. Convergence of the tunnel wall, and usually crest settlement and spring-line closure.
2. Deformations at ground surface including settlements and tilts of surface structures.
3. Deformations in the ground around the tunnel.

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) (Hisatake 1999).

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 tunneling 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.

In this paper, briefly describes the deformation monitoring requirements, and then discusses the deformation monitoring at ground surface, in the ground and in the tunnel separately, furthermore gives an example of traditional vertical convergence monitoring, at last mainly introduces the Automatic Deformation Monitoring method.

2 BASIC REQUIREMENTS

The basic requirements are: lay out monitoring benchmarks, monitoring targets timely, take measurements regularly, analyzes the survey data and feedback information to relative departments in time (Kavvadas 1999).

Measurement accuracy depends on the purposes of the deformation observation. In order to ensure monitoring accuracy, Operating personnel must be familiar to the purposes and equipment operating rules, survey team members should corporate and work carefully.

Each monitoring step should abide the "four fixed" principle (Liu 2006). The so-called "four fixed" principles namely: instruments and rods fixed, observing staff fixed, monitoring method fixed and monitoring environment fixed.

The first step in deformation monitoring is to carry out a basic survey, consisting of individual surveys inside a narrow time frame. All following surveys will be compared to the results of this survey. It is therefore important that this survey is carried out before the deformations to be observed can be expected to occur and it is also important that the basic survey is carried out with a high degree of reliability regarding results, as it is obviously impossible to follow up with check-surveys after deformations have taken place or can be expected to have taken place. It is recommended that the first elevation result should be figured out in the average of at least two times of monitoring (Liu 2007).

The equipment being used should be tested before the first time monitoring, after continuously use for 3–6 months the equipments should be tested again (Kaiser 1993).

Benchmarks and stations and Monitoring points inside the tunnels should be set in area where rocks are stable. Benchmarks and stations inside the tunnel are installed in special brackets, which forced centered (Kontogianni & Stiros 2002, 2003).

3 MONITORING ACCURACY DIFFERENCE BETWEEN MOUNTAIN AREA AND URBAN AREA

3.1 *Objectives difference*

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. (Mihalis & Kavvadas 1999).

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 behavior 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.

3.2 *Monitoring accuracy difference*

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.

1. 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 rock mass 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 convergences 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.

2. 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 convergences 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 are much smaller than those in deep mountain tunnels. Due to the small ground deformations induced by tunneling (usually less than 10 mm at ground surface and occasionally less than 5 mm), measurement precision and the early installation of the measuring devices is of utmost importance.

4 DEFORMATION MONITORING AT GROUND SURFACE

Measurements of deformations at ground surface are crucial in urban tunneling 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 Level, total stations and GNSS), or with geotechnical instruments like Electronic Liquid Level Gauges, Electrolytic Tilt Sensors (electro-levels) surface clinometers/tilt meters, precise taping, and crack-meters.

Precise leveling and façade monitoring are the most common methods for monitoring displacements at ground surface. The accuracy of these measurements is typically 0.2 mm (over about 100 m lengths) for precise leveling and $1''$ for angles and ($1\,\text{mm} + 2\,\text{mm}\ 10^{-6}\text{D}$) 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 (Moaveni 2003):

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 0.3 mm.
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 meters 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$1''$.
3. Surface clinometers (tilt meters), precise taping using invar tape between fixed anchor points and various types of crack-meters are also used in measuring deformations at ground surface.

5 DEFORMATION MONITORING 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.) (Sakurai 1981).

Such measurements are performed with geotechnical instruments including single- or multi-point borehole rod extensometers, magnetic extensometers, sliding micrometers, inclinometers, probe deflect meters (often called sliding curve meters) 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 (radically from the tunnel wall or along the tunnel axis ahead of the excavation face).

6 DEFORMATION MONITORING IN THE TUNNEL

Tunnel wall convergence (closure) between references points (hooks) bolted on the tunnel walls is usually measured with standard metal tape extensometers. For distances up to about 10–15 meters, 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 tunneling 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 15–20 m) 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 stations1 (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 100 m) is about 2–3 mm for lengths and ±2″ 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 of measuring the geometry of tunnel walls in cross section (and thus assess the deformation in the interval between two measurement epochs) is the Tunnel Profile Scanners (profile meters). In addition to measuring tunnel wall convergences in time, profile meters 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 profile meters are fully digitized photogrammetric measuring devices.

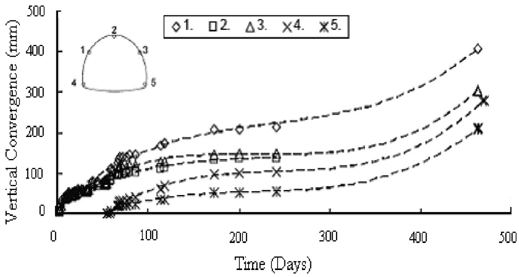

Figure 1. An example of settlement monitoring result (Villy Kontogianni et al. 1999).

A typical such system 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 meters.

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.

6.1 *Traditional geodetic measurements*

Three dimensional coordinates of object points (deformation points) which will be constructed on ceiling, sole, and side walls of cross- section determined at different intervals on tunnels were measured by electronic instruments. The coordinates of object points which were constructed on ceiling, sole, and side walls were measured at determined period intervals. By using coordinates measured at different periods, forming movements were determined. (Figure 1 is an example of settlement monitoring result).

6.2 *Automatic deformation monitoring*

6.2.1 *Automatic deformation monitoring requirement*

High-quality precision optical monitoring targets mounted on support of excavation and tunnel linings, with fully automated motorized total stations under computer control to monitor remotely the three components of movement. Also required was a measurement precision of 1 mm for sight distances up to 100 m, with wireless data links to the control site. The robotic total stations would have to be totally automatic and operate unattended 24/7 under all weather conditions, and also be insensitive to refraction effects caused by temperature or pressure variations. Each target would have to be "hit" at least every 30 minutes.

Multiply TCA2003s, located where they could monitor hundreds of target prisms to be affixed at predefined intervals to the structures to be monitored. The measurement data would be transmitted at specified intervals via radio data links to a central location, situated miles from the actual instrument monitoring stations. The total network would be tied together and controlled by GeoMoS (Geodetic Monitoring Software) system.

6.2.2 *Installation challenges*

There were two TCA2003 total station sites on each side, for a total of four. The total stations were permanently mounted on fixed location with vented heavy-duty glass enclosures to protect the system from the elements. Each installation included an intercom radio and modem with directional antenna to transmit data from the site to the controller. Band pass filters were added to overcome the high levels of RF activity in the airport environment. The pedestals were isolated to eliminate vibration and movement.

The GeoMoS software was installed on the computer network, and was configured so that data can be accessed via a secure IP link by authorized personnel and the resident engineer. Protecting the remote sites from wind and weather presented special challenges. The glass enclosures had to be robust and rugged, capable of withstanding heavy winds, rain, snow and ice, and they had to be non-reflective so as not to distort the EDM signal. Necessity being the mother of invention, they experimented with a number of different types of enclosures including clear round dog igloos until they found the right solution.

6.2.3 *Monitoring software*

The GeoMoS software is a powerful tool for controlling the network of the remote sites, as well as collecting data, providing alarms, post-processing, reporting and visualizing data. The software represents the data and results in graphical or numerical format. You can select a time-line graph showing the trends of movement over selected time periods (Burland 2001). Multiple points can be viewed simultaneously in the same graph. Alternatively, you can select a vector view that shows displacement for a selected area, to easily see where the greatest movement has occurred.

Senior-level project engineers and other authorized personnel can access the GeoMoS data through a real-time web-based portal from any PC or laptop. They can log onto the secure GeoMoS site and download system status and reports. Measurement tolerances are established and loaded into the GeoMoS system, If any of these tolerances are exceeded, an automatic alarm is activated (Figure 2 is an example of tabular report).

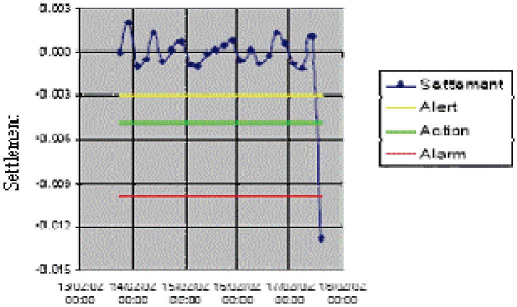

Figure 2. An example of tabular report of Automatic Deformation Monitoring for Hong Kong KSL Railway (Tang et al. 2007).

7 CONCLUSION

In order to determine deformations of the subway tunnel in soft ground, deformation monitoring must be taken on the ground surface, in the ground and in the tunnel. Practice shows that the traditional deformation measurement can be achieved with 0.5–1 mm displacement accuracy, but deformation measurements can also be recorded, processed and evaluated in real-time by digital recording and telecommunication systems. Real-time processing of ground deformations offers the possibility of rapid response to upcoming situations but requires advanced technology and an appreciably higher cost. So real-time monitoring is limited to cases where rapid response is absolutely necessary, i.e., mainly in urban tunnels near sensitive structures.

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