MONITORING USED AS AN ALARM SYSTEM IN TUNNELING

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ABSTRACT

This paper presents the ground settlement monitoring system used during the construction of two tunnels bored by two EPB TBMs, beneath the existing and active railway embankment in Bologna (Italy). The tunnels run close to large buildings and beneath bridges and other infrastructure.

Data are collected from remote total stations and from electrolevels installed directly on the railway tracks. The automated monitoring system acquires and analyses data then sounds an alarm in the event that there is a problem. Alarms are sent out in case of excessive tilt or settlement.

Data is provided through a dedicated web application for multiple-party access, to gather, manage and store monitoring data.

INTRODUCTION

In 2000, the joint venture of S.Ruffillo (Necso/Acciona Infraestructuras—Salini—Ghella) awarded the construction of one of the most critical sections of the new High Speed railway line between Naples and Milan. This section of the railway is to pass under the city of Bologna, starting from the S.Ruffillo quarter south of the city, to the new Central Rail Station of Bologna, located in the city's center (see Figure 1).

Golder Associates—Italy (Golder) was chosen to design and manage the monitoring system of lot n.5 which consists of:

1. Two Earth Pressure Balance (EPB) tunnels ("Pari" and "Dispari" tunnels), single track, 9.4 m diameter, 6 km length, 15 m interaxis; and
2. A NATM tunnel (115 m length) double track, 14 m wide, connecting the two tunnels to the Central Station.

The excavation was conducted mainly in heterogeneous alluvial and marine strata (see Figure 2) composed of sea clay and loose sandy deposits (Pliocene Clay and Yellow Pleistocene Sands) and of Savena river deposits, mainly gravel and sand strata with a high percentage of fines (lenses of clay and silt).

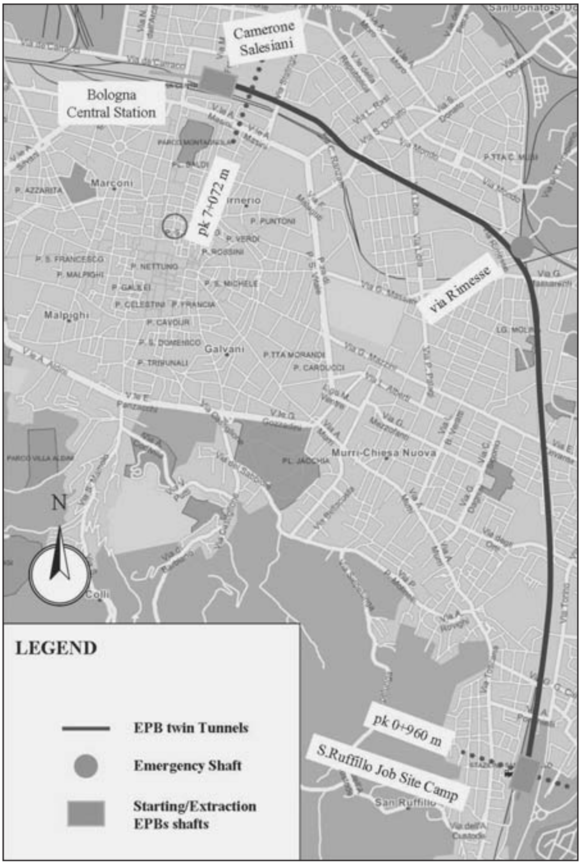


Figure 1. Urban track of the tunnels

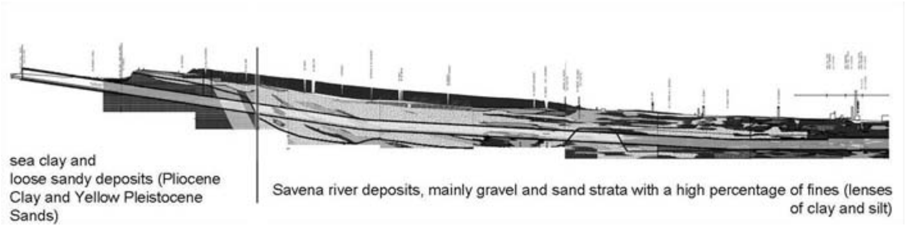


Figure 2. Geological section along rail track

The heterogeneity of the subsurface was a critical aspect of monitoring excavation activities in regards to potentially rapid change in surface settlement and the TBMs' behavior.

The excavation of the two EPB tunnels started in July 2003. The original monitoring plan was only designed to evaluate geotechnical sections for soil behavior with the tunnel progress.

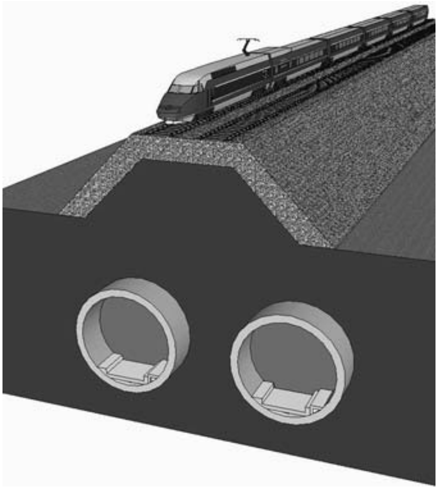


Figure 3. Cross section of the tunnels under railway embankment

Typical geotechnical sections were composed by in-place inclinometers, multi extensometers, and piezometers. All data readings were collected by dedicated data-loggers, interrogated with a server through a GSM system and were then available through a dedicated, protected web site named GIDIE (Golder Instrumentation Data Interpretation and Evaluation). The tunnel lining was also equipped with strain gauges to evaluate stress-strain behavior.

As the tunneling progressed under buildings, bridges and the existing Bologna-Firenze railway (the most important section or railway in Italy, connecting Rome with Milan, Figure 3) it became evident that the project needed a more complex monitoring system.

Golder proceeded with re-designing the original monitoring system in order to accomplish the main goals of monitoring both underground movement as well as the surface settlement. The final system was composed of the following:

- geotechnical monitoring;
- automatic topographic survey monitoring by means of total stations;
- TBM parameter monitoring; and
- monitoring of rail track geometry by means of electrolevels.

All the monitored data were collected through a dedicated Web server which allows users (Owner, Contractor, Costruction Manager, Designer) to access the monitoring data, query the database and display results by means of a dedicated WebGIS application.

On June 31st, 2006 the two EPB tunnels were completed (see Figure 4) and, at present, the NATM tunnel is in progress.

This paper focuses on the details of the monitoring system and its usage as an alarm system, therefore focusing on electrolevels and total stations.

Figure 4. EPB's breakthrough

Figure 5. Longitudinal electrolevel

INSTRUMENTATION

Electrolevels

As the EPB tunnels were driven under the active railway, there was a risk of causing a derailment on one of the busiest Italian railways. To reduce this risk, it was decided to monitor the tracks inclination.

Railway displacements were monitored with a series of Electrolitic Tilt Sensors (240). These sensors were installed onto the rail track in two different orientations:

- on the long axis of the rail track (Longitudinal Tilt, Figure 5); and
- on the long axis of the ties (Transversal Tilt, Figure 6).

The Longitudinal Tilt measured the variation of inclination of the rail track while Transversal Tilt measured the twist of the rail track, which was defined as the difference of transversal inclination on a 3 meter section of rail. Tilt sensors were installed and removed following the tunnels' progress underground.

Data from Electrolitic Tilt Sensors were acquired on a time interval of every 5 minutes and data were collected through short range modem connection, processed and uploaded to the Web Server for real time data interpretation.

Figure 6. Transversal electrolevel

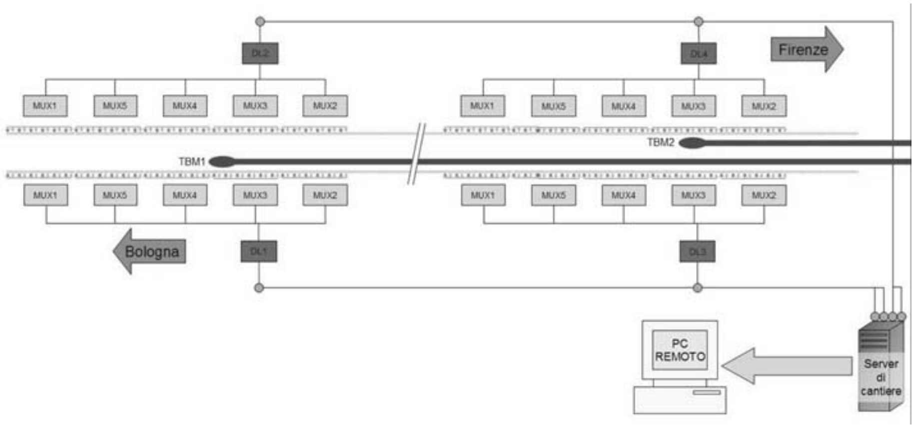


Figure 7. Modules' scheme

To follow the progress of the tunnels, tilt sensors were grouped in modules of 12 (6 longitudinal and 6 transversal), and were all connected to a dedicated multiplexer (see Figure 7). With a module it was possible to cover 54 m of rail track. It was necessary to use 20 modules to guarantee the necessary coverage (2 tracks with two EPB) with a maximum excavation speed of 30 m/day.

Total Stations

For the excavation of the two EPB tunnels, Golder designed a monitoring system for surface movements. The system was designed with total stations (TS—automatic theodolites) and topographical prisms installed on the railway embankment, on the buildings and existing structures (bridges and underpasses) that could potentially be affected.

Leica servo-controlled total stations, TPS System 1100—TCA 1101 Model with ATR 2 self-collimation devices were chosen for the monitoring.

The TSs were installed on dedicated tripods, adequately stiffened, powered by solar panels and connected to a GSM modem for data transfer (see Figure 8).

Figure 8. Typical TS installation

For every data cycle, at each monitoring point, the TS measured:

- slope distance;
- azimuth angle; and
- vertical angle.

After every cycle, the TS created an ASCII file with raw data for all the points' position.

The TSs were installed at the top of embankments so that they could "see" a large number of prisms. Because of this, the TSs were inside a potential subsidence basin and they had to be considered as mobile TSs. Therefore, before the calculated position of each monitoring point, it was necessary to identify any station movement.

Golder developed dedicated software, named GETS (Golder Elaboration of Total Stations), in order to process the measurement of topographical data. The software uses a statistical method for verifying the stability of the points measured by the TS. The most stable points are then used as reference points.

GETS chooses, among all the measured points, the ones showing the most homogeneous 3D displacement-vector (i.e., the 3D vector with the smaller variance). Such displacement vector is then applied to the TS position providing, for each cycle of reading by means of least square method, the actual displacement of the TS in a 3D space.

In spring of 2006, as the tunneling work proceeded, Golder was requested to design the monitoring and alarm system for two buildings during the completion of the NATM tunnel. It was easy to see that TS would be a good instrument to use for this task.

The Project

The NATM tunnel is being constructed under two buildings (see Figure 9) where the Italian railway service (FS) has their own offices. Golder is monitoring these building with 4 TSs and 79 prisms.

For each building, all prisms are monitored with a cycle of readings every hour and all the data are automatically downloaded and collected to a server that processes them. In addiction to the monitoring system designed for the EPB tunnels, Golder has

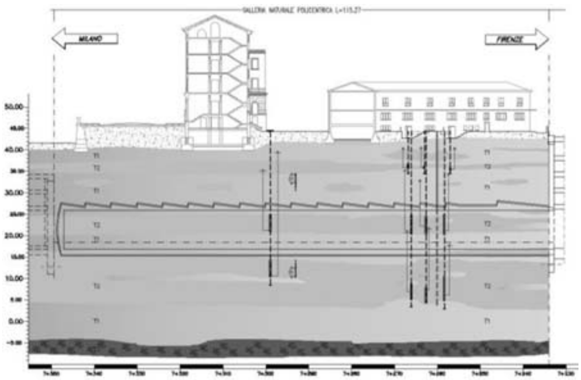


Figure 9. NATM tunnel under buildings

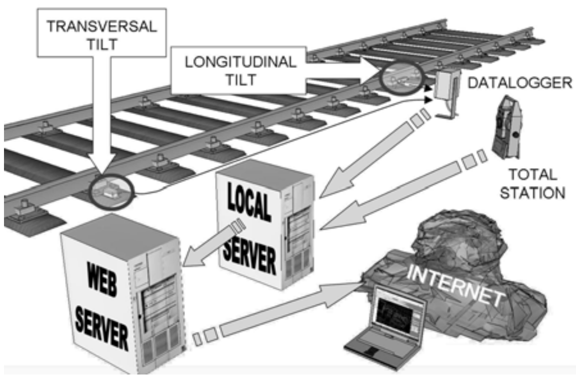


Figure 10. Hardware configuration of monitoring system

developed an automatic alarm system that processes all data to evaluate two parameters (Beta and Inflection rate) to signal potential danger to the structures.

DATA MANAGEMENT

Data Loggers and Total Stations store the collected measurements in their internal memory.

A dedicated server can communicate with instruments via a LAN connection. If a LAN connection is not possible due to distance or access issues, a GSM is provided instead.

The server periodically downloads the new data from the instruments (see Figure 10). By the mean of a LAN it is possible to get data every few minutes. With a GSM connection, a lower frequency of downloading is allowed.

Software developed expressly for this system, checks that all the instrumentation is reachable and that every sensor is responding correctly. In the event that the server should encounter communication problems with an instrument or sensor, the software

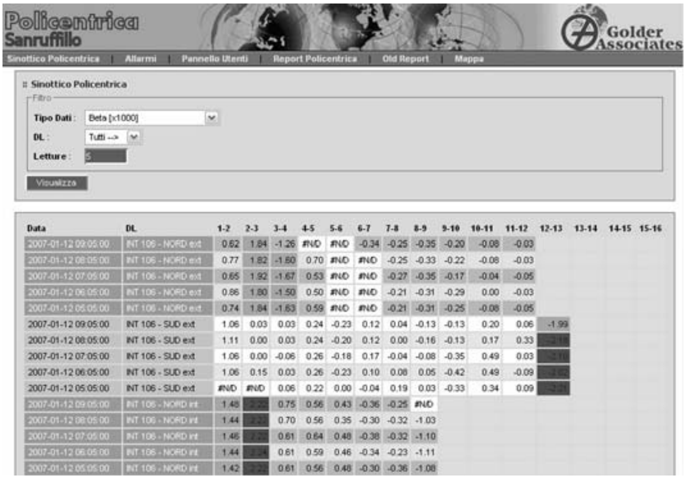


Figure 11. Data panel

will notify an analyst, by means of continuously placing phone calls to dedicated mobile phone until alarm is managed.

The software then calculates engineering data (mm, degrees, degrees/meter or else) from the electrical measurements it receives. When a sufficient amount of data is collected (i.e., no less than 5 data points) a statistical computations determines if the measurement is at a peak.

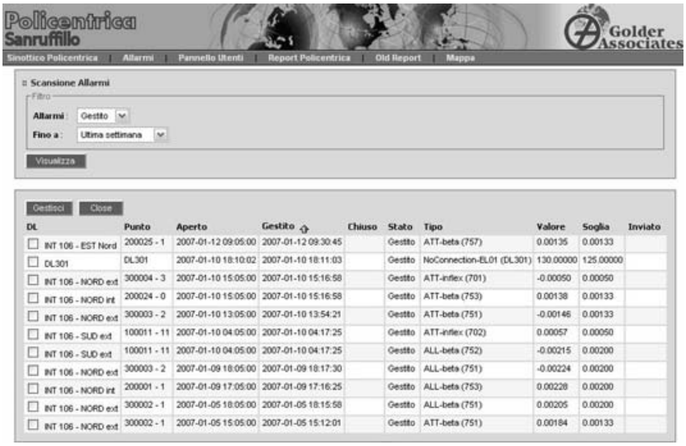
In the case of one peak measure, the event is logged but it doesn't raise any flag. In the event of many peak events on the same sensors a flag is recorded.

In the event that calculated measurements, such as track twist, gradient variation, beta or inflection ratio or other calculated parameters, are greater than prefixed thresholds, a new flag is arisen. Many thresholds are possible. For example: pre-attention (warning, something may go wrong), attention (some action must be taken), pre-alarm (warning to analyst), and alarm. Then the software analyzes the flags and it takes up the necessary actions to be submitted to the analyst. When the system creates a new alarm the server calls the analyst by mobile and repeated SMS are sent until alarm is taken into account by the analyst.

The analysts can log onto an Internet control centre (see Figures 11 and 12) from which they can examine all the raw data, calculated measurements, alarms and logs; in data table or graph form.

When a new alarm is created the analyst can check which measuring point created it, he can view the history of the measurements, and change the status of the alarm to "managed" (no new alarms will be created for the same threshold for that point, higher thresholds alarms are possible) or to "closed." If the analyst thinks that something significant has occurred, they would call the construction management to verify the data with manual instruments and take necessary safety measures (issue a warning to rail authority, etc.).

The control centre allows the user to schedule analysts' shifts. The server will call the analyst on duty, if the analyst on duty does not manage the alarm within a given amount of time, the server will then call a backup operator. In the event that this analyst doest not manage the alarm within a given amount of time, it will finally call all the operators in its list.



DL	Punto	Aperto	Gestito	Chiuso	Stato	Tipo	Valore	Soglia	Inviato
INT 106 - EST Nord	200025 - 1	2007-01-12 09:05:00	2007-01-12 09:30:45		Gestito	ATT-beta (757)	0.00135	0.00133	
DL301	DL301	2007-01-10 18:10:02	2007-01-10 18:11:03		Gestito	NoConnection-EL01 (DL301)	130.00000	125.00000	
INT 106 - NORD ext	300004 - 3	2007-01-10 15:05:00	2007-01-10 15:16:58		Gestito	ATT-inflex (701)	-0.00050	0.00050	
INT 106 - NORD int	200024 - 0	2007-01-10 15:05:00	2007-01-10 15:16:58		Gestito	ATT-beta (753)	0.00138	0.00133	
INT 106 - NORD ext	300003 - 2	2007-01-10 13:05:00	2007-01-10 13:54:21		Gestito	ATT-beta (751)	-0.00146	0.00133	
INT 106 - SUD ext	100011 - 11	2007-01-10 04:05:00	2007-01-10 04:17:25		Gestito	ATT-inflex (702)	0.00057	0.00050	
INT 106 - SUD ext	100011 - 11	2007-01-10 04:05:00	2007-01-10 04:17:25		Gestito	ALL-beta (752)	-0.00215	0.00200	
INT 106 - NORD ext	300003 - 2	2007-01-09 18:05:00	2007-01-09 18:17:30		Gestito	ALL-beta (751)	-0.00224	0.00200	
INT 106 - NORD int	200001 - 1	2007-01-09 17:05:00	2007-01-09 17:16:25		Gestito	ALL-beta (753)	0.00228	0.00200	
INT 106 - NORD ext	300002 - 1	2007-01-05 18:05:00	2007-01-05 18:15:58		Gestito	ALL-beta (751)	0.00205	0.00200	
INT 106 - NORD ext	300002 - 1	2007-01-05 15:05:00	2007-01-05 15:12:01		Gestito	ATT-beta (751)	0.00184	0.00133	

Figure 12. Alarm panel

The server has a AMD Sempron™ Processor 3100+ with 1 GigaByte of RAM and two 160GB hard drives in raid1 configuration. It is equipped with Linux Operative System, Apache WebServer, MySQL Database server and all the software was developed using php and C++ languages.

ALARM SYSTEM

The alarm system is conceptually the same for both the rail tracks and for the buildings. It automatically retrieves data, processes the data by calculating the control parameters, and calls an analyst if an exceedance of a threshold limit occurs to decide if the exceedance warrents alarm procedures.

For rail tracks there are two parameters that can activate alarms: twist and gradient.

In building monitoring system both beta (angular rotation) and inflection ratio are compared with threshold limits and can create an alert.

Rail Tracks

The monitoring system allows a great number of readings and geometric parameters of the tracks that can be monitored continuously with measurements taken every 5 minutes.

In the event of a threshold limit exceedance (defined by railway regulations) the system activates the automatic alarm procedure and calls the analyst.

Geometric parameters analyzed by alarm system are:

- twist (on 9 m); and
- gradient.

Twist is calculated by dividing the difference between the transversal levels of two contiguous transversal electrolevels by their relative distance (measurement base of the twist) across two rails.

Transversal level is the measurement (in mm) of the difference in height between two contiguous rolling tables. It is the height of a right-angle triangle with 1,500 mm hypotenuse with a summit angle calculated as the angle between the rolling plane and an horizontal reference plane.

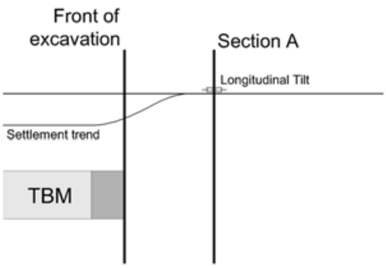


Figure 13. Longitudinal section undisturbed

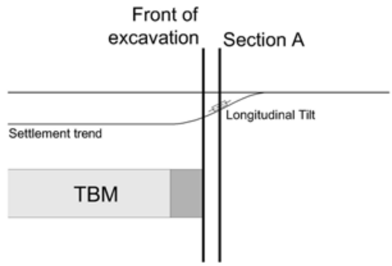


Figure 14. Longitudinal section next to excavation front

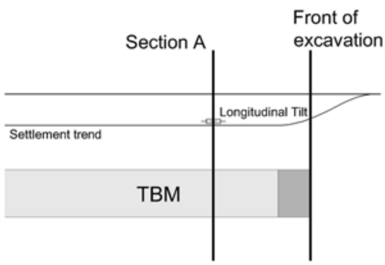


Figure 15. Longitudinal section, case "A"

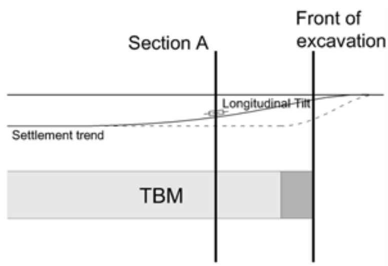


Figure 16. Longitudinal section, case "B"

Twist (expressed as ‰), is calculated on a 9 m base with the following formula:

$$\gamma_9 = \frac{(l_9 - l_0) \cdot b}{d}$$

where

l_0 = is the slope measured by the first transversal electrolevel (as mm/m)
l_9 = is the slope measured by the following transversal electrolevel (as mm/m)
b = is the rail interaxis (1,500 mm)
d = is the distance between two consecutive transversal electrolevels (9 m).

Therefore, by measuring transversal slope it is possible to calculate twist.

The Gradient is defined as the variation in time of the difference between two consecutive longitudinal slopes (i.e., the first derivative of the curve of the longitudinal slope measurement).

It was considered that these three parameters are the most important for the railway safety. Twist is considered the most dangerous geometric fault and can cause derailments. Longitudinal slope and gradient allow identification of rotation occurring on a surface passing through the tracks and the speed of the phenomenon.

Initially only a longitudinal section of the tunnel is considered. Figures 13–17 shows settlements trend versus advancement of the face of excavation. Before the arrival of the front, the longitudinal electrolevel, set in section A, is not affected by rotation (see Figure 13) As an excavation front advances, the electrolevel measures the inducted rotation (positive according to right hand law, Figure 14). When the front gets over section A there are three possibilities:

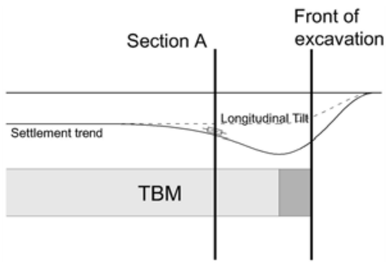


Figure 17. Longitudinal section, case "C"

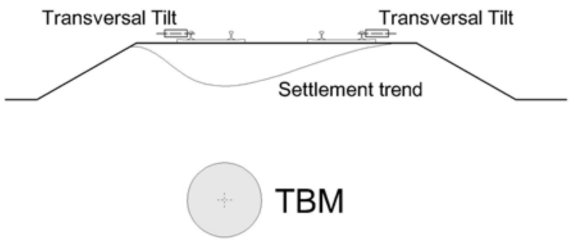


Figure 18. Transversal section

1. if settlements measured ahead are similar to those in section A (Figure 15) electrolevel returns to the initial condition with null rotation
2. if settlements measured ahead are smaller than those in section A (Figure 16) electrolevel still measures a positive rotation
3. if settlements measured ahead are larger than those in section A (Figure 17) electrolevel measures a negative rotation.

When the excavation front passes through a transversal section, the electrolevel measures a rotation (in fact the excavation is external to rail tracks axis, see Figure 18). This rotation changes depending on drilling advance. Considering a portion of 9 m of tracks with two transversal (one at the beginning and one at the end) and one longitudinal electrolevels (at the centre of the portion, 4.5 m) it is possible to identify the rotation of the rolling plane given by the tracks. With a sequence of electrolevels it is possible to identify every movement of the tracks.

Beta and Inflection Ratio

Every hour, the topographic monitoring system verifies the attitude of the buildings related to all onsite operations (not just the tunnel boring itself but also the grouting process) connected to the construction of the tunnel. With a relevant number of prisms and the adopted configuration, onemeasure in an hour because the TS reading cycle takes 20–45 minutes depending on prism visibility.

In case of a threshold exceedance, the system activates the automatic alarm procedure and calls the analyst.

Topographic measuring targets are fixed on horizontal alignments along building facades. On GIDIE it is possible to see the movement (horizontal and vertical) of these targets in function of time.

Sagging measures allows the calculation of two parameters:

- Beta (angular rotation); and
- Inflection Ratio

Beta is calculated for every two contiguous targets and is given by dividing the difference of sagging between the two points by their relative distance.

Inflection ratio is expressed by the ratio between the distance of the rigid configuration of the building from its deformed configuration and the length of the building (or of its portion) affected by movements

Referring to Figure 19 it is possible to calculate the inflection ratio at every point (except the outermost points) with following method:

$$\text{Inflection ratio point B} = \max\left\{\frac{\Delta_{B-AD}}{L_{AD}};\frac{\Delta_{B-AC}}{L_{AC}}\right\}$$

$$\text{Inflection ratio point C} = \max\left\{\frac{\Delta_{C-AD}}{L_{AD}};\frac{\Delta_{C-BD}}{L_{BD}}\right\}$$

The software that elaborates all TSs readings provides all possible combinations of calculations along each wall of the building. For example having twelve targets means that 220 inflection ratios must be calculated. The alarm system uses these two parameters to determine possible damage to the structures.

ALARM PROCEDURES

Railway Tracks

In the case of a threshold exceedance, the alarm system automatically advises an analyst (or a group of specialists) that is constantly available. The analyst has different instruments to verify the cause of the alarm:

- time series of electrolevels data and parameters (see Figure 20);
- measurement of all the electrolevels in the alarm area;
- movement of the near topographic targets (data on GIDIE, Figure 21); and
- EPB parameters.

In 30 minutes, if the alarm is confirmed, the analyst has to inform the construction supervisor and the administrator of the railway. They will quickly meet to decide if it is necessary to stop the excavation and to further evaluate the risk to trains.

The redundancy of the system allows that the analyst can even evaluate if abort the alarm procedure in case other data confirm absence of risk and/or greater reliability.

The system controlling the railway tracks has been active for more than 6 months and in that time two alarms have been sent out. In both cases, the alarms were validated; however the presence of track ballast under the tracks caused the parameters to come back within threshold limits, in a few hours.

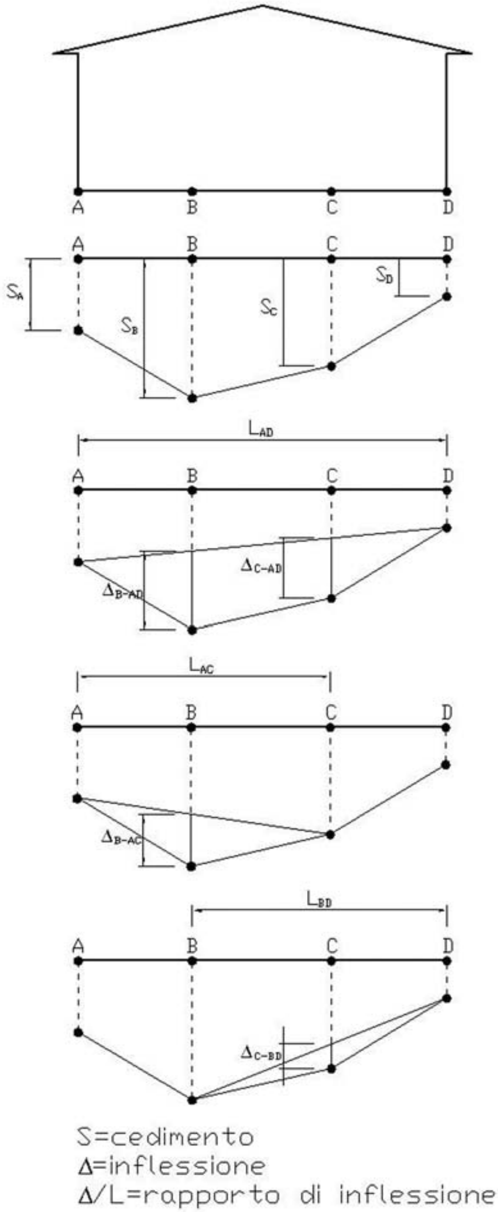


Figure 19. Inflection ratio

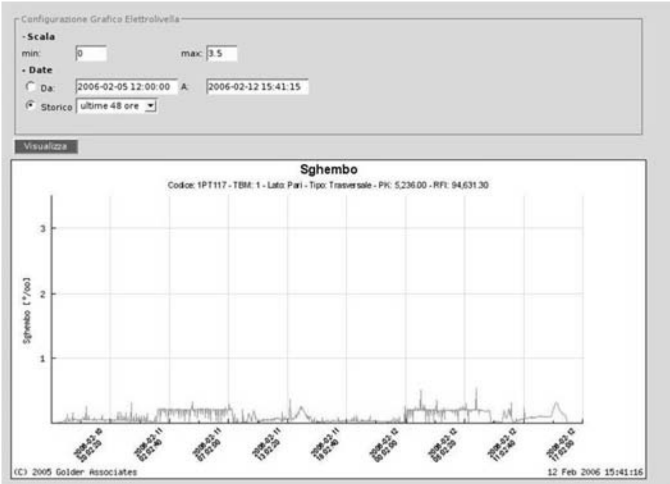


Figure 20. Twist versus time

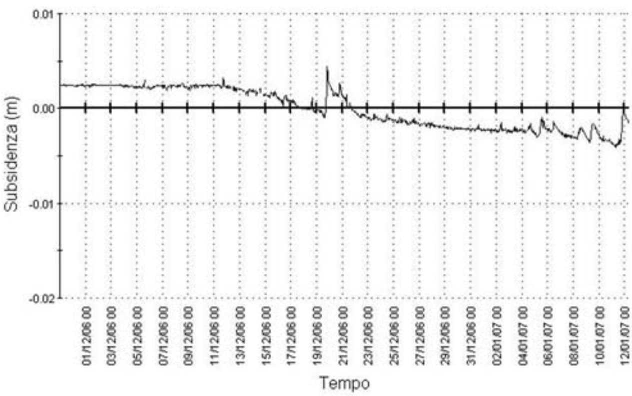


Figure 21. Graphic on GIDIE

Buildings

The TSs take nearly an hour to complete their reading cycle (measurement, data download, measurement calculation and publication on web), so the analyst has less data to evaluate alarms with. Because of this it is also very difficult to evaluate weather peaks are temporary or not.

For that reason it is important that analyst is kept informed of all the activities performed in the area and the behavior of every target. Inside the buildings, 68 structural electrolevels have been also installed allowing the analyst to have further data to evaluate alarms.

Since inflection ratio is a parameter whose theory is well known, but its evaluation is less intuitive than beta or differential settlement, more responsibility was charged to the analyst in determining the validity of alarms. In four months, the system automatically gave more than 100 alarms but the analyst only validated 11 of them (see, in

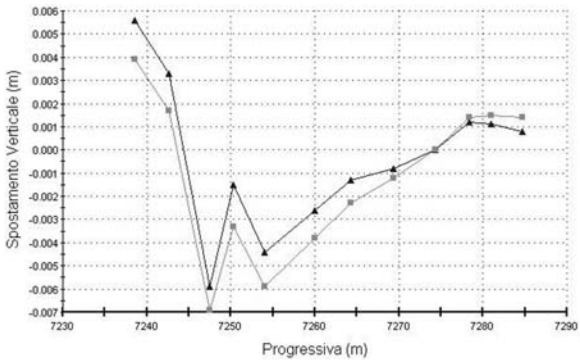


Figure 22. GIDIE, longitudinal section

Figure 22, a longitudinal section for an alarmed area) providing a valuable assistance to the site operation during grouting underneath the building.

After every alarm, the work supervisor was informed of the alarm and work was stopped three times to take precautions before proceeding.

CONCLUSIONS

Golder Associates designed, developed and deployed a monitoring system to prevent major infrastructure from damage from the construction of twin tunnels passing beneath the Bologna metropolitan area. The system allows for real time data interpretation of all data coming from total stations, geotechnical sensors, and electrolevels via the web, and provides an automated, real time alarm system.

The power of such a system allows the contractor as well as construction management to monitor, and therefore control, the effects that the excavation of the two tunnels has on the surrounding environment. The monitoring analyst becomes an important figure in the tunneling work, being responsible for validating and investigating alarms in real time and providing a safer and more efficient work procedure.

ACKNOWLEDGMENTS

The authors wish to thank Valentina Marchionni, Massimo Secondulfo and Fernando Minguez (S.Ruffillo s.c.a.r.l.) for their assistance in the setup of the whole system.