PROGRESSING MONITORING OF TUNNELING UNDER RAILWAY EMBANKMENT

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ABSTRACT: Construction of the Bologna section of the Naples-Milan high-speed railway comprises the construction of two tunnels. The tunnels, 9.4 m diameter, are driven by two Earth Pressure Balance Tunnel Boring Machines (EPBM) below the existing and active railway embankment. Soil cover ranges between 10 and 21 m. The tunnels pass close to major buildings and beneath bridges and other structures. Tunnel construction requires a comprehensive monitoring system to analyze ground conditions, underground movements and stress-strain change in pre–cast lining segments; as well as surface displacements. Golder Associates has designed the monitoring system, implementing GIDIE (Golder Instrumentation Data Interpretation and Evaluation system) to permit multiple–party access, to collect, to visualize and store monitoring data. Monitoring system is composed of geotechnical instrument sections, robotic total stations, topographic survey sections, structural instruments and TBM parameters acquisition. Due to the strict site conditions, total stations are installed in the potential subsidence basin and are relocated with relation to the progress of the TBMs. This constraint implies a need for proper data processing to detect subsidence anchoring the topographic system to external reference points. All of the data collected is transmitted to a dedicated web-server, managed by GIDIE application. GIDIE permits the visualization of all units, profiles, tunnel advance diagrams and alarms; as well as the querying of each sensor on a GIS based map, including the monographic details of each monitoring point. Real-time monitoring, using GIDIE, allows the contractor, the construction management and the designer to verify tunneling progress; and permits the emplacement of corrective actions as a function of soil condition changes and TBM parameters adjustments.

RÉSUMÉ: La Construction de la section auprès de Bologne de la ligne Grande Vitesse Naples-Milan, prévoie la perforation de deux tunnels. Les tunnels, de 9,4 mètres de diamètre, sont réalisés avec deux Earth Pressure Balance Tunnel Boring Machines (EPBM) au-dessous du remblai du chemin de fer existent et actif. Le sol qui les recouvre a une épaisseur compri entre 10 et 21 mètres et ils passent tout près des importants bâtiments et au-dessous de ponts et d'autres structures. La construction de ces tunnels exige un système de surveillance complet pour analyser les conditions du terrain, les mouvements souterrains et les variations des états d'effort dans la bâche du tunnel, ainsi que les déplacements de la surface. Golder Associates è conçu le système de surveillance à travers la réalisation de GIDIE (Golder Instrumentation Data Interpretation and Evaluation system) qui permet un accès Multi-Utilisateur au fin de ressembler, visionner et mémoriser les données. Ce système de surveillance se partage entre surveillance des sections géotechniques et des sections topographiques et ses stations de surveillance de l'affaissement sont replacées en relation avec l'avancement du TBM. Tous les données sont transmis au web-server managé de GIDIE qui permet la visualisation de toutes les unités, les profiles, les diagrammes d'avancement du tunnel et offre aussi la possibilité d'interroger chaque sonde choisie sur une carte GIS, tout en comprenant la visualisation des détails monographiques de tout point de surveillance. Enfin GIDIE a un module TBM qui montre en temps réel tous les données du TBM sur le web. Ce surveillance en temps réel permet à l'entrepreneur qui utilise GIDIE la gestion du travail et aux concepteurs de vérifier l'avancement du tunnel, en pouvant mettre en place les éventuelles actions correctives et l'ajustement des paramètres du TBM en fonction du changements des conditions du sol.

1 - INTRODUCTION

The new High Speed Rail Line Milan-Naples, crossing the city of Bologna, an intense urbanized area, is located for the most part underground.
Two EPB (Earth Pressure Balanced) machines are excavating two, parallel, single track tunnels, approximately 7 km long, which run mainly below the existing line of the Florence-Bologna railway embankment. The tunneling has started from the south of the city to downtown.
In order to minimize excavation effects on potentially affected surface structures, two EPB Machines have been chosen for the realization of the tunnels.
Classic issues relating to tunneling operations have to be considered; however aside from these issues, there is the fact that the tunnels are being driven beneath an existing railway embankment with the highest traffic density within Italy and within a densely-populated urban area.
The complexity of the project is reflected in the complexity of the monitoring plan, which encompasses different technologies and data gathering systems that supply data to a centrally managed database and a web application that allows users to access data in a controlled and traceable way.
The following activities have been implemented within the monitoring system:

- structural and geotechnical monitoring
- automatic topographic survey monitoring by means of total stations
- TBM parameters monitoring.

All of the monitoring data is collected through a dedicated Web server which allows users to access the monitoring data, query the database and display results by means of a dedicated Web GIS application named GIDIE (Golder Instrumentation Data Interpretation and Evaluation system) developed by Golder Associates.

2 - PROJECT DESCRIPTION

In 2000, the joint venture S.Ruffillo (Necso Entrecanales – Salini – Ghella) awarded one of the most critical sections of the new High Speed railway line between Naples and Milan: passing under the city of Bologna, starting from the S.Ruffillo quarter, south of the city, to the new Rail Central Station of Bologna, located downtown.
The Project starts at the North abutment pier of the Savena Bridge (km 0+000) and ends at the new Central Station (km 7+375) and consists of the following main infrastructures (see Figure 1):

1. A trench tunnel (Intermodal Area), double track, from km 0+000 to km 0+812;
2. A launch shaft, connecting the trench tunnel to the two EPB tunnels, from km 0+812 to km 0+958;
3. Two EPB tunnels ("Pari" and "Dispari" tunnels), single track, 9.4 m diameter, starting from km 0+958 to km 7+075;
4. An Emergency Shaft ("Via Rimesse" Shaft) at km 4+820;
5. A ventilation shaft at km 6+857;
6. A transition shaft (TBM's exit and "Bologna" parking) from km 7+075 to km 7+235. This shaft will be a 3 level underground parking facility and the railway line will run at the bottom level;
7. A NATM tunnel, double track, from km 7+235 to km 7+350, connecting the transition shaft to the Central Station.

The excavation for the first EPB tunnel started July 2003 and the second excavation started in November 2003.
Currently, 32% of the “Pari” tunnel and 23% of the “Dispari” tunnel have been completed.
Completion of excavation of both tunnels is scheduled for April 2006.

2.1 Characteristics of the tunnels excavation

In order to minimize the effects induced at the surface during the excavation, a mechanized excavation was required and 2 EPB machines (LOVAT RME370SE 19660 and 19700 series) were chosen.
As already mentioned, the alignment of the two tunnels, start at the S.Ruffillo quarter, south of Bologna, and end just before the new Central Station (under construction). The tunnels run, for the most part, below one of the main Italian railways in operation: the Bologna-Florence line that lies on an 8 to 12 m high embankment.
The average overburden thickness ranges from 15 to 21 m.
The two tunnels, 9.4 m excavation diameter, are parallel for most of the alignment and the distance between the axes is 15 m.
Furthermore, the two EPB tunnels will pass under three important interferences (historical underpasses and railway bridges) that, during the excavation will be subject of compensation grouting using HDD (Horizontal Directional Drilling) technology for the sleeved–pipe installation.

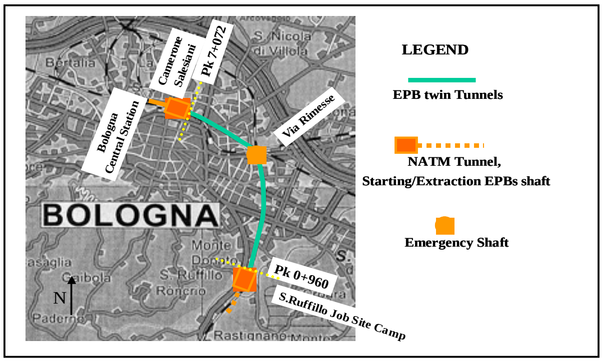

Figure 1 – Bologna Project Layout

2.2 Geological and hydrogeological conditions

The excavation is located in highly heterogeneous alluvial strata.
In the first part of the alignment, up to km.2+150, the tunnels are excavated in sea clay and loose sandy deposits (Pliocene Clay and Yellow Pleistocene Sands) below the water level; the second part from km 2+150, consists of Savena river deposits, mainly gravel and sand strata with a high percentage of fines (lenses of clay and silt).
The heterogeneity of the ground excavated is a critical aspect because the excavation conditions, either in term of surface settlement response and machines’ behavior, change very rapidly.

3 - MONITORING SYSTEM

The monitoring system has been developed in order to collect all the required information for the understanding of the soil behavior and the potentially affected structures response during the different excavation phases.
All the parameters that allow the measurement of surface settlements, such as soil strains, precast lining stress and excavation data, including the TBM’s, are included in the monitoring system. In particular, the following measurements are comprised into the system:

<u>In the soil around the excavation area:</u>

- Soil deformation above the crown up to the surface (measured by multipoint extensometers);
- Horizontal deformation around the face excavation (measured by in-place inclinometers);
- Soil deformation of the ground between the two tunnels during the passage of the 2nd TBM (measured by multipoint horizontal extensometers from the 1st tunnel Pari);
- Pore pressure modification in the soil around the excavation area (measured by piezometers).

<u>In the precast lining</u>

- Stress in the precast segments (measured by strain gauges).

<u>On the surface areas potentially affected by the excavation (in this case, the monitoring is collected by the total stations)</u>

- surface settlements
- existing buildings and structures settlements
- bridges and underpasses settlements.

<u>TBM Parameters</u>

In particular, the attention is focused on the followings:
- EPB Chamber Pressure
- Grouting injection (Grout volumes and pressure)
- Volume extracted
- Torque and Thrust
- Ground Conditioning.

The description of the instrumentation used for the monitoring of the above mentioned parameters is presented below.

3.1 Geotechnical monitoring sections

A total of 19 monitoring sections, with different in–hole instrumentation have been installed; concentrated mainly where a change of geological conditions is expected. This datalogged system provides all the real time information regarding ground behavior during excavation.

The installed instrumentation consists of (see Figure.2):
- *Vibrating wire multipoint extensometers*: in order to measure the vertical ground displacement around the tunnels, especially above the crown; grouted, vibrating wire, multipoint anchored extensometers have been installed along the alignment of the tunnels. The individual transducers measure up to 50 mm displacement with a resolution of 0.05 mm. The same kind of instrumentation has been installed horizontally, in the 1st tunnel (Pari) already excavated for monitoring the differential horizontal ground displacement in the area between the two tunnels induced by the excavation of the 2nd tunnel (Dispari).
- *Vibrating wire and accelerometer inclinometers:* in-place inclinometers (6 sensors each inclinometric probe) have been installed along the alignment for monitoring the horizontal soil deformation (longitudinally and transversally to the tunnels alignment). For the in-place inclinometers either uni-axial servoaccelerometric sensors and vibrating wire sensors are used.
- *Vibrating Wire Piezometers:* for measuring the pore pressure modification in the soil during excavation at two different depths, being groundwater subdivided in two aquifers in southern part of tunnel stretch.

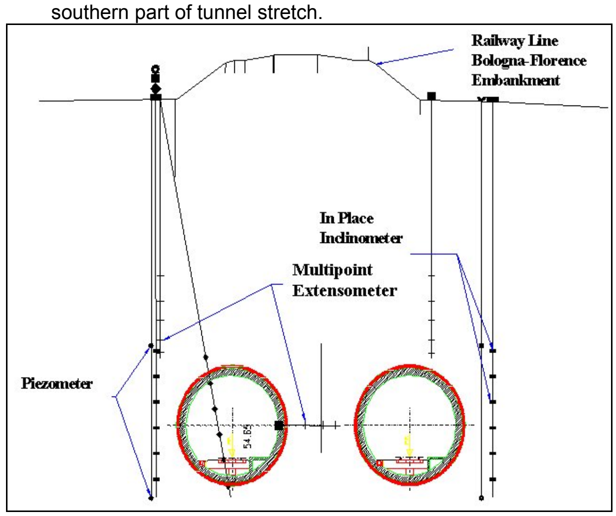

Figure 2 – Typical geotechnical section

The energy supplied for each instrumented section is obtained by properly dimensioned solar panels. All acquired data is collected by dataloggers equipped with a GSM telemetry module in order to allow remote download.
The inclinometers installed at the front of the TBMs face are removed approximately 1.5 m before the machines pass by.

3.2 Structural monitoring instrumentation

Strain gauges have been installed on the rebars of the reinforced precast lining segments. Each concrete ring is formed by 6 segments, each identified by a code number, and 1 keystone.
Two pairs of strain gauges are installed in the centre of the "even" segments, circumferentially oriented, and 25 cm from the lateral edges. In the "odd" segments (Figure 3) 6 pairs of strain gauges are installed (3 for each edge of the segment, 80 cm form the contact faces); the nearest to the edges instruments are circumferentially oriented, while, the others are longitudinally oriented.

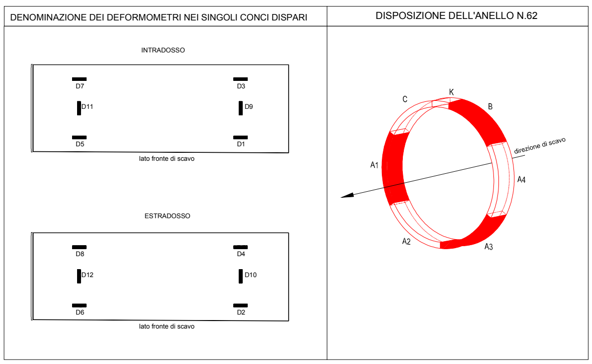

Figure 3 – Strain gauges layout inside precast concrete rings

3.3 Total Stations

Manual topographical surface settlements measurements were initially foreseen by the Designer. Due to the sensitivity of the urban area above the excavation, and in particular of the existing railway embankment, after the first month of excavation, the designer asked for a continuous topographical monitoring system.
The system has been realized through total stations (automatic theodolites) and topographical prisms installed on the railway embankment, on the buildings and existing structures (bridges and underpasses) potentially affected.
Leica delicate servo-controlled total stations (TS), TPS System 1100 – TCA 1101 Model with ATR 2 self-collimation device have been chosen for the monitoring.
The TS on site are powered by solar panel connected to a GSM modem for data transfer. The TS are installed on dedicated tripods adequately stiffened.
Every reading cycle, for each monitoring point, the TS measures:

- slope distance
- azimuth angle
- vertical angle.

All the measurements are recorded in an ASCII file (.gsi), transferred and processed in order to calculate the coordinate for each monitoring point.
Approximately 230 topographical sections, with a 25 m spacing, perpendicular to the alignment of the tunnels; allow the monitoring of the embankment. Sections with 8 or 2 topographical measuring points succeed one another:

- 8 points (identified with "even" code numbers): the prisms are installed on the top, at the middle and at the bottom of the embankment (Figure 4).
- 2 points (identified with "odd" code numbers): only 2 prisms are installed at the top of the embankment (n.4 and 5).

The total stations are usually installed at the top of the embankment, subsequently they lay inside the potential subsidence basin. For this reason it is necessary to post-process the raw readings (distance, vertical and horizontal angle) coming from the TSs that are subject to the settlements induced by the tunnels excavation. Before the position calculation of each monitoring point, it is necessary to identify any station movement.

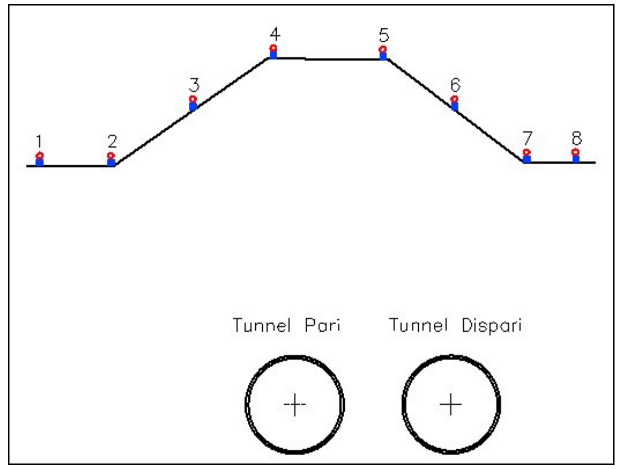

Figure 4 – Typical settlement points section on railway embankment

For each tunnel, the potentially affected area is constantly monitored with a cycle of readings every 3 hrs and all the data are automatically downloaded and collected into a server that processes them.
The TS movements are calculated as a function of the readings on stable monitoring points (reference points). In order to obtain correct computation, it is necessary to have, for each measuring cycle, at least 3 reference points.

Figure 5 – Prism on railway embankment pedestal

In such difficult conditions (theodolites installed on a railway embankment subject to vibrations, heat and the ballast reverberation), it has been verified that in order to obtain ±2 mm measuring precision, a maximum distance between the measuring point and the total station of approx. 100 to 120 m is recommended.
Four TSs have been initially used for the monitoring; however, due to the increase of the distances between the advance of the TBMs, in order to get the required measuring precision, it has been necessary to increase this number up to 7 TSs.
The ideal configuration for a similar topographical system consists of a pair of TS (one installed on the left side of the embankment and, the other one, on the right side) at the same chainage, approximately 200 m distant from the previous and the next pair of TS.
The topographical sections and the potentially affected structures are monitored 50 m ahead and 130 m behind each machine's face.
During the time interval between the passing of the 1st TBM and the arrival of the 2nd one, one measuring cycle a month is collected.
The TSs and the measuring points stay in place up to the end of the monitoring phase for the 2nd TBM passage.
After the 2nd TBM has passed the location, the single topographical section is removed and the prisms are installed ahead of the 1st TBM for the progression of the monitoring.

When a single TS doesn't have any active measuring point, it is removed and reinstalled ahead of the 1st TBM.
In this way the TSs and the prisms are continuously removed and re-installed depending on both TBMs' excavation advance rate (up to 22 m/day). The average life-cycle for each TS location is 4 months.

Figure 6 – Total station installation

Every pair of TS can control approximately 9 topographical sections and a number of points installed on buildings and other structures as a function of the single point/station intervisibility.
The three following parameters, calculated on TSs's readings, are used for the evaluation of the risk:

- angular distortion for the buildings (Boscarding and Cording 1989)
- Volume Loss (calculated for odd numbered topographical sections by a dedicated software)
- differential settlements.

<u>TBM parameters</u>

In order to constantly monitor the excavation, both machines are equipped with a recording system of the TBM machines (Figure 7) parameters. All the parameters are available, on line and in real time, to the Contractor or the Client and the Designer.
Approx. 200 parameters are constantly recorded every 5 minutes. Data is analyzed and comparing the driving values with the settlements on surface it is possible to best calibrate the excavation.
Monitored parameters are:

- propulsion total thrust
- propulsion rate of advance
- rotational speed (cutterhead)
- torque (cutterhead)
- material extraction rate
- earth pressure in the cutterhead
- extension of the articulation
- total thrust of the articulations
- runtime (screw conveyor)
- rotational speed (screw conveyor)
- torque (screw conveyor)
- opening of the guillotine gate (screw conveyor)
- totalizer of belt conveyor scale
- cutterhead runtime counter
- deviation from the designed tunnel axis
- position of laser targets
- TBM pitch
- TBM roll
- percentage of tunnel excavated
- pressure of the propulsion groups
- pressure of the propulsion pump
- pressure of the main drive pump
- pressure of the main drive motor displacement
- hydraulic pressure of grout pumps
- air pressure in airlock chambers
- pressure of injection (ground conditioning system)
- air pressure (ground conditioning system)
- flow rate of mixture pump (ground conditioning system)
- soap pump in operation (ground conditioning system)
- soap pump pressure (ground conditioning system)
- flow rate of soap pump (ground conditioning system)
- polymer pump in operation (ground conditioning system)
- polymer pump pressure (ground conditioning system)
- flow rate of polymer pump (ground conditioning system)
- extension of propulsion cylinders
- methane monitor in the screw conveyor discharge
- carbon monoxide monitor in the back up gantry
- carbon dioxide monitor in the back up gantry
- oxygen monitor in the control cabin
- n° of grout pump strokes
- grouted volume
- grout pressure
- air flow rate in lines
- percentage of opening of the flood doors.

Figure 7 – EPB machine at start-up

4 - DATA MANAGEMENT

All raw data (geotechnical, structural, topographical and TBM's) is stored in the job-site dedicated server (in the S.Ruffillo monitoring office), where periodically GIDIE web database is self-updating in order to provide a real time refresh of data to be interrogated on-line by the authorized users.
The scheme of flow control is shown in Figure 8.

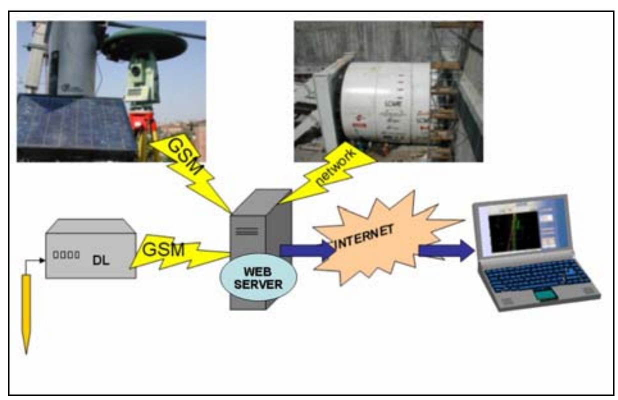

Figure 8 – Data flow chart

Data are flowing from each measuring unit (Datalogger, Total station, TBM PLC) by means of GSM or network to the local server. Then the raw data goes directly to GIDIE web Database together with the processed data.

In addition, the topographic data is contemporarily processed in real time by GETS (Golder Elaboration for Total Stations) which calculates any topographical measuring point movement and subsequently another dedicated program calculates the Volume Loss based on a complete set of measures along each section.

4.1 GIDIE

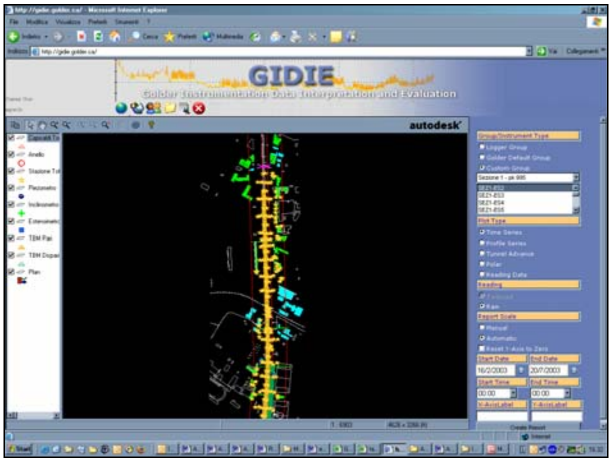

Figure 9 – GIDIE

GIDIE is a web–based application specifically developed for a comprehensive monitoring system of urban mechanized tunneling. The application was designed and developed by Golder Associates with collaboration between our Canadian and Italian offices. The application is based on a relational database which stores monitoring data and which can be interrogated by users via a dedicated web interface. Users are given the capability of querying the database and display results both by means of tables as well as graphs; data can be exported by users in different formats suitable to be further analysis and/or inserted in reports. The database has been provided with a Web GIS interface (Figure 9), providing users with a dedicated interface for interrogating and displaying data having a spatial component.

The centralized management of database ensures consistency of data while avoiding redundancy of data which need to be shared among users.

The power of having the data in its entirety available in real time on the web, allows the client, the construction management and the designer to monitor real time information related to the excavation advance, settlement induced on surface and the TBM parameters. This enables enhanced safety of the system providing a key for addressing corrective actions on the tunnel driving as a function of soil condition changes and TBM parameters adjustment.

As a matter of fact, GIDIE is a SQL web application with the following characteristics:

- a flexible and efficient database that allows the user to set the instrumentations pattern
- all the data are accessible on Internet in order to let any authorized user to download and visualize the readings, in the proper manner
- user friendly
- typical output including tables, diagrams and dedicated graphs
- GIS-interfaced
- a system that can manage a high range of instrumentation
- all the monitoring data can be exported for further analysis or elaboration
- the ability for authorized users to be able to access the data across the web from any computer that has internet access and from anywhere in the world.

4.2 GETS – Golder Elaboration for Total Stations

For every measuring cycle, the total stations create an ASCII file with all the single points position raw data.

Golder developed the software, GETS, 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 TSs. The most stable points are then used as reference points.

The TS movements are defined as a function of the reference point readings and, as a consequence, defining the position (North, East and altitude) of any topographical monitoring point.

GETS pops-up, from the raw data files, all the information about the TS state at the moment of the reading and, for each monitoring point, the code number and the position (spherical coordinates) with respect to the TS position.

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. GETS application has become necessary due to the fact that TSs are inside the subsidence basin and sometime reference points cannot be defined 100% stable. Figure 10 shows the settlement of TS vs. Time as calculated by GETS.

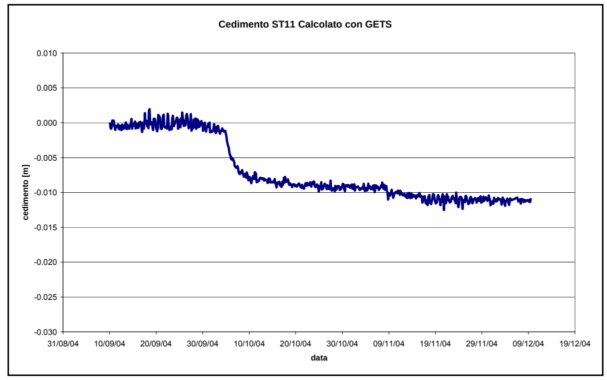

Figure 10 – Total station settlement calculated by GETS

Using GETS, the reference system is automatically checked and confirmed once verifying its steady conditions. This application prevents the risk that anomalous readings of a single reference point may affect the reading of all the measuring points, thus avoiding false alarms. In fact, if the calculation for the displacement-vector of the TS does not have enough steady reference points (set in the system configuration phase), the entire reading cycle is rejected.

The absolute coordinates of each monitoring point are then calculated in each reading cycle. Either raw readings and processed data and coordinates are collected in a temporary database before being transferred to GIDIE.

4.3 Volume loss calculation

One of the most important parameters used for the risk evaluation of surface structures is Volume Loss (Peck, '69; O'Really and New, '82). This parameter (a percentage of the excavated volume) represents the ratio between the unit volume of the subsidence basin (calculated interpolating the measured surface settlements) and the volume of ground excavated.

A Java application has been developed to interrogate a specific Mysql database, which calculates the Volume Loss for each full topographical section on the surface.

The Volume Loss is calculated using the latest topographical data available. The Volume Loss values are then sent to GIDIE allowing a real time visualization of the data on web.

4.4 TBM Module

In order to have a unique vision of the work in progress, Golder developed a system for the management of the operational parameters of the two TBMs, with real–time availability of the data via a secure, internet web site.

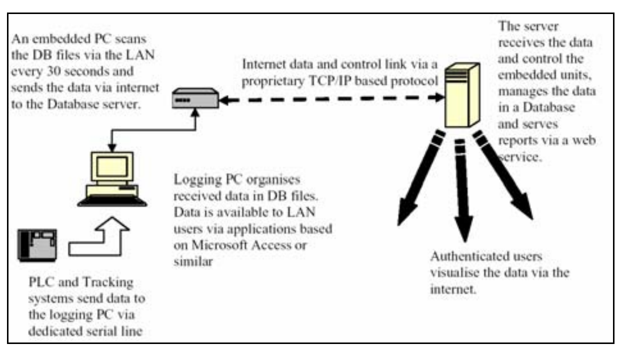

Figure 11 – Data flow (TBM)

The system is based on a client–server configuration. A dedicated web server with a scan interval of 5 minutes is collecting, all the data (200 parameters) available from San Ruffillo on-site machine's PC, where TBM data is stored coming from two PLCs located inside the two head TBM units.
The web server stores data in the database, which can be shared by authenticated users in the form of graphs and reports via internet.

The real time data acquisition, having a scan interval of 5 minutes, allows the real time refresh of graphs during the progressing of the tunnels excavation. The graphs can show the actual situation ahead of the tunnel face with up to 200 parameters. Graphs can be combined with various options in order to visualize in the same graph both data vs. time as well as vs. ring number advance. This allows an immediate visualization of each TBM activity, enabling the check on even the most delicate phases such as the extrusion of ring out of the shield going to into contact with the surrounding ground. At this point the grouting operation has an important effect in soil stabilization and stress distribution along the concrete ring.
Typical output on the web visualization page is presented in Figure 12.

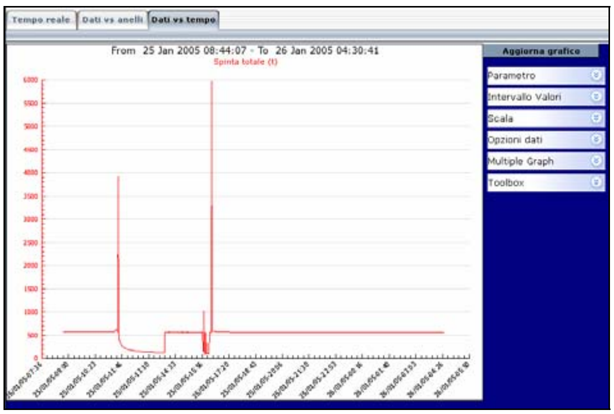

Figure 12 – Cutter head total thrust vs. time

5 - WEB REPORTING

All data available in GIDIE Web Database can be processed in order to be visualized in the best way to comply with the data analysis as well as the prompt view of eventual anomalies.
The diagrams can be available either by double clicking on the GIS map, zooming in the required zone, or selecting the sensor, the settlement point, or the instruments on a scrolling list.

The followings graphs can be visualized on the web site:

Time series diagrams :

- Strains in the precast concrete rings - Figure 13

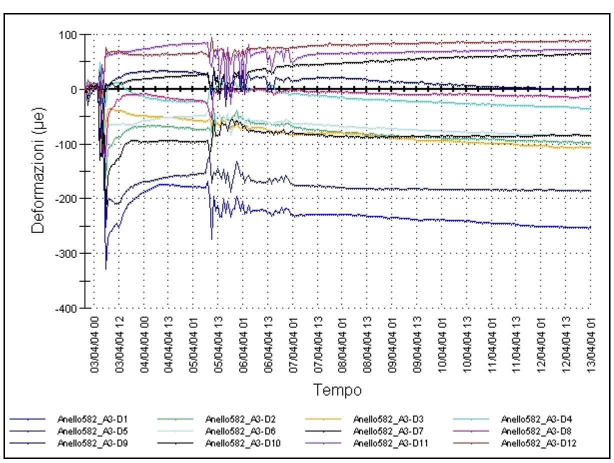

Figure 13 – Concrete ring strain vs. time

- ground pore pressure (piezometers)
- angular deviations (inclinometers)
- ground deformation (multipoint extensometers, Figure 14)

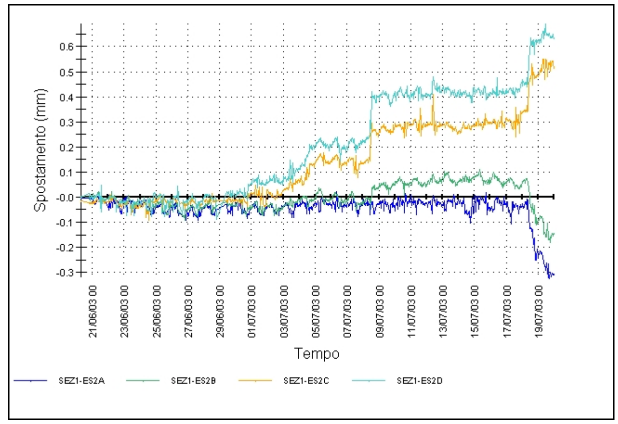

Figure 14 – Extensometer vs. time

- differential settlements (topographical measurements) for the single measurement points settlements (Figure 15)

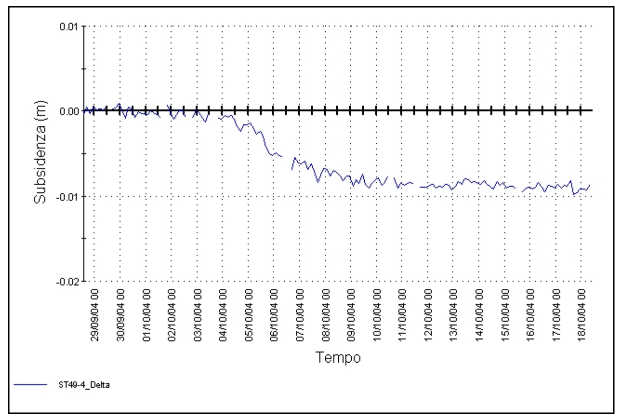

Figure 15 – Topographic point settlement vs. time

- Volume Loss for the full topographical sections (at least 6 measuring points). In Figure 16, the volume loss increasing during the 2nd TBM passage (green curve) is shown. The initial value for this parameter can be seen and is approximately half of the last values recorded after the 1st TBM passage (blue curve) since the ratio is evaluated with both tunnels excavated.

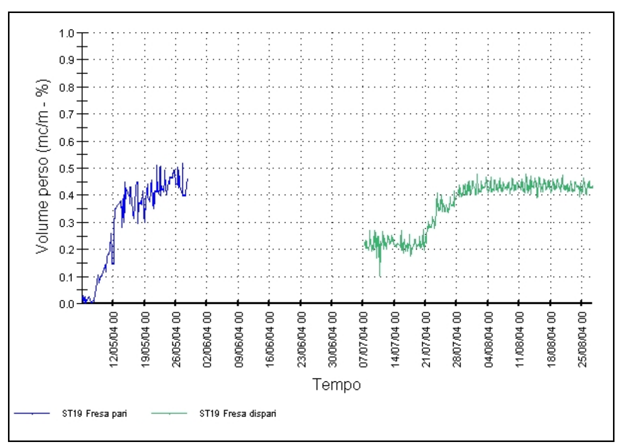

Figure 16 – Volume loss vs. time

- TBM advance (vs. Time) give the progression of the tunnel driving
- All the recorded TBM parameters. Besides the parameter values vs. time graphs, it is possible to visualize these kinds of parameters in the same graph. In the Figure 17 the rotation cutterhead speed and the installed ring numbers are shown.

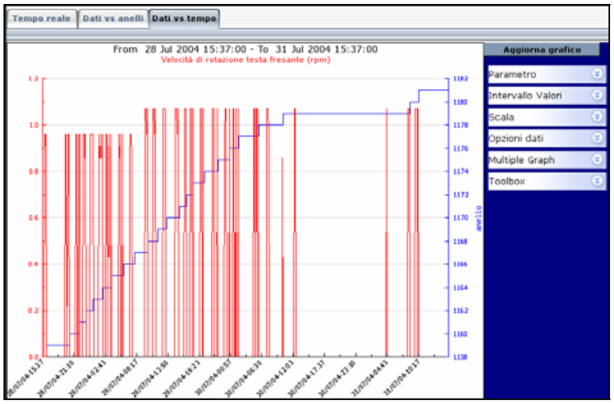

Figure 17 – Cutterhead rotational speed & ring number vs. time

Profile diagrams:

- Inclinometers: horizontal strain vs. depth (Figure 18)
- Transversal or longitudinal profiles (multipoint) settlements. (Figure 19).

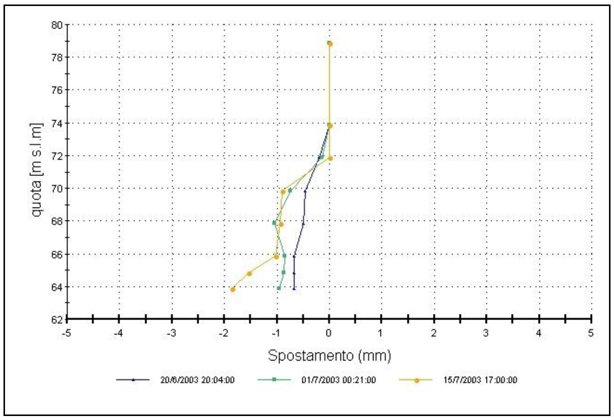

Figure 18 – Profile of an inclinometer chain

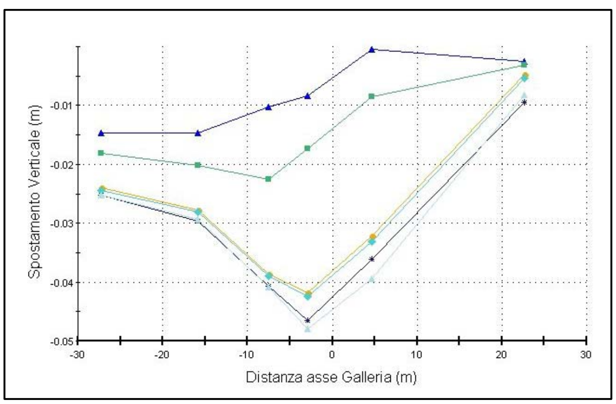

Figure 19 –Settlement profile on a transversal section

TBM advance diagrams:

All above described parameters, that have time series presentations, can also have diagrams as function of TBM advance:

- strains (strain gauges in the precast lining segments)
- ground pore pressure (piezometers)
- deviations (inclinometers)
- ground deformation (multipoint extensometers)
- single points settlements (topographical measurements) (Figure 20)
- volume loss (calculated for the full topographical sections).

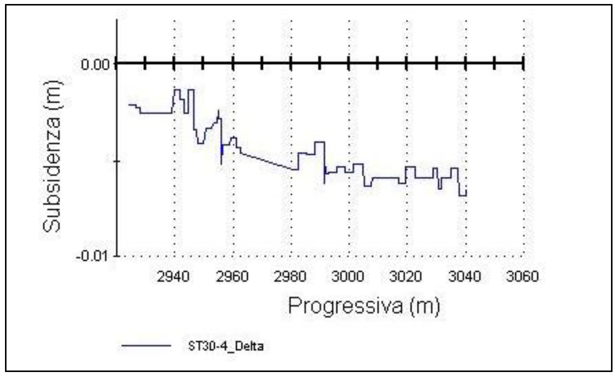

Figure 20 – Topographic point settlement vs. tunnel advance

Polar plots:

- planimetric movements of the surface: topographical measuring points. In these graphs, the user may define, besides the scale, two levels of confidence: one as alarm and one as alert level (Figure 21).

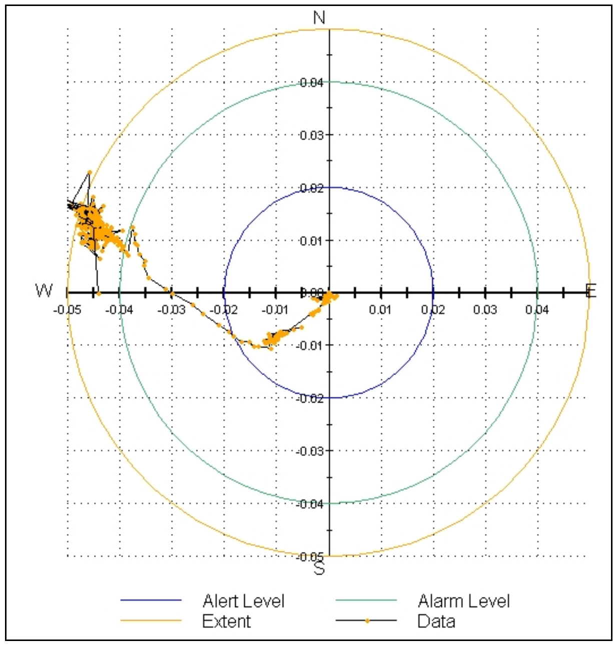

Figure 21 – Polar diagram for topographic point

Data Export/ Data Reporting

All the monitoring data in the database can be exported in .csv format. In this way, it is possible to process and analyze all the data without modifying all the information in the database.

6 - POWER OF THE SYSTEM

The use of GIDIE software allows the contractor as well as the construction management to control all the interaction between the excavation of the two tunnels and the surrounding environment.

The conduction of the work is evaluated in real time by analyzing key parameters. The complexity of the monitoring system can be reduced depending on the type of work: it is possible to decide which parameters are useful to be monitored.

GETS represents an innovation in the elaboration of total station data: it allows using a “free to move” total station with an analysis of its stability. Before the development of GETS, an analyst was necessary in order to identify at least three reference points judging the last available data. This operation required some hours and didn’t allow an actual real time monitoring.

Using GIDIE, the risk of having too much information entering in different formats (papers, excel tables, etc.) has been suppressed: the data in its entirety is on the web and the user can decide whether it is needed and in which format.

Hence, the real time comparison of TBM data with settlement information available in a unified system and in a single web location, allows a comprehensive analysis of the tunneling progress.

The power of such a comprehensive system has been valuable when critical zones are detected after the 1st TBM passage having relevant settlement beside the railway embankment.
When the 2nd TBM approached, close attention was dedicated to evaluate the settlement changes.
Diagrams of adjacent settlement points have been used to evaluate and control the stability and the effectiveness of countermeasures emplaced in the area of a sink hole which developed. The sink hole was filled up with lean concrete, whilst the monitoring system was intensified with readings every two hours. After about ten hours, no increase in settlement was registered and the sinking was completed.
Figure 22 shows the longitudinal section of the settlement developed along the embankment alignment.

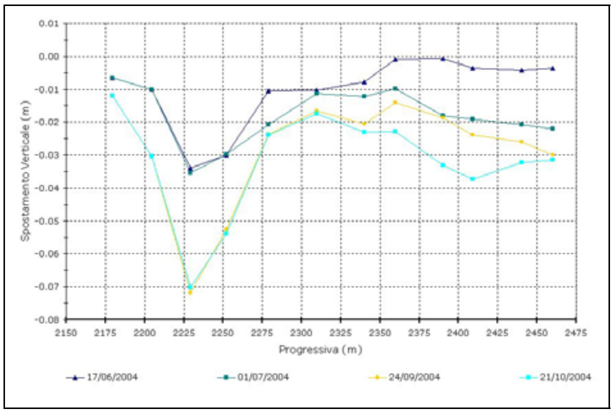

Figure 22 – Longitudinal section settlement diagram

During sink hole development, very strict controlled conditions were inplace. This was able to show how important the connection is between the data provider, responsibility of data reliability, data analyzer and site personnel whom depend on the measuring data to be able to enforce the countermeasures.

Future enhancement of such a system will be an automatic control of the main parameters, with alarms and a refinement of automated output in case of an alarm event.
At present, Golder is planning a system that permits automatic interpolation of topographic settlement of points and to have them reproduced on a 3D graph which is processed and available in real time (Figure 23).

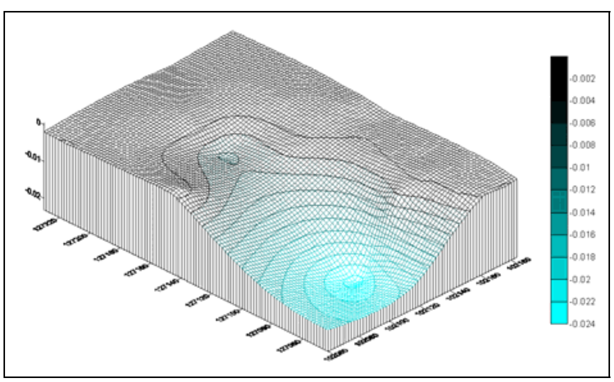

Figure 23 – 3D subsidence basin

7 - CONCLUSIONS

Golder Associates designed, developed and deployed a monitoring system for a major infrastructure, such as the construction of twin tunnels under passing the urban area of Bologna. The system allows real time data interpretation of all data coming from total stations, geotechnical sensors, strain gauges embedded in precast linings and EPBM units, via the web.
This enables the owner, contractor(s) and construction management to gain access to real time information on the progress of the tunneling, settlement induced by excavation and the EPBM parameters. Such a system provides enhanced safety and a key for addressing corrective actions on tunnel driving as function of changes in soil conditions and EPBM parameter adjustment.

8 - ACKNOWLEDGMENTS

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