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Line C in Rome: Remote monitoring system

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ABSTRACT: The complexity and dimensions of the design of Rome's Line C underground and the variety of interferences between construction and territory required the development of an automatic and remote controlled monitoring system. The monitoring system used, involves a great quantity of instruments and guarantees real time data management, publication and evaluation; the system collects, processes, and delivers data, to the appropriate agencies involved in the construction, and it also provides a historical overview during all the building phase.

1 LINE C—ROME UNDERGROUND

1.1 *Introduction*

Rome's Line C subway, under construction by General Contractor Metro C S.c.p.A. since 2007, is a fully automated underground railway line characterized by an automatic train control system; The trains are "driverless" and platform doors will slide open simultaneously with those of the train on arrival, increasing station safety and improving service quality.

The line, with its 30 stations, crosses the Capital from the south-east side (Pantano) to the northwest area (Farnesina), stretching over a distance of 28,2 km. The construction of Line C will almost double the area covered by the current underground network and it represents one of the most important works ever built in an urban context.

The main characteristic of the stations is the length of the platforms, 110 m long in order to accommodate the purposely planned and constructed trains, made up of 6 cars for a total length of 107 m. The train has a maximum transportation capacity of 24.000 passengers per hour in each direction, and a maximum frequency of 3 minutes during rush hours.

The eastern part of the line, 8,7 km long, emerges onto the surface just outside the "highway ring" (G.R.A.) until Pantano, running along the Casilina state road, on the existing path of the Rome-Pantano railroad. Along this section of the line there are 11stations, of which 10 existing that will be adapted to subway standards.

The Line C Depot/Workshop, situated in Graniti on an area of 22 hectares, is the operating and technological core of the new line. This area will be used to house the complete rolling stock fleet of line C and the Operation Head Office, located in a dedicated building, will be responsible for remote train steering and control.

The main part of the line runs inside the "highway ring" (G.R.A.) for approximately 18,5 km, and is characterized by two single railroad tunnels, with a distance between centre lines variable between 18 and 40 meters.

Each tunnel has a diameter of 6,70 m. In order to avoid interference with archaeological findings, which in some downtown areas are located up to 16–18 meters from the surface, and at the same time limit the effects of settlements due to excavation, the tunnels run between 20 meters and 35 meters under ground level.

This route is expected to have:

- 11 deep "box shaped" stations, with few exceptions, made with the "bottom-up" method; stations are on average 20 m deep below the water table;
- 8 special box shaped shafts, including 3 for TBM erection and dismantling and 5 for the implementation track junctions;
- 11 circular vent shafts, for line ventilation and water collection, located in the lower points of the line;
- 4 blind-hole tunnels of about 180 m length for turnout tracks;
- 900 m of platform tunnels built by TBM tunnel enlargement. Due to territorial interferences, it was not possible to position all station platforms inside "box shaped" stations.

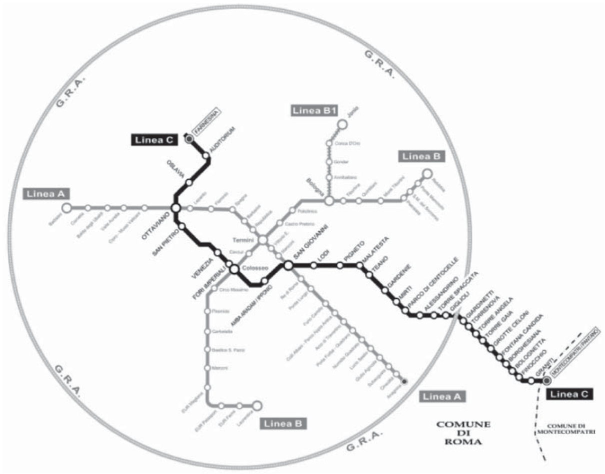

Figure 1. Subway network.

Figure 2. Subway train.

The main characteristics of Line C are:

	Length (km)	Tunnels (km)	Stations (n°)	Shafts (n°)
Pantano—Farnesina	28,2	39,0	30	38
1st functional phase (in execution):				
Open air line	8,7		11	
Underground line	**9,8**	**19,6**	**11**	**19**

1.2 *Execution of works*

From 2007, after a complex campaign of archaeological and geotechnical surveys, along the First Functional Route from San Giovanni to Pantano, more than 14,000 m of tunnels (external diameter 6,40 m and internal diameter 5,80 m) have been constructed, 37 work sites have been opened and 3 base camps are currently active.

As of June 2010 work completion is more than 60%.

In the Graniti site the construction of the Depot/workshop is almost complete and the first trains have arrived and are ready to start the tests of functionality and interface between the systems.

Figure 3. Line C Depot/Workshop in Graniti area.

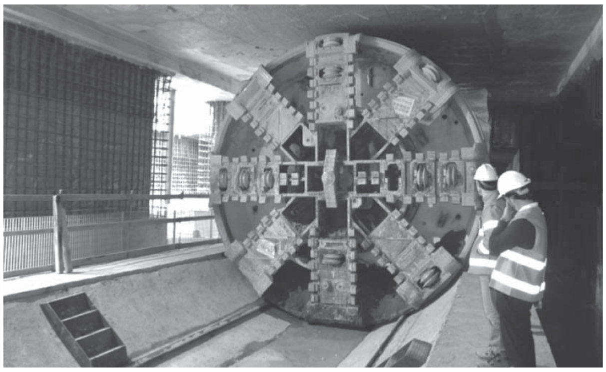

Figure 4. TBM across the Station.

The main issues faced during the execution of the works have been those linked to archeology and to the interaction with the urban context. The urban context is characterized by not only the pre-existing buildings but also by the historical-monumental sites, by the underground facilities, and by the underground caves that characterize most of the underground path.

Overall, the works of Line C, are characterized by the following quantities:

- deep excavation 4,500,000cu.m.
- concrete 1,600,000cu.m.
- steel 280,00t
- rails 7,400t
- copper 150t
- cables 110 km
- pre-cast tunnel lining segments 25,000

Moreover Metro C has acquired 4 Herrenknecht TBMs, and has ordered from Ansaldo Breda a fleet of 30 trains (length 107 m), each consisting of 6 cars, available form 2010 at the Graniti workshop.

1.3 *The monitoring of the activities as a priority*

The concurrence of all the processes mentioned above, located in different sites at the same time,

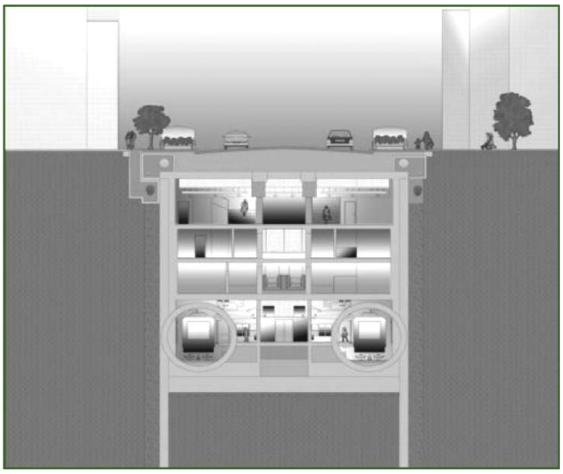

Figure 5. Box shaped station.

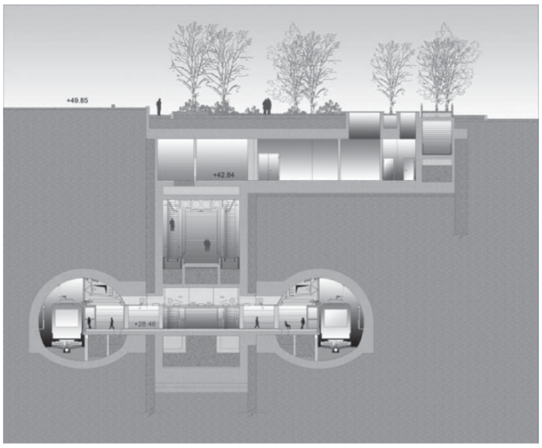

Figure 6. Station built by widening TBM tunnel.

mostly all underground and in urban areas with distinctive characteristics of historical and archaeological sites, requires the establishment and development of a complex automatic monitoring system, able to check the compliance between existing building, environmental situations and design assumptions and prevent unchecked negative developments regarding the safety of buildings, staff and the urban context, by fostering the necessary remedies.

The overall goal of monitoring while constructing is, not only verifying the compliance between the actual behavior of the land, facilities and environment and what was expected, but also taking care of the safety of workers and residents, and the maintenance of existing buildings: buildings, sewers, water and gas mains, etc.

It is therefore necessary that the monitoring has the following features and requirements:

- complete information;
- reliability of the system (of the component as well as of the entire structure) and counter checks of the required precision;
- well-timed information related to activities in progress;
- minimization of human error;
- flexibility in the system's usage, interpretation and adaptability.

The system must also be usable in real time by numerous people, from different institutions, in total security.

In fact, this system should be configured so that it can simultaneously handle a large number of instrumental groups, about 933, including:

Stations and shafts:	90 geotechnical sections
Along the TBM line:	60 geotechnical sections
	198 topographical sections
	60 instrumental rings
Ordinary buildings:	329
Sensitive buildings:	196

The monitoring tools for this configuration are about 20,000, divided as follows:

Table 1. Monitoring instrumentation.

Type	Quantity
Basic devices	
Triaxial accelerometer	4
Fixed extensometer	15
Strain gauge	5.192
Levelling pin	3.335
Load cell	83
Wall clinometer	457
Sliding deformeter	10
Rod Extensometer	173
Inclinometer	283
Prism	6.514
Crackmeter	4
Casagrande Piezometer	396
Electrical piezometer	127
*Automated systems**	
Pressure sensor (piezometer)	372
In place inclinometer sensor (inclinometer)	1.415
Displacement sensor (rod extensometer)	519
DAU (Data Acquisition Unit)	177
RTS (Robotized Total Station)	185

*232 km of cables are provided for measuring and centralization of control systems.

This complex and articulated configuration of instruments needs a system able to handle a large amount of data, in order to ensure a smooth flow of information starting from the instrument and reaching the planning area, the construction area, the works manager, the board of testing and clients.

The work flow has to allow ongoing verification of the compliance of design parameters, especially in case of pre-arranged events as "expected trend" or exceeded thresholds, and process with reliability a large amount of information coming daily from the instruments. This is impossible with the traditional monitoring systems.

It is also necessary to handle a great amount of documents such as monitoring reports, history and development of all the instrumental measurements and data consultation, visualization and storage.

In fact, during the first 3 years of construction the monitoring system processed more than 60 million records concerning geotechnical data and 40 million records regarding topographical data.

In order to fulfill the requirements and cover the needs described above, considering the enormity and simultaneity of works, the main goal was to characterize the monitoring system with a widespread presence of automatic processes, in order to allow quick scalability, independence from human factors and, at the same time, highlight in advance among a huge amount of information trends which are critical compared to expected values.

2 ARCHITECTURE OF THE MONITORING SYSTEM AND ITS PERFORMANCE

2.1 *Scenario analysis*

During the analysis for the definition of the requirements for a monitoring system which could satisfy the previously discussed objectives, a number of peculiar elements were highlighted:

- great variety of installation sites;
- great variety in the characteristics of monitoring instruments;
- simultaneous operations;
- great amount of data;
- long operating lifetime of the system.

The installation sites include: tunnels, station sites, civic buildings, residential buildings, monuments and architectural works along the Line C route, urban streets, highways, light railways and railroad hubs.

The long list of instrument types and the differences in their characteristics (e.g. sensors with manual reading or automatic and remote instruments), needed to be handled with a versatile system, able to take into account new instruments not foreseen within the initial design.

Works involve different and parallel decisional structures. Sites and their management structure are coordinated by the engineering office which modulates the monitoring architecture according to site phases. These structures are spatially distributed (de-localized) and mutually independent from each other, relatively speaking. The overall system also needs to address people with different specializations. A unifying system, in terms of monitoring data handling and distribution, was required.

Information concerning the amount of data analyzed during the first three years of operation, efficiently show the volume and complexity of the system being developed. A constant flow of data that keeps increasing on one hand shouldn't hamper works with false alarms, on the other hand has to guarantee a strict control for the safety of the work environment, of pre-existing structures and of citizens.

2.2 *System architecture*

The system implemented to answer the requirements of the above-described scenario is made of well-defined elements summarized as follows:

- basic devices (with manual or automatic reading);
- automatic and remote systems;
- Data Processing System, DPS;
- Data Dissemination System, SDD.

In order to assure adequate frequency of sampling and at the same time minimize human intervention, the design of the monitoring system provided, at the executive level, Smart Automated Systems. These are implemented by DAU (Data Acquisition Units) (Fig. 7), which are remotely programmable according to control needs.

Very high precision RTS's (Robotized Total Stations) are instead used for topographical checks

Figure 7. DAU (Data Acquisition Unit).

Figura 8. RTS (Robotized Total Station).

(Fig. 8). While the first ones can guarantee constant readings of nearly all of the geotechnical and structural monitoring instruments, the second ones can guarantee cycles of geodetic readings both within a station work site and along the TBM excavations, following it step-by-step along the line galleries.

A quick response and access to data can be guaranteed by an innovative computer-based system, a hardware/software platform which can handle an increased number of data, response times and workload. Quick response time includes the entire monitoring management process: from data acquisition to its availability to system users—designers, people in charge of the site, Construction Management and General Supervision—by giving clearly readable layouts available in light and well-known digital formats (PDF, Excel and so on) ready for printing and presentation.

All this is made possible by a software environment that includes webGIS components and automatic procedures for data acquisition and processing. By enabling the remote management of the monitoring network, it minimizes the time gap between data acquisition and processing and its availability.

2.3 *DPS, Data Processing System*

The DPS, Data Processing System, is the core of the entire system. It is composed of specialized operators, dedicated software and hardware and a complex data transfer network based on wired and wireless (UMTS or Radiomodem) links.

Its innovative design required the development of software applications which could:

- acquire measurements;
- automatically process data;
- perform validation checks;
- generate automatic warnings when pre-defined attention and alert thresholds are exceeded;
- automatically archive documents;
- distribute the data using the DDS, a dedicated web-based platform with webGIS components.

The automatic routines that perform these tasks are specific for each instrument and for every kind of data exchange (manual or automatic). They are designed to minimize human errors through data entry forms (for those kind of instruments wich are not automatic neither do not support remote control), and to minimize the risk of data loss or data mix-ups, which is very serious if connected to false alarms or, worse, to missed alarms.

In detail, the DPS:

- provides the tools necessary to manage the data monitoring of Rome's Line C subway in specific routes, meeting the requirements of high speed processing, validation and distribution of data and emergency management;
- collects and organizes data coming from the instruments;
- analyzes and validates data imported from remote-controlled, automated and manual instruments, through automatic routines that prevent transcription errors; analyzes data identifying instrumental errors and exceeding of the thresholds of attention and alarm;
- produces reports and statistics;
- produces updated maps;
- manages the SSAT** and SSAL**;
- stores data;
- has an interface dedicated to the publication of data via the Web called SDD, Data Distribution System.

The DPS works by applying a series of standard operating procedures (SOP), which regulate the flow of information and the data output (graphs and tables). These procedures have the task of minimizing the error introduced.

The DPS manages data from the instrument to the final storage. The path of the data is illustrated in the figure below:

The first area, A, manages the acquisition of data: in field personnel and automated systems (remote-controlled or not) collect data in formats and ways compatible with the following (B) procedures for processing and storage. The data transfer routine check the consistency of the data before their storage.

The final area, C, is responsible for data processing and data validation, for charts elaboration and layouts development according to design changes during construction.

**Superamento Soglia di Attenzione e Superamento Soglia di Allarme (that is: exceeding of the alert threshold and exceeding of alarm thresholds).

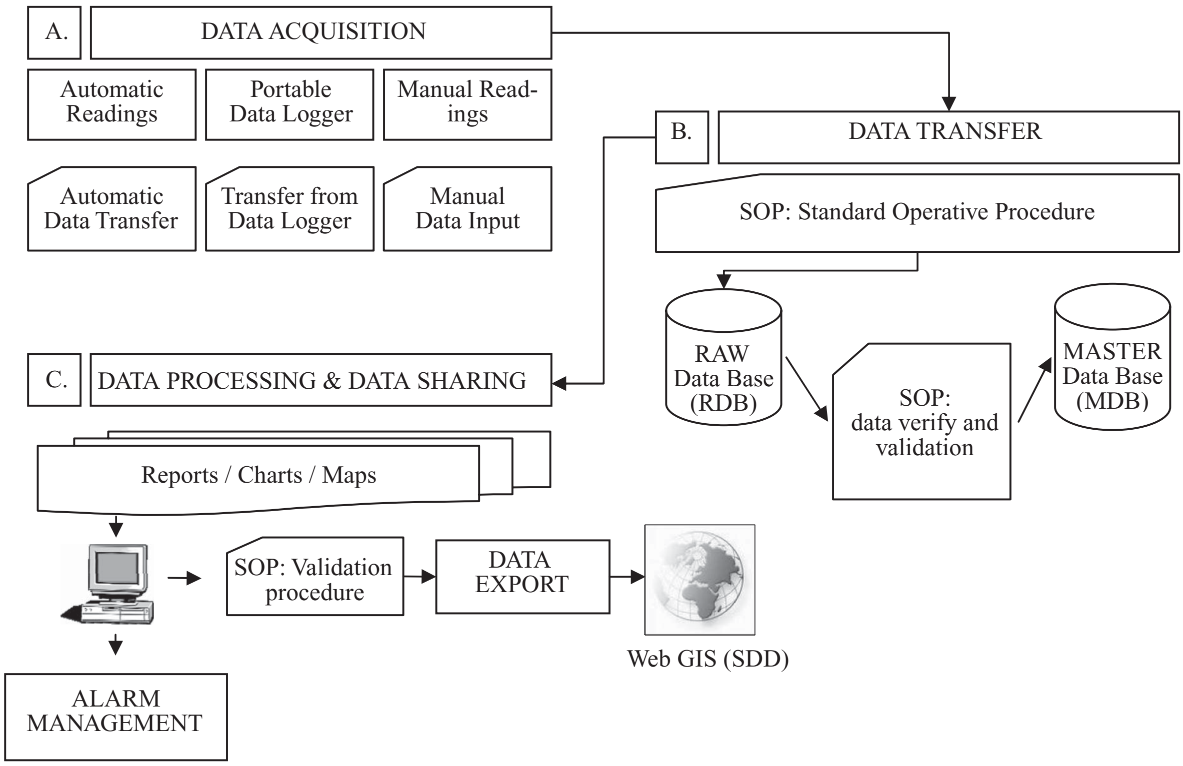

Figure 9. DPS Data flow chart.

Operators use the DPS data transfer routine to transfer the information from monitoring tools to dedicated databases. The system is structured to handle all the instruments during the different stages of processing. Some instruments, however, do not support remote control or support remote control only in some phases, because of design requirements. Data from these instruments require intermediate steps such as field reading operations, transcription and manual data entry in the database. For these data too entry forms allow you to minimize errors.

The following images in Figure 10 show some of the forms of computer data management tools developed for the different sectors of line C (T3, T4, T5, T6a, T7) and for Graniti Depot.

2.4 *Alert thresholds and Alarm thresholds*

To allow the monitoring staff and users to distinguish, in the continuous flow of data, sensitive information, a key role is played by the Alert Thresholds (SAT) and the Alarm Thresholds (SAL). They allow to focus on critical aspects of design, abnormal behaviors, especially on their evolution when corrective action is taken.

- Event SSAT (Alert threshold exceeded)
- Event SSAT (Alarm threshold exceeded)

The procedures to be undertaken once the event SSAT (or the next SSAL) occurs are clear, defining timing and participation and communication mechanisms. The reporting is gradually available on the platform, SDD, until the critical event is solved.

Figure 11 shows the flow chart which describes the procedures adopted in the case of SSAT and SSAL.

Until now, during processing, there were 9 SSAL events and 39 SSAT events, all settled and solved (Resolved planning corrective procedures with redefinition of the new SAT/SAL).

2.5 *SDD (Data Dissemination System)*

The SDD is a web-based application which enables access to monitoring data from any location. The application core has been developed using standard languages, like PHP (on the server-side) and JS (on the client-side), while complex and multilayered maps and other innovative location-based functions are managed by integrating UMN Map Server with the rest of the system (UMN Map Server, now a project by the Open Source Geospatial Foundation, was originally developed by the University of Minnesota).

A minimalistic design approach ensured that the user interface is fast and efficient and at the same time clean and multi-browser compatible, despite the typical shortcomings of web-distributed applications.

All the data are stored in a MySQL-based relational database synchronized by a replication mechanism with a subset of the main DPS database.

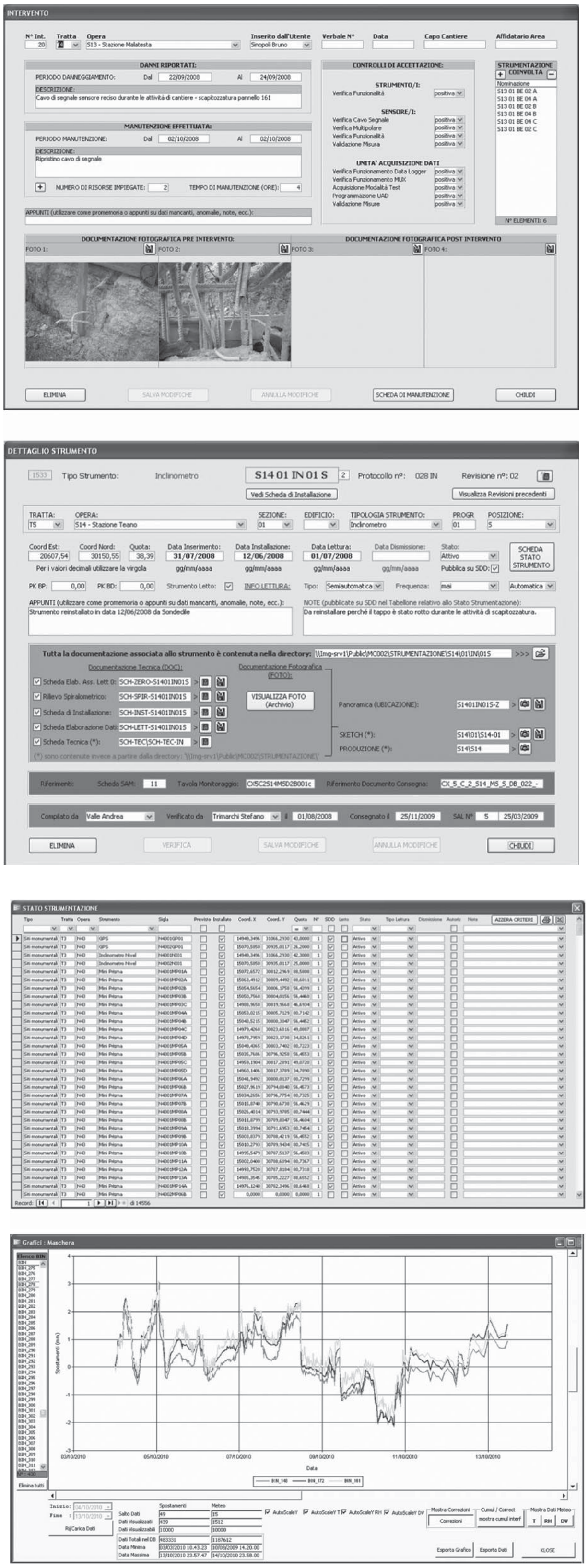

Figure 10. DPS. Examples of informatic tools.

The design and development of the SDD is successfully based on open-source products and technologies. The result is a stable, fast and easy to upgrade application, adjustable and scalable to other monitoring contexts.

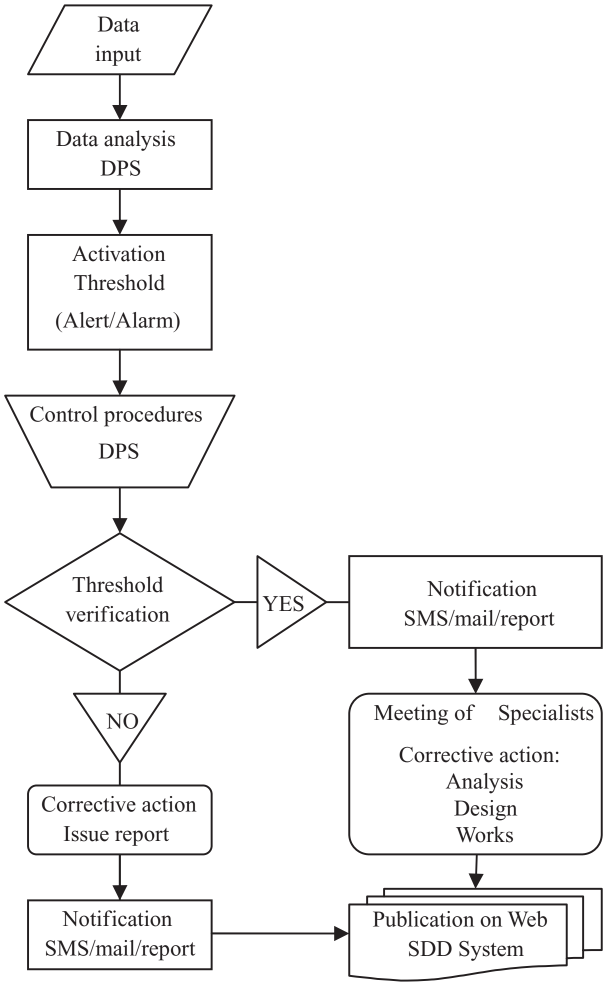

Figure 11. Management of SSAT/SSAL. Procedure chart.

In order to create a modular, extensible and flexible system, it was decided to provide two types of user interfaces: map priority views (Fig. 12) and data priorities views (research papers, warning event handling).

The map priority view offers the possibility to search for tools and monitored objects by exploring the area with typical Web-GIS interface (similar to the widespread regional consultation systems such as Google Maps), which are selected by the instruments, sensors (individuals or groups) or monitored elements (e.g. buildings or sections of monitoring) with the selection cursor that changes depending on the context. By selecting an entity on a map, you can get a list of documents (spreadsheets and data processing, installation sheets) associated with it (Fig. 13).

For monitoring purposes, the SDD is provided by a data form which allows the user to access the numerical data database via the web, making them exportable in standard formats (xls, csv,

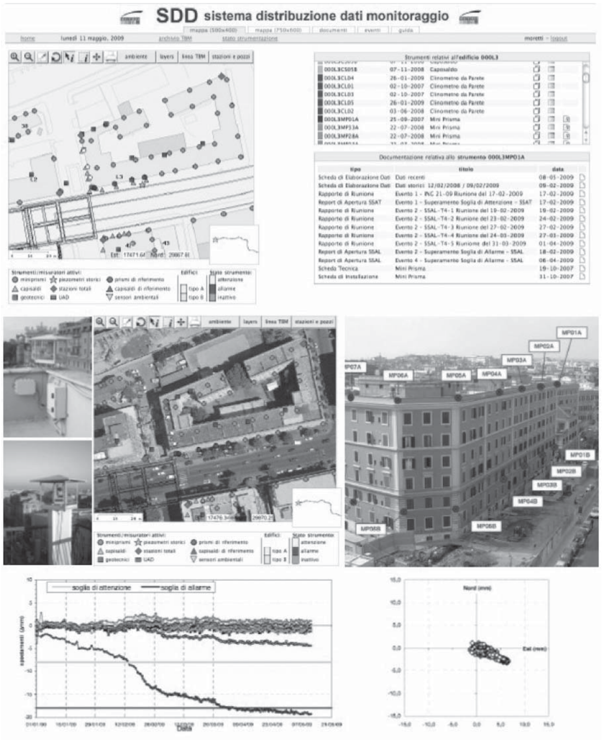

Figure 12. SDD. Example of priority map wiew.

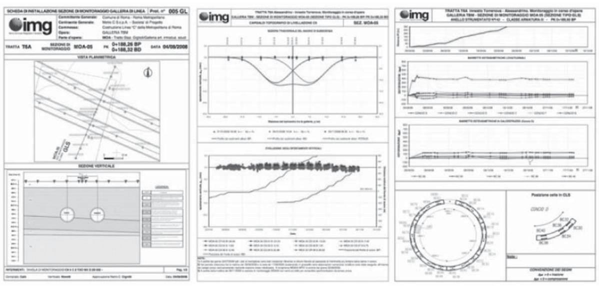

Figure 13. SDD. Example of monitoring layouts.

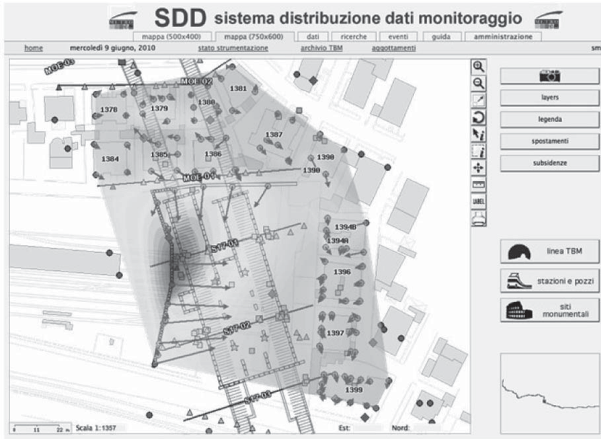

Figure 14. SDD. Example of settlement analysis (subsidence & displacement vectors).

Figure 15. Monumental sites. Monitoring tower for the Basilica Maxentius.

dat) and displayed in graphical format directly into the web browser, for capillary remote controls, by the designers, building site, the Construction Management, the General Supervision and Commissioning.

The DPS and SDD server, hosted in two servers houses, also provide backup and disaster recovery.

The evolution of the DPS-SDD is developed together with the design requirements. The peculiarities of some portions of the track and, in particular, the crossing of the historical and monumental area of the city from San Giovanni district to the right bank of the Tiber River, required the addition of functional tools such as data module and modules which allow the synoptic representation of events.

Among the many tools available, the modules for the settlements due to excavation and movement, allow you to view changes in the statistical distribution of horizontal and vertical alignment of data, directly on the map, making it easier and more immediate to understand the areal development of a phenomenon, and the evaluation of the adequacy of the readings between nearby points.

3 CONCLUSION

Automation, remote monitoring tools and data distribution via the web were the winning choices. The possibility of data projection during decision-making meetings has undoubtedly improved the time needed to prepare them. No paper, no plotter to work on, no volume to browse or design plan to roll on the meeting table. It is estimated that on a daily average basis about

Figure 16. Basilica Maxentius. Particular of geodetic prism.

Figure 17. Particular of monitoring tower of Basilica Maxentius.

80,000 monitoring records are analyzed, while the SDD platform is powered by over 1300 report data, excluding the supplementary documentation (technical data sheets and installation tools, graphics, production, etc.).

The overview of project-data-territory is available 24/7 from any position, with a computer connected to the Internet.

The entire monitoring system described above has been extensively tested on the works of the T4 to T7 sectors of the line and can be considered fully efficient and capable of being interfaced with ease with all the monitoring equipment already in use. In addition, from May 2009 a pre-trial monitoring phase on some buildings of special architectural and historical value on the portion T3 of the line (Palazzo Venezia, the Vittoriano and the Basilica Maxentius) is in progress.

In particular, the Basilica Maxentius is constantly monitored by an integrated system consisting of modern geodetic monitoring equipment: Leica TCA 2003 robotic total stations, GPS sensors, ground radar interferometer IBIS-L, in addition to constant monitoring by SAR Interferometry System.

The preliminary monitoring of the section T3 of the line has the following objectives: to define the deformation behavior of the structures in undisturbed conditions, to test equipment such as innovative monitoring instruments such as Ground Based Radar Interferometry (Gb-InSAR from earth surface) and to provide for these usage protocols and how to manage data from DPS and the SDD.

After the two-year planned preliminary monitoring, the DPS and SDD management system will be able to integrate and automatically manage the data collected, whether they come from the most traditional instruments, or from those of last generation, This feature makes it one of the most advanced and complete monitoring system for the control of major projects in urban areas.