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Rome Metro Line Monitoring System: the C Line experience

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SUMMARY:

The new line of the Rome Metro network, identified as Metro C, connects the East periphery to the center of the city. The first part, to the city center develops for 21 km, 8.5 above ground and 12.5 underground, 20 to 60 m from ground level, with a total of 24 Stations. The underground part runs in heavily urbanized area and below very important historical monuments (Colosseum, Basilica di Massenzio, Fori Imperiali, Basilica di S. Stefano Rotondo, Mura Aureliane, Foro di Nerva) The need to evaluate the design assumptions as well as to guarantee the safeguard of such important monuments which are visited every years by millions of tourists, led the to the design and installation of a huge amount of instruments to monitor the behavior of the soil and of the monuments.

Metro C S.c.p.A. the contractor, has started the monitoring system in 2006 and systematic monitoring activities started in 2007, in the first track of Line C construction. All together some 30,000 measuring points have been installed ant relevant measurements have been implemented in the managing software – DDS – enabling a continuous monitoring of the parameters and management of the system.

The paper describes the results from the experience - which is still in progress (the end of the activities is foreseen on 2021) – with regards to the management of such a large system and to the reliability of the components: instruments, data acquisition units, data transmission and data management. Special attention is dedicated to the requirement of such systems in terms of resources to be dedicated to the measurements, management, procedures to be applied and interference with the construction activities. The most critical issues, such as the system management and maintenance are discussed. Moreover the implementations / modifications to the initial design related to the gained experience are presented as possible suggestion for future similar works.

KEYWORDS: Metro Line – Monuments – Monitoring – Management – Maintenance.

1 INTRODUCTION

The new line of the Rome Metro network, identified as Metro C, connects the East periphery to the center of the city and was originally plant to continue to the North-West Quartieri. The total length was originally 25,6 km. The first part, to the city center develops for 21 km, 8.5 above ground and 12.5 underground, 20 to 60 m from ground level, with a total of 24 Stations. The underground part runs in heavily urbanized area and below very important historical monuments (Colosseum, Basilica di Massenzio, Fori Imperiali, Basilica di S. Stefano Rotondo, Mura Aureliane, Foro di Nerva) The need to evaluate the design assumptions as well as to guarantee the safeguard of such important monuments which are visited every years by millions of tourists, led the to the design and installation of a huge amount of instruments to monitor the behavior of the soil and of the monuments which is a UNESCO World Heritage site. In order to safeguard all the monuments Metro C has constituted a specific Scientific Technical Committee (STC) presided over by Professor Michele Jamiolkowski which includes world- famous Experts: Professor Carbonara, Prof. Burghigoli, Prof. Kovari, Prof. Macchi and Prof. Funicello (who died in August 2009).

The STC indicated the monitoring requirements for controlling the construction works and, mainly, to guarantee the safety of the monuments having, as main aim to ensure high quality research methods and to analyze potential interactions between the new line and the historical monumental heritage.

The STC studies included three main steps:

1. preliminary studies: identification of the construction stages, identification of the type, the materials and the geometry of the foundations, identification of the material characteristics and of the building technologies, structural and crack pattern survey and geometrical survey;
2. interaction analyses: which consist of geotechnical analyses and structural analysis;
3. drawing up of guide lines for the design of the most appropriate geotechnical and structural protection measures and the monitoring system.

The paper deal mainly with the monitoring aspects.

Metro C S.c.p.A. the contractor, has started the monitoring system in 2006 and systematic monitoring activities started in 2007, in the first track of Line C construction. All together some 30,000 measuring points have been installed ant relevant measurements have been implemented in the managing software – DDS – enabling a continuous monitoring of the parameters and management of the system.

Instrumentation can be divided in two main families:

- Monuments /structural monitoring
- Soil /Geotechnical Monitoring

Monuments monitoring included both static and dynamic systems with automatic data acquisition and transmission systems to measure the following parameters:

- Overall movements (by means of Automatic Total Stations –ATS - with geodetic prisms)
- Local movements / deformations (by means of joint meters, crackmeters, pendulums, tiltmeters, el-beams,)
- Load / Forces (by means of load cells and Strain Gauges)
- Environmntal conditions (by means of temperature gauges, wind gauges, rain gauges, humidity sensors)
- Dynamic / Seismic actions (by means of Seismometers, accelerometers)

Soil monitoring included both manual measurements and automatic data acquisition and transmission systems t measure the following parameters:

- Vertical movements (Settlement) (by means of Rod extensometers, incremental extensometers, ATS)
- Horizontal movements (by means of manual inclinometers, In Place Inclinometers, Extenso-Inclinomteters)
- Pore pressure and Water levels (by means of electrical piezometers, Casagrande piezometers, pressure transducers)

Figure XX. A view of Fori Imperiali Station construction site

Great care has been given to the definition of the installation procedures on the monuments to avoid damages and permanent effects. This has led to a complex analysis of the material properties, performed together with the Rome Superintendence of Cultural Heritage.

For underground installation, the Archeological Superintendence has supervised all the drilling activities to evaluate the importance of the findings. Moreover, due to the soil profile which include

an upper layer of 14 to 21 m of filling materials, attention has been paid to the grouting mx to use and to solutions to limits the volume of injected grout.

2 GROUND CONDITIONS

Based on the research carried out, the subsoil of T3 stretch can be roughly divided into the following lithological units, from the newest to the most ancient:

- Ancient and recent backfill, which generally consists of heterogeneous mixed loose soils, with a sandy-loam matrix, at times clayey;
- Recent alluvial slope deposits, mainly consisting of clayey and sandy loams as well as medium-fine-grained loamy sands;
- Pyroclastic soils, consisting of an alternance of cinerite levels, more or less pedogenized—tufa soils—and lapillus-scoriaceous levels, more or less cemented—granular tufa;
- Pleistocenic volcanic deposit complex, consisting of sandy and at times clayey loam and yellowish loamy sands;
- Pleistocenic complex of fluvial-lacustrine and fluvial-palustrine sediments, whose horizons can be described as follows: the top one is mainly made up of loamy sands, the intermediate one is made up of weakly sandy clayey loams and the bottom one consists of a heterogeneous coarse bank gravel in a sandy matrix;
- Complex of Pleistocenic fluvial-lacustrine and fluvial-palustrine sediments made up of substantial marly clays, with frequent intercalations of very dense sands.

Based on the survey performed, the piezometric surface of the water table in the pyroclastic soil complex in the underlying Pleistocene lacustrine and fluvial soils and in the more recent alluvial sediments is found between 26 and 13 m below sea level, at a depth of 8-10 m from ground level.

3 CONSTRUCTION TECHNOLOGIES

Box stations and shafts are excavated by the “CUT & COVER” method to reduce side work dimensions and construction time. This method starts with perimetral diaphragm walls excavations and develops with slabs construction underpinning the diaphragm walls during box station excavation until the foundation slab. The natural soil supports the slab during the concrete casting. The internal walls are realized bottom – up at the end of the excavation to waterproof the box station.

For the construction of the tunnels presently operating - about 19.5 km – the General Contractor used 4 EPB TBMs, whose cutter head diameter is 6.70 m and the precast lining is 30 cm.

[a] [b]

Fig. XX- [a] The 2 TBMs used to tunnels excavation and a TBM handling

About 1.5 km of the tunnels presently operating are realized with the traditional open face method because the TBM transversal section is not enough to hold the railway with the platforms. Also, each Line C TBM tunnel includes a single track, so this method has been used to realize a tunnel to receive a railway connection.

[a] [b]

Fig. XX– Tunnels excavated with the traditional open faced method

4 THE SAFEGUARD OF MONUMENTS AND THE METHODOLOGICAL APPROACH

The T3 stretch is presently under construction and it will run under the historic centre of Rome with its inestimable archaeological remains. The T3 stretch starts with San Giovanni Station and it is about 3 km long. It includes two stations—Amba Aradam and Fori Imperiali—and two shafts

with ventilation systems - shaft 3.3 and shaft 3.2. The tunnels are going to be excavated by two EPB TBMs at a depth of 30 m to 60 m (Figure 2).

The line tunnels have a circular section with an excavation diameter of 6.70 m and a 30 cm thick prefabricated lining of 5.80 m internal diameter.

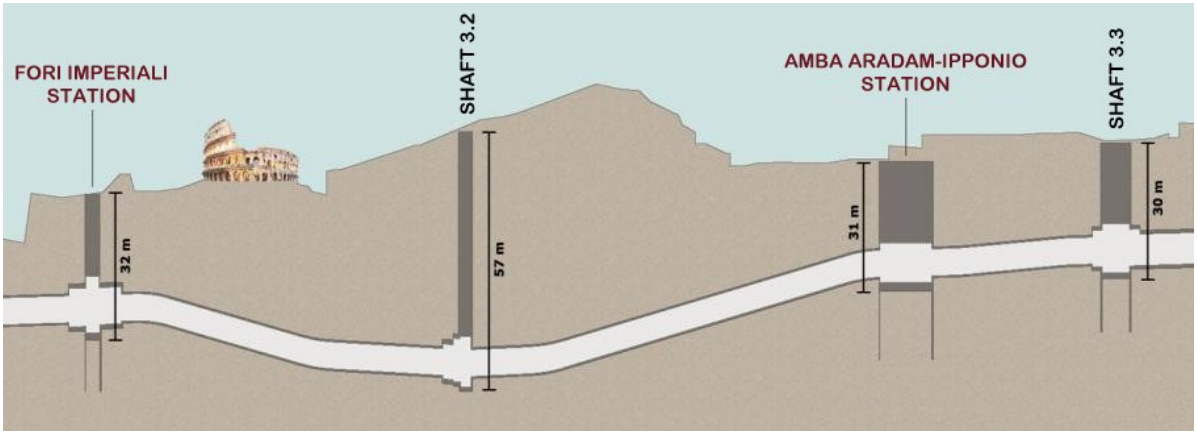


Figure XX. Longitudinal profile of T3 stretch

The Line C T3 stretch is characterised by the presence of historic buildings and monuments of great value such as the Colosseum, the Aurelian Walls and Basilica of Maxentius. The historic centre of Rome is a UNESCO World Heritage site and in order to safeguard all the monuments Metro C has constituted a specific Scientific Technical Committee (STC) which includes world-famous professors.

The STC was presided over by Professor Michele Jamiolkowski and consists of Professor Carbonara, Prof. Burghigoli, Prof. Kovari, Prof. Macchi and Prof. Funicello (who died in August 2009).

The aim of this Committee was to ensure high quality research methods and to analyze potential interactions between the new line and the historical monumental heritage.

The architectural history of each building was reconstructed, checking if and how the structural interventions made in the past may have altered its statics. Façades and internal structures have been inspected to detect the presence of possible cracks while the foundations were inspected to detect their type and depth.

The Committee coordinates and supervises the activities of working groups of specialists. These perform a range of activities aimed at defining the status of 40 historical buildings of particular relevance, (including Palazzo della Cancelleria, Palazzo Venezia, Palazzo Sforza Cesarini, Sant'andrea Della Valle) and 13 monuments (including the Colosseum, Basilica of Maxentius, Colonna Traiana and Vittoriano) in relation to the construction of the new underground.

The 5 work teams—consisting of university professors and specialists—operate in the following fields: Geology, Geotechnical Engineering, Restoration and Preservation, Structural Engineering, Monitoring System.

In 2007 Metro C instituted a permanent Technical Panel with the Ministry of Cultural Heritage and Activities officials in order to jointly analyze and share the project pipeline to follow for the safeguard of the monuments as well as the conclusions achieved by the STC through the analyses implemented by the Working Groups. The interaction studies, carried out by the team over two years, defined a methodological approach that can be roughly divided into 3 important steps:

- preliminary studies that consist of historical study and identification of the construction stages, identification of the type, the materials and the geometry of the foundations, identification of the material characteristics and of the building technologies, structural and crack pattern survey and geometrical survey;
- interaction analyses, which consist of level 1 and level 2 geotechnical analyses and structural analysis;
- drawing up of guide lines for the design of the most appropriate geotechnical and structural protection measures and the monitoring system.

The aim of the interaction studies is to evaluate the possible effects on the historical buildings induced by the displacement field generated by tunnelling and deep excavations. The expected damage evaluation was carried out with reference to the classification of damage by Burland (1995), based on the combination of the computed horizontal tensile strain and deflection ratio.

At a first stage, simplified analyses were performed using the semi-empirical method and neglecting the building stiffness and weight. The resulting displacement field was applied by the structural engineering group to a 3 D linear elastic or non-linear finite element model of the structure under examination. Based on the results of the geotechnical and structural evaluations, the study ended if the damage was considered negligible, or continued to a higher level of complexity (Level 2 analyses).

At this second stage, the interaction between the tunnels and the historical buildings was studied through full soil-structure interaction analyses, performed in both 2D or 3D conditions, accounting for the stiffness and weight of existing buildings and considering possible long-term effects. The computed displacement field was applied again to the structural model and damage was re-evaluated, independently, by both groups. Depending on the computed results, either damage was considered acceptable, or prospective remedial techniques must be designed.

The remedial measures can be geotechnical or structural. The geotechnical active measures consist of compensation grouting injections, whereas the geotechnical passive measures are cross walls. The structural active measures are bars or steel ropes and the structural passive measures are temporary supports.

The interaction analyses with the line tunnel mechanized excavation were carried out both with a design volume loss ratio of 0.5% and in a conservative condition with a twice as much ground

loss ratio of 1%. In case of tunnels excavated with the traditional method the analyses were carried out with the design ground loss ratio of 2% and of 4% in the conservative condition.

The first section of the T3 stretch TBM tunnels will run under the Aurelian Walls at Porta Metronia, while the other end of the tunnels will run along Via dei Fori Imperiali, very close to the Colosseo and the Basilica of Maxentius (Figure 3). These interesting examples may well illustrate the methodological approach that was adopted in the interaction studies.

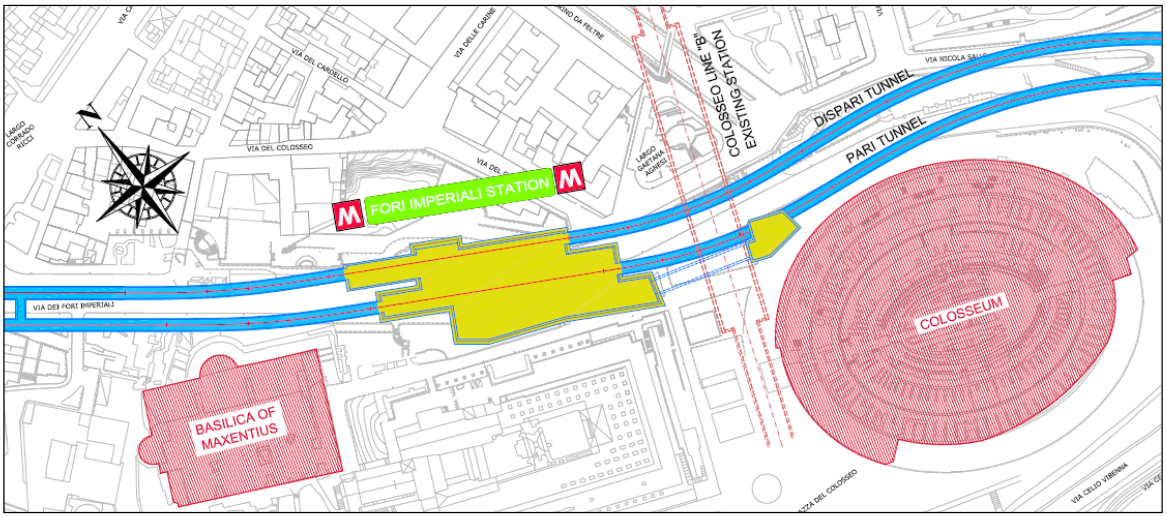


Figure XX. The interaction between tunnels and the historic centre of Rome

5 WORK PROGRESS

The construction of the T3 stretch started in 2013 with the beginning of the containment works of the station and line artefact excavations. In 2017 the two TBMs were lowered within the multifunctional shaft 3.3 from which the tunnel excavations are starting in the first semester of 2018. Starting from January 2019 the TBMs will undertake the line C gallery excavation in the historical centre of Rome. Once undercrossed Amba Aradam station, the TBMs will run under the Aurelian Walls at Porta Metronia (8) to interact with the Church of Santo Stefano Rotondo (7), the Celimontano's Aqueduct (6) and the Church of Santa Maria in Domnica (5). Afterwards the gallery route will pass tangentially to the Colosseum (4) and go along Via dei Fori Imperiali next to the Basilica of Maxentius (3), to the Colonnacce of the Foro di Nerva (2) and the Columns of the Foro di Cesare (1) after running under the Cloaca Maxima (Figure 14).

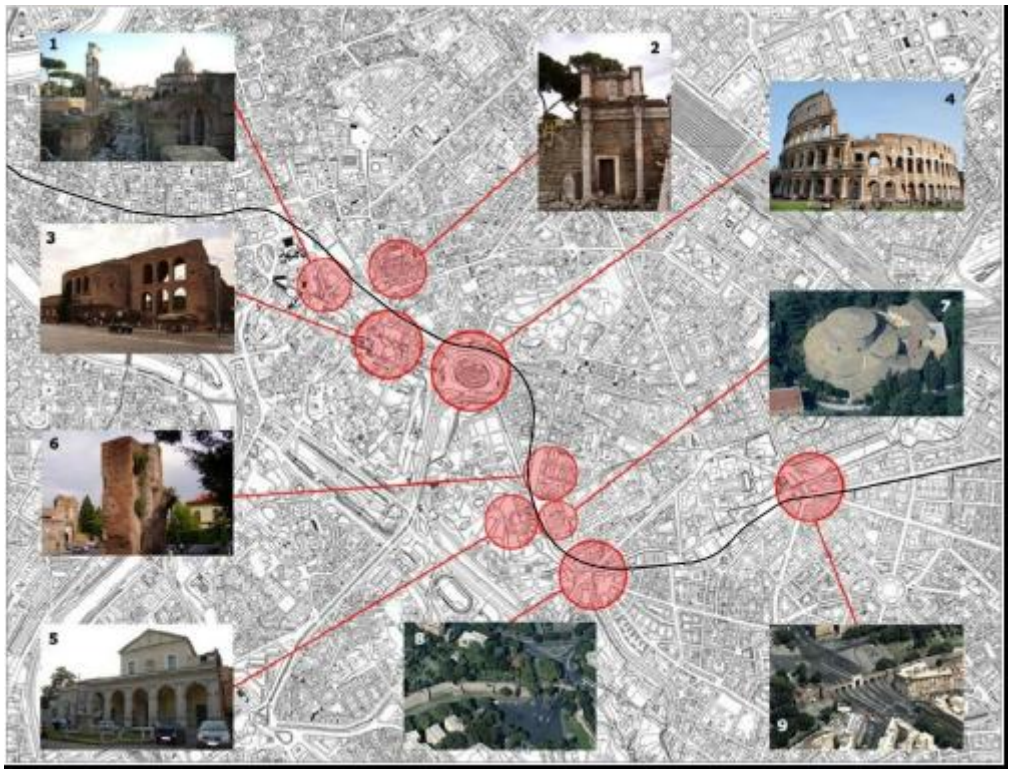


Figure XX. The downtown section and the interaction with the historic city center

6 THE MONITORING APPROACH

A complex monitoring system was developed and implemented with the following aims: check during construction of the design prediction; validation of the models adopted for the interaction analyses and calibration of the physical and mechanical parameters; implementation of the observational method for the activation of the settlements compensation measures or for the activation of specific back analysis. The monitoring systems consist of structural monitoring, geomatic monitoring and geotechnical monitoring systems, with different instrumentation. Monitoring systems are to be installed in advance (well before the beginning of works) in order to acquire the necessary reference basis with regard to the variations produced by seasonal and daily thermal cycles and to keep under control the damage already present and the possible unfavorable evolutions of the mechanisms activated or to be activated. Monitoring systems include laser and optical techniques, inclinometers, electric tiltmeters, vibration monitoring, thermometers and accelerometers. The results of the monitoring are part of a data bank to be used as real time information system to be used by all the insiders to follow the evolution of the deformative phenomena and promptly introduce possible changes to the gallery excavation process.

As per December 2017 (the works are still in progress) the following types and quantities of instruments have been installed on the whole C line:

Table A: quantity of instruments installed on the whole C line

Instrument	Installed Quantity	Readings
Prisms	10.218	Automatic
Levelling Pins	5.731	Manual
Strain Gauges	5.643	Automatic
Wall Clinometers / Tilt Beams	781	Automatic/Manual
Casagrande Piezometers	551	Automatic/Manual
Joint Meters / Crackmeters	431	Automatic/Manual
Inclinometers	384	Automatic/Manual
In Place Inclinometers	209	Automatic
Rod Extensometers	172	Automatic
Electric Piezometers	115	Automatic
Load Cells	67	Automatic
Extenso-Inclinomneters	3	Manual
Pendulums	165	Automatic
Triaxial Accelerometers	110	Automatic

Altogether, more than 700 buildings and historical heritages have been instrumented and continuously monitored.

To install instruments into the soil, more than 50 km of drilling (boreholes) have been performed. More than 300 km of electric cable have been installed to connect instruments to data loggers / reading panels.

For the Monumental part of the line, called T3, the following instruments have been installed as per March 30, 2018:

Table B: quantity of instruments installed on the T3 – Monumental – stretch of the C line

Instrument	Installed Quantity	Readings
Prisms	3012	Automatic
Levelling Pins	1467	Manual
Strain Gauges	1050	Automatic
Wall Clinometers / Tilt Beams	353	Automatic/Manual
Casagrande Piezometers	88	Automatic/Manual
Joint Meters / Crackmeters	286	Automatic/Manual
Inclinometers	105	Automatic/Manual
In Place Inclinometers	564 (1128 ch)	Automatic
Rod Extensometers	42 (126 ch)	Automatic
Electric Piezometers	88	Automatic
Load Cells	43	Automatic
Extenso-Inclinomneters	67	Manual
Pendulums	2	Automatic
Triaxial Accelerometers	161	Automatic
Total of measuring points	**7976**	**Automatic/Manual**
Data Acquisition units	74	

7 THE MONITORING INSTRUMENTATION

Due to the duration of the construction of the new Metro Line and, consequently, the duration of the monitoring systems, it has been considered that the initial choices could have been adapted to technological developments and to the availability of new instruments introduced by the Manufacturers. Moreover the experience gained during the construction has been used to improve the system reliability by using more appropriate components/instruments.

7.1 Type of Instrumentation

The monitoring instrumentation can be divided in two main families:

- Instrumentation for Building & Monuments / Structural monitoring
- Instrumentation for Soil / Geotechnical Monitoring

Monuments monitoring included both static and dynamic systems with automatic data acquisition and transmission systems to measure the following parameters:

- Overall movements (by means of Automatic Total Stations –ATS - with geodetic prisms) and manual leveling devices with leveling pins;
- Local movements / deformations (by means of joint meters, crackmeters, pendulums, tiltmeters, el-beams,)
- Load / Forces (by means of Load Cells and Strain Gauges)
- Environmental conditions (by means of temperature gauges, wind gauges, rain gauges, humidity sensors)
- Dynamic / Seismic actions (by means of Seismometers, accelerometers)

Soil monitoring included both manual measurements and automatic data acquisition and transmission systems to measure the following parameters:

- Vertical movements (Settlement) (by means of Rod Extensometers, Incremental Extensometers, ATS)
- Horizontal movements (by means of Manual Inclinometers, In Place Inclinometers, Estenso-Inclinometers)
- Pore pressure and Water Levels (by means of Electric Piezometers, Casagrande Piezometers, Pressure Transducers)

7.2 Measuring Principles

The monitoring instrumentation has been selected in order to provide for high reliability and robustness to reduce the maintenance activity which could be very critical in urban area and especially o the historical building where access is limited and controlled by archeological authority which has to release special permission for each intervention.

According to these assumptions, the following measuring principles have been selected:

Joint Meters	Potentiometer

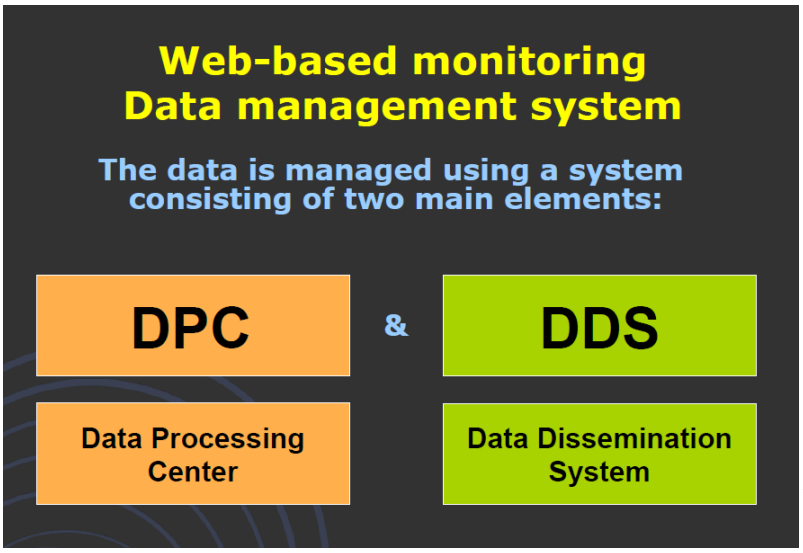
Crackmeters	Vibrating Wire
Strain Gauges	Vibrating Wire
Wall Clinometers / Tilt Beams	MEMS
Inclinometers	MEMS
Rod Extensometers	Vibrating Wire
Electric Piezometers	Vibrating Wire
Load Cells	Resistive Strain Gauge
Estenso-Inclinometers	Potentiometer-MEMS
Pendulums	Magnetic / Optic
Triaxial Accelerometers	MEMS

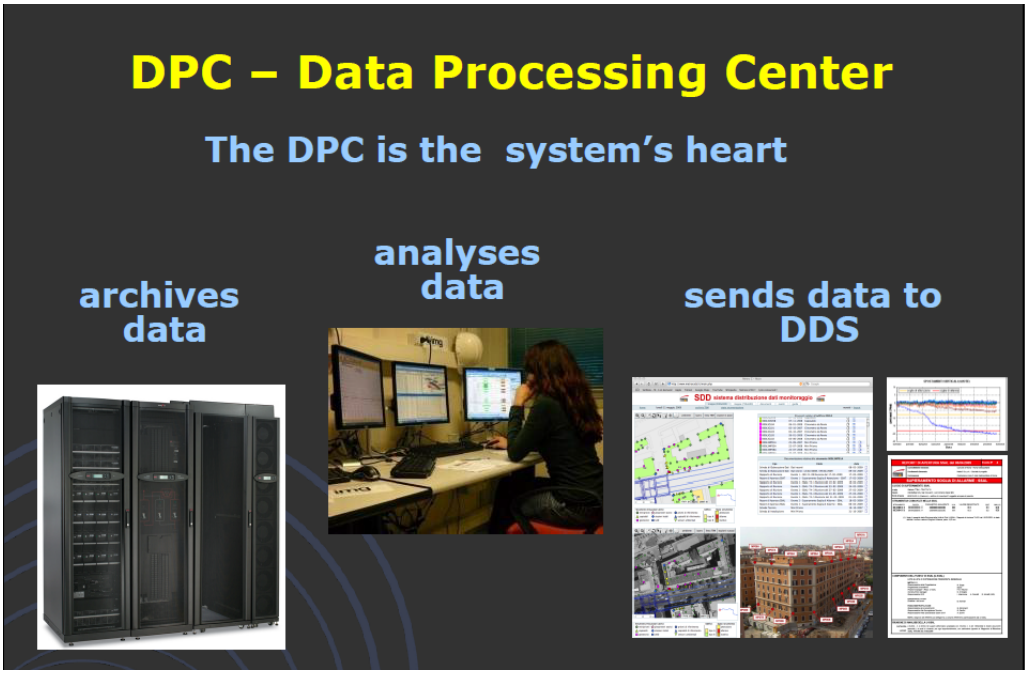
7.3 Data Acquisition

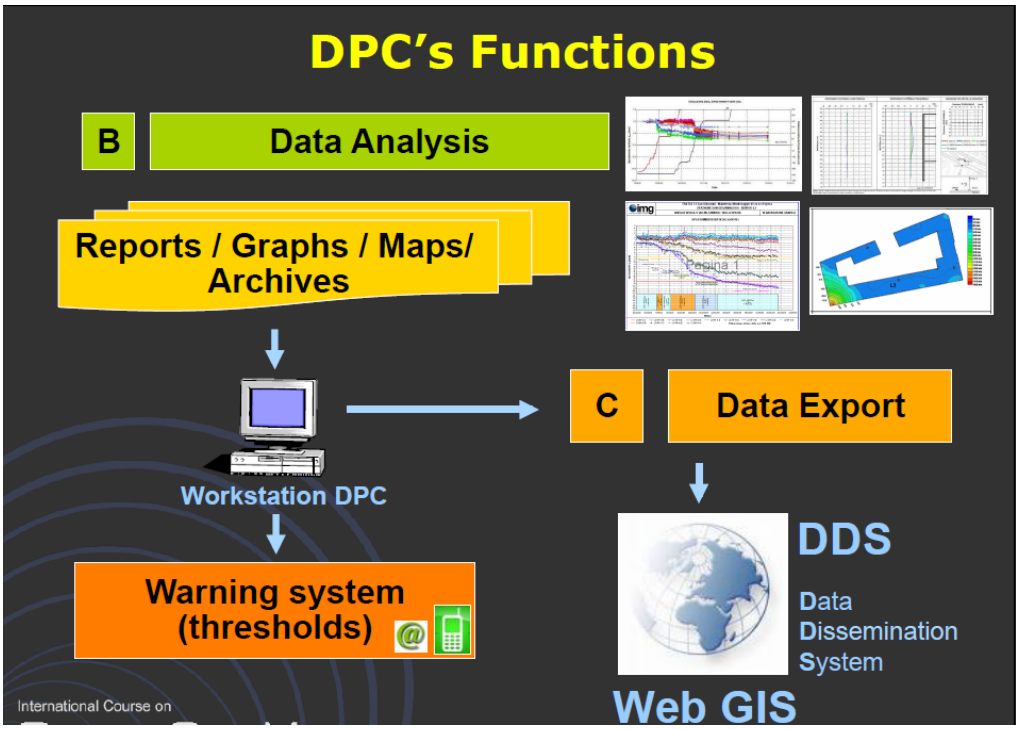
As indicated, data are collected both manually and automatically.
Most of the measurements are collected automatically due to the huge quantity of data to be gathered.

The general Layout of the data collection system is based on the use of:

- A: automatic data loggers connected to the Monitoring Centre by means of wireless connection devices. (see scheme A):
- B: data processing, analysis and reporting system by means of the dedicated DPC (Data Processing Centre) and SDD (Data Dissemination System) software packages which have been developed for the Metro Line A and B in the eighties – nineties by IMG.




DPC – Data Processing Center
The DPC is the system's heart
archives data
analyses data
sends data to DDS


DPC's Functions
B
Data Analysis
Reports / Graphs / Maps/ Archives
Workstation DPC
C
Data Export
Warning system (thresholds)
DDS
Data Dissemination System
Web GIS
International Course on

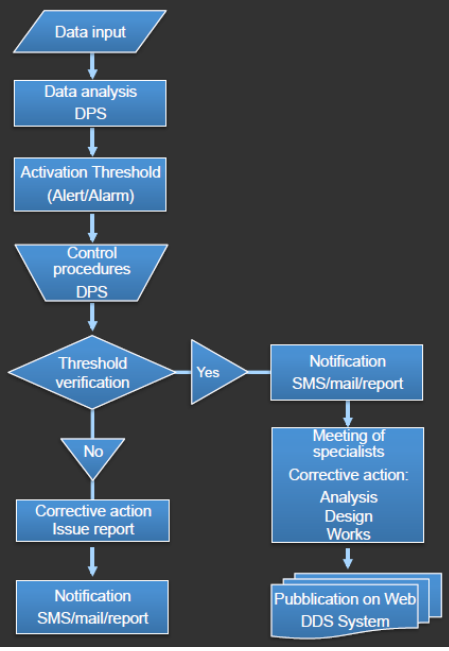
DPC's capacity to handle critical issues

DPC has the ability to:

- recognize noteworthy information
- immediately communicate when pre-established values have been reached
- when reference values are reached, an automatic procedure begins.

Attention Threshold

Alarm Threshold



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Sharing Data
DDS- Data Dissemination System

The DDS is the system that allows the sharing of the monitoring data

- it's a browser application ;
- allows easy access to information ;
- no special training is needed ;
- doesn't require any software installation ;
- can be used with any web browser;
- allows rapid sharing of the monitoring reports ;
- data, reports, and graphs are available anytime and anywhere ;
- the only requirement is an internet connection .

7.4 Installation

Installation of the instruments has been one of the most challenging task of the work due to the quite unique conditions which have to be faced.

In fact, a large number of instruments have been installed on the monuments – Colosseo, Basilica d i Maxenthium, S. Stefano Rotondo, Fori Imperiali, etc… - which are under the control of the Archeological Ministerial Office which has imposed very restrictive specification to the installation procedures.
On most of these monuments, drilling holes was not allowed as well as the use of resins or grout was restricted. Moreover instruments had to be hidden or at least covered not to disturb the view of the monuments. As well as the allowed holes had to be plugged, at the end of the monitoring, by using the original material collected during drilling.

In order to overcome these problems, special care has been used in drilling by minimizing the number and diameter of the holes – max 6 mm – and by collecting the stones' powder produced during drilling, and to use it at the end of the monitoring to close the holes mixing it with special resins indicated by the archaeological superintendency.

For instruments to be fixed by resins, special resins have been indicated by the archaeological superintendency. Tests have been conducted under the supervision of the Archaeologists before defining the actual solution.

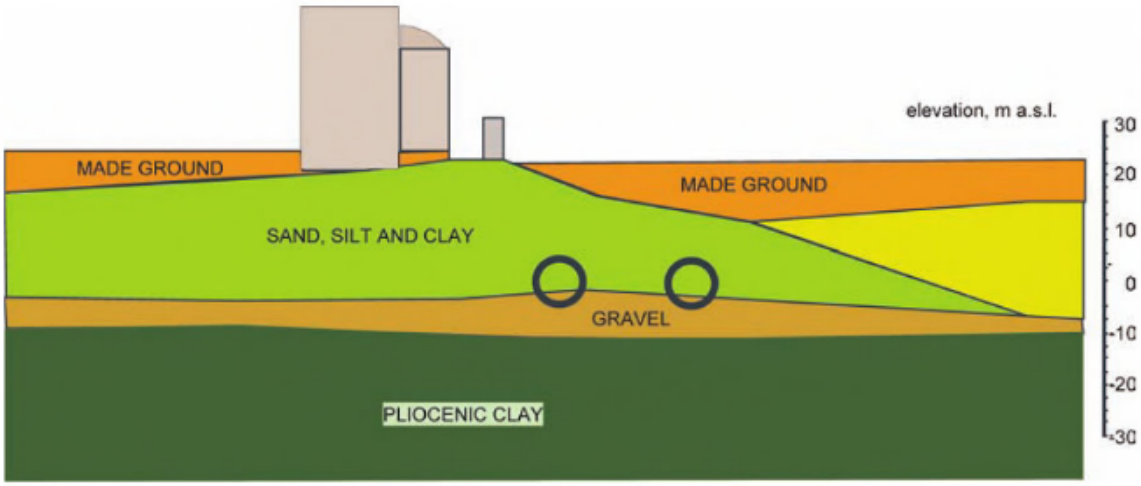
Connections between instruments and switching panels or data loggers have been made by cables. This decision was taken because at the beginning of the installation – 2012 - the wireless technology was not commercially available and not well tested for suitability in urban environment where the line of sight among the wireless units is limited and the interference by a number of sources (cell phone networks, public utility communication networks, etc..) as well as for restriction due to public security regulations have led to select the wiring solution.
This has increased to problems of installation on the monuments because the request to hidden them to reduce the visual impact. Moreover the need for fixing and protecting them has induced added difficulties and time / costs related to the need of using elevators (up to 30+ m) to install them.

It is clear that nowadays the wireless solution should be considered and selected to reduce costs and time for installation and maintenance as well as the reliability of the system being cables subject to problems due to overvoltage and lightning. This reduction of costs have been evaluated to be enough to results in global costs reduction if compared to the cost of purchasing, installing and maintaining the cables, without considering, furthermore, the increase of the overall reliability of the system.

For instruments to be installed into the soil, the major problems were:

a) The soil stratigraphy
b) The interference with archeological remains
c) The grouting of the instruments

a) The soil stratigraphy in the centre of Rome is quite complex. (fig. XX)
The upper layer consists of 15 to 18 m of filling material with presence of archaeological remains. This required the presence of the archaeologist to check for the presence of significant elements to be classified and filed or even to came to the decision to change the borehole position. Moreover the first 2 m of the boreholes had to be drilled by hands using an auger and recovering the material very carefully to analyze the soil for possible presence of evidences of historical or archaeological remains.
Below the filling layer, a quite variable layer of silty clay extends from 18 to 23-27 m.
Below this, a 3 to 8 m thick layer of sandy gravel is present.
Below this, there is a thick pliocenic clay layer which extends down to 50 m, and more, which is the depth limit of the installations.
The typical depth of the tunnels is 22 m – top - to 29 m – bottom - from G.L., inside the



Silty Clay and Gravel layers.

Fig. XX – Typical soil profile in the centre of Rome

b) The interference with archaeological remains are a critical aspect. Any borehole, excavation, trench or man hole which are interesting the soil below the ground level require the presence of an archaeologist who has he right to stop any activity in case something with archaeological value is found.
This is increasing the time requested for installation and make the activities to be uncertain because conditioned by the findings.
Moreover, as it will be indicated in the next point, the presence of archaeological remains alter the permeability od the soil (it is much lower than expected) increasing the volume of grouting to use for instruments installation.

c) The complex soil profile and mainly the presence of the upper layer of filling material have created a major problem in grouting the instruments inside the boreholes.
There have been example of installation where the actual volume of grout has been up th 5 times the theoretic one.
Foe a 35 m deep installation of inclinometric casing as well as for Trivec casing, the average theoretic volume of grout is between 350 to 450 liters. The actual volume was normally 150% of the theoretic one, up to 500%+ .
This has a double impact: cost & time for installation.
Cost increase is due the cost of grout components and to the time needed to grout the instruments. Grouting had to be done during a period of min 2-3 days necessary to let the grout settle into the borehole and to let it cure. During this time frame the drilling rig cannot work reducing the production with increase of the overall costs.
Moreover it has to be considered the geotechnical problem related to the fact that the conformity of the installation is reduced because a large volume of soil is interested by the grouting infiltration with consequent different strength and stiffness of the soil with respect to the undisturbed conditions.

8 THE RELIABILITY OF THE INSTRUMENTS

With reference to table B, the following table C provifde for the number of failure recorded during the monitoring period 2011 – 2017.

As it is clearly shown, the main cause of failure / damage is ligthting, not considering dmages due to construction works (excavation, demolitions, earth works, ect..) which are to be considered as “physiologica” in this kind of activities and are normnally considered in the definition of the quantity and location of the measuring points.

It has to be pointed oput that the small number of failure during installation or during the monitoring time is probably due to the care that has been given to the installation activities and to the procedure which have been applkied. This was mainly due to the consideration that most of the istruments were to be instyalled on monuments where each intervention is quite critical, time consuming, expensive and subject to authorizations from authorities. Therefore the installation procedures have been developed accordingly, takng into consideration that the cost for recovering and reinstalling and instrument to be repaired would have been much higher that the cost for an accurate installation with the necessary control, the required protection and, mainly with the supoervision and assistance by qualified personnel, even if time requiring and, apparently, not economic.

This is probably the main factor which led to have this quite low percentage of failure.

Instrument	Installed Quantity	Failed Instruments	Failure cause
Prisms	3012	**27**	Vandalism
Levelling Pins	1467	**50**	Site activities – Excavation
Strain Gauges	302	**43**	Concreting – Cabling – Lightning – Not identified
Wall Clinometers / Tilt Beams	353	**2** **21**	Vandalism Lightning
Casagrande Piezometers	88		
Joint Meters / Crackmeters	286	**4** **4**	Impact Lightning
Inclinometers	105		
In Place Inclinometers	564 (1128 ch)	**12 (24 ch)**	Not identified
Rod Extensometers	42 (126 ch)		
Electric Piezometers	88	**3**	Damage during Installation
Load Cells	43		
Extenso-Inclinomneters	67		
Pendulums	2		
Triaxial Accelerometers	161	**7**	Lightning
Total number of failure		**173**	
Failure of Data Acquisition Units	74	**2**	Lightning

The noeverall percentage of failure of 173/6580 = 2.63% is a very small percentage, much smaller than expected and smaller than "normally accepted rate of failure" for monitoring projects which is between 4 and 8-10%.

These general figures are obviously to be considered as reference only. They can vary according to

the conditions of the project and to the number and variety of the installed instrumenbts and, not to forget, the communication device: cables or wireless.

9 THE MANAGEMENT AND MAINTENANCE STRUCTURE

MERTO C S.c.p.a. has invested a lot on the monitoring and on the and on its management.

As mentioned at chapter 1, a specific Scientific Technical Committee (STC) was appointed to overview all the design criteria and to indicate the monitoring requirements for controlling the construction works and, mainly, to guarantee the safety of the monuments having, as main aim to ensure high quality research methods and to analyze potential interactions between the new line and the historical monumental heritage.

This was the basic conditions for designing the monitoring system and to define the solutions to apply. Moreover the continuous supervision of the STC to the installation activities was another key point to improve the quality level of the activity and to reduce the failure rate enhancing the resulting data quality.
Again it has to be considered this not as a major cost but as an investment to obtain reliable measurements and to reduce the maintenance costs.

The low failure rate is a consequence of the investment METRO C did on the STC and on the installation and maintenance team. A qualified and well trained group of technicians from IMG. Coordinated by the METRO C Monitoring responsible, together with all the Technical Department personnel in continuous contact with STC Experts as well as a number of other experts have led to enhance the reliability of the monitoring systems and to provide for high quality data to be used for on and off-line processing.

An important aspect to consider is the problem related to manual measurement which require for skilled personnel, reliable instruments, ad-hoc procedures and back up tools in case of problems / failures. This problem is enhanced during the tunnel excavation phases which requires for an high frequency of measurement.

Again METRO C as faced it by ensuring the support of m trained personnel and qualified site responsible as well as for data processing, analysis and presentation.

This have been the key points which led to obtain a high reliability system with a quite low failure rate.
Related costs have to be compared to costs and problems related to intervention on the monuments during activities with consequent increase of the overall costs and lost of important information and opportunities in a quite unique scenario.

10 CONCLUSIONS

The high reliability of the monitoring system in such a challanging and critical scenario as the monumental part of the new MetroLine in Rome have been achieved by approaching it in terms of dedicated design, appropriate working procedures as well as supervision to the activities and continuous feed-bak from site to designers and Experts.

Costs related to the purchasing of the instruments as werll as costs for installation have been considered as part of the overall budget and not, as unfortunatelky very often happen, the forst point to consider.

Moreover large part of the positive results have to be assigned to the decision of supervising all the activities by Committed and well trained personnel and by the continuous iunteraction between site activities / results and Designer / Consultants.

These, together with a selection of adequate insytrumentation and the commitment of the instrumentation Manufacturers have given the opportunity of reaching a very good level of overall relaibiulity oif the system and a very good quality in acquired data.

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