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The High Speed Railway Hub of Florence: 4D-Monitoring - Data Integration and real-time post-processing during Construction Phase

P. Cucino[1], G. Eccher[1], C. Meyer[2]

[1]*Monitoring department, SWS engineering, Trento, Italy*

[2]*Monitoring department, Terra International ltd, Othmarsingen, Switzerland*

ABSTRACT: The ongoing execution of the urban tunnel for High Speed Railway in Florence requires special monitoring care. Excavation in soft soil, below water table, under passing sensitive buildings and historical structures, leads to demanding monitoring requirements including real time interpretation of surveying results. Real time interpretation comprises the definition of building and geotechnical critical parameters, the ability to correlate data coming from different data sources, e.g. TBM Vs monitoring measures, and the need to compare and correlate measurements to further improve the measurement accuracy or reliability. A quick, almost real-time, interpretation capacity can only be achieved by means of a reliable monitoring platform, retrieving and reducing manual and automatic measures, combined with a post-processing platform able to perform data integration and manipulation in real time. This paper complements the contribution describing the workflows of the monitoring system implemented in Florence, and focuses on the technologies developed to cope with data sources integration and derived parameters calculation. Furthermore, the paper describes the capabilities of the post-processing platform to interface with compensation grouting activities and to offer user-friendly visualizations and comprehensive export facilities enabling engineers, work supervisors and contractors to retrieve complete information required to double check data and ensure excavation safety.

1 Introduction

Monitoring activities related to urban underground works had become a complex universe: a large number of physical domains to monitor (geodesy, geotechnical science, hydrology, hydrogeology, vibrations, noise, pollution); complex machineries and special techniques to control (e.g. TBM, compensation grouting, ground freezing, etc.); many sensors technologies to handle (vibrating wire, hydrostatic cells, fiber optics, etc.); large amounts of data to screen; heterogeneous data sources to combine. Each point of the list requires special expertise, know-how and dedicated tools.

New technologies have developed accurate, reliable and resistant sensors and receivers to trace physical parameter evolution in space and time. Automatic sensors and receivers can automatically forward electrical readings at high frequency to well structured database for their validation, reduction and storage. The unit cost of readings has significantly reduced in time allowing for a large number of parameters at hand to assess risk for underground worksite and for existing superstructures, facilities and environment. Nevertheless, the large amount of data available has introduced problems related to data handling, interpreting and reducing. An efficient underground work monitoring cannot be performed without dedicated tools which can handle, analyze and post-process data as fast as they are produced by the monitoring sensors and instruments installed.

The ongoing execution of the urban tunnel for High Speed Railway in Florence is a good example of how a demanding monitoring task is being tackled.

2 Florence high speed railway tunnel and monitoring project

The tunnel to be executed is part of the European high speed train network towards Rome. The underground works consist of: 6.5 km double tunnel excavated with an EPB TBM; a northern portal in Riffredi area; a southern portal at Campo di Marte (which is also the TBM launching pit); and a new underground central station in Belfiore area (Figure 1). Excavations techniques employed comprise mechanized and conventional tunnel excavation, cut and cover and deep excavation. Florence soil is characterized by soft clays and sands. The water table lays above the tunnel crown for most of the track. The tunnel under passes more than 150 buildings, many of which can be regarded as historical buildings, with a cover between 5 m to 20 m.

Passive and active protection measures have been designed to guard existing buildings, bridges and rails. In particular, compensation grouting has been foreseen in the southern part of the tunnel where two buildings are going to be under passed with a cover between 5 m to 10 m, and also at about 3 km in the north of the southern portal to protect the ancient Fortezza Da Basso (represented in Figure 1).

An intense monitoring layout has been designed and installed to insure work execution and existing structures safety. About 10.000 monitoring sensors (3D topographical targets, piezometers, multibase extensometers, tShapes, inclinometers, hydrostatic cells, crack-meters, strain-gauges, leveling points, etc.) guard soil, buildings and facilities surrounding the excavation areas as well as the temporary and permanent retaining underground structures.

Automatic instrumentation has been intensively employed to insure the reading frequency demanded by the client. Monitoring data are systematically validated, reduced and stored in a remote database accessible in real time through a well-established web interface (SwissMon).

Furthermore, a special software tool (tManual) has been developed to cope with manual readings, allowing for "manual data" to flow within the remote database with almost the same ease, reliability and speed of automatic data.

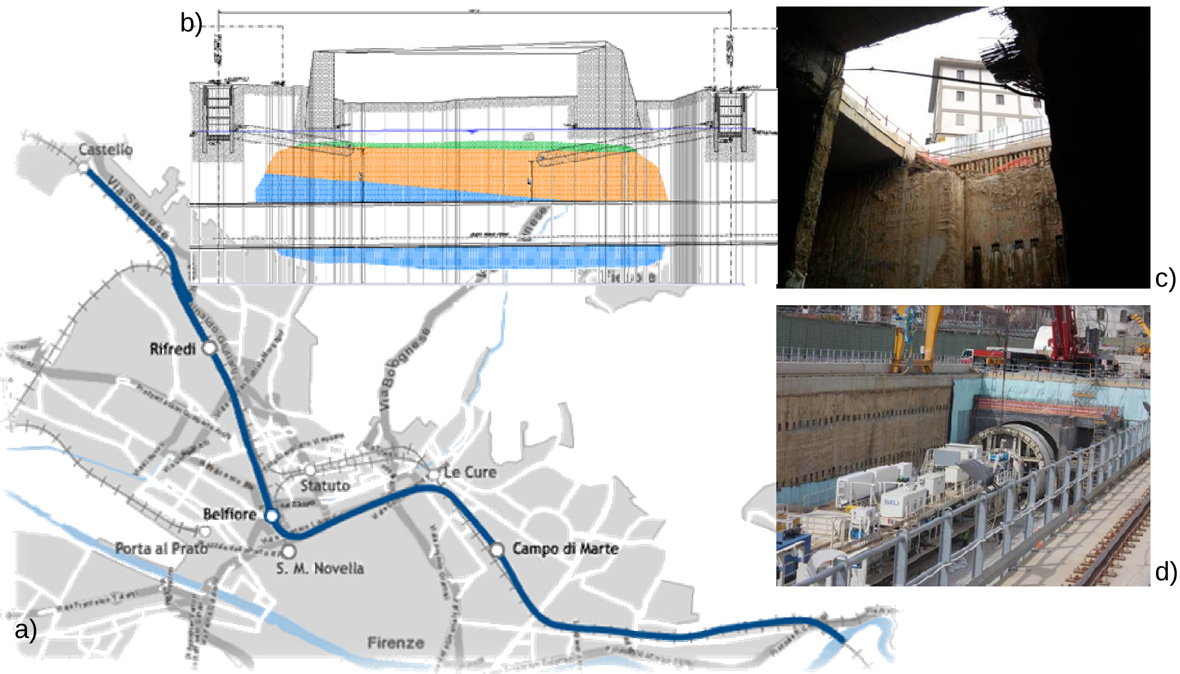

Figure 1. Florence project highlights: a) planview; b) longitudinal section at Fortezza Da Basso; c) TBM extraction shaft at the northern portal; d) TBM installed at the southern portal

3 Data interpretation critical requirements

Florence monitoring system, together with TBM data-logger and driving system, and work supervisors provide a comprehensive set of information where to base engineering interpretation for the overall project risk assessment.

Nevertheless, monitoring platforms or boring machines data-loggers are not always able to provide the data in the format and in the combination required by the engineers for an immediate interpretation. Engineering considerations are often based on derived parameters better than on pure readings, or, furthermore, on the comparison of correlated parameters that may belong to different data sources. As an example we list some of the data interpretation critical requirements in Florence project, which may be common to many other urban underground project, that could not be directly solved accessing real-time measures.

3.1 Building risk assessment

Florence sensitive buildings are monitored through 3D optical targets, precision leveling points, hydrostatic level cells and crack-meters. Whereas the latter supply a direct measurement of the building structural health, immediately forwarding information about existing cracks opening, the readings obtained from the remaining targets have to be combined to assess the actual building risks. As extensively described in the relevant literature (Boscardin and Cording 1989, Burland 1995, Mair 1996-2008, Peck 1969, Potts and Addenbrooke 1997, Standing 2001), building structural health is strictly connected to bending or shear deformations which introduce local tensile stress concentrations which lead to structural cracks formations.

Alert triggers for building risk assessment (Figure 2) shall be not only the displacements, δ_{max}, read by monitoring instruments, but also parameters derived from those measures, such as the maximum relative rotation between two measured points, θ_{max}, and the maximum deflection ratio, δ/L_{max}, which are direct causes of localized tensile/compressive stresses within the structure.

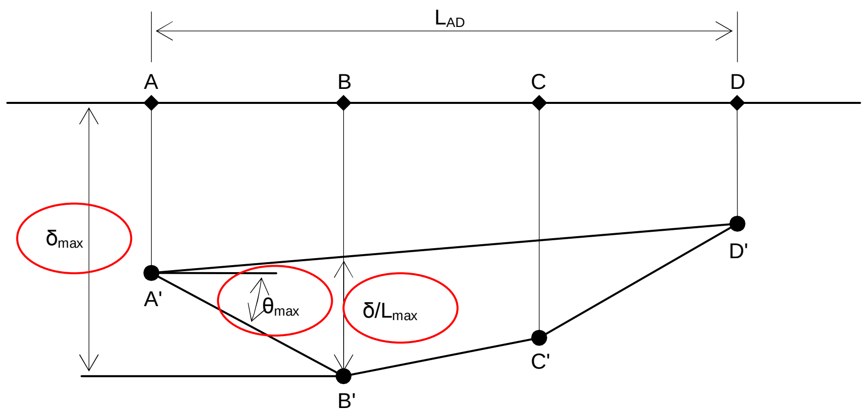

Figure 2. Building risk assessment principal parameters

Sensitive buildings of Florence are monitored by automatic instrumentation at a frequency that, in critical phases of the excavation, can rise to one reading every 15 minutes for more than 20 sensors for each building. Considering that normal monitoring platform can handle automatic alarming only on the direct measurements, this would have lead to critical problems: either not to have alarming on the most important parameters to be screened, or to provide 24/7 the staff required to focused on real time derived parameters calculation.

3.2 Compensation grouting activities

Compensation grouting activities are strictly connected to building monitoring activities previously described. In Florence, as in many other similar projects, three compensation grouting phases are foreseen: pre-treatment; concurrent grouting; final compensation. The first and the last phase can be correctly handled with a sound compensation strategy based on the real-time control of total displacements of the monitored building: the desired heave or displacement is assessed for each displacement control sensor and the grouting strategy is designed to produce a balanced movement of the building foundation, avoiding distortions. Concurrent grouting requires a further step. Concurrent grouting may be triggered by measured displacements exceeding threshold values, and also by calculated distortion or deflection ratio exceeding limits (Schweiger and Falk 1998, Kovacevic et al. 1996, Wisser et al. 2005). Nevertheless, the aforementioned calculated parameters shall be automatically derived as soon as deformation measures are available to insure an effective concurrent grouting.

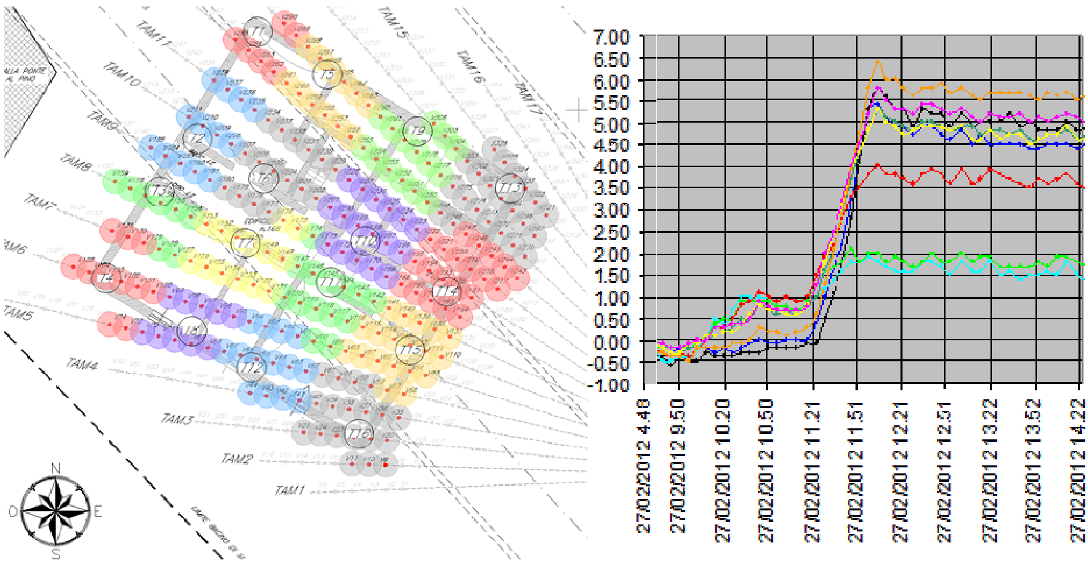

Figure 3. Example of compensation grouting detailing in Florence: plan view of grouting ports and reference monitoring target; graph of heave achieved during pre-treatment phase

3.3 Structural monitoring

Tensions are to be monitored in key structural elements of Florence projects to insure that service loads are compatible with design assumptions. Typical key structural elements are precast segmented lining rings and temporary struts for retaining wall stability. Also in this case control parameters cannot be directly obtained from the monitoring sensors and shall be computed.

Tension is indirectly measured by means of strain-gauges installed on principal reinforcing bars in precast concrete segments and installed directly on steel struts for temporary supports (Figure 4). Strains measured by monitoring sensors shall be cleaned by the thermal component to get the actual strain component which results in structural stresses. Furthermore, for overall project economy, there is not a one-to-one correspondence between strain sensors and temperature sensors, so that often more than one strain-gauge is referred to one temperature sensor. Thermal compensation shall than be analyzed for each case.

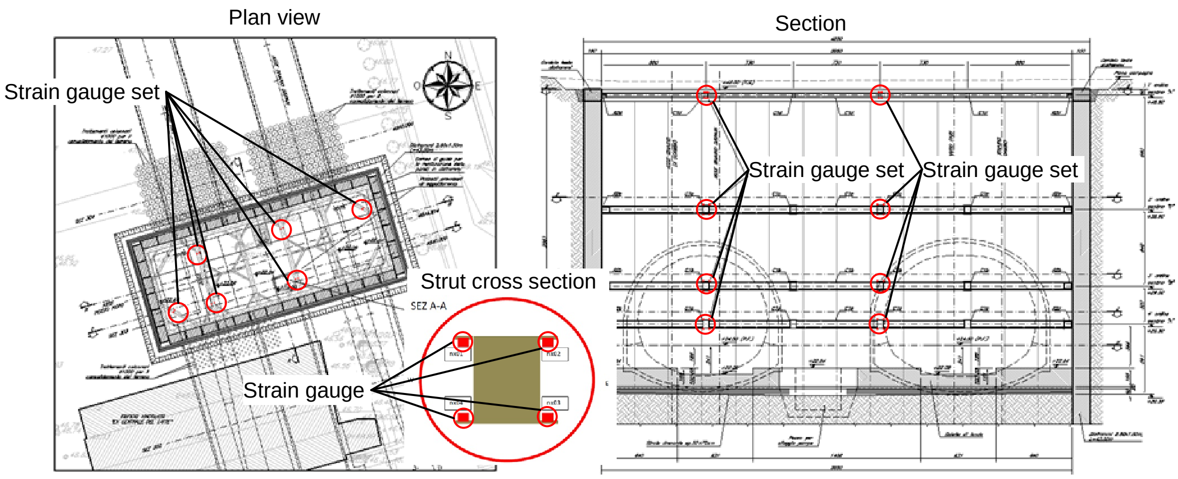

Figure 4. Example of structural monitoring in Florence: plan view and section of strain-gauge sets locations; position of strain-gauges on the strut cross-section

3.4 Real-time access to TBM data storage and reporting

TBM are equipped with dedicated data-loggers and driving systems which record at high frequency the machine state parameters and its position in time. In Florence, the client and the work supervision asked for a real-time access to, and an effective storage of the most important machine state parameters, such as pressure at front, EPB volumes and pressures, excavation weight, thrust, torque etc. The aim is to cross-check monitoring data with TBM data to find specific correlations in case of critical events. This task cannot be easily fulfilled simply by storing logs of the TBM but requires a higher level of integration with monitoring data, i.e. to have TBM data available on the same platform/database where monitoring data are stored to extract combined reports correlating TBM parameters with monitoring data.

3.5 Data reduction and reports

A final critical requirements for Florence data interpretation is the periodical reporting: a record of the principal monitored parameters evolution in time, mutual correlations and overall project risk assessment.

Due to the required reporting frequency and to the large number of sensors to be reported, a manual access to the monitoring platform and to TBM logs for data retrieval, statistical reduction in time (average, media, etc. over a reasonable time range for a better data representation) would have not been affordable in terms of resources to employ to fulfill deadlines.

4 Post-processing platform

Along with SwissMon monitoring platform, a dedicated web platform (Figure 5) has been developed to fulfill data interpretation critical requirements and to allow monitoring and interpreting team to focus on readings quality and overall project risk assessment better than deploy a large amount of time and resource in data gathering and formatting, manually repeating standard procedures. Some of the principal characteristics of the post-processing platform are detailed in the following chapters.

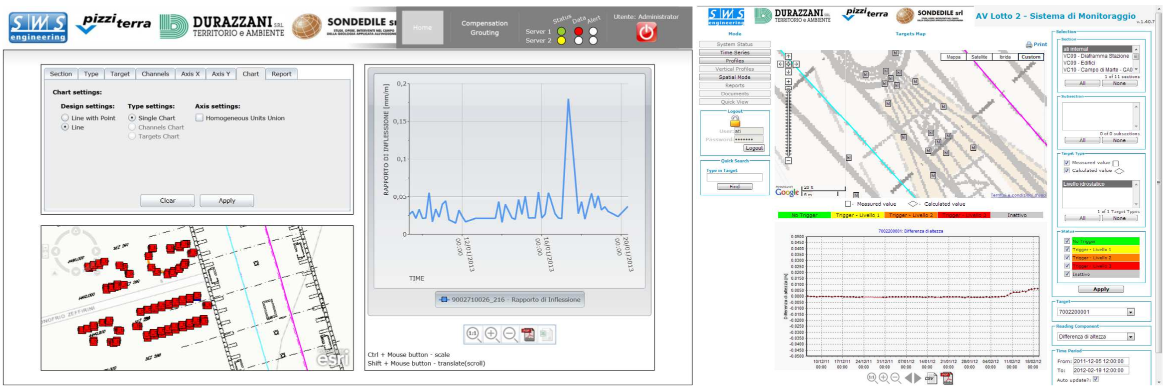

Figure 5. General layout of SwissMon (left) and Post-processing (right) platforms for Florence

4.1 Data sources integration

The first critical issue to be solved was to establish a formalism able to automatically access and integrate the different data sources. In Florence project, SwissMon monitoring platform (Figure 5) performs a first main step for data gathering and integration. Geodetic, geotechnical, hydro-geological data coming from manual and automatic instruments and targets are consistently collected in an organized database. Usually, monitoring databases are not open to external sources and can be queried only through their dedicated software platforms which do not allow a comprehensive export of all monitoring information required for a complete data interpretation. Nevertheless, an exchange protocol has been established to formalize an automatic data forwarding. As soon as SwissMon platform retrieves data from manual or automatic instruments, the readings are made available in a self-contained data package on a dedicated FTP folder, directly accessible by the post-processing platform.

TBM data-loggers continuously record machine state parameters and position. These files are locally stored in the machine control unit and, generally are not accessible. A periodical automatic export has been established to have TBM logs available in open format files directly accessible on a dedicated FTP folder.

The post-processing platform automatically gathers data from the FTP folders and consistently stores monitoring and TBM readings in a central database. Dedicated automatic routines have also been established to forward data back to SwissMon platform for a consistent storage and representation.

A schematic view of the data exchange is shown in Figure 6. The data exchange protocol established allows to create a continuously updated database containing the required information for a complete data interpretation.

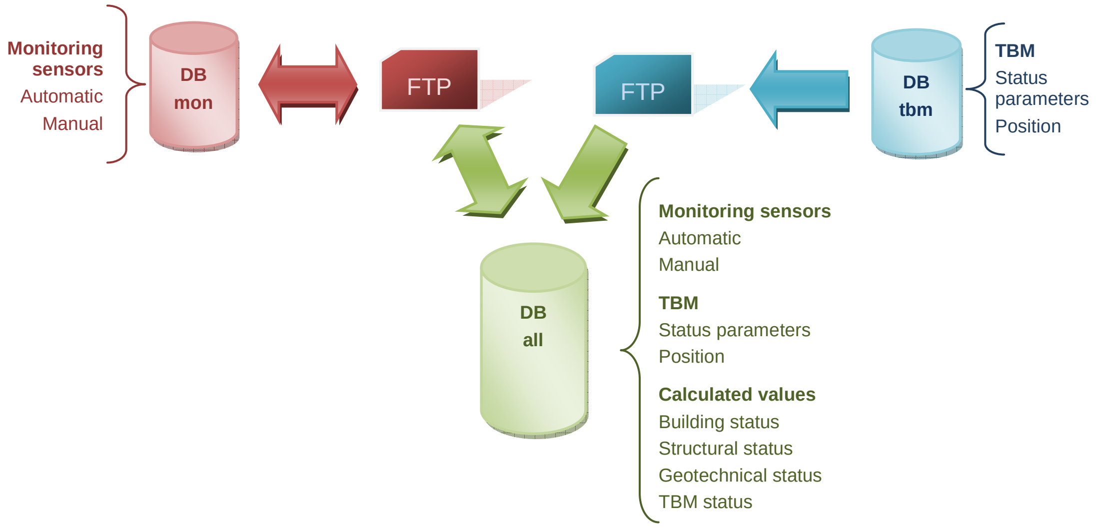

Figure 6. Data flowchart between data sources

4.2 Automatic derived data calculation - calculated values

Each time that the post-processing platform receives a complete series of data from the external data-sources, automatic calculations are performed to derive critical interpretation parameters such as building deformation and maximum deflection ratio, volume loss during excavation, characteristic soil *k*-coefficient, mechanical strain in structural members, displacement distribution along inclinometers derived from point-wise inclination values.

Each calculated value belongs to an "artificial target" which is univocally defined by an ID and a position. Artificial targets are shared with SwissMon together with the calculated readings so that users can access both project platforms (monitoring or post-processing platform) to find monitoring readings along with calculated parameters. Figure 7 shows how the same maximum deflection ratio is represented in both platforms.

This parallelism allows for a consistent data presentation and a consistent alarm management. Standard alarming utilities of SwissMon monitoring platform can be applied also to calculated values. Threshold values can be set on calculated values (e.g. on maximum deflection ratio) in the same manner used for monitoring parameters. Potential hazard on buildings or on excavation stability is in this way completely defined and traced in real-time.

In order to represent also TBM data on both project platforms, TBM state parameters have been treated as calculated values and forwarded to SwissMon platform.

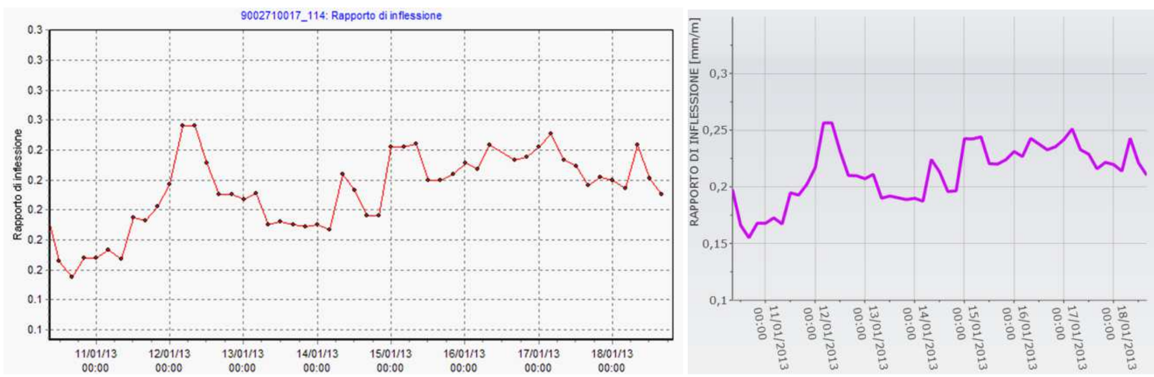

Figure 7. Calculated values representation in the two project platforms (maximum deflection ratio)

Automatic calculated values calculation is at the base for compensation grouting control. A dedicated module integration is currently being developed to guide grouting activities in real time, integrating readings from the monitoring system, calculated values and information from the grouting utilities (grouting volumes, pressures, etc.).

4.3 Data correlation

To correlate data interdependence is in general particularly useful to plot selected variables trend on the same graph. Usually, monitoring platforms are focused on sensors readings validation and analysis and allow only for single sensor plots.

To support data interpretation, the post-processing platform has focused on the ability to plot multiple charts (Figure 8). Combined graphs can be obtained for one or more sensors using one or more their channels (e.g. a 3D target, the three channels easting, northing and height can be plot together on the same graph). This allows for example to compare readings obtained with different sensors in the same position (e.g. comparing height differences measured with an hydrostatic cell and a 3D target Figure 8 left), or to compare the influence of temperature on some readings (Figure 8 right).

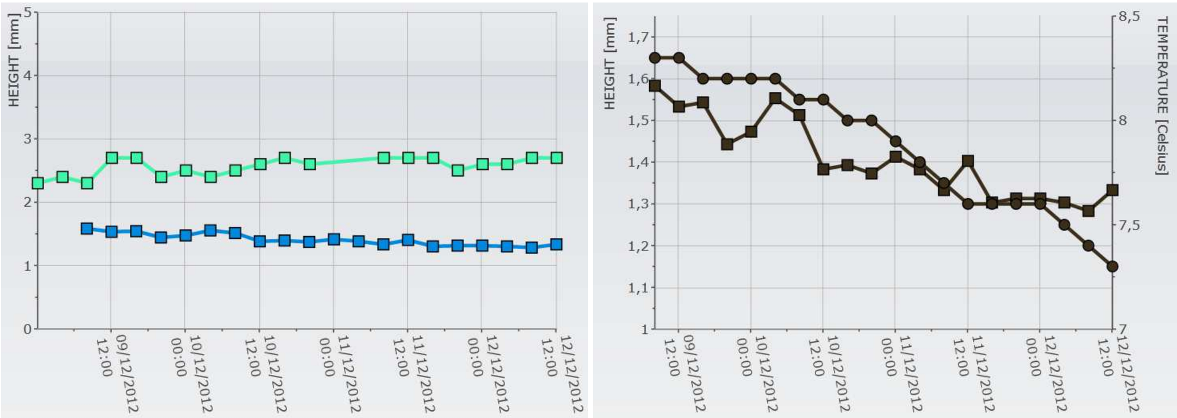

Figure 8. Examples of data correlation in the post-processing platform

4.4 Reporting and data reduction

Periodical reports are meant to capture a particular evolution in a given time-frame for a reasonable sampling rate. Depending on the phenomenon to be analyzed, the time frame can vary from minutes to months and very seldom the interval of readings corresponds with the desired readings sampling frequency. In many cases, statistical operators shall be applied to the readings in order to "clean" the information from continuous oscillations and spikes. Figure 9 shows an example where a daily median is applied. In order to support the monitoring team and the engineers, a reporting tool has been implemented in the post-processing platform. The user is able to select the sensors of interest, the time-frame, the sampling rate and the statistical operator to obtain a systematical graphical output to be inserted in the report, saving time and reducing the risk of introducing manual errors in data formatting and reducing.

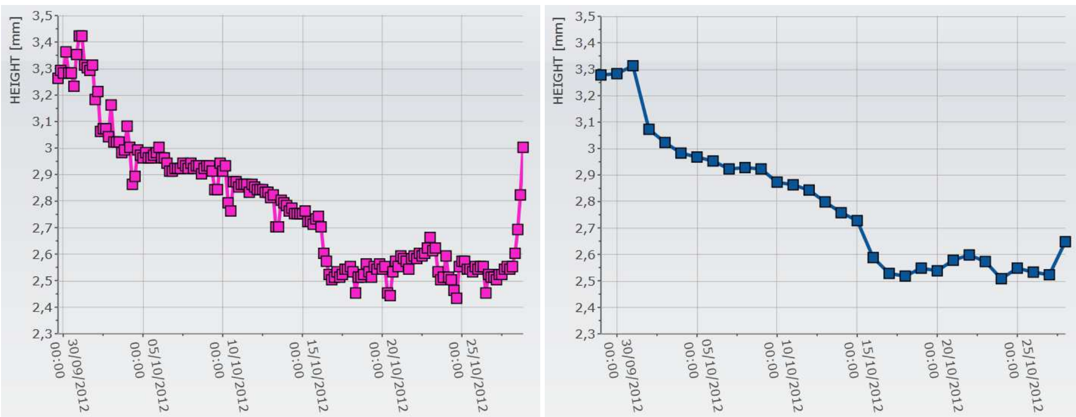

Figure 9. Examples of data reduction for reporting

4.5 Comprehensive data exporting

A comprehensive export utility is finally being developed on the post-processing platform. This utility is meant in particular for work supervision or client independent data analysis. Sensors of any type and number can be selected together with the desired reading channels, time-frame and sampling rate, to obtain an open format file export containing all required information (sensors and calculated values readings and sensors location) for any further analysis or alternative storage.

5 Conclusion

High speed train tunnel in Florence is a representative example of demanding monitoring and risk assessment task. New sensors technologies, informatics and information technology are fundamental tools that shall be extensively use to allow human resources to focus on selected data interpretation and risk assessment. The paper described how a dedicated data post-processing platform allowed to increase the synergy between monitoring team, TBM experts, designers and work supervisors, sharing data, technologies and know-how towards the common scope of a safer work management.

6 Acknowledgements

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