CONSTRUCTION TBM TUNNEL - OPERATING DATA REAL TIME – RED AND GREEN LINE METRO IN TEL AVIV (ISRAEL)

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ABSTRACT: Elpa Project is a joint effort of Elpa and Rina Consulting S.p.A (appointed by NTA Ltd that is the responsible for the design and construction of a mass transit system for Tel Aviv) to establish a clear classification of the findings of Red and Green Line Metro TBM excavations in Tel Aviv and clearly communicate them. The tunnels extend from Nordau Shaft to Levinsky Shaft (Green Line Metro) and from Bat Yam to Petach Tikva (Red Line Metro) and are some of the most heavily used traffic corridors in the Tel Aviv Metropolitan area. 11 TBMs of internal diameter of 6,50 m have completed the underground Metro excavations adopting EPB methodologies in calcareous sandstone under and over sea water table in a very urbanized area. Elpa's effort produced a novel approach to the analysis and the communication of findings and corrective actions to Contractor and Engineer during excavation monitoring. This method merges a strong expertise in TBM analysis with state of art tools for Big Data management. The Elpa method aims to speed up, simplify and to render more intelligible the communication of findings and the performing of corrective actions during an excavation with a TBM. It configures itself as the missing link between the analysis of raw data from TBM sensors and the high level of operability of construction management. It enhances the control (on behalf of the client) of the work of those responsible for construction and works management. The power of this solution is in its full-stack, comprehensive approach: on one side, the development of software to manage BigData and a strong knowledge of the mechanical structure of TBM, on the other side the production of a set of reports and diagrams of differing granularity to allow effective communication. An example of practical implications of Elpa methodology is the assessment of potential long-term sinkholes in days (not at the end of the excavation) reducing the cost of corrective actions, saving money and reducing damage to TBM or Tunnels. This kind of approach allows being quickly aware of anomalous situations, finding the root causes and acting to take counter measures with a clear understanding at any level of the organization of the actors involved. The vision behind the Elpa method is to be able in the future to shorten the lifecycle of excavation monitoring to analyse/act in real time in this complex task by improving the proactivity of this solution (Machine Learning based approach) and working on the formalization of reports that will be clear to non-experts of an excavation.

1. INTRODUCTION

Elpa Project is a joint effort of Elpa and Rina Consulting S.p.A (appointed by NTA Ltd that is the responsible for the design and construction of a Mass Transit System for Tel Aviv) to establish a clear classification of the findings of Red Line and Green Line Metro tunnel construction in Tel Aviv and clearly communicate them. The tunnels extend from Nordau Shaft to Levinsky Shaft (Green Line Metro) and from Bat Yam to Petach Tikva (Red Line Metro) and are some of the most heavily used traffic corridors in the Tel Aviv Metropolitan area.

Elpa's effort produced a novel approach to the analysis and the communication of findings and corrective actions to Contractor and Site Engineer during excavation monitoring. This method merges a strong expertise in TBM analysis with state of art tools for Big Data management. The Elpa method aims to speed up, simplify and to render more intelligible the communication of findings and the performing of corrective actions during an excavation with a TBM. It configures itself as the missing link between the analysis of raw data from TBM sensors and the high level of operability of construction management. It enhances the control (on behalf of the Client) of the work of those responsible for Construction and Works Management. The power of this solution is in its full-stack, comprehensive approach: on one side, the development of software to manage Big-Data and a strong knowledge of the mechanical structure of TBM, on the other side the production of a set of reports and diagrams of differing granularity to allow effective communication. An example of practical implications of Elpa methodology is the assessment of potential long-term sinkholes in days (not at the end of the excavation) reducing the cost of corrective actions, saving money and reducing damage to TBM or Tunnels. This kind of approach allows being quickly aware of anomalous situations, find the root causes and act to take counter measures with a clear understanding at any level of the organization of the actors involved. The vision behind the Elpa method is to be able in the future to shorten the lifecycle of excavation monitoring to analyse/act in real time in this complex task by improving the proactivity of this solution (Machine Learning based approach) and working on the formalization of reports that will be clear to non-experts of an excavation.

The Red Line has a total length of approximately 24 km and has a central underground section of approximately 12 km. The Red Line will be double track through all its length.

The underground section consists of twin bore single-track tunnels with segmental lining of an inside diameter of 6.5 m. 8 TBMs completed the underground Metro excavations adopting EPB methodologies in calcareous sandstone under sea water table (Porat, Wintle & Ritte 2014) in a very urbanized area (Fig.1).

The Green Line has a total length of approximately 39 km with about 4.2 km of twin tube tunnels with n.3 TBMs and a segmental lining of an inside diameter of 6.5 m, in calcareous sandstones as in the Red Line project. Four stations located along the bored tunnel alignment, which run from south to north, are as follows: Carlibach, Kaplan, Rabin, Arlosoroff west. Additional top-down structures along the alignment are two launching shafts at Levinsky and Nordau positions (fig.2).

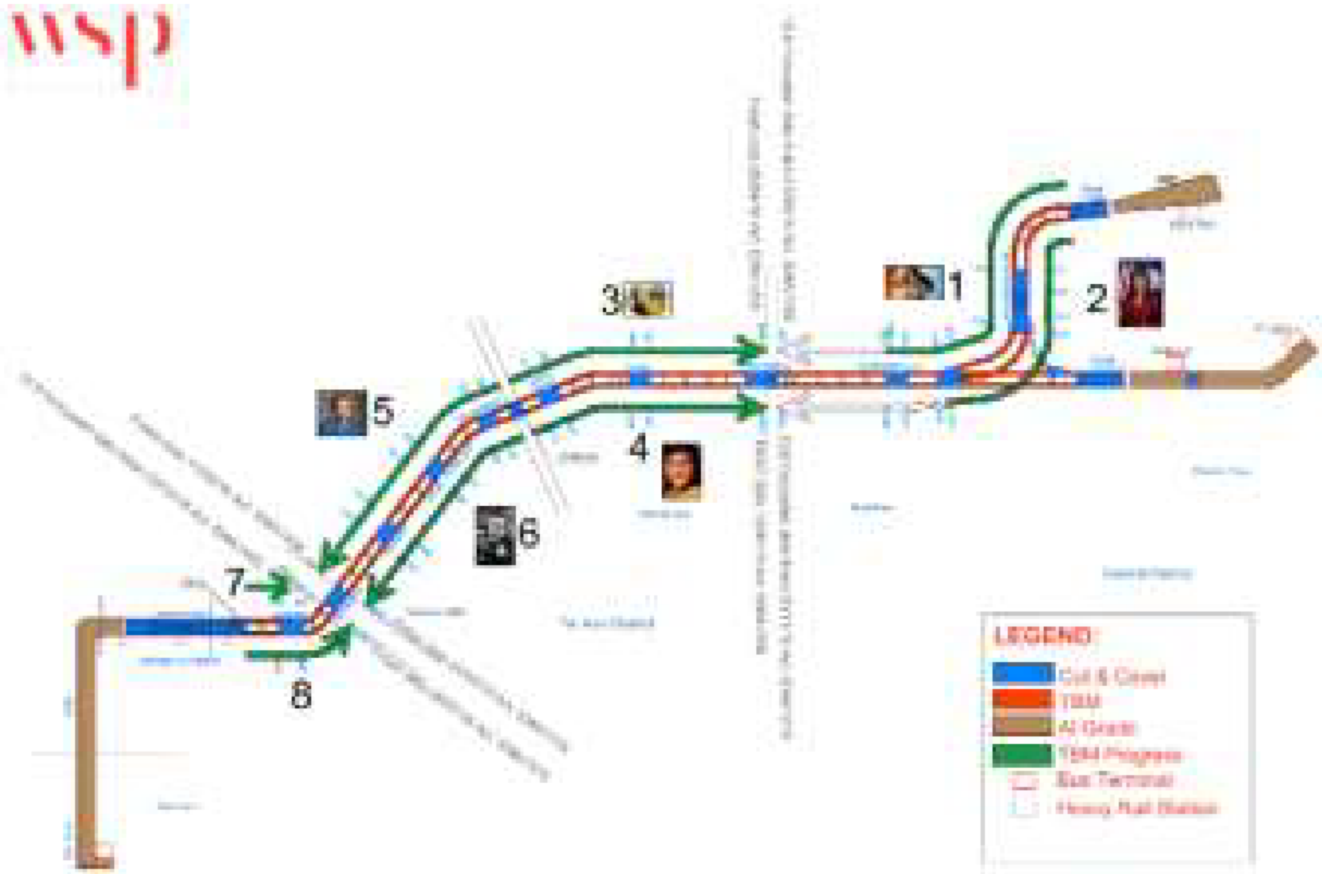

Figure 1: Red Line – TBMs route.

Figure 2. Green line key plan

2. BRIEF DESCRIPTION OF RINA AUDIT ACTIVITY

Rina Consulting has been participating, as technical advisor, in the Red Line and Green Line Project in Tel Aviv since 2016 and is currently involved in several audit review and control activities.

The assurance management and technical auditing services provided by RINA are related to all the activities of the Metropolitan Tel Aviv Transit System.

The entire project will be constituted by the three new light rail lines (Red Line, Green Line and Purple Line) under construction and the new Metro Lines M1, M2 and M3 to be realized in the next years with an estimated cost of €40 billion for the entire project and an extension of more than 150 km twin tube tunnel and 109 stations.

3. TEL AVIV METRO LINES TUNNELLING TBM OPERATING DATA MONITORING

In tunnelling works there are many important daily tasks to perform: the Contractor needs to check the quality of work; the Project Manager needs quality assurance; monitoring data produced by TBM machines need to be collected by the Project Manager and Site Engineers, analysed and delivered to the Contractor in the form of reports.

TBM monitoring data can be difficult to read just as it can be difficult to measure the deviation between design parameters and machine specific construction parameters.

NTA's senior management (the Owner) need to understand the practical meaning of the main operating parameters of the TBMs and need to capture the gap between design and construction parameters in order to make recommendations and carry out corrective actions.

The objective of the real-time monitoring of the TBM has been defined by the owner NTA in light of the need to communicate quickly, easily and comprehensively the excavation activities (standard progress as well as critical situations) to its senior management and to give indications to both Contractors and Site Engineers. This effective communication helps to meet contractual requirements.

Data from the TBMs sensors are transferred daily from the Contractors to the TBM's Auditors with the Elpa Method and are neither modified nor elaborated. Only the original outputs produced by the TBM are transferred.

Together with TBM data, surface settlements (Bilotta, Russo & Viggiani 2002) above the TBM shield are also collected and analysed in order to correlate findings related to the excavation activities with the geological and geomechanical characteristics of the excavated soil (Gvirtzman, Shachnai, Bakler & Ilani 1984).

All operational data collected during TBM excavation monitoring are archived to have the possibility to use them in case of future legal disputes between NTA and other parties.

The weekly and monthly reports sent to NTA by Rina Consulting/Elpa auditors allow to the owner to conduct discussions on a monthly basis to clarify the reasons of the findings and to indicate how to correct them.

4. THE PROBLEM WITH TBM'S DATA ANALYSIS

One of the problems that is encountered when working with TBMs is that generally there is some proprietary software that is able to report simple metrics only coming from the huge set of sensors related to the instrument.

On the other side there can be engineers or specialists with a background in construction theory but with poor experience in the management of TBMs sensor readings.

In this context there is often space for some home-made solution based on Excel to aggregate data: this kind of approach is not scalable, it is, in general, difficult to manage and, without a good analyst on the reading side, can be pointless.

Even good data visualization tools, however, require the experience of a good analyst: only a specialist that knows the mechanics, structure and problems that can result from a TBM's management can make sense of its data flow (Fig. 3).

Moreover, there are no synthetic indicators that are able to convey important findings, or to communicate the needs for adjustment to a non-technical audience on the Contractor side.

Finally, in case of legal disputes it is not simple to show what went wrong or to collect evidence of operator's mistakes or of problems with the TBM manufacturer.

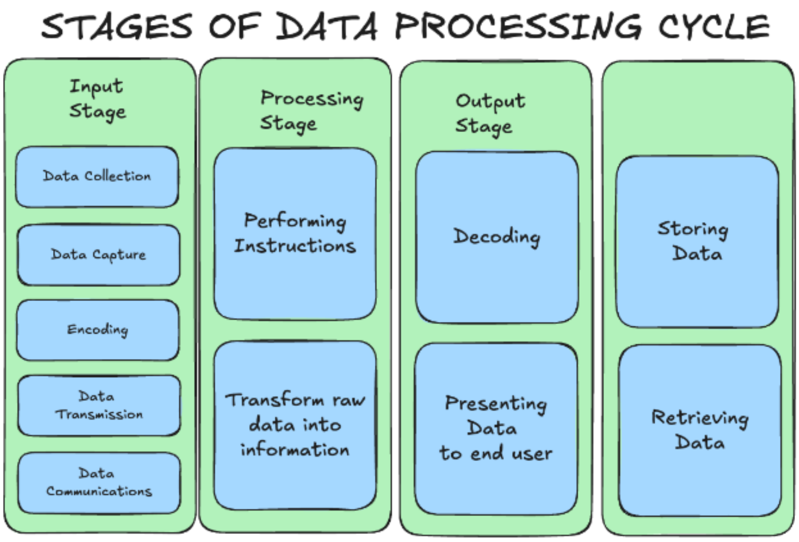

Figure 3. Elpa process.

5. ELPA METHOD FOR TBM'S DATA ANALYSIS

The main characteristics of Elpa TBMs' Data Analysis are: acquisition, cleaning, validation, storage, real time and batch analysis of Big Data coming from TBMs sensors, the analysis of status and synthetic reporting of critical observations to the Contractors (Fig. 4).

Sensor data extracted from the TBMs are used to report progress of excavation, status of rings construction; reports are collected on a monthly and weekly basis (Fig 4).

Elpa analysis made it possible to detect non-conformities related to work-site activities and give indications of the recommended corrective actions.

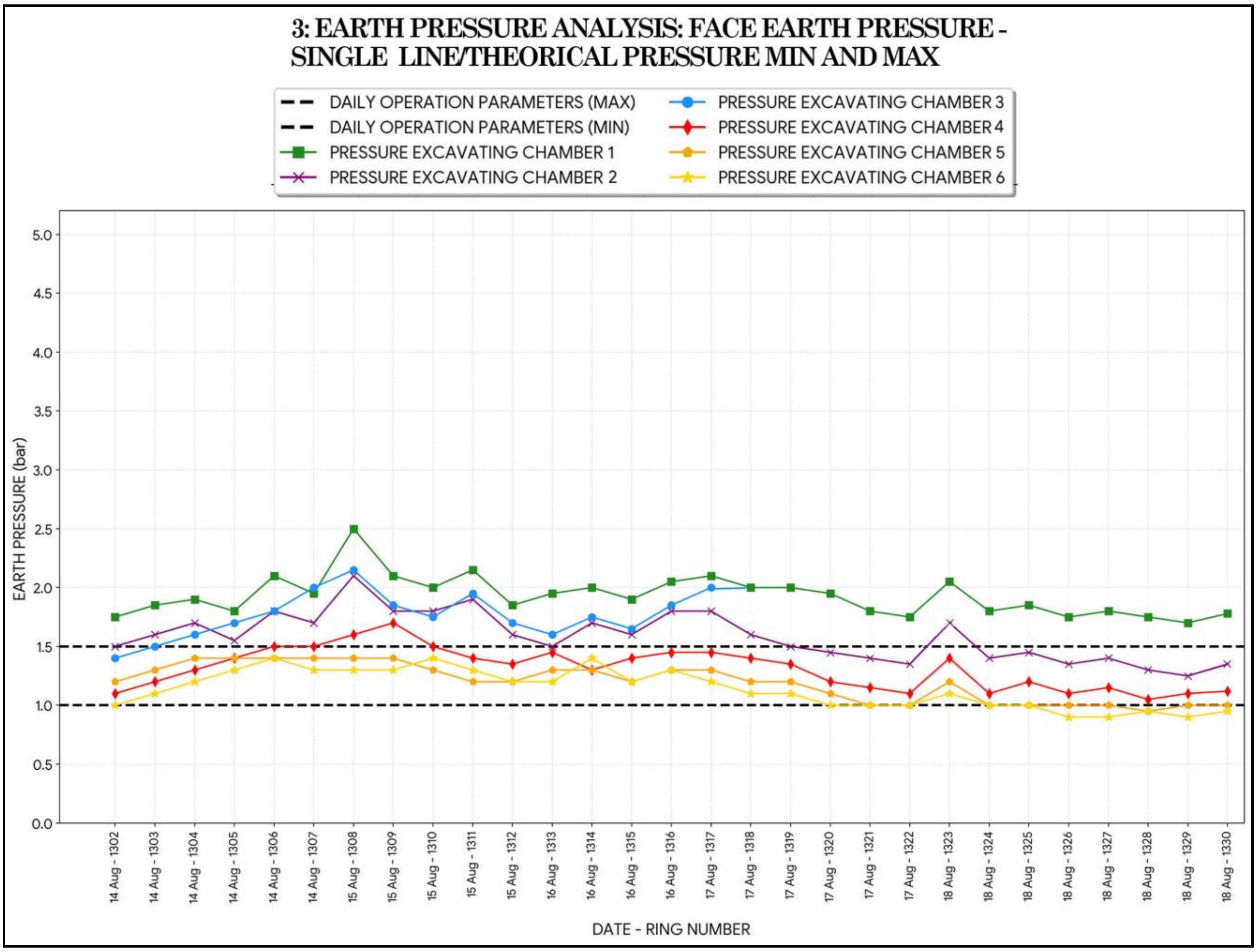

Figure 4. Example of weekly report graph

5.1 "TRAFFIC LIGHT" REPORTS

Monthly and weekly reports give a lot of synthetic information on the behaviour of the TBMs, but are not enough to make prompt decisions. Elpa created a new way to alert the Contractor based on the semantic of traffic lights (Fig. 5).

Figure 5. "Traffic Light" reports

Like a real traffic light Elpa delivers a particular report aimed at highlighting how much the behaviour of excavation metrics deviates from the expected. This report helps to show a particular dimension of the rings advance (related to torque or foam or progress for example) with a simple three colour pattern: a code is red when something needs attention in order to take decisions on work in progress (ALARM); a red starred code is used in case of immediate necessity of intervention (ALARM*); yellow provides a warning but the work can keep going (ALERT), and green is used if everything is going fine (OK). Alerts are categorized in minor and major parameters so that a site manager can act after a quick glance to a single dashboard. This kind of construction made it very easy to communicate dangers, unusual behaviours and suggest proper adjustment (by mean of a short text description in the rightmost column of the report).

5.2 BACK ANALYSIS

Another contribution of Elpa is the long-term storage of data after validation, analysis and report production. This allows the back analysis of all the TBM's excavations. Since Elpa operates as an autonomous and independent third party during the progress of work, stored data can be retrieved in order to perform legal analysis or to assess if a problem, occurred during excavation, was due to problems in manufacturing of the TBMs or to a misuse of the TBMs.

Table 1. Major and minor parameters analysed.

TBM Components*	**Major parameters**	**Minor parameters**
Cutter Head	Rotation / Torque	Penetration
	Advance	
Cylinder	Force main thrust	Thrust cylinder press
Screw conveyor		Rot. Speed / Torque
Exc chamber	Earth press.	
Muck	Weight	Volume
Foam	FER FIR	Volume
		Flow press.
		Flow liq.
		Flow air
		Flow / Vol. polymer
		Vol. bentonite
Tailskin	Grout Volume	Grease vol./weight
	Grout Pressure	Grease Pressure
TBM guidance	Ringbuild	Roll
	Mining	Pitch

* In addition the analysis of the topographic data near the

5.3 TECHNICAL DETAILS

Data produced by more than 300 sensors was collected on a daily basis with a traffic of more than hundreds of Megabytes per day per TBM; the monitoring was up and running for a long period of time. Elpa organized and cleaned data in order to deal with: different columns ordering and headers (some in Chinese, some in English), deletions, files of reduced size and retransmissions. This first effort is mandatory and not trivial to have a very good and clean data-set to analyse. Software used to process Big Data is the state-of-the-art in Computer Science for Statistics and for data manipulation. Even if each TBM has its own software to produce reports (in fact it is possible to see values related to different rings and metrics), there is no possibility to see relations between metrics or to carry out statistical operations (average, minimum, maximum…).

Elpa developed proprietary software in order to fine-tune reports and metrics. The software gave the possibility to rapidly inspect data in order to assess their validity or to identify peculiar behaviours. Finally, the software is used to identify relations between metrics and to predict anomalies to be communicated to the client.

5.4 FURTHER IMPROVEMENTS

Elpa is developing a Machine Learning based software in order to predict anomalies. In the common approach an analyst explores and analyses a given set of data in order to assess the anomalies and produce reports and suggestions. Generally speaking, the Elpa reporting solution shortens the access to critical data but remains not scalable. In fact, even with a good data visualization technique, the task becomes more difficult as the number of TBMs or the size of the dataset increases.

As further improvements, Elpa is developing a system to process data in an automatic way in order to classify anomalies with an Artificial Intelligence approach. Anomalies found by this classifier will help the analyst to start looking at more meaningful data instead of spreading his attention over the complete domain. This approach does not eliminate the need for human intervention, which remains a key point of analysis but will be a useful tool to reduce the complexity of data space to analyse and to spotlight some events faster.

5.5 SITE INSPECTIONS

As requested by NTA, every month Rina – Elpa Technicians carried out site visits to the Tel Aviv construction sites in order to check directly for each TBM, the actual implementation of the corrective actions indicated in the weekly reports. In a climate of active collaboration with Site Engineers and Contractors, many construction items are discussed in order to improve the excavation activities.

Figure 6. Picture taken during a site inspection before a relaunching.

In case of launching or relaunching operations of TBMs from shafts or portals, the Rina – Elpa technicians were also in charge of auditing the Site Acceptance Tests made by the Contractors and the Site Engineers on the following but not exhaustive list of items:

Table 2. Launching of TBM - List of items

TBM items	Parameters/elements	Functioning
Cutter Head	Rotation	General condition
Overcutter	System testing	
Excavation chamber	Face pressure sensors	System testing
Air valve	Connected and clean	
Screw conveyor	Rotation	General condition
Gate	Opening/closing	
Segment erector	Vacuum	General condition / System testing
Segment feeder		General condition / System testing
Cylinders		Movements / alignments
Tailskin	Grease Lines	Grease pump
Grout Lines	Grout pump	
Brush ring	General condition	
Foam system	Lines	System testing
Bentonite system	Lines	System testing
Conveyor belt	Scale(s) belt	Cleaned and calibrated
Fire curtain	System testing	

5.6 MONTHLY MEETINGS

In order to finalize the Audit activity and maximize the sharing of knowledge, monthly meetings of the Rina – Elpa team of auditors with Contractors and Site Engineers are held at the NTA offices in Tel Aviv.

In these meetings, the monthly data graphs, correlated with critical factors like settlements or TBM excavation problems, are discussed in order to improve the TBMs performance. The Contractors are requested to provide a written response to the recommendations presented by the auditors.

The monthly reports sent to the Client allow him to open discussions with the Project Manager or with the Contractor to find the most appropriate solutions to understand the reasons for and reduce the gap between design and operational values.

6. RISK ANALYSIS ON SPECIFIC ITEMS

As an example of the possible applications of Elpa's method, in this section we present the back analysis that Elpa has conducted with the aim of assessing the potential for long-term sinkholes (depressions extending to the ground surface generated by the collapse of cavities created during the TBM excavation).

To understand the possibility of having a long-term sinkhole (Shirlaw, Ong, Rosser, Tan, Osborne & Heslop 2003) in the completed sections of the tunnels, Elpa carried out a detailed analysis of the excavation parameters for each single installed ring. All the most significant parameters strictly correlated to the potential occurrence of sinkholes have been collected: Major parameters (Stop of TBM, Muck weight, Earth pressure), (Lunardi, Mancinelli & Zimbaldi 2015) (Chiriotti, Jackson & Taylor 2010) and Minor Parameters (Cutter head torque, advance speed, grout volume), (Bezuijen & Talmon 2006).

For each parameter a risk factor has been calculated based on the divergence between the value measured by the sensor and a set of reference values provided by the Contractor in the TBM Shift Instruction.

Finally, the set of risk factors calculated for each parameter, was combined and weighted to create a synthetic indicator called risk index percentage. With this analysis, Elpa was able to evaluate the probability of a late-sinkhole event in a given area. This analysis led to the identification of potentially dangerous areas along the tunnel route and to take actions to ensure the safety for the public.

During excavation Elpa was also able to produce another type of back analysis after stopping the work of the TBM due to force majeure: the cutter head was blocked by excavated material.

The analysis of the available data (Cardu & Oreste 2011) substantially confirmed what was observed during the excavation phases: the front pressure was fluctuating, which increased the difficulty of maintaining the front pressure according to the operating parameters; the values of thrust force and torque increased until they reached the safety shutdown value; it was difficult to maintain a constant speed; other problem was that the two belt scales to measure the weight of the excavated muck showed very different values from the beginning of each push.

Based on this particular analysis several corrective actions were recommended before the restart of the TBMs: calibration of scales, study of the pressure parameters at the front, study of the conditioning of the materials for possible improvements, intervention in the excavation chamber.

Only after the corrective actions were carried out, the TBM was allowed to restart.

7. CONCLUSIONS

The Elpa method aims to speed up, simplify and to render more intelligible the communication of findings and the performing of corrective actions during an excavation with a TBM. It configures itself as the missing link between the analysis of raw data from TBM sensors and the high level of operability of Construction Management and the Site Supervision (PMC). It enhances the control, on behalf of the Client, of the work of those responsible for construction and works management. The power of this solution is in its full-stack, comprehensive approach: on one side, the development of software to manage Big-Data and a strong knowledge of the mechanical structure of TBMs, on the other side the production of a set of reports and diagrams of differing precisions approaches to allow effective communication. The use of this Elpa method consent, through the weekly reports and the monthly meetings, to discuss and solve construction problems expected and/or unforeseeable among the parties (Constructor, Site Engineers, Project Control and Client) and consent to avoid contractual controversies.

The vision behind the Elpa method is to be able in the future to shorten the lifecycle of excavation monitoring and to analyse/act in real time in this complex task by improving the proactivity of this solution (Machine Learning based approach) and working on the formalization of reports that will be clear also to non-experts of an excavation.

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