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Intensive application of the TBM data management system for the work supervisor of the largest worldwide TBM-EPB project

M. Marchionni[1], A. Selleri[2], F. Stahl[3], L. Messina[4]

[1]*Spea Ingegneria Europea - Gruppo Autostrade per l'Italia, Mechanized Tunnelling Responsable, Milano/IT*

[2]*Spea Ingegneria Europea - Gruppo Autostrade per l'Italia, Works Supervisor Director, Milano/IT*

[3]*Babendererde Engineers, Software Development, Bad Schwartau/DE*

[4]*Spea Ingegneria Europea - Gruppo Autostrade per l'Italia, Mechanized Tunnelling, Milano/IT*

ABSTRACT: In the last decade TBM technology underwent tremendous steps to cope with the increasing level of project requirements like the demand for large tunnel diameters to allow for full-size highways without lane size limitations. The more the tunnel diameter increases the more the tunnelling systems complexity increases. Very large diameter TBMs pose additional challenges in operation as well as in supervision and quality control. The large volumes and heavy weights moved inside a powerful XXL-TBM do not allow for loosing attentiveness in operation and monitoring. This paper will discuss the customised solutions for monitoring what is currently the largest tunnelling operation in the world, the Sparvo Project in Italy where a 15.7m EPB-TBM is being used.. The project poses some additional challenges like the presence of large gas volumes in the ground as well as mixed face conditions and other geotechnical challenges. The paper will further present the experiences of the first 2.5 km long tunnel excavation in the twin tube project. Several key performance indicators will be compared in relation to soil conditioning efforts. Furthermore some special monitoring features of this TBM will be presented such as observed pressure distribution inside the shield ring gap. Some typical issues with the lining, such as cracks or joint offsets will also be discussed in relation to operational parameters.

1 The Sparvo Project: Main Challenging Tasks

The Sparvo Tunnel is part of a body of work for the "Variante di Valico Autostradale (Vav) – Autostrada A1 MI-NA" project in which more than the 75% of the length is composed of tunnels, for a total length of 28,600m per each line. The tunnel, object of this paper, is the first of two tubes (length 2,500m) that have been realized using what is currently the largest tunnel boring machine (TBM), a 15.7m Earth Pressure Balance (EPB) machine.

The technological evolution and proliferation of the mechanized excavation technique in Europe and worldwide, particularly the excavation of large diameter tunnels (typical for highway tunnel sections), gave the client Autostrade per l'Italia (ASPI) the opportunity to evaluate and finally to apply this method for the first time on a project. Originally the Sparvo project tunnel was expected to be excavated using conventional techniques, but due to extremely difficult geological conditions this method would have taken 6 years to complete the excavation. Alternately the use of the TBM on this project would allow the new Vav to open 2 years sooner than originally predicted, so for this reason the Client has advised and supported the Contractor during the proposal of the project modification from traditional to mechanized, participating also to the risk related to this solution.

The geological conditions are one of the main difficulties of the project. The tunnel is excavated in soft rock typical of the Apennines Mountains: Argillites (Argille a Palombini APA), Claystones (Breccie argillose poligeniche BAP) of the Leo tectonic unit and highly clayish Sandstones (Scabiazza SCB) of the Sestola-Vidiciatico tectonic unit. The entire area is characterized by over slides of the tectonic units for rising of the mountain chain. Inside the APA it's possible to find decametric ophiolitics and basaltic boulders characterized by a degree of high resistance. (OFI) Fig.1. With this hypothesis it was easy to preview difficult mixed face excavation conditions for the TBM.

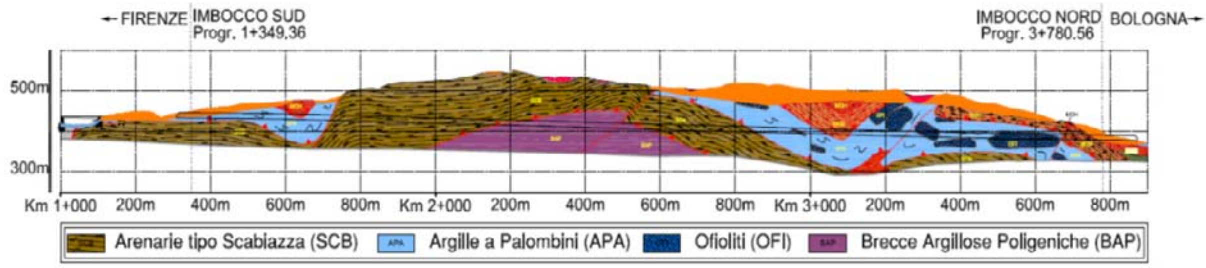

Figure 1. Geological section of the Sparvo tunnel

In addition to the difficult geological conditions, the APA and BAP formations were expected to contain high quantities of natural methane gas (Grisù). The local safety and health authorities (AUSL Emilia Romagna and Toscana), since 1998 released special guidelines to be applied during any tunnel excavation in this area in order to warranty the safety of the workers involved, one of the guidelines set up during the years has been dedicated to the risk related to the potential formation of explosive atmosphere during the tunnelling in geological formation with high presence of methane. Until the Sparvo project those guidelines, originally designed for the excavation of large section tunnel using traditional method, have been never applied to the mechanized tunnelling technologies.

With the cooperation of ASPI, Spea Ingegneria Europea, Herrenknecht, AUSL and the University of Bologna, it was possible to realized a TBM concept that met all safety requirement already present in the above mentioned guidelines. Afterword a new guidelines has been realized by the safety and health authorities in order to cover this field of application of the mechanized tunnelling technology.

Considering the given rule:"The system must not allow the contextual presence of potential explosive atmosphere and ignition sources", it has been possible to use a World Wide biggest TBM under gassy conditions, without extensive use of Ex-Proof equipment.

Also due to the new technique the final lining was modified from the traditional concrete section to a universal ring composed of 9+1 segments. Also the segments respect the exceptionality of the project. Every segment, with the exception of the key, is 4.7m in length, 2.0m deep, and 0.7m wide for a total weight of 16t each, with two types of concrete resistance of 45 and 50 MPa. Such a massive ring was required by the designer to guarantee long term stability of the tube in the formation given the bad geomechanical characteristics such as APA with high overburden of around 100m. The EPB technique also required that the ring would be able to sustain the thrust forces during the excavation. As a reminder the machine was designed to push with a maximum total thrust force of more than 400'000 KN (at 500 bars in the thrust cylinders). To produce these segments, a brand new factory was installed in the jobsite area producing 8 rings per day in a continuous process as achieved by a carousel plant.

2 Organization and Tasks of the Work Supervisor

The Sparvo Tunnel represents the bottle neck for the full opening of the complete Variante di Valico (more than 40 km of a new highway with a lowered alignment) so became the top key project for Autostrade per l'Italia that need to avoid any further delay in opening in order to get in operation one of his investment plan. Beside the geological risk, already minimized by an extremely detailed geological investigation done during the different design phases, Autostrade per l'Italia had to face with the first world wide application of a very large TBM into a project with a confirmed presence of methane and the related risk of project delay or stoppage.

A top quality TBM operations by reducing any deviation of the parameter from the design as well as the full compliance of the lining segment and related assembly procedure is not just necessary to get a final result (the tunnel) in compliance to the design but is a must to avoid any dramatic scenarios that might be originated by the interference of the methane with the tunnelling: in case of methane presence along the back up the TBM was not allow to advance. Finally the Client, which is a full private company, need a tunnel made according to the approved design otherwise will not be accepted by the Owner (Public Administration) and within the time frame related to his investment plan.

The Vav Work Supervisor (WS), lot 6 and 7, which Sparvo Tunnel is a part of, is SPEA Ingegneria Europea S.p.a. The company is 100% owned by the company Autostrade per l'Italia which is also the Client for the work in progress.

The different tasks of the WS are:

- Verify that the work fulfils the executive project approved by the Public Administration and the Client
- Prepare and validate the "Interim Payment Certificate"
- Prepare "Not in Compliance" communications and verify the related resolutions
- Approve or not approve enhanced project proposals from the Contractors
- Coordinate the Contractors involved in executing the work and prepare the meeting papers
- Produce appropriate "Service Orders"
- Produce "Corrected Work Execution Certificates"

In some case of lining defect, where a repair action would have been normally possible, in the Sparvo tunnel need to be prevent otherwise the complete Back-Up would have been exposed to explosion risk.

The TBM was expected to be continuously operating, 24/7, in order for the tunnel to be completed, so the Spea, under the request of Autostrade per l'Italia, decided to organized a team able to warranty a 24/7 supervision of the TBM activities.

The WS team was composed of 1 Jobsite Inspector and 6 Assistants, with a defined time schedule which specified the following manpower be present on the jobsite:

- Monday, Friday, and Saturday: 3 Assistants; 8hr shift each (covering 24hrs) + 2 Assistants in the office (8:00-17:00)
- Tuesday, Wednesday, and Thursday: 3 Assistants; 8hr shift each (covering 24hrs) + 3 Assistants in the office (8:00-17:00)
- Sunday: 3 Assistants; 8hr shift each (covering 24hrs)

One of the people doing the office work was covering the role of Assistant Coordinator, with some particular duties. With this timetable it was possible to organize a continuous presence on the TBM and the necessary inspections at the segment precast plant.

At the end of the shift the WS assistants delivered a report containing advance main parameters and notes about delays and problems together with a sheet for each installed ring reporting "Not in Compliance" events that were pointed out during building of the rings. At the end of the day the Assistant Coordinator had to summarize in a report information about production and critical activities that occurred in the tunnel, in the muck temporary storage areas (muck subject of characterization procedure) and at the precast plant.

The WS's continuous presence permitted constant and uniform checks of the work executed, including prompt advice to the Contractor in case of critical events monitored during the tunnelling process: a prompt segment repair in the gasket area has reduced the formation risk of potential explosive atmosphere as well has reduced the need of further intervention of the Contractor on the lining in case of leaking.

Beside human presence on-board, also the availability of TBM Data in real time allow easy back-analysis in case of critical events, allow a real time warning on specific parameters identified as key-factor for the advance and is useful to better approach any Contractor claim.

The WS 's team and the Data Management system has to be considered as a one-piece tool to reduce the residual risk related to this first time application of a mechanized technology.

3 Data Management System

Based on the high project requirements, Spea Ingegneria Europea - Gruppo Autostrade per l'Italia decided to use TBM Monitoring Software to track the project in real-time and to simplify routine work.

Babendererde Engineers were selected to deliver TPC, Tunnelling Process Control, as the Data Management System software for the project. At a minimum, the software met the following specifications:

- User friendly interface accessible from a standard Windows computer
- Real-time monitoring
- TBM monitoring frequency of every 5 seconds
- Manual data import for instrumentation measurements
- Automatic report distribution
- Trigger and Alarm System functions
- Compliant with SPEA IT policies
- Available at different site locations

The implementation strategy for TPC was to set the system up in 4 separate steps:

STAGE 1: Hardware, Network and Software Design (Fig.2)
Based on the software specifications for the TBM Data Management System, a concept by Babendererde Engineers was developed to record data in real time and make it available to authorized personnel. Because of the different locations of the Server, TBM and end users a network was developed which sent the data directly from the PLC (Programmable Logic Controller) of the TBM to the server and provided the WS's team with remote access from different site locations. Since the server was not installed on the site, a Data Acquisition Box (DAB) was installed in the contractor's office. This box retrieves real-time data from the TBM and forwards it to the server. In the event of an interruption in the internet connection the DAB cache has all of the available data. Once the connection is restored, the data is transferred directly to the server. A virtual server was implemented for the end user allowing simultaneous access for up to 25 users.

STAGE 2: Preparation and Pre-Installation
In the preparatory phase of the installation, all the indicators and calculated rules are defined. Due to the large diameter of the TBM, the number of available indicators quadrupled in comparison to other projects. For example, there are more than 130 indicators only in the conditioning system. This is based on such indicators as the 22 injection lines into the excavation chamber, screw conveyor, the available flow rate, consumption of foam, pressure of foam, FRI, FER and temperature. In total 1,950 directly measured or calculated indicators are available. Also around 400 failure messages are available through the PLC of the TBM. Due to the expected high volume of information the TBM Data Warehouse (DWH) developed by Babendererde Engineers (BE) was optimised before the excavation began.

The goal of this optimization was to satisfy the requirements of consistently fast database queries. Data optimization was achieved by adapting a special partitioning method to meet the requirements for mechanized tunnelling.

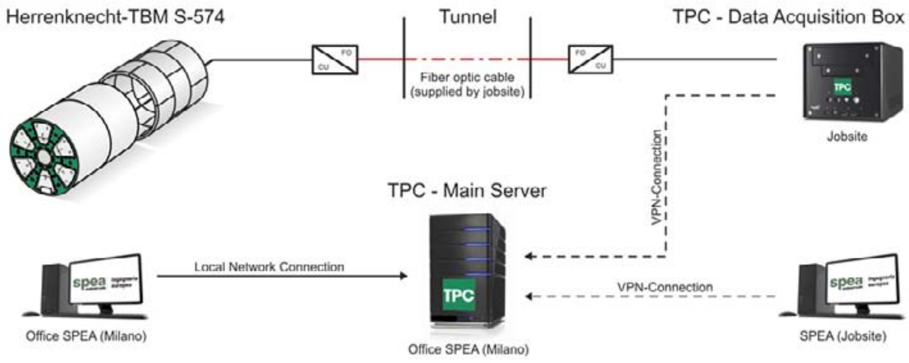

Figure 2. Network Setup

STAGE 3: On-Site Installation and Training

Advanced preparation and testing with a demo database reduced the installation time on site by two days. The saved installation days were used for additional user training. The training was performed as a hands-on interactive workshop. After the training, all users were able to create their own real-time monitoring pages and even create customized complex reports. These reports were then incorporated into the existing report delivery system.

STAGE 4: Customisation

In the last stage, TPC was specifically tailored to meet the needs of the construction supervisors. This included the production of daily, weekly and ring reports. Quality requirements for the ring and segment repairer process were entered. User rights and the automatic delivery criteria for reports were defined. Also a model of the waiting times was included at this time.

User defined parameters can be automatically monitored by TPC. A primary activity of the WS at this stage was to setup important indicators that were configured as triggers. If a key parameter substantially differs from the intended target value then the system immediately informs the WS via Internet, SMS or email. The large number of parameters and their warnings makes this systematic evaluation of all data very challenging. One approach is to use the TPC Watchdog feature. This is a rule-based system that works on top of the trigger levels. It provides real-time information about the current driving situation. Fig. 3. shows how information is displayed on a mobile device or TPC Watchdog cube.

Additionally to the standard pages, the WS's added several pages dedicated to the critical key-parameters of the TBM, for example a dedicated page was focus on the excavation chamber filling level monitored by radars and sonic level sensor.

Figure 3. TPC-Mobile with Watchdog

4 TBM Parameter Report versus Geological Profile

Babendererde Engineers Tunnelling Process Control (TPC) system permits a great deal of parameter customization. For example, in addition to the usual advanced parameters recorded by the Data Acquisition System supplied by the TBM manufacturers such as “Cutter head Torque”, “Advance Speed”, “Total Thrust Force” and “Cutter head Trust Force”, it has been possible to highlight and monitor some different parameters like the “Net Thrust for Advance” and the “Net Thrust for Excavation” which are less influenced by operator intervention as they are better linked to the geo-mechanical rock mass changes and so more useful in understanding TBM behaviour and in obtaining confirmation about the real geological condition met during the excavation.

These parameters are calculated from the data that is coming from the machine's PLC system. The “Net Thrust for Advance” represents the necessary thrust to win the attrite around the shield and provide information about excavation convergences. It is simply calculated using the Total Thrust Forced deducted by the necessary force to win the force generated by the pressure against the Bulkhead. This parameter justifies the bi-component grouting volume reduction injected behind the segments which occurred between progressive 2+925 and 3+050. Looking at Fig.4, it is possible to highlight that the “Total Thrust Increase” is mainly related to the improvement of the friction around the shield as a direct effect of ground convergence. This phenomenon was expected and compensated the 300mm radius overcut required by the Designer. The low grouting volumes injected would have been a “Not in Compliance” event, but by the use of the available data, this event was justified and so, no further actions were necessary. This parameter was also used to assure correct monitoring of potential danger of shield to get stack by the clay convergence.

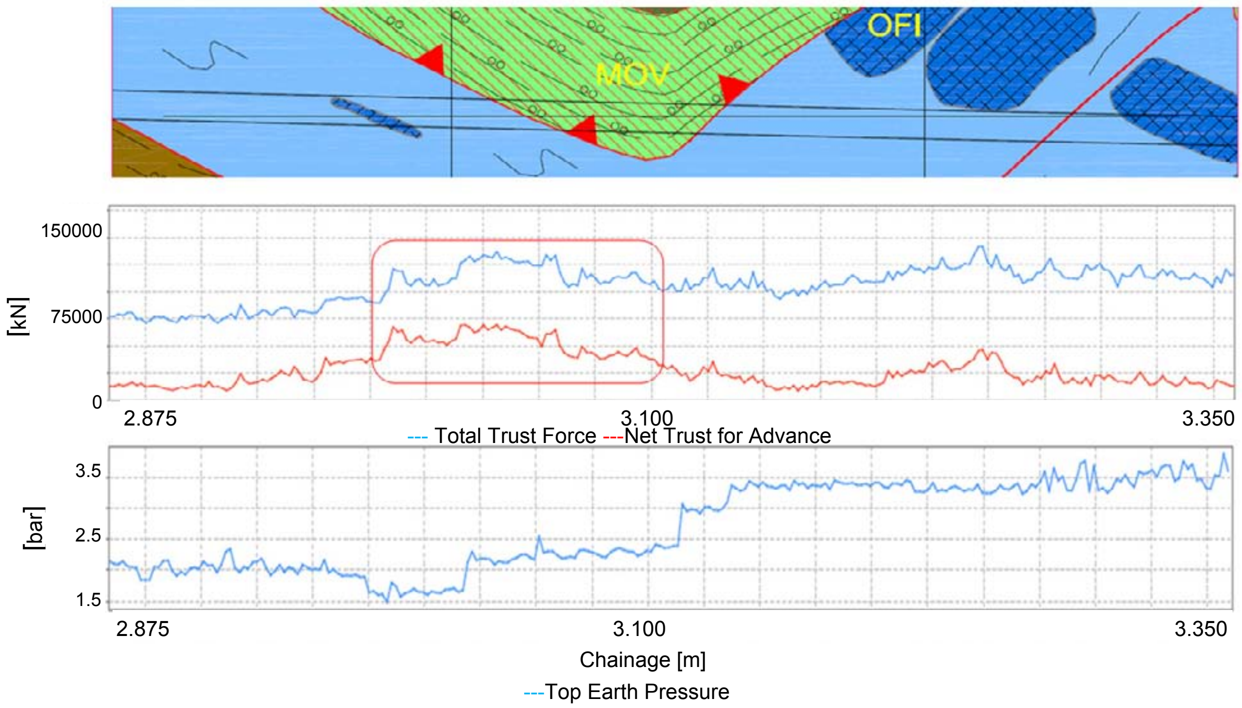

Figure 4. Variability of the "Net Trust for Advance"

After chainage 3+100, it was decided to increase the earth-pressure to support the excavation face, this means also increasing the Total Thrust Force. Also in this case the new parameter was useful to indicate better behaviour of the ground: as can be seen in Fig.4, the "Net Thrust for Advance" shows more sensitive behaviour to the events occurring around the shield. A decease in friction is clearly noticeable around the shield proving the effect of the increased front face pressure against the tendency to converge. The Total Thrust Force doesn't give the same information because was heavy influenced by the chamber pressure that, especially for Large Diameter TBM, is generating a great force against the shield advance.

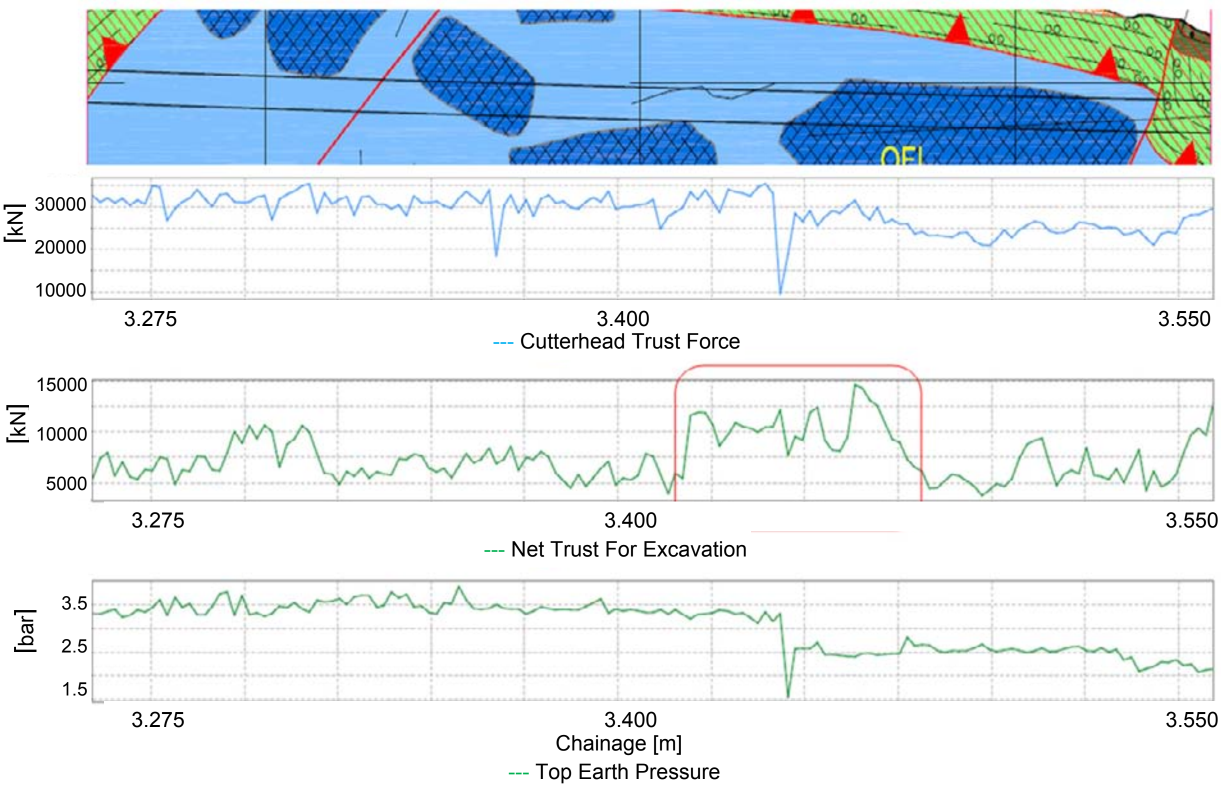

Figure 5. Variability of the "Net Thrust for Excavation"

Another example (Fig.5) is the “Net Thrust for Excavation” that roughly represents the necessary force needed to guarantee cutter tool penetration. This parameter is calculated taking out the acting force applied on the centre plate of the cutter head support due to the earth pressure inside the excavation chamber. The force generated on the central plate is relevant and so it is important to deduct this value from the parameter given by the TBM system. The “Net Thrust for Excavation” does not only highlight geo-mechanical rock mass changes, but also provides useful information about any irregular phenomena inside the excavation chamber like clogging and tool wear. For example, in Fig. 5 it is possible to notice the presence of a hard rock section between chainage 3+400 and 3+475 where the “Net Thrust for Excavation” moves from 6.000 kN to 10.000 kN (+100%) while the “Total Contact Force” was decreasing due to reduced chamber pressure.

5 Lining Quality Control and Off-Quality Events Management

Lining quality control represents one of the main WS tasks in the field because it will have a direct effect on the final result of the tunnel delivered to the client. On the Sparvo project a precise flow chart was followed in order to accomplish this assignment:

a) The Shift Assistant controls the ring building in the field and fills out the Ring Report.

b) At the end of the shift the Ring Reports are delivered to the Assistant Coordinator who inserts the “Not in compliance” events in the TPC System.

c) The Assistant Coordinator prepares the TPC Ring Reports and the official communication of the “Not in Compliance” events for delivery to the Contractor.

d) The Contractor proposes repair solutions for the identified events.

e) The WS Quality Control Manager accepts the solutions.

f) “Not in Compliance” events are closed with the repairs.

With this procedure the WS obtains complete, homogenous, and continuous control of the lining quality and a map of the different “Not in Compliance” events. Also by being in the field 24/7 it is possible to monitor and repair events that would have not been evident after ring installation is complete. For example, Fig. 6 shows concrete cover damage over the gasket housing in segment (a). This damage would have created problems in the design which required water-tightness. The damage was detected during the installation of the ring, and was possible to repair by using an approved procedure (b) before the ring erection. This damage would have been reported on the Ring Report but with the repaired remark.

Figure 6. a) Concrete cover damage detected before installation b) Segment after repair

These events occurred with decreasing frequency as shown in Table1. This simple statistical evaluation is immediately identified by the TPC system. It provides proper control and a record of the events. Without the presence of WS Assistants in the field these kinds of damages could have been ignored.

Table 1. Occurrence of damages to concrete cover and gasket housing

From Ring	To Ring	Events
0	200	40
201	400	14
401	600	5
601	800	3
801	1.000	5
1.001	1.200	4

6 Conclusion: Benefits and Further Implementation

The use of a TBM data management system combined with permanent monitoring on site allowed the WS to assure state-of-the-art tunnel execution without any relevant delay to the tunnelling production enabling performance to reach an average of 12 meters/day during the excavation of the first pipe. Considering that this project represent the first experience for the company SPEA as WS where TBM is being applied it become more a successfully picture.

A firm supervision on board, a prompt indication of corrective measures and the knowledge of the complete TBM Data set has allowed a quick establishment of the required quality level (see table 1), while the Contractor has trained himself to improve the production rate.

TPC has provided SPEA with the ability to store, observe in real time, and review large quantities of multidimensional data, all with less processing time and powerful built-in reporting tools. The real time acquisition of data and the architecture of the TPC system provides the ability to know the status of the TBM from anywhere at any time, so the SPEA headquarter where the Mechanized Tunnelling Dept is based on, was able to be aware of any critical scenario. The software eliminates the need for time-consuming reviews of data. TPCs customisable querying and reporting tools are used to quickly generate useful and presentable information on an on-going basis. The software also allows manually collected data to be added to the digital data retrieved from the TBM. This data includes, ring damage and repair information, pictures, geotechnical instrumentation data, and classification of TBM down time from tunnel inspection (Shift Report). All of this data has been used to assure the execution of a Top Quality tunnel, to reduce any repair intervention after the breakthrough and to monitor the compliance of the defined safety specification related to the gassy condition.

Continuous checks of the segment during ring erection can create a significant map of every defect. By cross checking this information with the TBM data, it is possible to identify the correct solution to reduce further defects. Table 1 shows a constant reduction of the example defect to the minimum level possible.

The availability of a full database permits a reliable forecast for the production of the second pipe and also a prediction for the reliable hand over of the tunnel to the Client and finally to the end user. Complete knowledge of TBM data, meter by meter, will allow for efficiently organizing the WS team during the excavation of the second pipe.

7 References

Autostrade per l’Italia, 2007, Autostrada A1 Milano – Napoli Adeguamento del tratto di attraversamento Appenninico tra Sasso Marconi e Barberino del Mugello, Progetto Esecutivo, Galleria Sparvo – Relazione Geomeccanica, 110163-07-PE-R-GSP-GEN-OST-RE-01-A.

Autostrade per l’Italia, 2007, Autostrada A1 Milano – Napoli Adeguamento del tratto di attraversamento Appenninico tra Sasso Marconi e Barberino del Mugello, Perizia di Variante, Galleria Sparvo Parte Generale – Canna Nord, Profilo Geomeccanico e progettuale di previsione, 310119-02-PV -GSP-CGN-GET-FU-01-A.

Babendererde Engineers GmbH, 2010.Tunneling Process Control – Manuale utente, Versione 1.5.00, Italiano.

Babendererde Engineers GmbH, Frank Stahl, 2005, Entwicklung eines Data Warehouse Systems für Vortriebsdaten im Tunnelbau.