World Tunnel Congress 2013 Geneva
Underground – the way to the future!
G. Anagnostou & H. Ehrbar (eds)
© 2013 Taylor & Francis Group, London
ISBN 978-1-138-00094-0

First results of the use of "Martina", the world's largest EPB-TBM (15.62 m in diameter), to bore the Sparvo Tunnel (A1 Motorway)

P. Lunardi[(1)], G. Cassani[(1)], M. Gatti[(1)]

[(1)]*Rocksoil Spa, Milan, Italy*

ABSTRACT: The results concerning the use of the EPB-TBM "Martina" for the excavation of a tube of the "Sparvo tunnel" are here given, with particular attention to the most critical point, from both a geotechnical viewpoint and due to the presence of gas deposits, consisting of the *Argille a Palombini* formation. The evidence collected during the exacavation, both regarding the behaviour in progress of the TBM and regarding the data from the chosen monitoring system, is therefore highlighted.

1 Introduction

During the works concerning the construction of the new "Variante di Valico" of the A1 Milan-Naples motorway, between Sasso Marconi (Bologna) and Barberino di Mugello (Florence), the construction of the *Sparvo Tunnel* – due to its length (approximately 2,600 m), the diameter of the excavation (15.62 m) and the geological context – is a unique challenge in the field of underground excavation. The difficult geo-mechanical conditions, especially in the section running through the *Argille a Palombini* (APA) and slope deposits, and the consequent uncertainties concerning the speed of advancement, led the Contractor, in agreement with the Client, to consider the use of an EPB-TBM, manifacturesd by Herrenknecth AG. The choice was made even when considering the high probability of "squeezing" in that stretch which is heavily covered by APA – up to 100-120 m of overburden – and brought about the need, following a detailed analysis of the stress-deformation conditions of the rock during the excavation phase (according to the ADECO-RS Approach (Lunardi 2008) during the design phase) to conservatively resize the technical and operative characteristics of the machine. In particular, the TBM's maximum applicable thrust was chosen, according to the risk analysis, so as to prevent the machine from blocking down due to the pressure from the excavated rock mass, even in severe geo-technical conditions (Gatti 2011). The geo-technical qualities of the APA were carefully assessed - both on the site and in the laboratory - and the possibility was considered, following numerical simulations, of reducing the parameters of resistance and deformability of the rock mass in order to take into account those aspects which were difficult to schematize during the design phase; and linked to the possible presence – along the alignment – of faults with poor geo-mechanical conditions, local anisotropic conditions or tectonic stress. Taken together, the design analyses were necessary in order: on one side, to determine the appropriate levels for the main operative parameters of the TBM, such as the pressure in the excavation chamber, and the following thrust in accordance with the different geotechnical contexts; and on the other side, to equip the TBM so as to be able to face the most difficult situations, and continue its advancement without interruptions. Although the analyses conducted during the design phase where such as to be able to face the tunnel excavation with extreme confidence, in spring 2011 – as preparations were made for the TBM's departure - trepidation was high for the future progress of the excavation; for the problems that would come up during the works; and, especially, for the curiosity of discovering if "Martina" would have been able to meet the promise of advancing 10 m a day, for which reason she had been chosen over conventional tunnelling. The TBM started working in August 2011, moving through a stretch of artificial tunnel, and a brief stretch of tunnel that had been pre-excavated conventionally; the first tube of the *Sparvo Tunnel* began in the month of September 2011, and was concluded on the 27 of July 2012. Later in this paper - after a short description of the main characteristics of the *Sparvo Tunnel* and of the excavated geological context - the progress of the advancements and the main evidence collected during the excavation will be described in terms of operative parameters, of deformation response found by the chosen monitoring system. Rocksoil was involved in the final and detailed design of the tunnel and in technical assistance during TBM excavation.

2 Project data and geological context

To give an idea of the project, the Sparvo Tunnel has a length of approximately 2600 m, with longitudinal gradients always less than 4% and planimetric radii of curvature between 1,400 m and 3,000 m. It has two tubes, with the distance between centres varying from a minimum of 30 m to a maximum of approximately 70 m, each with an inner diameter of 13.6 m, and with each carriage way consisting of 2 lanes of 3.75 m, 1 emergency lane of 3.75 m plus lateral clearance of 0.25 m on the right and 0.70 m on the left; there are then two sidewalks with a width of 0.60 m. The two tubes are connected by pedestrian passage ways every 300 m of tunnel and passage ways for vehicles every 900 m. Safety measures are completed with S.O.S. bays at intervals of 150 m on the right hand side of the carriage way. The final lining will consist of rings of precast concrete segments (9 + key) with a length of 2.0 m and thickness of 0.70 m, with reinforcing steel bars. The segments are fitted with EPDM gaskets, as a waterproofing system, and connected by fastenings located on the outer sides (steel bolts) and the longitudinal side (steel pins). A guide bar is used to ensure that they are properly aligned. The extrados of the lining will be backfilled with a fast setting two component grout, for an excavation diameter of 15.62 m and a total excavation area of approximately 190 m.

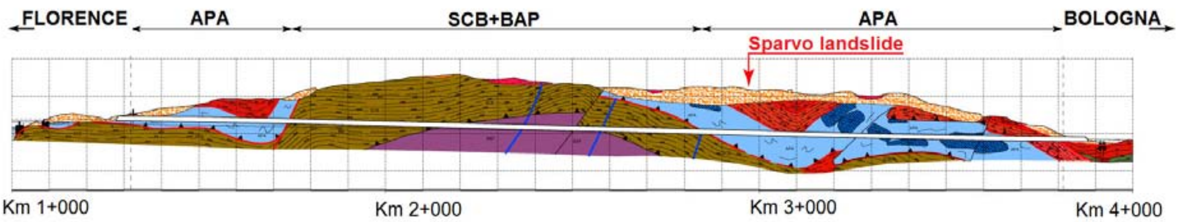

Figure 1. Sparvo Tunnel geological longitudinal section

From a geological point of view, the tunnel, moving from the south portal on the Florence side, first passes through a gentle slope characterised by clayey-silty deposits with a thickness of greater than 10 m on average. It then enters a substrate consisting of the *Argille a Palombini* (APA) formation until overburdens of 30-35 m are reached. These are intensely deformed clays and argillites in thin strata with calcareous (Calcareous/Argillite ratio <<1) or sandstone inclusions. The passage into the *Arenarie dello Scabiazza* formation (SCA) occurs through a tectonic contact. This formation consists of sandstones with intervening siltite and argillite strata. A series of tectonic contacts result first in the passage into the *Brecce Argillose Poligeniche* formation (BAP), consisting of clays with clasts of varying lithological nature and then back into the *Arenarie dello Scabiazza* and the *Argille a Palombini* formations. Overburdens in this second section of the tunnel where the APA is present reach 120 m with an abundant presence of ophiolites ranging in size from a few metres, to hundreds of metres consisting of basalt breccias, gabbros and serpentinites. Deposits of the Sparvo landslip are also present on the surface in this zone down to a depth of 30-50 m. Finally, a fault contact again leads to the Monte Venere formation (MOV), consisting of alternating sandstones with intervening strata consisting of argillites, siltites and clayey marls up to within 25 m from the north portal on the Bologna side, where silty-sandy detrital deposits are present along a medium steep slope. The reconstruction of the stratigraphy (Fig.1) was performed on the basis of data acquired from various survey campaigns performed since 1985, with a total of 70 boreholes and seismic surveys. No continuous water table was found along the route of the tunnel, even if some samples from the APA had a high water content. Detailed information regarding the geomechanical characteristics are reported in Gatti (2011).

3 Geological data collected during the excavation phase

Analyses of the geological conditions of the tunnel were carried out during work progress, through constant control of the material being extracted and transported on the conveyor belt; through periodic inspections of the excavation chamber during stops for verification of the excavation cutters' wear and necessary substitution; and through the use of the "BEAM system", which proved to be a good instrument for inspection during work progress. The system geo-electrically detects the physical-mechanical characteristics of the material being bored, using electrodes placed on the cutterhead.

Two parameters were collected: the resistivity of the soil, measured in Ωm, and the effective porosity value, measured in %, indicating the percentage between empty space and the volume of analysed rock mass. This data made it possible to detect in advance the contact position of the main formations encountered by the TBM; particularly, between the APA and flysch formations. Indeed, the first type of formation presents a high level of saturation and low permeability (APA), while the second (SCB) presents a medium-high secondary permeability and a lapideous consistency.

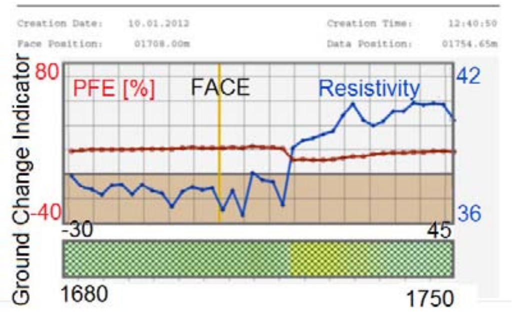

Figure 2. Record “BEAM System” (Km. 1+708)

Figure 3. Km. 1+525 Face Condition

For example, Figure 2 reports the Beam system readings at chainage Km. 1+708, regarding investigation on rock mass placed 45 m beyond the excavation face (the x-axis shows distance from the face of the TBM); the sudden increase in resistivity can be noticed (blue line, from 37 to 41 Ωm) at 15-20 m beyond the excavation face, in correspondence with contact between the APA and SCA individuated by the geological profile at about chainage Km. 1+720. The BEAM system individuated, with sufficient approximation, a few intra-formation differences in the SCB: the sectors with a higher resistivity can be associated with rock mass of higher lapideous consistency, while those with a lower resistivity indicate the presence of clayey-silty interstrata, with possible water stagnation. In general, the data collected during the excavation corresponded well to that which had been projected during the design phase; for about the first 1400 m underground, the projected stratigraphic and tectonic limits were confirmed by the surveys conducted in progress. In the final sector, in correspondence to SCB-APA tectonic contact, a slight northward translation of all stratigraphic and tectonic limits was observed (about 30-40 m), however without varying the geometric relation between the formations; in particular, a syncline was found in MOV, inside the APA, at the interval between rings 850-890, also translated a few tens of metres from the original profile, probably due to a lower rejection of the overthrust of the SCB on the APA. The entrances into the excavation chamber, conducted in normal baric conditions, allowed local geomechanical investigations of the rock mass, and allowed examination of the degree of compactness and the present discontinuity systems. In general, the APA – being made of clays and black fissile shales – proved to have a good consistency, despite presenting ductile deformations and large volumetric variations if subject to detensioning during the excavation. Figure 3 shows a partial vision of the face in APA at chainage 1+525, through the openings in the cutter head. Examination of the mass belonging to the SCB showed mainly lithoid conditions, with a high presence of sandstone facies and minor pelitic portions; cohesive masses were also observed for the BAP formation, these presented pseudo-lithoids, characterized by a grey clay matrix supporting skeleton formed by different types of clasts: limestone, sandstone and argillite.

4 TBM Production data analysis

Figure 4 reports the monthly production - in terms of rings placed - on behalf of the EPB-TBM “Martina”, starting from August 2011 until the completion of the first bore of the tunnel, in July 2012. As can be seen in the figure, the productivity of the TBM can be divided into three main phases: the first phase lasted from August to December 2011, and registered a low level of production, not only for the usual period necessary in order to set the main operational parameters for advancement, and for the training of the work groups (“learning period”); but especially for a 60 day stop, caused by a mechanical failure in the main drive hydraulic circuit. Work was carried out for only 35 days out of 109; little more than 30%, considering the work days we have an average production 4.8 m per day. The second phase lasted from December to February 2012, and production increased greatly, often placing 7-8 rings per day (14-16 m per day). However, production was not constant, as progress was stopped for a work injury, and to change the cutters wasted; work was carried out for 42 days out of 71 – around 60% - with an average production progress of about 10.7 m per day (6.4 m per day average over the entire period). In the third phase, which lasted from March to July 2012, the machine gave its best performance, both in terms of daily peak production (up to 11 rings per day, or 22 m per day), and in terms of production constancy. In this last phase, the TBM advanced for 134 days out of 149 (90%), only stopping for 15 days for routine inspections of the excavation chamber, in order to inspect and replace the tools. The net production average was 13.2 m per day (11.9 m per day if averaged over the entire period). Altogether, besides the two main long stops (the main drive failure and the injury) neither of which were directly related to the normal management of a mechanical excavation, “Martina” kept on her promise with an average daily production of 11 m. Even when taking into account the two long stops, which both heavily penalized the TBM’s performance (114 days out of 331, equal to more than 30%), daily performance averaged at a little more than 7 m per day – still a decisively higher rate than that of conventional tunnelling, even when taking into account the preparation of the excavation site and the TBM assembly. Details of monthly production, seen in figure 5, show a constant increase of the machine’s performance; in the final period, from March to June 2012, net monthly production rose to 13-14 m per day (the record months were March and April, with a monthly production of 400 m of tunnel).

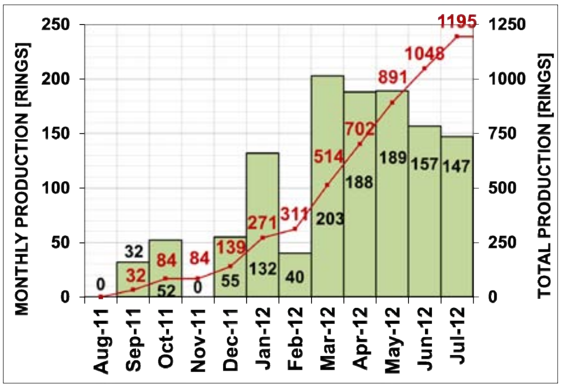

Figure 4. Monthly production (in rings)

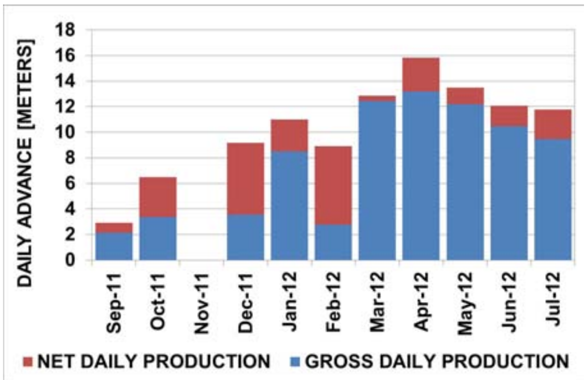

Figure 5. Daily advancement per month

About production data, the most important aspect is the speed of advancement in the single geological formations bored. When observing the net daily production averages (having therefore subtracted those stops which were not directly linked to advancement), it becomes clear that the TBM’s advancement speed is not heavily conditioned by the type of rock mass bored; such as is the case in conventional tunnelling, where the need to consolidate poor rock mass significantly penalizes advancement. The best performance took place in the presence of flysch material: 12.9 m per day in SCB; 12.3 m per day in MOV; 14.7 per day in BAP (which is a little less resistant than the SCB). Even in the presence of the APA – which, in conventional tunnelling, requires systematic consolidating procedures that heavily penalize advancement – the TBM was able to maintain high levels of production, especially in the second sector, which was the most covered, where advancement progressed at 9.7 m per day, with a reduction of only 30% when compared to a mass with the best geomechanical conditions. The slowing in the APA, in those sectors which were more heavily covered, owes mainly to the necessity – also due to the presence of buildings on the surface – of keeping a high pressure level in the excavation chamber, over 3 bars. Finally, the following considerations can be made by examining the production cycle: the “thrust times” gradually diminish as the advancement progresses; passing from average thrust times of about 2 h (per 2.0 m segment) to levels a little higher than 1 h – showing the tuning of the advancement parameters, especially regarding the conditioning of the cake in the excavation chamber. An increase in the thrust time took place only in the heavily covered APA sector; presenting a squeezing behaviour, mostly composed by clay, alternated with high lithoid portions, heavily resistant to advancement (intrusive basic rocks correlated with ophiolitic formations). In this sector thrust times equal to 1.3 h were registered, with peaks of up to 2 h. The amount of time necessary for the “ring assembly” was also reduced, from 2 h per ring at the beginning, to about 1 hour, as the production cycle and the work teams’ skills were optimized; these times – about 1 hour – then remained constant throughout the final sector of the APA. Besides the previously described and exceptional long-lasting stops; during the normal advancement phase, stops were made for the excavation chamber inspections, in which the tools were checked and replaced (generally around 48 h, max. 72 h), as well as stops for the extension of the supply line (water, air, two component grout, electric lines), and of the conveyor belt (lasting from 4 to 12 hours). There were 8 main stops, on average one every 300 m, in normal baric conditions; in the final stretch of the APA, for about 600 m – between around chainages Km. 2+850 and 3+445, no inspections were conducted in order to avoid stopping in an area with buildings on the surface.

5 EPB-TBM advance parameters

Each TBM has a computer which archives both the data regarding the various mechanical, hydraulic and electrical components of the machine (pressure and main circuits' oil temperature, data regarding the electric engines, etc.), as well as the data pertaining to the TBM's operative settings. This system of data archiving, called PLC (programmable logic controller) gathered real time information for more than 900 parameters pertaining to “Martina's” functions and thus allowing a systematic control of the machine's functions while the work was in progress. In the following paragraphs, the readings of the main operative parameters will be commented and confronted with those that had been projected during the design phase.

5.1 Weight of extracted material

The weight of the material being extracted was examined through systematic weighing in two points of the muck conveyor, and was most important in order to individuate the presence of overbreaks (such as the release or break of rock along the excavation profile) and therefore intervene promptly on the cavity during the following phase of backfill behind the concrete segments. In order to correctly evaluate the weight of the extracted material, the quantity of liquid used for the conditioning of the material must be deducted from the readings measured on the belt; in the examined case, up to a maximum of about 1000 KN input in the excavation chamber, plus about 500 KN directly on the face.

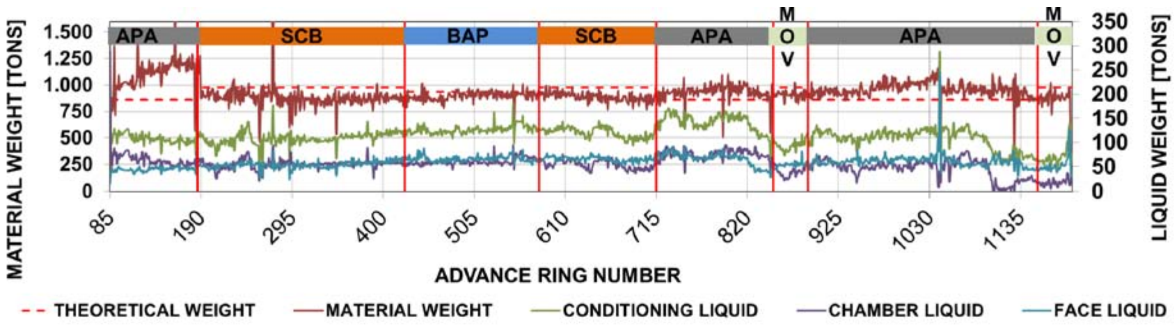

Figure 6. Weight of extracted material

As reported in Fig. 6, this brought about – for every thrust of 2.0 m in length (~383 m^3) – a value in weight of about 8500 KN for the APA (except for a brief stretch where a big ophiolite was bored, and a value equal to 9500 KN was reached) and about 8000 KN for the flysch, SCB, BAP and MOV formations. While the APA formations presented specific weights equal to 22 KN/m^3, in line with design projections, the other formations presented specific weights equal to 20-21 KN/m^3, 24-25 KN/m^3 lower than the design projections. The difference can probably be linked to a size effect which sees, in important volumes of mass, a greater lithological heterogeneity of the face, as well as the presence of fractures – some of which quite large – which did not appear in the lithoids studied in the laboratory. During the advancement, no important overbreaks were observed.

5.2 Penetration rate and thrust forces

The advancement speed was at its highest in the central stretch of the tunnel, boring through SCB and BAP, in the range of 25-30 mm/min up to 50 mm/min, while the most irregular result was in the APA; especially in the ophiolitic stretch, where the speed often dropped to 15 mm/min due to the toughness of the basalt bodies. The speed was also often conditioned by the wear of the tools and by the clogging of the excavation chamber; systematically, speed increased greatly after cutterhead maintenance stops. The sizing of the thrust forces had been examined carefully during the design phase, for fear that the squeezing behaviour of the heavily covered APA would block the progress of the TBM; in particular, the pressure in the excavation chamber had been evaluated so as to keep the rock mass in elastic domain and to avoid, as much as possible, the detensioning of the mass, in the spirit of the ADECO-RS Approach of pre-confining the core face (Lunardi, 2008). Furthermore, the probable pressure on the shield due to convergence and possible overbreaks had also been evaluated; the analyses had appraised a total thrush value – taking into account the necessary safety factors of the risk assessment – of 270 MN, by 57 jacks. Furthermore, alongside HerrenKnecth AG, the possibility of increasing the operative pressure of the jacks from 350 bars to 500 bars had also been evaluated; thus creating the possibility of operating a spike force of 390 MN, in order to unblock the TBM (Gatti, 2011). During most of the TBM's progress, as can be seen in Figure 7, thrusts remained below 100 MN; in the APA stretches of the southern entrance, and the SCB and BAP stretches, the total thrust values remained in the range of 60-80 MN. Starting from ring 800, entering the sector heavily covered by APA, the total thrust values increased, and reached a peak value equal to 160 MN (about 60% of the nominal strength of the TBM), and keeping values within an average range of 120-130 MN. Fortunately, the feared severe thrust conditions of the design phase were never reached, but the stretch in question clearly highlighted the expected squeezing behaviour (see chapter 5.6). The thrust values of the construction phase lead to understand that, thanks to the confinement of the face, the decay of the geotechnical parameters of the APA was very contained; furthermore, in the real tunnel scale, the mechanized excavation system was able to disturb the mass decisively less than in the extraction of samples and the following laboratory analyses, upon which the geotechnical characterization of the masses had been operated. At the moment, following the first back-analyses which are still to be elaborated upon with the data collected from the excavation of the second bore, it is believed that the most representative geotechnical parameters for the APA are close to the higher limit of the projected range, with a decay rate which did not reach the residual value (Gatti, 2011).

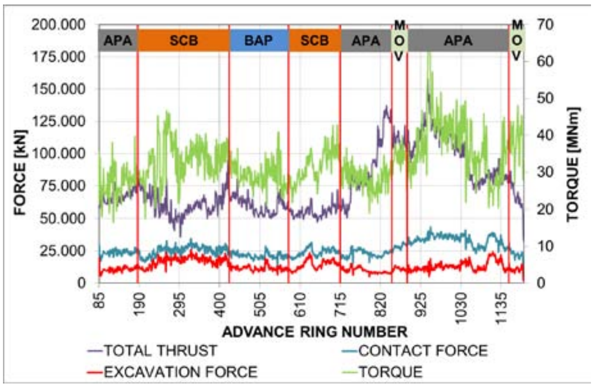

Figure 7. Thrust forces

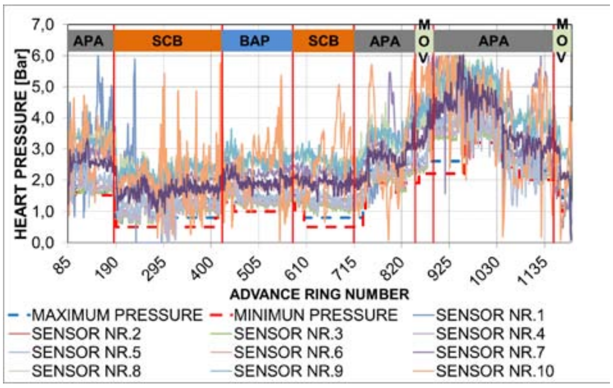

Figure 8. Excavation chamber pressure

The torque values also remained below the dimensioning limit of the TBM, equal to 100 MNm. The first sector of the tunnel, which presented APA at the entrance, and formations of SCB and BAP, registered values between 25 and 40 MNm; there was an increase, as for the thrust value, in the sector most heavily covered by APA – between rings 900 and 1000 – where a maximum value of 65 MNm was reached. Localized increases of the torque were verified in the presence of excavation chamber clogging. Another useful parameter for the evaluation of the energy expended by the TBM through the tools in excavation is the "excavation force". This force can be calculated starting from the "contact force", equal to the value of force exercised by 15 jacks collocated in contrast with the cutterhead, subtracting the pressure in the excavation chamber acting on the connection plate between the cutterhead and the jacks; the excavation force presented average values between 10 and 22 MN, with maximum values in the most lithoid stretches, such as the SCB sector and the main ophiolitic body. As for the torque, the "excavation force" also showed anomalous increases in the presence of clogging, weighing down the cutterhead, and reducing the fluidity of progress.

5.3 Conditioning parameters

Conditioning is a core element for the correct functioning of the TBM; it influences the upkeep of excavation chamber pressure, control over the forces acting on cutter head and wearing down of the excavation tools, as well as the consistency of the extracted material, and its disposal management. In the first period of excavation, much work was put into finding the right balance between quantities of water and foam, in order to: on one side to avoid clogging in the presence of clay materials; and on the other, to extract a material which was not excessively liquid, so as to dispose of it more easily. The final configuration saw the insertion of 6 extra lines of liquid input for the excavation chamber, corresponding to the main drive, in which the water was input so as to make the material in the chamber more fluid and homogeneous. A second amount of liquid, with foam, was input directly at the excavation face, in order to lubricate the face material. Altogether, 1100-1500 KN of conditioning liquid was used, of which 500-800 KN for conditioning of the face (Fig.6), and using 1200-1900 L of foam per stroke; therefore, in percentages which varied from 3.0% to 2.2%. The highest values of conditioning were found in those areas containing clay materials, and belonging to the APA. As for the foams, FER (foam extension ratio) values were used in the range of 6-8, reduced to 5-6 in the APA sector, and values of FIR (foam injection ratio) equal to 80-120% on average, with a maximum value of 160% in the APA.

5.4 Excavation chamber pressure

Definition of the value of pressure to be maintained in the excavation chamber is certainly the most important trait when planning an EPB-TBM mechanized excavation. It is important to keep the deformative behaviour of the core-face under control in order to manage the deformative behaviour of the cavity and associated pressure (Lunardi, 2008); especially in those masses, such as the APA, where the strength are heavily dependent upon the deformations taking place, since the constitutive law is non linear, with a strain softening behaviour. The front pressure values, due to the impossibility of counterbalancing the geostatic pressures in consideration of the large overburdens (100-120 m), were therefore chosen in order to keep the face deformations low, possibly in an elastic field. The numerical analyses, supported by extrusion tests conducted in triaxial cells, showed the need to use pressures over 3.0-3.5 bars for the APA (Gatti, 2011). Figure 8 shows the progress of the pressure levels in the excavation chamber along the tunnel, as detected by the sensors placed at different levels of the bulkhead; the designed minimal and maximum levels are also reported. The values reported in the tunnel are the following: in the first stretch of the APA, covered up to about 35 m, with pressure equal to 1.5-1.9 bars; in the stretch of the SCB, with pressure levels equal to 0.6-1.0 bars - not so much as to keep the face confined but rather in order to keep the excavation chamber full for gas management; in the BAP stretch, with values in the range of 0.9-1.6 bars; while in the APA, covered up to 100-120 m, with values up to 3.3-3.6 bars. In the final stretch of the tunnel, the pressure levels progressively diminished to values of 1.0-1.5 bars. The use of high pressure levels in squeezing condition made it possible to limit the detensioning of the rock mass and to contain pressures acting upon the shield; the use of lower pressure levels, equal to 1.9-2.2 bars, in the first stretch immediately triggered an evident squeezing behaviour, making higher thrust levels necessary.

5.5 Back-filling

The filling of the ring gap between the excavation profile and the estrados of the concrete segments takes place in the tail of the shield, by injecting fast-setting two component grout, in order to avoid the convergence of the cavity and ground loss volume. The maximum injectable volume, not considering extra excavation, is equal to 29.6 m^3 (stroke: 2.0 m), being the difference between the diameter of excavation (15.62 m), and the estrados diameter of the lining ring (15.00 m). As the shield tapers, equal to 7.25 cm of the radius, the final volume available for filling is reduced to 22 m^3, if convergence took place. During the excavation, injection values remained near the maximum volume almost entirely throughout, except for the heavily covered APA stretch, where the filling values were reduced to the minimum volumes of 22-23 m^3 from about ring 800 to 1000, caused by the APA's squeezing behaviour. The injection pressure values used were often 0.5-1.0 bars above the values of pressure in the excavation chamber, in order to avoid the mix from flowing towards the face.

5.6 Considerations upon the heavily covered APA stretch

The combined analysis of the data collected during progress has allowed the evaluation of the TBM's performance and to calibrate the operative parameters. The most important stretch of the tunnel is certainly the heavily covered APA sector, between rings 800 and 1000, which required special care from the design phase onwards. Figure 9 charts the combined progress of a few main parameters, previously discussed, and highlights their mutual interaction and the importance of correlating them for a correct interpretation of the progress modalities. It can be seen that, from ring 810 onwards, in the presence of face pressure levels equal to about 1.8-2.0 bars, the TBM thrust gradually increased, although the excavation force remained for the most part unchanged; therefore, there was an increase of the thrust associated with ground-shield friction (up to 80 MN), also registered by the increase of pressure levels in the sensors placed on the shield, where the bottom level of 6 bars was quickly reached, and the reduction of the back-filling volumes, from 24-26 m^3 (in presence of 4-5 cm radial convergences) down to minimum values of 22-23 m^3 (with the ground in contact with the shield). The collection of data confirmed the squeezing behaviour of the mass; the pressure on the face was therefore increased, up to values higher than 3.0-3.3 bars, so as to contain the problem. Although this increase did not stop the mass from converging upon the shield (back-filling volumes remained constantly at minimum levels), a reduction of pressure on the shield was still seen, with the associated squeeze diminished to 20-30 MN, later increasing in the most critical point, when encountering the fault bored around ring 740, without however reaching the previous levels met in the presence of lower face pressures. This evidence confirms - also in the field of mechanized excavation - the importance of face confinement in keeping the stability and the deformation control of the cavity.

Confinement of the excavation face was also important, in this sector of the tunnel, due to the presence of many buildings on the surface, located on a landslide slope. The vulnerability of this area, which had already been compromised by past movements of the slope, caused a significant deformative response at the ground level, despite the high level of coverage present and the use of mechanized excavation, which causes a decisively lower loss of volume than conventional tunnelling. Figure 10 reports the movements of some significant topographic points: it is possible to see settlements equal to 40-70 mm, in the presence of movements, equal to 50-110 mm. The ground level was disturbed when the excavation face was 50-70 m from the topographic measure point, while a tendency towards asymptoticity was observed in the movements; once the excavation face went 150-200 m beyond the measure point (around 1 month after the TBM had passed).

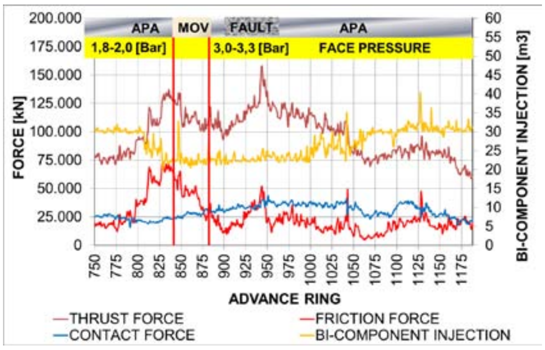

Figure 9. Heavily covered APA data

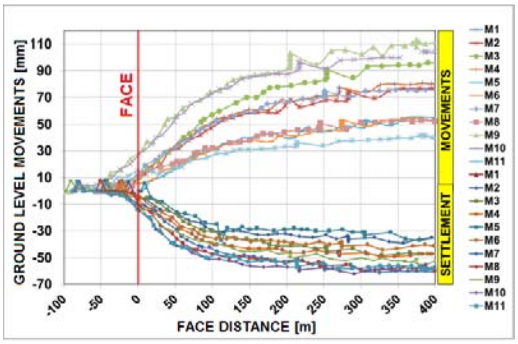

Figure 10. Monitoring data

6 Conclusions

The paper presents the first evidence collected during the excavation of the first tube of the *Sparvo Tunnel*, executed with an EPB-TBM with the record diameter of 15.62 m and completed in July 2012. After a first period of tuning of the operative modality, the construction process was industrialized up to an average production of 13.2 m per day (with a record of 22 m/d) in the period of March-July 2012, above expectations. An important aspect is that production values were not significantly conditioned by the lithologies bored, with only a reduction of 30% in the most difficult formation of APA, where a conventional tunnelling process would have required extensive consolidating. The pressure parameters at the face were in line with design projections, needing high pressure levels of 3.0-3.5 bars when boring through the heavily covered APA; in this sector the expected squeezing behaviour of the mass took place, although the necessary thrust for the progress of the TBM (maximum value equal to 160 MN) did not go over the dimensioning limit of the machine, also thanks to the confinement operated at the face. The tuning of the conditioning parameters of the material was of particular importance, as it avoided the clogging of the excavation chamber and consequent negative effects on the TBM's performance and the tool's wear; in particular, 6 liquid input lines were added to the centre of the main drive. Geotechnical monitoring during the work made it possible to evaluate the interaction between the excavation and the existing buildings on the surface. Monitoring of the gas concentrations in the excavated material (which reached values up to 0.15-0.20%, on average equal to 0.03%-0.05%), alongside the procedures discussed in Lunardi (2012), made it possible to manage this delicate aspect of construction.

7 Acknowledgements

The authors wish to thank their colleagues G. Lodigiani, for his active co-operation in perfecting the design, and I. La Rosa for his precious technical assistance provided on site during construction. They would also wish to thank TOTO Constructions for the fruitful collaboration in constructing the work.

8 References

Gatti, M., Lunardi, P., Cassani, G., 2011. The largest TBM-EPB machine in the world, designed to the Appennines. The experience of the Sparvo Tunnel. 1st Int. SEE Con. «Using underground space», Dubrovnik.

Lunardi, P., 2008. Design and Costruction of Tunnels – Analysis of Controlled Deformation in Rock and Soils (ADECO-RS). Berlin, Springer.

Lunardi, G., Selleri, A., 2012. Design of « Martina », the World's Largest EBM TBM. Geological and geotechnical issues. Swiss Tunnel Congress Colloquium, Luzern.