Giuseppe Lunardi, Dott. Ing., Managing Director, Rocksoil S.p.A., Milan/I
Alberto Selleri, Dott. Ing., Head of Operational Unit, Spea Ingegneria Europea S.p.A., Milan/I

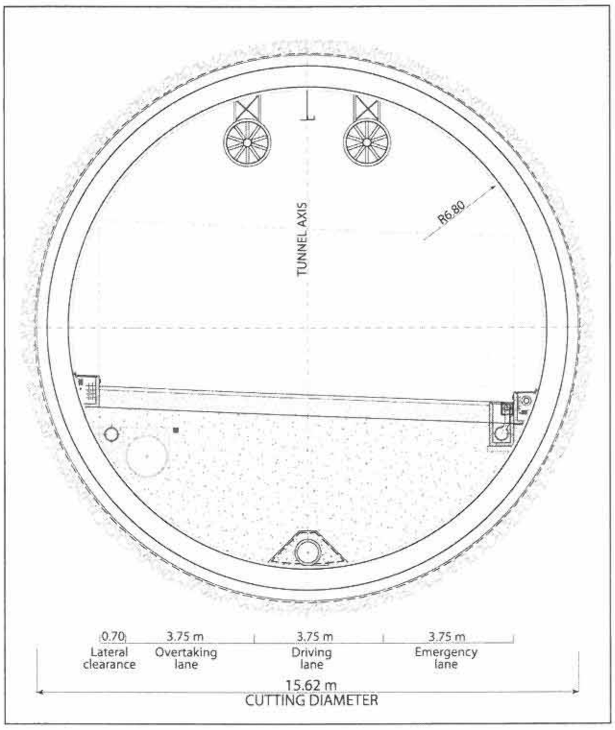
Design of "Martina", the World's Largest EPB TBM

Geological and geotechnical issues

A description is given of the geological and geotechnical assessments performed to select the type of TBM to employ for the excavation of the "Sparvo Tunnel", which has an exceptional outer diameter of 15.62 m, on the A1 Milan–Naples motorway in the section between La Quercia (Bologna) and Barberino di Mugello (Florence). The technical characteristics and operating parameters for the design of the machine are identified, with particular attention paid to the most critical context from both a geotechnical viewpoint and because of the presence of firedamp, consisting of the Argille a Palombini formation.

1 Introduction

Improvements to Italian infrastructures include upgrading the section of the A1 Milan–Naples motorway between Sasso Marconi (Bologna) and Barberino di Mugello (Florence). This operation is particularly significant because it involves a large number of underground projects including the "Sparvo Tunnel" which, because of its length, the diameter of the excavation and the geological context, is critical for opening the section of motorway between La Quercia and Barberino di Mugello. The underground alignment is approximately 2600 m in length and twin bore (inner diameter of approximately 13.60 m) (Fig. 1, Table 1). It runs through a slope affected by numerous dormant landslides and active local phenomena – at times very extensive and large, such as the Frana di Sparvo (Sparvo landslide) – and through geological formations belonging mainly to the Complessi di base Liguridi, such as the Arenarie dello Scabiazza (SCA) and the Argille a Palombini (APA).



1 Sparvo Tunnel section layout

The difficult geomechanical conditions, especially in the section running through the Argille a Palombini, and slope deposits, and the consequent uncertainties concerning the speed of tunnel advance led the contractor, in agreement with the client, to consider the use of a TBM. The contractor had estimated that this choice would be more advantageous than conventional methods, especially in terms of saving of construction times, in consideration of the poor geomechanical characteristics of the ground and the possible presence of gas deposits within the rock mass to be excavated.

2 Geological and geomechanical context

2.1 Geological conditions along the tunnel alignment

The alignment runs through a slope affected by numerous dormant landslides with local phenomena of instability, which are also quite extensive and substantial (Sparvo landslide) and it contains geological formations that are notorious in terms of their difficulty for tunnelling (Fig. 2):

- the "Argille a Palombini" (APA), at the 2 portals for a total of approximately 1600 m, consisting of intensely deformed clays and argillites, with calcareous (C:A ratio <<1) or sandstone inclusions, in thin strata

Client	Autostrade per l'Italia
Contractor	TOTO Costruzioni Generali
TBM Supplier	Herrenknecht AG
Construction Design	Rocksoil
Construction Supervision	Spea Ingegneria Europea
Technical Assistance	Rocksoil

Table 1 *Project data*

Konstruktion von „Martina", der weltgrössten Erddruck-TBM

Geologische und geotechnische Herausforderungen

Der Artikel beschreibt die geologischen und geotechnischen Analysen für die Auswahl der geeigneten TBM beim Vortrieb des Sparvo-Tunnels mit einem aussergewöhnlich grossen Aussendurchmesser von 15.62 m auf der Autobahn A1 Mailand–Neapel im Abschnitt zwischen La Quercia (Bologna) und Barberino di Mugello (Florenz). Die technischen Merkmale und Betriebsparameter für den Aufbau der Maschine werden benannt. Dabei wird besonders auf die schwierigen geotechnischen Bedingungen und die Probleme durch Grubengas bei der Formation Argille a Palombini eingegangen.

Conception de «Martina», le plus grand tunnelier du monde à pression de terre

Défis géologiques et géotechniques

L'article décrit les analyses géologiques et géotechniques nécessaires au choix du tunnelier approprié pour l'excavation du tunnel de Sparvo. D'un diamètre externe peu commun de 15.62 m, il est situé sur le tronçon de l'autoroute A1 Milan–Naples entre La Quercia (Bologne) et Barberino di Mugello (Florence). On évoque ici les caractéristiques techniques et les paramètres de service pour la conception de la machine. L'article insiste en particulier sur les conditions géotechniques difficiles et sur les problèmes induits par le grisou au niveau de la formation Argille a Palombini.

La costruzione di "Martina", la fresa EPB più grande al mondo

Sfide geologiche e geotecniche

Questo articolo descrive le analisi geologiche e geotecniche per la scelta della TBM adatta allo scavo del tunnel di Sparvo con un diametro esterno straordinariamente grande di 15.62 m sull'autostrada A1 Milano–Napoli nel tratto tra La Quercia (BO) e Barberino di Mugello (FI). Vengono descritte le caratteristiche tecniche e i parametri di esercizio per la struttura della macchina, approfondendo in particolare le difficili condizioni geotecniche e i problemi dovuti al gas di miniera nella formazione di argille a palombini.

- the "Arenarie dello Scabiazza" (SCA), for at total of approximately 700 m, consisting of sandstones with intervening siltites and argillite strata, interbedded by
- the "Brecce Argillose Poligeniche" (BAP), for a total of approximately 300 m, consisting of clays with clasts of varying lithological nature

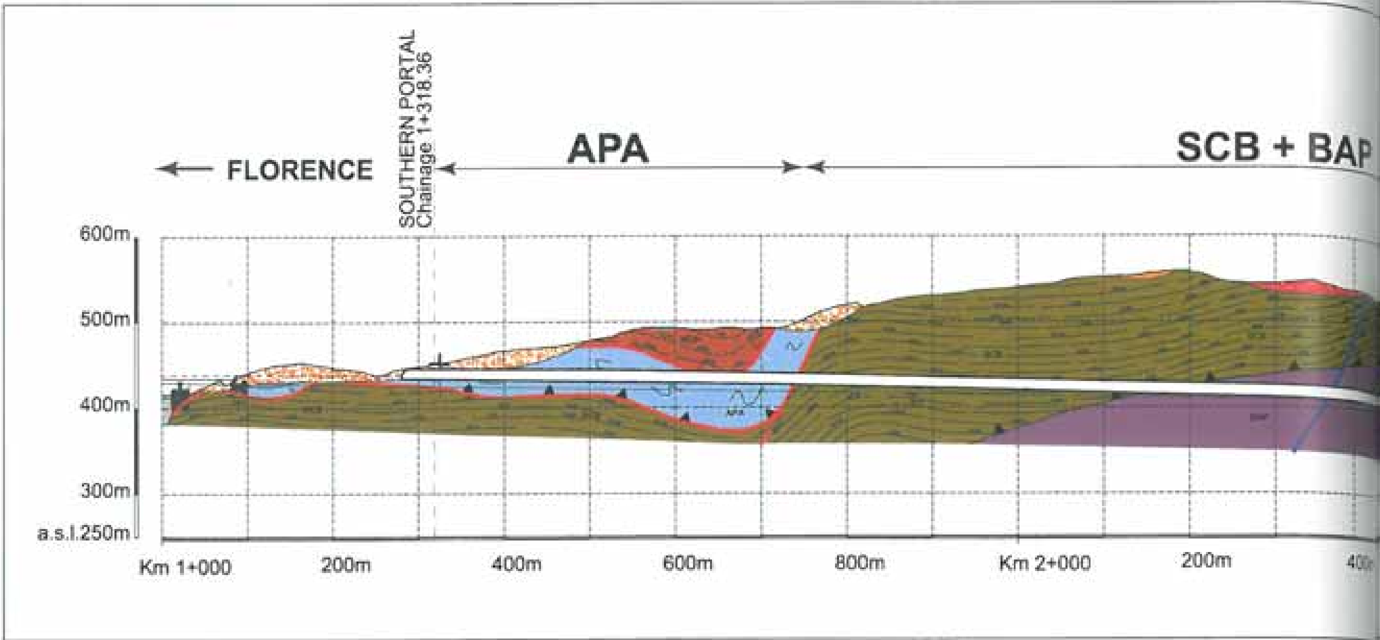
The passages from one formation to another mainly occur through tectonic contacts where pockets of firedamp are known to be present. The maximum overburdens are around 30 to 35 m in the first 800 m on the Florence side and afterwards they increase progressively to a maximum of approximately 120 m, when they diminish as the portal on the Bologna side is approached.

From a hydro-geological viewpoint, the rock masses present in the area are characterised by secondary permeability, due to fissuring, while the recent deposits and the landslide

Formation	Overburden [m]	GSI	γ [kN/m³]	k_o [-]	ϕ_p [°]	ϕ_r [°]	c_p [kPa]	c_r [kPa]	E_p [MPa]	E_r [MPa]	v [-]
Deposits	20	–	21	0.53	28	–	20	–	60	–	0.35
MOV	110	30	25	0.59	24	20	150	120	800	640	0.25
BAP	100–130	60	25	0.61	23	18	200	160	4000	3200	0.25
SCB	60–120	40	25	0.50	30	24	250	200	2000	1600	0.25
APA	25	–	22	0.70	16	11	53	37	163	100	0.35
APA-2*	25	–	22	0.70	13	10	42	29	130	80	0.35
APA	60–115	–	22	0.70	23	14	230	170	703	460	0.35
APA-2*	60–115	–	22	0.70	18	11	180	140	563	368	0.35

Table 2 *Geotechnical parameters of strength and deformability*

* *Geomechanical parameters 20 % poorer than APA are assumed*



2 Sparvo Tunnel geological longitudinal section

layers present reduced primary permeability due to porosity. Permeability only reaches higher values in the tectonised bands, and underground water flows can be detected (up to 100 l/min). On the other hand, those formations with a prevalent clayey component (APA, BAP) have very low permeability, with little water flow. No continuous water table was found along the route of the tunnel, even if some samples from the APA had a high water content.

2.2 Geotechnical characteristics

The main lithotypes along the alignment consisted of the SCA (35 % of the length of the tunnel) and the APA (45 %), which constituted the 2 main contexts studied to decide the method of excavation. The in situ and laboratory tests conducted and experience acquired in similar contexts during the construction of tunnels on the new high-capacity Bologna – Florence [1] line and other tunnels of the Bologna – Florence motorway [2] allowed the geotechnical parameters of strength and deformability given in Table 2 to be established for each lithotype.

Geotechnical parameters that vary with depth and with the degree of deformation reached during excavation are to be expected for the rock masses belonging to the APA, where the law governing the constitution is decidedly non-linear and of an elastic-plastic nature with "strain-softening" behaviour. Equations (1), (2) and (3) give the values for the strength parameters, angle of friction ϕ, cohesion c and deformability E as a function of depth (peak and residual):

$$\phi_{peak} = 15 + 0.07 \cdot z \, [°] \qquad \phi_{res} = 10 + 0.05 \cdot z \, [°] \qquad (1)$$

$$c_{peak} = 5 + 1{,}95 \cdot z \, [\text{kPa}] \qquad c_{res} = 1.5 \cdot z \, [\text{kPa}] \qquad (2)$$

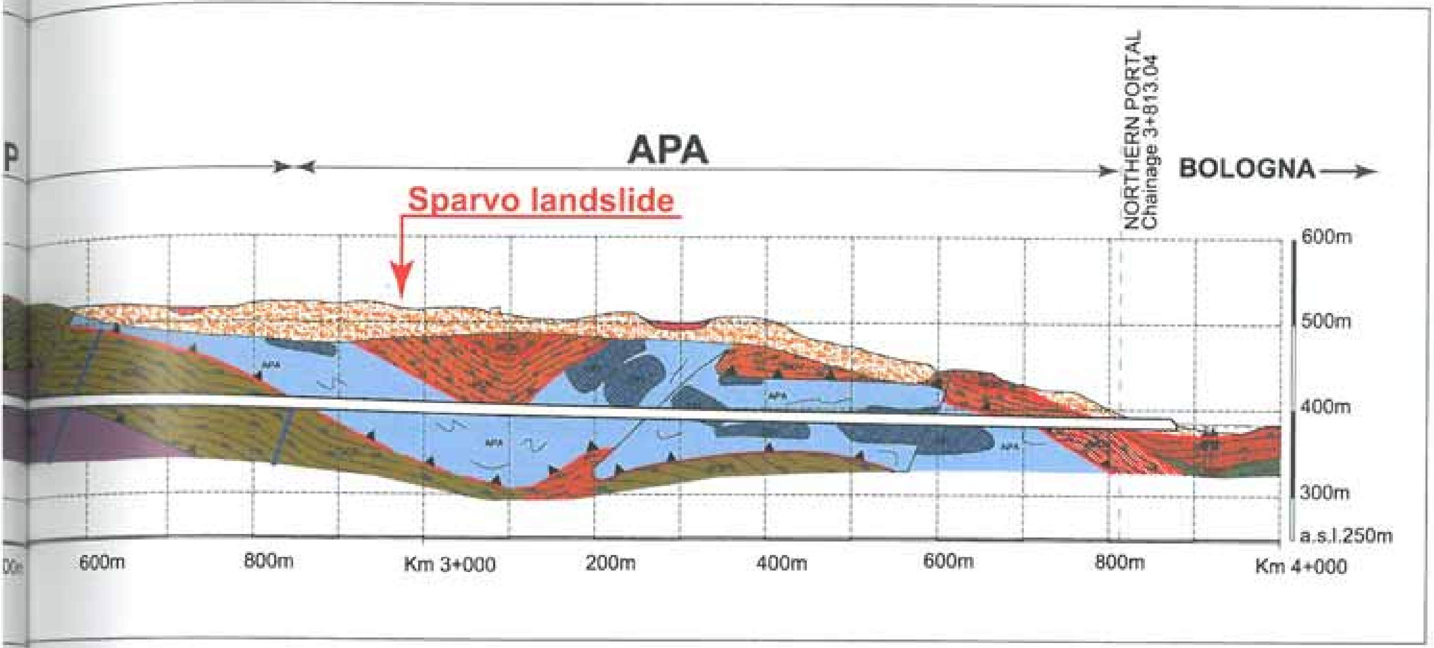
$$E_{peak} = 13 + 6 \cdot z \, [\text{MPa}] \qquad E_{res} = 4 \cdot z \, [\text{MPa}] \qquad (3)$$

Lastly, the main properties of the APA are given: granulometry analyses found the presence of silts and clays in proportions of 40 and 29 % respectively (S + C = 69 %), with percentages for gravels of 12 % and sands of 19 %. The liquid limit (LL) values were very scattered, ranging from 25 to 65 %, while values for the plastic limit (PL) were contained within 15 to 25 %, with a plastic index of between 10 and 40 %. The material is classified as "inorganic clay with medium to high plasticity". The relative consistency (RC) is much higher than 1 and therefore the rock mass can be defined as "a consistent clay". From a mineralogical viewpoint, 80 % of the rock mass consists of clayey minerals and 20 to 35 % of smectites. Finally, the water content is approximately 10 %, so the rock mass can be considered "non-saturated", even if some samples were found to contain higher levels close to saturation.

3 Design issues and decisions

The design of the tunnel excavation operations was conducted in consideration on the one hand of the difficulties of the geotechnical context and on the other hand of the need to ensure good advance rates in order to reduce construction times. The main difficulties with regard to the geotechnical context were:

- the alternation along the tunnel alignment of formations which were clearly rocky, such as the sandstones of the SCA with the slope deposits and clayey masses which were very poor in quality. This required the adoption of "flexible" excavation methods both in terms of face excavation and ground improvement and linings to be performed at the face and around the cavity



- the substantial decay of the strength parameters of the APA, as a function of the degree of deformation of the rock mass following excavation ("strain-softening" behaviour). It is absolutely essential to halt this phenomenon to prevent the progressive closure of the cavity and "squeezing" phenomena during tunnel advance
- the presence of dormant, and locally active, landslip deposits near the portals with shallow overburdens and near the village of Sparvo, which requires the adoption of fairly conservative excavation techniques
- the presence of gas deposits within the ground tunnelled, which required construction site organisation to include equipment and operating procedures designed to prevent gas explosions and to guarantee worker safety and normal construction work rhythms

Under these conditions, the decision to mechanise excavation by using EPB TBMs was taken jointly by the client and the contractor, following risk analysis in the conviction that it provided greater guarantees compared to conventional methods, with regard to construction times and with account taken of investment strategies linked to future reuse of the machine.

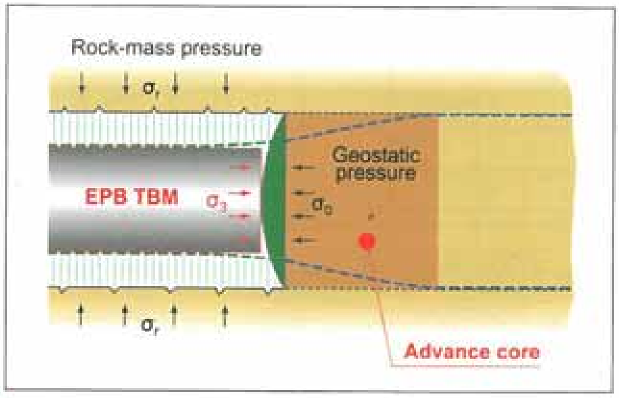
The design of the TBM was conducted by Herrenknecht AG with support from Rocksoil S.p.A. for the geotechnical dimensioning. It required major in-depth study and analysis, linked to the very exceptional diameter of the excavation (15.62 m). Study, design and testing of the following was required:

- the dimensions of the mechanical parts, especially the cutter head and the shield
- the thrust and the cutting torque, as a function of the pressure to be maintained in the excavation chamber and the pressure to be exerted on the rock mass around the shield, to prevent the danger of the TBM becoming jammed during tunnel advance
- special equipment with which the TBM (the first in the world in this respect, too) had to be fitted to work in safety in the presence of gas

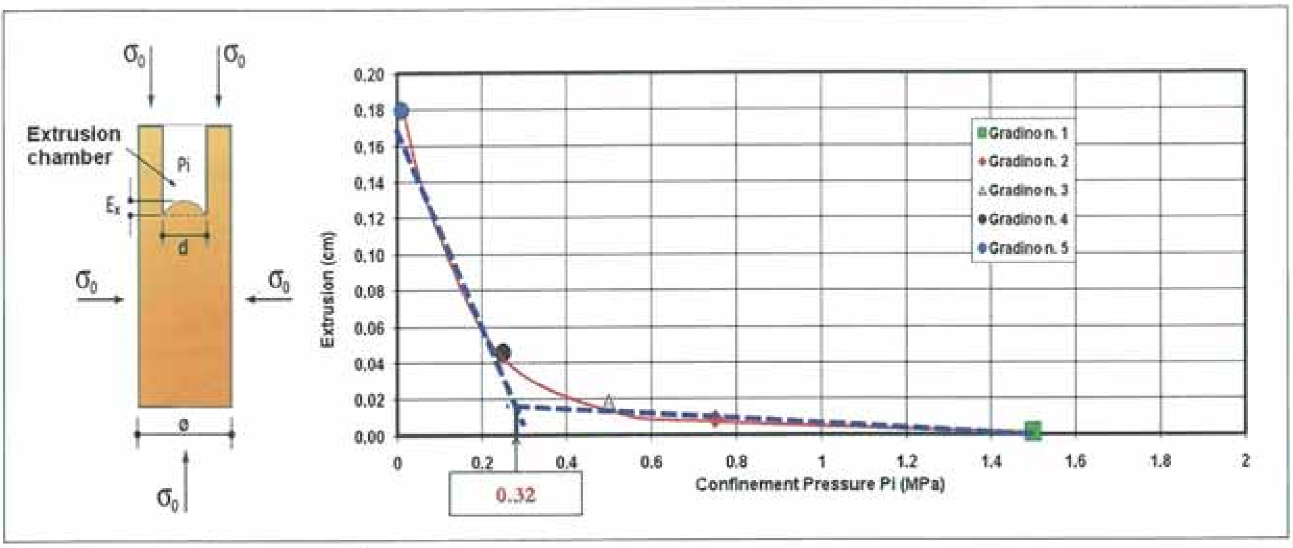
While details are not given here of the dimensions of the mechanical parts, which were the responsibility of Herrenknecht AG engineers, the sections below illustrate the criteria followed for the geotechnical dimensioning of the machine and the related problems of working in the presence of gas.

4 The geotechnical dimensions of the EPB TBM

As is well known [4], a close connection exists between extrusion produced in the face core of a tunnel during excavation and the subsequent phenomena of cavity preconvergence and convergence. It is also well-known that by



3 Analysis of the deformation



4 Triaxial extrusion test, extrusion-confinement pressure

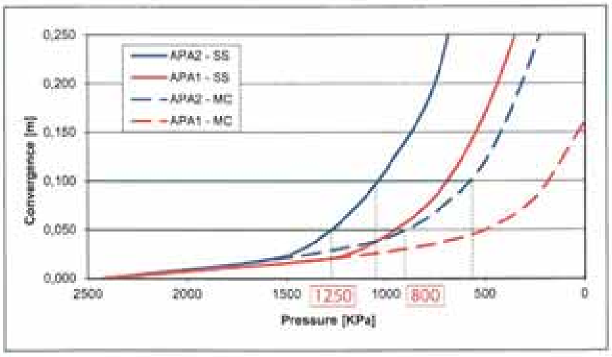
controlling extrusion, by means of appropriate operations for preconfinement of the core face, it is also possible to control consequent preconvergence and convergence and the pressures associated with these around the cavity [4]. With reference to Fig. 3, once the geostatic pressure σ_0 acting externally on the TBM is known, it is essential to accurately define the confinement pressure σ_3 to exert on the excavation chamber, because control of extrusion depends on it and it determines the effectiveness with which the advance core can counter deformation phenomena (preconvergence and convergence), by acting as a natural instrument for tunnel stabilisation. This is extremely useful above soil in rocks and soils like those of the APA, which are highly susceptible to "strain-softening" behaviour, where the application of appropriate confinement pressure σ_3 can considerably reduce the magnitude of the pressures acting on the shield as well as subsequently on the final linings.

4.1 Core face behaviour and excavation chamber pressure

Calculation of the pressure σ_3 to be maintained in the excavation chamber was performed with the objective of maintaining the rock mass at the face in the elastic field and therefore with little deformation. In consideration of the large overburdens of up to 100 to 120 m, it is in fact impossible to counterbalance the geostatic pressures exerted (σ_v = 20 to 25 bar = 2.0 to 2.5 MPa, σ_h = 14 to 18 bar = 1.4 to 1.8 MPa, assuming $K_0 = \sigma_h/\sigma_v = 0.7$), as is usually done for TBM excavation in urban contexts, in the presence of shallow overburdens.

The results of triaxial "extrusion tests", which simulate tunnel advance on a small scale, were particularly useful for calculating the pressure σ_3 according to the criterion just mentioned. Fig. 4 contains an "extrusion-confinement pressure" curve, obtained from numerous extrusion tests conducted. Study of this curve made it possible to identify, on the basis of the initial simulated stress state and the geotechnical samples of the APA employed, the value (0.32 Mpa) of the confinement pressure at the limit of the elastic field (linear section of the curve) which must be exerted at the face to contain deformation within desired values [4]. That value was then verified and confirmed by means of numerical analyses using FLAC software on axial symmetric models.

Analogous studies conducted for the SCA formation found no need, in this formation, to contain deformation phenomena that develop during excavation and to exert specific pressures in the excavation chamber.



5 APA (H = 110 m) – Pressure convergence curves

4.2 Frictional forces acting on the skin of the shield

Calculation of the forces acting on the shield was conducted by analysing the relationship existing between confinement pressure and convergence of the cavity according to the "convergence-confinement" method, considering the inevitable convergences of the cavity in the empty space existing between the diameter of the excavation and the extrados of the shield. An example of the curves calculated for the APA, with overburdens of around 110 m and using 2D analyses, is given in Fig. 5. Maximum pressures of 1250 kPa were found in the presence of 5 cm of convergence (normally managed by the excavation geometry of the TBM) or of 900 kPa, depending on whether a deterioration of 20 % in the geomechanical parameters is considered (blue lines) or not (red lines). Those same pressures declined to approximately 1000 kPa and 650 kPa for convergences of 10 cm (overbreak used in thrusting conditions). In that same Fig. 5, dotted line pressure-convergence curves are plotted, for the assumption of elastic-plastic behaviour of the material (without softening). The substantial reduction of the consequent pressures, with the same convergence values, demonstrates that it is fundamental to keep deformation levels low during tunnel advance, in order to prevent the material from loosening, by exerting adequate action to confine the core face through the pressure in the excavation chamber.

The pressures calculated for the SCA formation using the same method were around 160 to 200 kPa for convergence of 5 cm and virtually nil for convergence of 10 cm.

4.3 Thrust specifications for the dimensioning of the jacks

Calculation of the pressure to be maintained at the face and of the consequent pressures around it, with coefficient of friction values in the 0.25 to 0.35 range, made it possible to then calculate the thrust to be generated by the jacks for the advance of the TBM, taking into account a series of other factors linked to the following: the weight of the machine itself and of the back-up, the forces required to crush the rock mass at the face through the cutters and around the cutterhead, and the friction of the system of brushes on the tail of the shield. As shown in [5], the dimensioning of the thrust cylinders (T) is based on the sum of the individual strengths, including an extra safety factor (γ_f =1.1 to 1.2):

$T = \gamma_f \cdot \Sigma W$ (KN) $\Sigma W = W_{sk} + W_{supp} + W_{exc} + W_{sh}$ (KN)

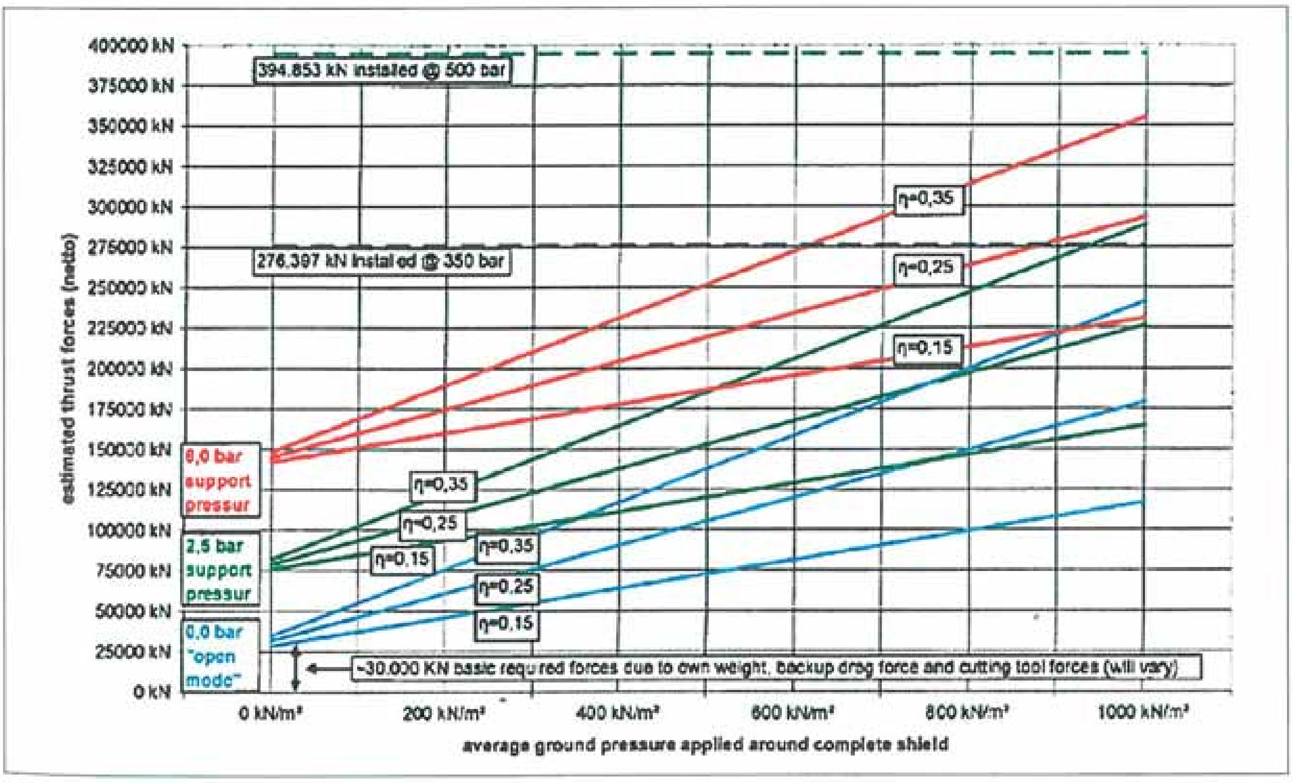
where W_{sk} is the force due to friction, W_{supp} is the force due to the pressure to be applied in the excavation chamber at the face, W_{exc} is the force required for excavation by cutters and W_{sh} is the drag force of the tailskin seal. The calculation of each of these components is considered more fully in [6].

The studies conducted led, in cooperation with Herrenknecht AG, to the creation of the graph in Fig. 6, where the value for the thrust force is identified as a function of the geotechnical conditions and the value assumed for the coefficient of friction.

By using a risk analysis approach, 2 working thresholds were identified: the first to generate 275,000 kN of thrust using 57 jacks working at 350 bar each; the second able to reach approximately 400,000 kN under squeezing conditions, bringing the working pressure of the jacks up to 500 bar.

4.4 Construction details

Construction details were designed to prevent the TBM from becoming blocked in the tunnel. These included a gap between the cutterhead and the tail of the shield of 72.5 mm in the radius (shield with a truncated cone shape) and the possibility of a further 50 mm of overbreak on the radius to manage the greatest convergence of the cavity. The shield was also fitted with lubricant injectors to reduce friction between the TBM and the rock mass (μ = 0.15).



6 Study of the total thrust of the TBM (Herrenknecht)

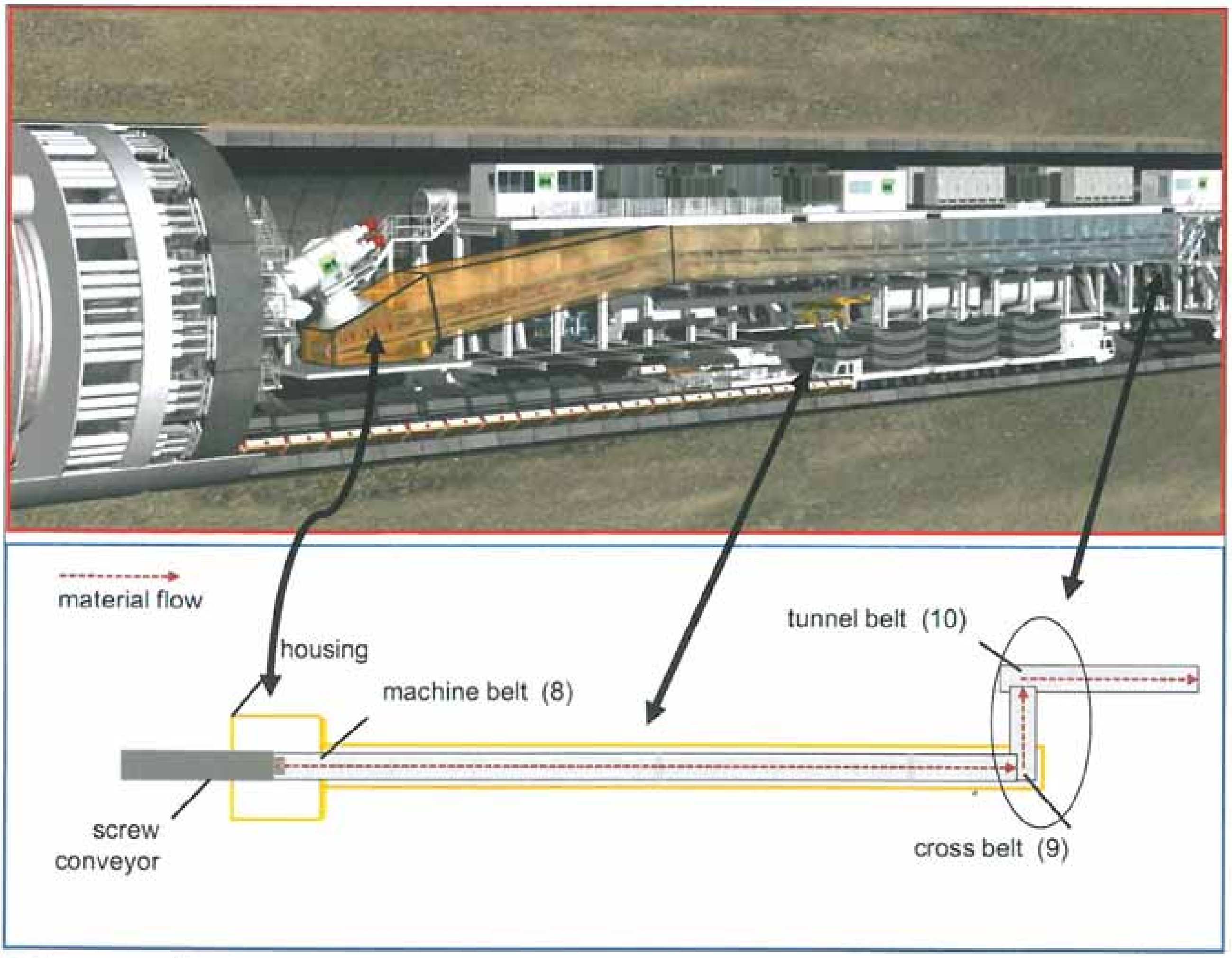
Rings consisting of 9 segments plus a key were erected for the final lining with a thickness of 70 cm and a depth of 2 m. The segments were connected using metal bolts for the longitudinal joints between segments and steel pins for the joints between rings. Water proofing is guaranteed by means of an EPDM seal (44 mm base) fitted around the whole perimeter of the concrete segments.

4.5 Safety measures for the presence of gas

When conventional excavation methods are employed, the presence of gas in the ground is managed using anti-explosion equipment and regimes, i.e. using work systems designed to prevent all possibility of explosions. The content of gas in the air is monitored systematically and it is diluted using appropriate ventilation systems. The issue is more delicate with TBM excavation because it is not possible to render the head of the TBM and the section covered by the shield explosion proof. The approach taken is therefore that of confining the gaseous mixture. TBM advance is always with a closed shield and the excavation chamber completely full, in order to prevent the possible formation of a "combustion chamber". Under these conditions of pressure, the excavated material plus water and an additive mixture guarantees that no critical conditions can arise even in the presence of firedamp, because the chance of explosion would be minimal and no conditions for flame propagation would exist. The main possibility for gas to enter the shield, and also the completed tunnel with the final lining in place, is through the screw conveyor which removes muck on a conveyor belt.

The unloading area at the screw conveyor outlet point and the complete back-up belt conveyor have been isolated from rest of the TBM using an encapsulated double shell system (belt channel) with a length of approximately 80 m. Any inflows of gas can be controlled by adjusting the screw conveyor extraction speed or the position of the closing gate, and it is possible to stop the flow at any moment by hermetically sealing the exit to the screw conveyor (Fig. 7).

Due to construction restrictions, the transfer belt conveyor and the loading chute to the tunnel belt are not covered so from this point the completely built tunnel is equipped with fully ex-proof equipment, as for conventional tunnelling. A



7 Belt conveyor configuration system

8a The Sparvo EPB TBM (named "Martina")

ventilation system and carefully studied safety devices and emergency exit routes complete the measures designed to mitigate the risk from firedamp.

5 Conclusions

This paper describes the analyses conducted to establish the geotechnical dimensions of the EPB TBM employed to drive the "Sparvo Tunnel" as part of the works to modernise the A1 Milan–Naples highway in the section between La Quercia (Bologna) and Barberino di Mugello (Florence). The TBM, with an exceptional diameter of 15.62 m, must excavate 2600 m of tunnel through a variety of difficult geological conditions and in the presence of gas.

Construction of the TBM was completed in December 2010 and in February 2011 it was transported to the portal on the Florence side, where it was assembled (Figs. 8a+b). Tunnel excavation started in August from the portal on the Florence side and now, in mid-January 2012, approximately 380 m have been excavated with normal production of approximately 5 to 6 rings per day (i.e. 10 to 12 m per day). After an initial phase of fine tuning the TBM with production of 2 to 3 rings per day, and a period when tunnel advance was halted for maintenance of the TBM head, today tunnel advance is satisfactory at constant rates. In this first section of tunnel, with maximum overburdens of 30 m, excavation chamber pressures in the range of 1.5 to 2.5 bar have been employed, with thrust values of 80 to 90 MN and torques of 30 to 40 MNm; advance speeds were maintained within a range of 20 to 25 mm/min. The main problems encountered related to clogging in the excavation chamber due to clays sticking to it, which led to the use of more powerful systems to condition the material in the excavation chamber. Interference with gas has been managed to date by means of the monitoring system in place, which systematically measures the concentration of gas dissolved in the muck extracted and present in the excavation chamber, especially when the TBM is halted for head inspections. The muck is diluted if necessary using the ventilation system installed for that purpose.

8b Facilities for housing the EPB TBM at the portal on the Florence side

References

[1] Lunardi, P. (2007), Cassani, G., Bindi, R. "From the ADECO-RS approach to the tunnelling industrialization", International Symposium on "Tunnelling for urban development", Pattaya City, Thailand

[2] Lunardi, P. (2007), Cassani, G., Gatti, M., "Design aspects of the new Apennines crossing on the A1 Milan-Naples motorway: the Base Tunnel", Proceeding of the AFTES Congrès International Monaco "Le souterrain: espace d'avenir", Monaco, France

[3] Lunardi, P., (2000), "Design & Constructing tunnels – ADECO-RS approach", Tunnels and Tunnelling International, special supplement

[4] Lunardi, P., (2008), "Design and Construction of Tunnels – Analysis of Controlled Deformation in Rock and Soils (ADECO-RS)", Springer, Berlin

[5] Maidl, B. (1996), Herrenknecht, M., Anheuser, L., "Mechanised Shield Tunneling", Ernst & Sohn, Berlin

[6] Lunardi, P. (2011), Gatti, M., Cassani, G., "The largest TBM-EPB machine in the world, designed for the Apennines. The experience of the Sparvo Tunnel", Proceedings of the 1st Scientific Congress on Tunnels and Underground Structures in South-East Europe on "Using underground space", Dubrovnik, 7–9 April 2011