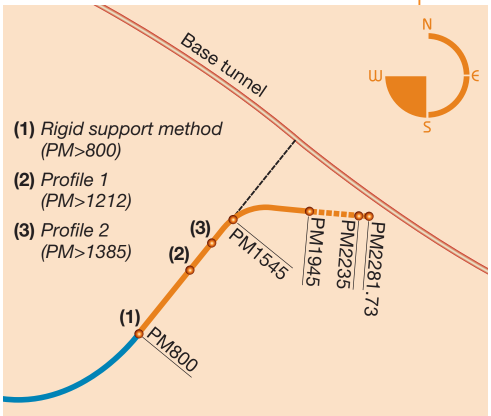
At the mercy of the mountain

The Saint Martin La Porte adit is a key element of the exploratory works for the Lyon-Turin Base Tunnel. Eric Mathieu, head of Razel's tunnel design department, describes the extreme conditions encountered



Above: Fig 1- Route of the SMLP adit
Left: Convergences in Profile 1

The new Lyon-Turin High-Speed Rail Link will incorporate a 53km twin-tube Base Tunnel between the French town of Saint-Jean-de-Maurienne and Venaus in Italy. With construction due to commence in 2010, the largely EU-funded tunnel will become a key component of the Trans-European rail network, providing increased capacity for freight movement through the Alps.

As part of the early works for the Base Tunnel, two access adits are currently being excavated, Saint Martin La Porte and La Praz, with a further adit, Modane, already completed. These adits play a vital role in the investigation of conditions along the Base Tunnel alignment, as well as assist selection of excavation and lining methods.

Despite being an investigatory heading, the 2200m-long Saint-Martin-La-Porte (SMLP) adit is a significant structure in its own right, with an excavated profile of 77m^2 to 125m^2 (for a final internal profile of 54m^2 to 63m^2), and will eventually provide construction access for the Base Tunnel.

The client, Lyon Turin Ferroviaire (LTF) awarded the construction works to a JV of Razel, Bilfinger Berger, Pizzarotti and GRA, which has a multiple role on the project: In addition to excavation, the JV also undertakes detailed analysis and mapping of the geological conditions encountered, convergence measurements, rock support design, construction design and proposal of methods - which are submitted for acceptance by the Project Manager (a JV of Egis Tunnels, Antea and Alpina).

Feeling the squeeze

Beginning on 01 July 2003, drill and blast excavation of the first 800m of the SMLP tunnel progressed steadily through landslide material then limestone, marly limestone and anhydrites. A full section heading advanced at an average of 155m a month, working 24hrs a day, five days per week.

However, as soon as the excavation encountered the carboniferous formation "Houillère Productif" (HP) at CH800, severe problems arose due to an extremely high degree of faulting and degredation of the rock mass. Exceptional convergences, of more than 2m in diameter, caused tunnel linings to rupture and the tunnel advance to slow to a virtual standstill.

The carboniferous formation proved to be highly heterogeneous, disrupted and fractured, alternating between black schists, sandstones, clay-like shales and cataclastic rocks, interspersed with layers of coal.

Laborious excavation of the first section of the adit (figure 1) through the squeezing ground conditions of the HP (CH800-CH1545), under overburdens of 150m to 450m, was performed between 01 March 2004 and 06 April 2007. This required the study of different multiple excavation and lining techniques in order to refine methods that could cope with the extreme conditions.

Work on the second HP section (to CH2200), where overburden rose to 650m, began on 02 May 2007. By September this year, excavation had reached CH1930; current excavation rates are 32m/month working 24hrs a day, seven days per week.

Finding a way forward

An observational method has been adopted for monitoring the excavation works - based on continuous observation of the geology, deformations of the rock mass and linings, and immediate in-depth analysis of all data collected. This data is also subject to back analysis and numerical modelling, the results of which are used with caution considering the uncertainties of geomechanical hypotheses and the digital model's limit - particularly for taking into account the heterogeneity of the rock. Nonetheless, the calculations have been an indispensable tool for guiding the choice of lining methods.

This approach of permanent adaptation called for a high level of flexibility from the contractor (studies, logistics, etc). So, to assist efforts, the JV established a task force of engineers from the worksite and from its designer Terrasol, assisted by geotechnical expert Prof Marc Panet. This task force, combining theoretical competence and tunnelling experience, works in close collaboration with the Project Manager and the following iterative process is adopted: implementation - observation, convergence measurement - back analysis - adaptation.

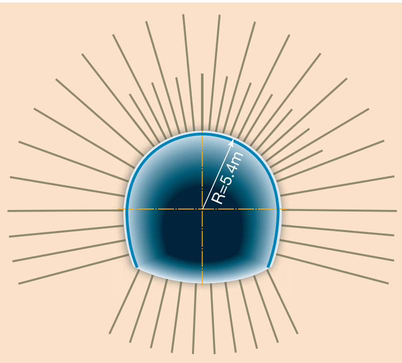
Understanding behaviour

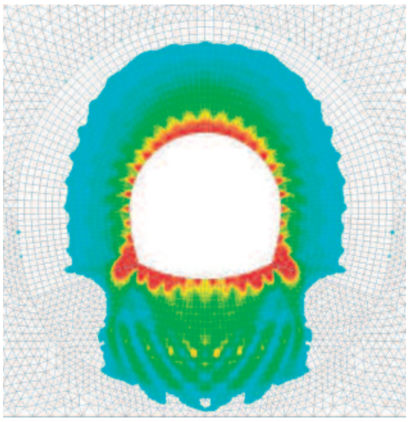
The first stage of excavation within the Houillère Productif (from CH800 to CH1385) began on 13 March 2004. Research and development of lining methods suitable for the exceptional conditions were undertaken, while remaining as close to the original scope as possible (optimisation of the 63m^2 horseshoe profile for the base tunnel).

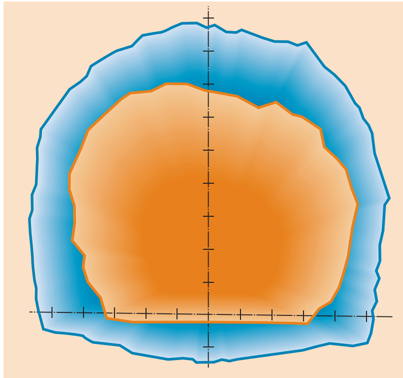
Geological variations were followed based on face mapping and probe drilling at the tunnel face (100m). The lining and the rock mass was extensively instrumented, with optical target monitoring sections placed every 5m and strain gauges equipping the majority of lining components. The extension of the excavation's zone of influence around the profile, in front of, and behind the tunnel face, was determined using 24m deep borehole extensometers around the profile and extrusometers installed 36m ahead of the tunnel face.

SMLP ADIT FACT FILE

Client: LTF (Lyon Turin Ferroviaire)
Project manager: Egis Tunnels/Antéa/Alpina
Client's consultant: Prof G Barla
Contractor: Razel/Bilfinger Berger/Pizzarotti/GRA
Contractor's engineer: Terrasol
Contractor's geotechnical expert: Marc Panet
Subcontractors: Fondazioni Speciali/GDTest
Adit cost: US$231M
Construction method: 780m D&B, followed by mechanical excavator with pick hammer
Construction finish: Mid 2009







Below left: Fig 2 - 'Profile 1' lining design
Above: Fig 3 - 'Profile 1' numerical modelling results
Right: Fig 4 - Comparison of excavated profile (blue) and deformed profile (orange) for 'Profile 1'

Persistence with rigid linings, until their theoretical limit (at an overburden of 250m), allowed some time for further consideration of the problem of lining in highly squeezing rock. Pursuing excavation at the mean rate of 2m/day, full section excavation (88m^2) was carried out in 1m steps using mixed excavation techniques (excavator or drill and blast). The rigid lining composed steel ribs (HEB180) with invert arches and a 600mm shotcrete shell. These arches deformed as soon as overburden reached 230m, with plastification appearing quickly - at less than 20m from the face - and evolving rapidly.

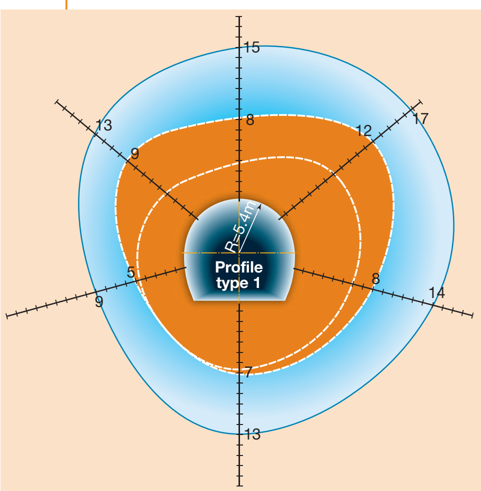


Fig 5: Extension of deformed (blue) and plastified (orange) ground for 'Profile 1'

Measurements recorded on the steel ribs showed load capacity was reached almost immediately after installation, exceeding the yield stress (275MPa). Different stabilisation attempts were undertaken, including reinforcement with 12m long self-drilling bolts and shotcrete, but this did nothing to halt the rupture process. The choice of a higher steel grade (E36) slightly extended the scope of this lining. But when overburdens of more than 250m were reached (CH>1215m) all rigid structures implemented at the face, such as continuous shotcrete shells or steel ribs, had to be abandoned.

Using worksite data, the geomechanical characteristics of the rock mass were re-evaluated through back analysis (Elastic modulus E = 500MPa, cohesion C = 200KPa and a friction angle Φ = 25°), this lead to the project's first flexible lining 'Profile 1'.

Profile 1 was implemented over a length of 170m with overburden of 250m to 350m. Full section mechanical excavation (93m^2) was carried out in 1m steps, with immediate dense radial bolting around the profile (figure 2), including the invert, in association with sliding ribs (TH 44/58). Bolting consisted of 10 x 4m long Swellex MN12 in the crown (for immediate action) and 34 x 8m long self drilling bolts (R32S, with an ultimate load capacity of 360kN) injected with mortar.

Originally, Profile 1 had a discontinuous 200mm thick shotcrete shell including 4 or 5 x 300mm wide longitudinal slots. However, less than 10m from the face, the slots completely closed and the shell, which became rigid, evolved toward rupture. It was rapidly abandoned. Profile 1 was therefore completed with a shotcrete ring designed to close the section and block deformations. The moment of closure (distance from the tunnel face) depended on the evolution of convergences and the achievement of a stable state or progressive stabilisation.

Calculations made with an elasto-plastic model and Mohr-Coulomb failure criterion provided for an extension of the plastic zone of about 6-8m and convergences about 1000mm in the short term. Follow-up on-site measurements of Profile 1 confirmed the anisotropic character of the deformations. The amplitude of the convergences after 145 days at a distance of 60m from the tunnel face exceeded 2m, this increased with overburden. Convergence rates varied from 50-30mm/day at the face with 50% of total deformation taking place in the first 20m.

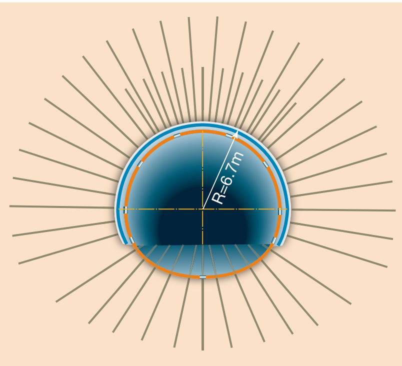
Analysis of measurements over sufficiently long excavation shutdown periods (15 and 20 days) showed that the distance of influence of the tunnel face was about 50m. Beyond this, deferred deformations were characterised by a continuous and regular, almost linear evolution without any sign of stabilisation - the convergence rate remained about 7-8mm/day. The excavation's zone of influence extended 12-15m around the profile and developed rapidly, with 80% taking place less than 5m from the face and maximum extension measured at 20m.

The 'plastic' zone, considering rock mass failure criterion is reached as soon as radial deformation is greater than 5 x 10^{-3}, rapidly developed in the first 20m after the excavation and then continued to progress versus time. At 60m from the face it extended 8m-12m around the profile, reaching a maximum at the invert and the right hand side. Extrusion of the face remained limited; involving only the first 4m of the tunnel advance and with amplitude at the face not exceeding 50mm.

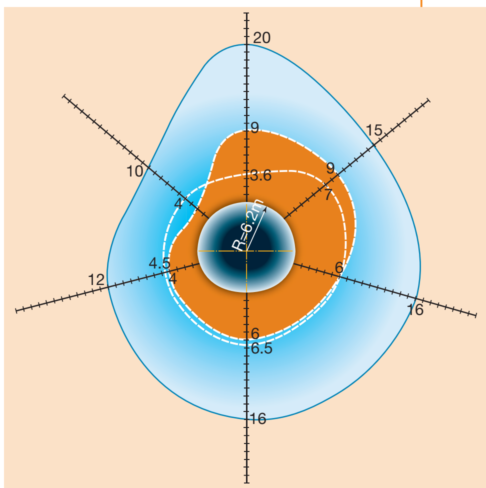
All this data was used by Terrasol in a new back analysis to re-evaluate the rock mass characteristics (E = 100MPa; C =150KPa; Φ = 25°). Yielding ribs (TH) significantly improved safety in the tunnel and regularity of the excavation was controlled with the use of forepoling. But they had no effect on the evolution of the deformations. After 600-800mm of diametric convergence (reached 30m from the tunnel face), they stiffen and enter plasticity. The extent of convergences and absence of stabilisation meant this zone had to be reprofiled (by a thickness of 1m) and covered with an 800mm thick concrete


Major convergences of Profile 1 and the new Profile 2


Solexpert's hiDCon compressible concrete elements



Left: Fig 6 - Profile 2 lining, with Phase 1 marked in blue and Phase 2 in orange
Right: Fig 7 - Extension of deformed (blue) and plastified (orange) ground in Profile 2
Below: Fig 8 - Profile 2 numerical model with Phase 1 (left) & Phase 2 (right)



ring 60m from the tunnel face.

As the convergence rate was still high at the time of concreting, this induced rapid loading of the ring. The maximum stress recorded was about 17MPa and it evolved at a rate of 0.6MPa/100 days after 1 year. The average rate of excavation during this time was about 18m/month due to the many reinforcements and interventions.

New lining for Houillère Productif

Experience from the first HP section provided a better understanding of the rock mass. HP's behaviour follows a complex viscous-elasto-plastic model, which is yet to be completely defined. Owner LTF awarded the modelling studies of the future Base Tunnel to Prof Giovanni Barla (*T&TI* May p15).

Monitoring of the adit is being carried out using a simple elasto-plastic model. Creep is taken into account by activating degraded rock characteristics in concentric crowns of growing thickness incremented at each new calculation step until an 8m thick crown is obtained in the final step (concrete ring). The degraded rock's cohesion is considered to be zero and Young's modulus is also low. Anchors are partially and progressively deactivated according to plastification.

A new lining method was studied by the contractor to respond to the specific problems at the SMLP – it was necessary to release rock mass stresses near the work face, by accepting key convergences before controlling deformations, to avoid excess degradation of the rock and reduce lining stresses. Exceptionally high convergences and the extension of the traversed zone make the adit an extremely rare, if not unique, case - and there are many approaches for defining lining methods, including varying experiences or different empirical, and sometimes cultural, approaches. The JV therefore consulted several design firms to benefit from different philosophies and experiences:

The solution proposed by Müller+Hereth was based on a two stage heading-bench excavation, in 2m steps, with a flexible lining composed of anchors and shotcrete installed at the work face: A crown of 22 x 9-12m long self drilling bolts (roof and walls) spaced every 1m; a thin flexible shotcrete shell (100mm thick) with arches spaced every 1m; closure of the invert 50m from the face with a 200mm shotcrete layer.

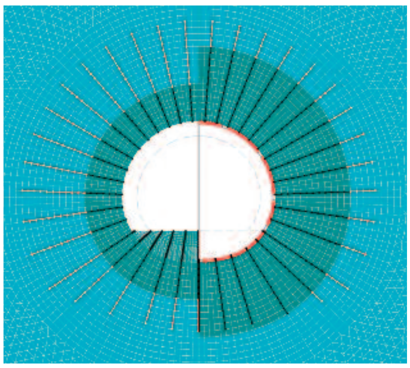
The solution proposed by Geodata SpA consisted of a full section advance, in 2m steps, with a relatively rigid lining designed to rapidly block deformations. Proposed reinforcement was 75 x 24m long fiberglass bolts (VTR); with rigid steel ribs installed at the face (double IPN20) and spaced every 1.25m; a 300mm thick shotcrete layer and 8 x 6m-8m long Swellex MN24 bolts in the side walls. The section is closed less than 15m from the face with a 500mm thick concrete invert and the shell reinforced with a 200mm shotcrete layer.

Prof Kalman Kovari (Zürich Federal Polytechnic School) and Prof Arno Thut (Solexperts) proposed the use of relatively new materials. For stretches of tunnel through squeezing ground on Switzerland's Gotthard and Lötschberg Base Tunnels, Solexperts developed a highly compressible concrete element named hiDCon.

The solution finally adopted for the SMLP was an amalgamation of these approaches, incorporating experience acquired on the worksite. "Profile 2" is a multiphase lining (three phases), which progressively rigidifies as the distance from the face increases.

The advance and the ground around the advance (2m thick crown) is reinforced with 120 x 24m long fiberglass bolts (providing 15 usable metres) to try to reduce the evolution of convergence in the first 20m behind the work face (amplitude, homogenization):

Phase 1: A flexible lining installed immediately after excavation, which follows



rock mass deformations and absorbs 30% of the total convergence (600mm max).

Phase 2: A secondary semi-rigid lining, installed 30m from the face, over the flexible lining. It consists of a closed invert arch capable of supporting 400mm diametrical convergences while providing sufficient confinement to control deformations. To create this yielding shotcrete lining, Solexpert's hiDCon elements are installed within the shotcrete shell. The elements can deform at a pre-set, constant stress level of 50% and after this load is reached, resistance begins to increase until a final value is achieved (v = 0, initial resistance of 8MPa, final resistance 15MPa.).

Phase 3: A final 1m thick rigid lining is cast 80m from the face, which blocks deformations and closes the section.

Full section excavation is carried out via mechanical excavator in 1m steps, with the three lining phases progressing concurrently. The horseshoe profile was abandoned for a near-circular profile, which was enlarged to take convergences and the new lining thickness into account. The new excavated section is $125m^2$ for a final profile of $54m^2$.

The new solution required reorganisation of logistics and resources: Increasing working hours to 24/7; increasing labour by 30%; abandoning the crusher and conveyor for loaders and dumpers; procurement of a 5m long mobile concrete form; and a rig to install the fiberglass bolts (an EGT 7100 equipped with 2 x 27m long booms).

Profile 2 was implemented from CH1385 under an overburden of 350m to 450m. The deformations on the Phase 1 flexible lining are still anisotropic and the amplitude of the diametrical convergences vary between 600mm and 800mm. The rate at 30m from the face is 17mm/day. These values remain close to those measured on Profile 1.

Phase 2's semi-rigid lining significantly slows down convergence. The amplitude is 400mm and convergence at 80m from the face is 1mm/day, while it was 7mm/day with Profile 1. Although stabilisation is not obtained, a slight inflection can be observed on the convergence curves. Therefore total convergence (compared with Profile 1) is reduced by 50%, even with an increased overburden of 50m. The excavation's distance of influence remains in the order of 50-60m. The extension of influence around the section varies from 12-16m. It rapidly develops at less than 5m from the tunnel face. The "plastic" zone remains large - 20m from the tunnel face. It extends between 7m and 10m around the section and undergoes an increase on the order of 20% (compared with Profile 1) linked to the increase in the overburden height (+25%).

Using Profile 2, excavation is progressing steadily at an average rate of 32m/month. The multi-phase lining is well suited to the unique conditions of SMLP and provides control of the convergences behind the face. The experience acquired is decisive and has provided some good lessons:

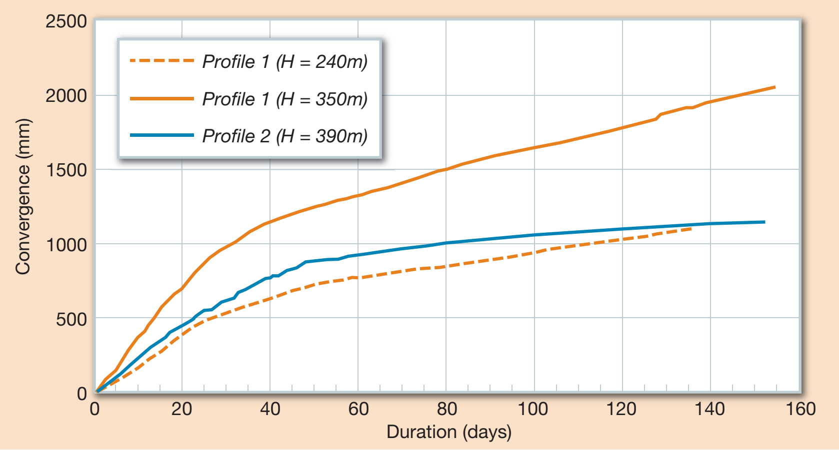
i) Pre-consolidation does not have any discernible impact on the evolution of convergences. When they exceed 600mm in Phase 1, or in the case of high anisotropy, the first rib has to be removed and reprofiling done before the semi-rigid lining can be installed. In this highly squeezing rock mass and under heavy overburden, convergences at the tunnel face cannot be controlled.

ii) The semi-rigid lining (Phase 2) allows good homogenization of the deformations and control of convergences. The secondary lining (Phase 2) still has to be installed 25m from the work face. Beyond convergences of 400mm (compactness limit of the hiDCon blocks), the shotcrete shell scales at the interface with the hiDCon blocks, leading to their expulsion, which reinforces the choice of a multi-phased lining.

iii) Bringing Phase 2 closer to the face does not affect total convergence (Phase 1 + Phase 2). The reduced amplitude obtained at the end of Phase 1 is compensated by an increase in the evolution of convergences during Phase 2. Ultimately, the total amplitude is exactly the same. These observations allowed validation of the results obtained on the digital models.

iv) The concrete ring loading curves show a significant drop in stresses (50-60% compared to those obtained with Profile 1). Over an equivalent period (130 days), the maximum stress measured in Profile 2's final lining is about 5MPa, while it reached 14MPa in the concrete ring of Profile 1. Over this same period, the loading rate plunged from 5MPa/100 days (Profile 1) to 0.8MPa/100 days (Profile 2). However, this stress gradient in the midterm remains in the same order, at approximately 1-1.5MPa per year.

In order to circumvent the Houillère Productif at the base of the adit, LTF modified the alignment of the SMLP (see orgininal in black on figure 1). As of CH1600, conditions have better, but deformations, although much less, still remain significant.



Above: Fig 9 - Characteristic convergence experienced with each lining profile

Conclusions

Along the 2280m of the SMLP, the Houillère Productif accounts for little more than 1400m and has a max overburden of 650m. The Lyon-Turin Base Tunnel will encounter similar conditions for a length of 1000m-1200m under overburdens of 550m-700m.

Calculating elasto-plastic behaviour with the Mohr-Coulomb failure criterion is, to a certain extent, limited in the domain of large deformations, as observed in the SMLP adit, and does not take into account the time factor required to estimate deferred deformations of the rock. Back analysis of convergence data allowed the creation of a short- and long-term rock behaviour model. The long-term stresses will be better evaluated by continuing measurements for several years on the final lining. Utilisation of a viscous-elasto-plastic model that takes time factors into account (Lemaître's Law) allows a better correlation with convergences measured in the adit. Terrasol is currently implementing this model in the finite difference modelling software FLAC.

The solution required for these conditions presents major and unexpected problems, which adversely affect costs and deadlines. As a result, the SMLP contract's conditions required the need for frank and in-depth discussions based on the analyses shared between parties. T&T

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