TBM Tunnelling for Maurice Lemaire Tunnel’s Safety Gallery: Experience Feedback

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1. Introduction

The 7 km long Maurice Lemaire road tunnel is located between Alsace and Les Vosges (France). It has been operated from the beginning of the 1980s by the company Autoroutes Paris – Rhin - Rhône (APRR). Following the new reglementations of August 2000 concerning safety in road tunnels, APRR put in place a renovation and safety improvement programme which has notably led to the construction of a safety gallery parallel to the existing tunnel as well as several cross-passages to permit in particular the evacuation of road users and the ventilation of the existing tunnel. The project design and construction supervision was awarded to the BG / Egis Tunnels joint venture. The civil engineering works were carried out by the Bouygues / Eiffage contractor joint venture.

The scope of this paper is a comparison of the prediction models of hard rock TBM performance and the actual rates measured during the works. It is important at the design phase to be able to estimate accurately the excavation period of the tunnel works.

2. Presentation of the project

2.1 The main safety works

The works to safeguard the very old road tunnel required the complete renovation of the existing structure (civil engineering works and operational equipment) and the creation of a lateral safety gallery. To optimise the investment of this safety gallery and to maximise the performance of the ventilation system, it was decided to use the lateral gallery for several main functions:

- protection and evacuation of road users;
- smoke extraction in the event of fire;
- supply of fresh air and extraction of polluted air during heavy traffic;
- safeguarding various services (electricity, communications, and fire fighting).
This 7,046 m long, 6.00 m diameter gallery was constructed parallel to the existing tunnel and at a distance of approximately 16 m. It has an upper compartment dedicated to smoke extraction and a lower compartment for road user evacuation, routing of services and supply of fresh air.

There are several cross-passages between the tunnel and the gallery:

- 16 shelters at 400 m centres for road users;
- 5 electrical sub-stations;
- 68 smoke extraction ducts connecting the crown of the tunnel to the upper compartment of the gallery.

Figure 1 – Cross-section of the gallery and a 3D perspective of the tunnel and gallery

2.2 Geological context

The Maurice Lemaire tunnel crosses the cristalline complexe of the Lower Vosges. This complexe is of hercynian origin and is characterised by a chain of moderate altitude of around 800 m in the north and 1,100 m in the south.

From Sainte-Marie-aux-Mines towards Lusse, the following large geotechnical units can be distinguished:

"Sainte-Marie-aux-Mines Gneiss" for a length of approximately 1,300 m. This is a formation of leptynitic gneisses and leptynitic garnets, weathered related to the presence of major tectonic disturbances.

"Crêtes Granite" for about 2,450 m. This is one of the most well known intrusive granits of the Vosges massif.

"Croix-Aux-Mines Gneiss" for about 1,200 m. This is an ordinary gneiss.

"Urbeis Gneiss" for about 1,300 m. These gneisses are formed by two series of metamorphosed pelitic quartz.
These various geological units are of good or very good quality, except for the portal sections that are in weathered gneiss. They are also affected by several tectonic disturbances. These structural aspects are described in chapter 3 below.

2.3 Boring of the safety gallery

The safety gallery was bored with a TBM apart from the portal sections in weathered gneiss which were excavated by traditional methods (335 m on the Alsace side and 396 m on the Vosges side). The total length bored by TBM was thus 6,226 m.

A 6 m diameter Herrenknecht hard rock tunnel boring machine was used for the gallery.

The TBM and the backup were composed of the following parts:

- The cutting head had 38 discs and scrapers for loading the muck;
- The maximum thrust on the head was 14,616 kN, the maximum torque was 4,347 kNm and the electrical power installation was 2.4 MW. The maximum recommended thrust was 10,150 kN (recommended load of 267 kN per wheel).
- Behind the head, a protection grid in the crown enabled the placing of the required primary support, either steel ribs placed with an arch erector or rockbolts, with two drilling
booms covering one side of the excavation profile each. The placing of concrete behind a formwork mesh was also possible in areas with poor quality ground. In other areas steel mesh was placed systematically in the crown;

- Some 60 metres from the cutting head, rockbolt and shotcrete installation completed the support; The muck was removed from the cutting head on a conveyor.

Four support profiles were used to support the excavation:

- profiles T1 and T2 consisting of between two and six rockbolts on average per metre of gallery and steel mesh in the crown providing protection against falling stones. A 3 to 7 cm layer of shotcrete was applied;

- profile T'3 consisting of a U section steel rib placed behind the cutting head in the crown and bench section, held in place by 4 rockbolts and steel mesh providing protection from falling stones. It was completed by 12 cm of shotcrete placed away from the face;

- profile T4 consisting of HEB 140 steel ribs at 1.2 m centres placed immediately behind the cutting head, completed by formwork mesh between the interior flanges of the ribs and filled with poured concrete. Concreting was generally carried out every three ribs.

2.4 Global review of TBM excavation

The light support profiles (T1 and T2) made up 74 % of the excavation length. The heavier profiles represented 19.5 % (profile T3) and 6.5 % for the heaviest profile (T4). These last two profiles were mainly located in the first part of the Alsace side, in weathered gneiss.

The average progress rates achieved by the TBM were approximately: 3 m/day with TBM in profile T4; 13 m/day with TBM in profile T3; 30 m/day with TBM in profile T2; 31 m/day with TBM in profile T1.

The average daily progress with the TBM was about 16.5 m with maximum rates of 55 m/day and 783 m/month.

The following graph summarises the progress of the safety gallery which took place from the 19th April 2004 to the 2nd June 2006, a little more than two years.
3. Geological and geotechnical context, exploration and testing

The various geological units are affected by several tectonic disturbances. On a regional scale, there is a large family of fractures principally aligned N-035°E, on which the Sainte-Marie-Aux-Mines faults, the intrusive Crétes granite and mylonite and cataclasite zones lie. A secondary line of fractures exists, generally aligned East to West, N-085°E.

All the lithological units are affected by joints. The thickness of the fault areas (except for the major ductile faults) is of one to several metres, generally with the presence of clay minerals and sometimes graphite (especially in the gneiss).

3.1 Croix-aux-Mines Gneiss

This formation, which followed on from the granite from chainage 3885, continued until chainage 5485. It included two lithological groups: to the South ordinary plagioclasic gneiss rich in garnets, albeit with quite frequent graphite layers, and to the North gneiss with garnets and cordierite. These gneisses, injected with subvertical veins of microgranite, are generally in a NE-SW direction with an inclination of 30° to 50°, up to 70° locally towards the Southeast.

3.2 Geomechanical rock characteristics

Series of laboratory tests have been carried out on samples of various lithological facies taken from cores. There is a relative homogeneity of gneiss characteristics of the different lithotypes, which have been classified as follows according to the AFTES guidelines:

- On the basis of a theoretical velocity $V_p$ of 6,000 m/s for the gneiss and the granites, it can be seen that these rocks present a "strong" to "very strong" matrix continuity.
- They have an "average" (RC4, 25 MPa < $\sigma_c$ < 50 MPa) to locally "high" strength (RC3, 50 MPa < $\sigma_c$ < 100 MPa).
- According to the Young’s modulus values they are "very stiff" (20 GPa < $E$ < 50 GPa).
- All the dilatometric tests carried out led to high Young’s modulus values (8 000 MPa < $E$ < 50 000 MPa < $E$) as well as high values of deformation modulus $\Gamma$. The values of the $E/\Gamma$ ratio between 1.1 and 2.0 permitted, according to Schneider’s criteria to qualify the rock massif as "compact" (absence of joints or open fissures).
- The Cerchar- Ineris tests classify them as "hard rock" (DU3: 40 < DU < 80 and "extremely abrasive rock" ($A_N^1$: $A_N^1$ > 4)
- The LPC tests classify the rocks as "average to high abrasivity" (ABR3 to ABR2: 1 000 < $A_{BR}$ < 1 500 to 1 500 < $A_{BR}$ < 2 000) and present a "low crushability" (25 < BR < 50).
- The 1989 Bieniawski RMR rating gives a value between 54 and 72 (63 average) for the granite and between 48 and 70 (59 average) for the gneiss.

The uniaxial compressive strength seems weak for this type of rock, whilst all the other test results are as expected. It has also been observed that the low RQD values do not correspond to a noticeable reduction of microseismic values. This apparent contradiction is explained by actual fracturation, which is seen during deconfinement. The matrix is also affected by microfissuring due to the tectonic history, which facilitates the start of the rupture during testing on cores. These test values are thus not representative of the state of stress applied by the rock mass (in triaxial conditions) to the TBM excavation.
4. Presentation of existing prediction models

TBM performance prediction models exist and are often used (see ref. [2], [3]). They allow the prediction of the rate of progress of the machine according to the type of rock that is bored and the characteristics of the TBM. There are two main types of models: semi-theoretical models and empirical models. Semi-theoretical models such as the CSM model developed by the Colorado School of Mines, are based on the measurement and evaluation in a laboratory of the cutting force on the discs. This approach allows a fine analysis of the rock cutting procedure and the establishment of a relationship between the force applied by the TBM and the depth of penetration in laboratory conditions of actual size discs. Empirical models try to establish direct relationships between the performance of the machines and the characteristics of the intact rock and the rock mass. The NTH model developed by the Norwegian University of Science and Technology belongs to this category [4].

Prediction models were used on the Maurice Lemaire tunnel site to allow a comparison between actual rates and the predictions given by models. The purpose of this study was to analyse the impact of the fracturing of the rock mass on the tasks performed during the works and on the aptitude of the prediction models to forecast actual progress rates. Two particular homogenous sections were chosen, their main difference being the state of fissuring of the rock mass.

5. Site data – chosen study areas

Two study areas were chosen and analysed in detail, priority being given to the homogeneity of the rock mass and the excavation conditions. For each area an analysis of the task distribution was carried out from the shift reports.

The first study area is between chainages 4751 and 5421, a length of 670 m. The rock mass is composed of sound gneiss with few fractures. The average daily progress in this area was 33 m/day. The ground support was mostly type T1 and occasionally T2. The second study zone is between chainages 4175 and 4290, a length of 115 m. The rock mass is comprised of weathered and fractured gneiss. The average daily progress in this area during the works was 23 m/day. The support type was T’3. Figure 5 indicates the distribution of tasks recorded on site for these two areas. The task distribution is taken from the AFTES guidelines “The analysis of timing and coefficients of TBM use [1]. The instantaneous drilling velocity was about 6 cm/min for both areas.

![Figure 5 – Recorded task distribution in the two study areas](image-url)
6. TBM progress prediction

Given the site records that were available to us and the purpose of the study, the Norwegian model NTH was closely analysed to be able to see to what point it took account of the state of fracture of the rock mass found in each area. Figure 6 shows the main results. The instantaneous penetration rate from the model is predicted at about 7 cm / min in both cases, knowing that the thrust on the discs was different in each area.

![NTH model prediction - T1/T2 rock support](image1)

![NTH model prediction - T'3 rock support](image2)

Figure 6 – Progress prediction in the two areas according to the NTH model

7. Analysis of the results

The TBM "Cynthia" was well adapted to the rock that it excavated. In the solid sections the rate of advance was determined by the instantaneous penetration and the regrip time (grippers and back-up), the support being applied during the boring time, at the same time as face activity. An advance of more than 21 m per 8 hour shift was frequently achieved.

In reality, the control of the TBM’s progress was obtained by maintaining the penetration rate as constant as possible. The pressure on the head was the adjustable variant. It also became apparent that after a certain level, increasing the rotation velocity of the head only had a very small influence on the penetration. For this reason, the driver generally set the rotation velocity at 6 revolutions per minute, which was the velocity considered as optimum for the peripheral discs (approx. 110 m/min). This limit was also economical in terms of energy consumption.

In areas of fissured rock where profile T'3 was applied, the time required to install the support was in the order of 23 minutes for a 1.2 m stroke, which was much greater than the time required for boring. The driver thus limited the thrust on the head to maintain the penetration rate at about 60 mm/minute.

These measures meant that the boring finished a little before the support installation, while minimising energy consumption and wear of the discs. Reducing the thrust (sometimes up to 3,000 kN, that is 30 % of the maximum recommended pressure per cutting tool) also had the advantage of reducing proportionally the thrust required on the grippers. Given the unfavourable orientation of the discontinuities, spalling frequently occurred in areas with high fissure density,
which implied substantial filling of overbreak which in turn reduced progress. By applying a lower
stress to the walls this phenomenon was reduced.

The comparison of the relationship between the prediction model and reality is conclusive for
solid rock masses. It is also convincing for fissured rock insofar as relevant input parameters are
chosen for the model. The two most important parameters from this point of view are the thrust
per cutting tool and the factor that characterises the fissuring of the rock mass.

By judiciously choosing these parameters the simulation gives a penetration rate close to the
actual penetration in the fissured areas, although slightly overestimated. It must be remembered
that in this type of rock mass, progress rates are more often determined by the rock support than
by the boring velocity.

If we compare the statistical task distribution, there is concordance between the prediction
models and reality. Only the maintenance periods were overestimated by the simulation. This
can be explained by the fact that for the areas in the study the machines and the crew had
become adapted to the conditions. The wear of the discs on this site was also inferior to the
norm for similar rock. This could be explained by the microfissuring of tectonic origin (responsible
for the low uniaxial compressive strength that was measured) which facilitated the boring. The
time required for changing the cutter discs was therefore reduced. Heavy maintenance of the
head was also programmed during planned downtime.

8. Conclusion

This study that was carried out during the boring of the Maurice Lemaire road tunnel safety
gallery and presented in this paper has allowed analysing in detail the influence of the fissuring of
the rock mass on TBM performance. This study has also allowed the simulation of TBM progress
from prediction models widely used in this field. Measured progress has shown the influence of
the fissuring of the rock mass on task distribution throughout the works. The application of
prediction models has shown that while knowing the TBM boring parameters and having a good
understanding of the state of fissuring in the rock mass, the prediction models can still
overestimate instantaneous progress rates but there is nonetheless a good correlation with actual
rates on site. The accuracy of the prediction model in the case of the Maurice Lemaire tunnel
result probably from the similarity between the bored rock and that having been used as a basis
for the NTH method development (cristalline rock mass).

9. References

d’utilisation des tunneliers »


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