Monte Carlo Tunnel: Multiphase Methodology to Repair a Tunnel under Swelling Marlstone While Maintaining Railway Traffic

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1. INTRODUCTION

The Monte Carlo double-track tunnel, with a total length of 3.1km, is under the responsibility of Réseau Ferré de France (RFF, French Rail Network). Located in France, it is a strategic railway link between France and Italy for passenger and freight traffic. The link also carries a dense suburban traffic between Cannes and Ventimiglia (a train every 15 mins).

This tunnel has undergone a problematic evolution since 1964. In June 2003, the lining suddenly broke over a length of 40m, leading to stop the railway traffic for eight months. Since 2005, additional problems appeared near this zone and an acceleration of the deformation was detected in November 2008.

This paper presents the design that was proposed to combat the rupture process and prevent any additional break of the lining in the zone concerned by this evolitional behaviour. The design consists in completely substituting the sidewalls and the invert initially over a stretch 100m long, the main constraint being that of keeping the trains running on one track. The complexity of the geological context and the behaviour of the tunnel mean that a multiphase methodology is required in order to guarantee railway circulation safety.

This paper is organised as follows: in section 2, the historical and geological contexts of the Monte Carlo Tunnel are illustrated. A multiphase methodology for repair of the tunnel while maintaining railway traffic is described in section 3. Finally, section 4 looks at the digital modelling of the multiphase design. We conclude with some final remarks.

2. HISTORICAL AND GEOLOGICAL CONTEXT: COMPLEX ISSUES FOR THE DESIGN

Built between 1958 and 1964, the Monte Carlo double-track tunnel (3092m) has been subject to evolution of swelling Cenomanian marlstone over a zone of 250m. The tunnel lining is made of poor quality concrete and quarry stone masonry [1].

The surrounding terrain is in a highly complex alpine geology of the “Arc de Nice” with water circulation. From the France portal, the first 750m of the tunnel are located in Jurassic limestone. As shown in the geological sections below (Fig. 1 and 2), the part of the tunnel located between PM 994 and PM 1033 is in a very particular geological context: in this area some 40m long, the tunnel crosses a very large thrust slice of aquiferous Lias limestone, in tectonic contact with the swelling Cenomanian marlstone. This Lias thrust slice is characterised by circulating water, and has an overburden of approximately 80 meters.

The area of the contact between the Thrust slice and the impermeable marlstone is a preferred path for the circulating water. The tunnel acts like a drain. The downward-going slope of the
tunnel is directed towards the France tunnel portal, facilitating the circulation of water towards decreasing PMs. Accordingly the upward-going platform towards the Italian side does not support circulation of the massif water.

The marlstones have been saturated by water and are of a poor geotechnical quality. They allowed their swelling potential to be developed.

Many geotechnical tests and mineralogical analyses were conducted in 2003 and 2007. The geotechnical tests performed on the Cenomanian marlstone revealed important swelling pressure values, particularly in the base of the left side sidewall, up to 0.9MPa [2]. The mineralogical analyses, on the other hand, highlighted a high percentage of argillaceous minerals (sometimes higher than 40%) within the samples. The argillaceous minerals are themselves made up of more than 90% of smectite, a well-known swelling mineral.

Since the tunnel was built in 1964, an unexpected behaviour has been detected of the structure located in the Cenomanian marlstone zone of 250m.
In June 2003, the lining suddenly broke over a length 40 m around PM1000, with water inflows under pressure and a local rupture of the invert (as shown in Figure 3). Maintaining railway traffic in this tunnel under this rupture process presented a very high risk. Thus the traffic was interrupted on this strategic link from June 2003 to February 2004.

Repairing the tunnel during the traffic interruption consisted in [3]:

- a 50m zone being reinforced with a new concrete lining ring, 40cm thick, and composed of heavy ribs HEB360, every 0.80 meters,
- 2 transition zones 8m long being added at both ends, made of a sprayed concrete shell 10cm thick.

Starting from 2003, the behaviour of the tunnel was analyzed every two months in technical inspections. During recent years, an increasing phenomenon of horizontal convergence of the sidewalls has appeared. In order to monitor this pathological evolution over time, an intensive tunnel survey and monitoring program was implemented over a zone that is 100m long: a device for automatic measurement of convergence in structural deformation based on the optical method (8 sections with 6 segments) was set up in spring 2007. Currently the deformations of the tunnel are highly accentuated near the PM 960, located in an unfavourable geological configuration. This evolution involved the horizontal sidewall convergence and the raising of the invert, caused by swelling of the surrounding marlstone. The speed of convergence is about 0.3mm/month.

In August 2008, a sudden acceleration of the sidewall convergence, exceeding a 5mm threshold on the lining, led to a raising of the track and to a local breaking of the invert. The automatically instrumented tunnel sections of PM 950, 960 and 970 detected three sharp increases of convergence on the sidewalls in just a few hours. Meanwhile, the sidewall convergence doubled in speed, with speeds in the order of 1 mm/month, and significant raising of the tracks. These reports confirmed the critical evolution of the behaviour of the lower structure of the tunnel.

In order to guarantee the safety of railway traffic, speed has been limited to 40km/h since August 2008.

In order to stop the evolution of the deformations in the structure and to prevent any breaking of the lining comparable to that of 2003, a zone from PM 950 to 970 was urgently reinforced with 20 rings (HEB180 + struts HEB240) associated with long anchors (Fig. 4 and Fig. 2 – zone II).

The work was done during a night shift, when the railway traffic is interrupted daily for about 5 hours.

In addition, drilling drainage and the central drain canalisation were built in order to reduce the circulation of water in the tunnel, mainly caused by marlstone hydration.
This behaviour is caused mainly by **swelling of the argileous Cenomanian marlstone**, due to high level of hydration of the water circulating in the direction of the invert, while the presence of Jurassic limestone down to a few meters below the underground structure supports the jack effect and the raising of the invert.

At present, the general trend is a stabilisation in the zones with heavy ribs and continuation of the sidewall coming together process in front of heavy ribs (decreasing PM direction) i.e. PM 940, but at a fairly moderate speed.

Despite this, the breaking generated by this evolution needs intervention in order to repair and reinforce the lining in the sector concerned. The work needs to be done under the constraint of keeping the trains running: it is not possible to stop the traffic in this suburban link again, as was done in 2003. The design of a multiphase methodology in this complex geological context is described in the following chapter. The work will comprise 2 phases, depending on the influence of the set deformations:

- phase 1, from PM 880 to 990, in 2010, as shown in Figure 2 - zone III (actual evolution)
- phase 2, from PM 780 to 880, as shown in Figure 2 - zone IV (possible evolution)

### 3. MULTIPHASE METHODOLOGY WHILE MAINTAINING RAILWAY TRAFFIC

To stop the breaking process, a complete substitution of the sidewalls and the invert is planned, the main constraint being to maintain railway traffic on one track.

The complexity of the geological context and the behaviour of the tunnel make a multiphase methodology necessary, with **alternate sections to guarantee railway traffic safety**. The whole length of the tunnel in the Cenomanian marlstone has to be repaired.

The total construction lead time is 9 months to realize the first zone of 100m.

#### 3.1 Preliminary reinforcement works

The following work will be done during a **night shift**, when the railway traffic undergoes its daily interruption for about **5 hours**.

First, a **Berlin wall** will be built in the area between the tracks. This element is essential to guarantee safety of the railway traffic, preventing displacement of the platform. The Berlin wall is also designed to counteract the effort due to the railway traffic and the lateral thrust of swelling going through the future invert (cf. section 4 – Model C). This Berlin wall consists of steel posts HEB220 every 1.00m, of 4.20m high, with a plug diameter of 400mm. Finally heavy ribs will be cut back at the up-level of the invert.

This will be followed by reinforcement of the sidewalls using long **self-drilling bolts** every meter, making it possible to produce a combined effect of reinforcement and containment without the risk of generating water inflows in the marlstone.

#### 3.2 Phased substitution of the sidewalls and the invert

The following work will be carried out **one track after the other**. Train traffic will be maintained with an alternating two-way traffic on a single track. Train speed will be reduced to **30km/h**.
The total time of these restrictive traffic conditions is 6 months. The Contractors will have to respect this main constraint, and carry out the work organized into 2 shifts per day, 5 days a week.

Work will concentrate first on side V2, with the traffic maintained on track V1, as shown in Figure 5. Traffic will then be flipped to new track V2, over the new sidewall – longitudinal beam – arch-invert unit associated with a dense steel reinforcement of the concrete, and work carried out on side V1.

![Figure 5: Multiphase methodology principles – Railway traffic maintained on track V1](image)

There are currently no plans to reinforce the vault of the tunnel. However, a longitudinal beam will now be inserted into the sidewall, related to the sections in underpinning, to allow quick, potential installation of heavy ribs in the future (HEB 180).

### 3.2.1. Substitution of the sidewalls – Phase A

As shown in Figure 5, the substitution of the sidewall is designed over a height of 2.70m. To avoid a breaking out of the ground, it has been decided to demolish the existing lining up to 0.35m deep, to keep a minimum thickness of concrete both in the sidewalls and the sidewalls base.

Experience has shown that demolition of the sidewalls must be conducted in alternate excavated sections of maximum width 2 m. The calculations from the design phase indicate that, despite the load on the structure due to the swelling of the marlstone, with a correct redistribution of the stress on both sides of the excavated section, two sections excavated simultaneously must be separated by at least five sections (that means 10 m at least) to avoid any influence of one section on the other.

Before any demolition, in order to facilitate work and limit the vibration on the lining, it is necessary to realize a preliminary sawing, which consists in pre-cutting the existing lining using a special saw.
The sections are made of reinforced concrete. The steel bars are adapted to each section. The method of construction by alternate sections does not allow a longitudinal continuity of reinforcement in sidewalls. Reinforcing cages are adapted to each section.

To create this necessary continuity, the works of underpinning the sidewalls base will be carried out in two phases:

- independent sections of 0.35m thick, 2.70m high, and 2m long in sidewalls, without continuity of reinforcement,
- a longitudinal beam (1.0m high and 0.30m thick) concreted uninterrupted over a length of 10m with reinforcement. This longitudinal beam will eventually be used later as a support for heavy ribs (concrete lining ring composed of heavy ribs).

The underpinning of the sidewalls base involves destruction of the present lining in the oldest concreted parts of the tunnel (in this zone, the tunnel was built in divided section, with two basement galleries on each side). It may thus be possible to meet old wood or metallic supporting work still present inside or outside the concrete.

The current reinforcement in the vault by HEB 180 between PM 950 to 970 must be kept in place. These ribs have to stay leaning on the new longitudinal beam relating the sections. Moreover, they must be blocked by shotcrete to complete lining in this zone.

3.2.2. Rebuilding of the invert – Phase B

As shown in Figure 5, the geometry of the future invert is counter-arched in order to sustain the load due to swelling, with a minimal thickness of 60cm of concrete.

The invert is rebuilt by ½ platforms. As seen in section §3.1, this first requires a Berlin wall to be built between the two tracks to maintain the railway traffic, and assure the load in the invert (due to swelling of the marlstone), with the opening of the half-section.

Demolition of the existing invert is done by sections 2m long at most. However in order to guarantee longitudinal continuity of the reinforcements of the invert, several sections are made and concreted uninterrupted over a length of 10m. That would limit the deformation of the platform under the track in the future. To guarantee the stability of several sections opened, struts (HEB220 each 1m) are placed between the sidewalls and the Berlin wall. These struts get support from a metal starter previously integrated into the reinforcement of the sidewall struts and from a vertical steel reinforcement of the Berlin wall.

4. DIGITAL MODELS

The construction works are validated by a complex digital approach involving simulation of:

- First, the behaviour of the existing tunnel under swelling marlstone tuning the model with the stress and the deformations measured in-situ.
- Second, several steps of the multiphase substitution track by track (reinforcement anchors, Berlin wall between tracks, sidewall reconstruction by 2m long pass, half-invert demolition and reconstruction, etc.).

In order to take into account the 3D situation of the project, the study used several digital calculation models. The intention was mainly to check stability of the structure, including the railway platform at the time the sidewalls are opened, and the stability of the railway platform. The digital calculation models are as follows:

- Model A: Transversal section of the tunnel - 2D (PLAXIS V8.6) This model takes into account the different construction phases.
- Model B-1: Longitudinal section of the sidewall - 2D (PLAXIS V8.6). This model checks the stability of the sidewalls with an excavated section of 2m x 2.70m high.
- Model B-2: 3D modelling (Millenium ROBOT) of the excavation in the sidewall, considering the stiffness effect of the invert.
- Model C: Dimensioning of the Berlin wall in the space between the two tracks (RIDO)

These three models interact between one another: the stress and deformations resulting from model A are used as data input for models B and C.

Modelling of the initial state before the works constitutes a complex stage construction. It required several iterative calculations and the simulation of the phases of construction.

This model takes into account the degradation of the tunnel since 1964 with poor quality concrete and a breaking zone in the middle of the invert.

The swelling potential in the marlstone has been modelled like a volume expansion (GYSEL theory, Fig. 6, [4]).

Figure 6: Mean Stress - Isovalues zones before swelling – Model A

This model obtains a stress and strain state in accordance with the surrounding terrain of the existing tunnel. The raising of the platform measured at PM 960 is in the same order of magnitude as the results obtained from the digital model, which validates the model.

The modelled phases take into account the primary realisation of the Berlin wall in the space between the tracks, and the reinforcement with long anchors. Then, for each track:
- Demolition and rebuilding by sections of the sidewalls base, with reinforcement and concreting of the unit “sidewall base + longitudinal beam”.
- Demolition and rebuilding of a ½ invert by sections
- Swelling action on the final rebuild unit (sidewall - longitudinal beam - arch-invert)

Figure 7: Finite Elements Model A - PM 960 – Phase Track V2- demolition of the 1/2 invert

From this initial stage, the study of various construction procedures makes it possible to confirm the choices made for the organisation of the works (model A): the results show that for each step of the opening of the sidewalls and the ½ inverts, the structure is stable and the stress remains within the acceptable limits. They also make it possible to obtain the strain to be absorbed by the new structure and thus to dimension it consequently, in particular with respect to swelling.

The calculations developed in models B-1 and B-2 show that the structure remains stable when a section is opened in the sidewalls, and confirm the need for works by alternate sections 2m long.
The calculations developed in model C show that this Berlin wall is stable and resists, on the one hand, the strain due to the railway loads and, on the other hand, the existing stresses in the invert at the time of the invert rebuilding works. It confirms that the strut (HEB220 every meter in the ½ invert) is important to limit the horizontal displacement of the head of the Berlin wall: the higher it is, the lower the displacements are.

The results of these digital models confirm that the multiphase methodology designed for the works ensures stability at each step of the project. This validates the new geometry of the unit sidewall - longitudinal beam – arch-invert associated with a dense steel reinforcement of the concrete in the final stage.

5. CONCLUSIONS

To stop the breaking process of the Monte Carlo tunnel, a complete substitution of the sidewalls and of the invert is planned, with the main constraint being to maintain railway traffic on one track, with a train speed reduced to 30km/h. The complexity of the geological context and the behaviour of the tunnel lead to designing a multiphase methodology with alternate sections to guarantee railway traffic safety.

The stability of the tunnel and of the railway platform is validated at each phase by the digital models.

A key factor to guarantee safety of the railway traffic is to implement intense monitoring during the construction works. This is achieved by designing an automatic measurement system using well defined threshold values to trigger alerts.

During the project execution phase, at the beginning of 2010, the Contractors will make their final choices for the detailed methodology and for the phasing, with a view to ensuring safety of the railway traffic at each step of the construction works. Given the high level of the residual risks of this project, any small change will require justification while the phases of the construction works are not modifiable. In particular, it is mandatory to work by excavated section 2m in length maximum.

The results of the execution and of the monitoring will be analyzed to confirm and improve the design for the next phases of works. A future paper will be presented with the lessons learnt from the execution of these construction works.

6. REFERENCES


