Overcoming Multiple Caverns: Successful TBM Tunneling in Karst Geology at Galerie des Janots

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ABSTRACT: In April 2019, a 3.5 m diameter open-type, Main Beam TBM and its crew broke through at the Galerie des Janots Tunnel in La Ciotat, France after encountering two large, uncharted caverns. The 2.8 km long tunnel, excavated in limestone known to have groundwater, karstic features, and voids, took two years to complete due to the challenges encountered. Limestone and powdery clays made for slow going early on in tunneling, until a cavern measuring 8,000 cubic meters in size was encountered on the TBMs left side at the 1,035 m mark. The crew had to erect a 4 m high wall of concrete so the TBM would have something to grip against—a process that took about two weeks. The first cavern, while the largest, was not the most difficult void encountered. At the 2,157 m mark, crews encountered a 4,500 cubic meter cavity extending directly below the bore path. This cavern required stabilization, filling, six bypass galleries, and four months of work to get through. This paper will document the extraordinary measures that the crew took to get a TBM through two large, uncharted caverns, and will seek to make recommendations for future projects bored in karstic conditions with the potential for large voids.

KEYWORDS: Karst, TBM, Cavern, Limestone

1. INTRODUCTION: BORING IN KARST

Employment of Tunnel Boring Machines (TBMs) in karstic formations has proven to be a vital option for many projects in the past. TBMs can handle all sorts of karstic conditions if the situation is identified at an early stage of the project and the TBM is designed for the conditions. The major problems related to karst occur when the conditions are either not identified at an early stage of the project or are not detected under the operation until it is too late.

Modern TBM technology offers a variety of measures and tools to handle karstic conditions and these include:

- Probe drilling and pre-grouting with parallel employment of the MWD analysis (MWD = Measurement While Drilling)
- Capabilities to stop water ingress

Karst is one of the most intricate geological conditions to properly identify prior to the project. The following are the most used pre-investigation methods:

- Analysis of surrounding area and relevant projects
- Detailed field mapping of the surface including aerial photos
- Core holes drilled in the relevant areas
- Geophysical methods
- Seismic methods

It is Robbins' experience that properly equipped Hard Rock TBMs are a very good choice in geological formations where karst can be expected and where water ingress is at a lower pressure. Past TBM performance on Robbins projects has been very good as long as the karstic formations are identified prior to hitting them, so they can be handled efficiently.

For further understanding of the specific geological characteristics of this geological formation, some salient features about karst are noted below.

1.1 Main Features of Karst

Karst is formed when carbonate rock types get degraded by acidic water. The phenomenon is common in all calcite rock types, such as limestone, dolomite and marble. The severity of the karstic condition is highly dependent on the degree of weathering. In younger karstic formations the karst will often be limited to smaller water-leading joints and pockets. In more mature karstic formations, more complex hydrogeological systems and very weak geology should be expected (see Figure 1).

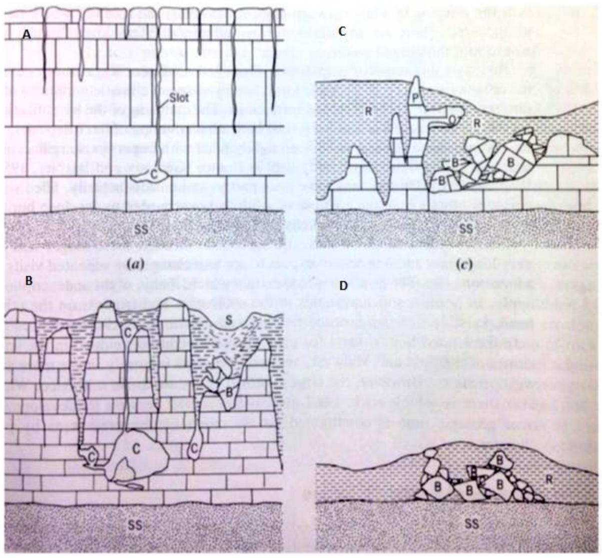

Figure 1 Development of Karstic formations A) Young B) Early Maturity C) Late maturity D) Old Age

The typical challenges connected to karst tunneling are:

- High water ingress
- Lowering of ground water
- Settlement at the surface
- Low stability in the rock mass
- Underground open caverns

The last point, when appearing without any warning and when located next to the TBM path, comprises a significant obstacle in tunneling and requires well-thought-out actions and measures. Underground caverns of very large size where a portion or even the entire machine could fall through deserve the highest possible attention.

2. THE GALERIE DES JANOTS PROJECT

The project is located in the Aix-Marseille-Provence metropolis and next to the community of La Ciotat at the French Mediterranean Coast. The 2,800 m tunnel is one of the fourteen operations designed to save water and protect resources, which are being carried out by the Aix-Marseille-Provence metropolis, water agency Rhône Mediterranean Corsica, and the French State Government. In this area, particularly in summer, temperatures can get extreme and rain fall levels can be quite low. The supply of water relies on employment of pipelines through an existing network with significant safety and vulnerability deficiencies: the pipes have estimated water losses of 500,000 cubic meters per year. Moreover, the current pipes have a capacity limited to 330 liters per second, which is largely insufficient in the summer months. With the new pipeline along the Galerie des Janots, the capacity will be increased to 440 liters per second.

The Galerie de Janots alignment will pass under Le Parc National des Calanques, with cover between 15 and 180 meters. Geotechnical studies of the area showed Limestone, with the possibility of both filled and empty karst caverns.

2.1 Main Beam Machine

A Robbins Open Type Main Beam TBM at bore diameter 3,50 m provided from the companies' rental fleet of TBMs was selected and delivered to site in the beginning of 2017. Prior to its employment during the rebuild, the machine was extensively modernized and upgraded (see table 1).

Table 1 Galerie des Janots TBM Specifications

Main Beam TBM Specifications		
Diameter	Bore Diameter	3.50 m
	Cutters	17-inch disc cutters, back-loading
	Number of Discs	25
	Recommended load per cutter	267 kN
Cutterhead Drive	Cutterhead Power	4 x 187 kW = 748 kW
	Cutterhead Speed	Max of 14.4 RPM
	Cutterhead Torque	496kNm
Cutterhead Thrust	Maximum Thrust	7,481 kN @ 331 bar
	Thrust Cylinder Stroke	1,550 mm
TBM Conveyor	Belt conveyor	500 mm width; 2.5 m/sec belt speed
Weights and Dimensions	Total length	135 m
	TBM weight	170 tonne
Turning Limits	Minimum curve radius (horizontal)	225 m
	Minimum curve radius (vertical up/down)	650 m/550 m

Assembly of the machine was conducted at the tunnel's portal with only limited space available. The TBM and Back-Up System were a combined 135 m long and could not fit at full length at the small jobsite abutting residences and other buildings. Very little on-site storage was allotted in the launch area, with just 25 m outside the portal for assembly--the exact length of the TBM from the head to the rear legs. The logistics of the machine arriving in sequence and being assembled on time was vital. Robbins crews assisted contractor Eiffage with a two-stage assembly. First, crews assembled the TBM and five decks of the back-up system, followed by the remaining decks after the machine had bored forward.

The machine, christened "Augustine", was commissioned on March 3, 2017 and crews began a 24-hour excavation schedule (see Figure 2).

Figure 2 Robbins Main Beam TBM "Augustine" at site assembly

At the machine's launch, the crew was optimistic about getting through the obstacles to be expected when in the karstic limestone. The tunnel boring machine was equipped with a probe drill to detect features ahead of the bore. If the karst were small, the plan was to fill it with concrete. If large caverns were encountered, small parallel galleries would be erected.

To further identify cavities ahead of the TBM, the crew installed a geotechnical BEAM system, standing for Bore-tunneling Electrical Ahead Monitoring. BEAM is a ground prediction technique using focused electricity-induced polarization to detect anomalies ahead of the TBM.

2.2 Augustine Underway

The Eiffage team were well prepared and knew that ground conditions were likely to be adverse – and this came up very soon after start. Conditions were particularly tough in the first 1,000 m of boring. The crew encountered limestone with powdery clays, but this became an obstacle when groundwater was added to the mix.

Areas of water-bearing rock that turned the material into a sticky clay were reported. It became necessary to unblock the cutterhead manually using a clay spade and shovel. Water spray at the cutterhead was reduced to keep the clay dry and better to cut.

Ground support in this area included resin-anchored bolts and rings, topped with wire mesh and a 10 to 15 cm thick layer of shotcrete. Some small filled and empty karst cavities were encountered, and these were systematically drained if needed and filled with grout or foam.

At mark 1,035 m, the machine hit a cavern on the TBM's left side. The cavern, studded with stalactites and stalagmites and measuring 8,000 cubic meters in size, was grazed by the TBM shield (see Figure 3).

Figure 3 Underground cavern encountered during bore

The view into the cavern was picturesque, and was a pristine space about 60 m below the surface where no human being had ever been before. The cavern was named "Grotte Marie Lesimple" after the site geologist.

During geological testing including vertical bore holes drilled from surface, there were no indications of this fairly big underground cavity. The TBM had grazed a corner of the cavern (see Figure 4), and would now have to pass through it.

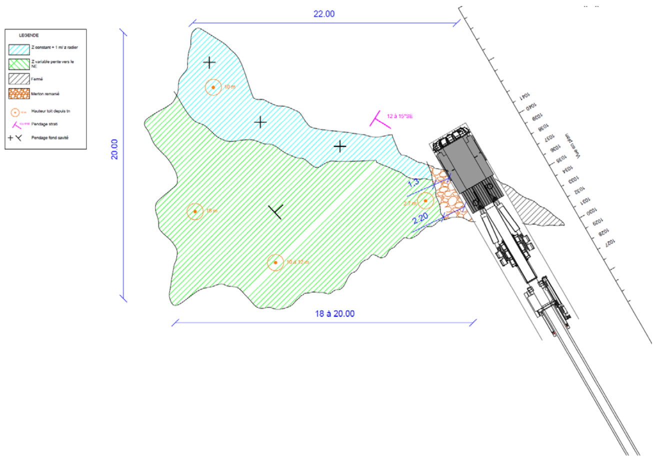

Figure 4. Layout of underground cavern and position of TBM's cavern encounter as seen from top view

To cross the cavern space, crews erected a 4 m high wall of concrete so the TBM would have something to grip against. The TBM was started up and was able to successfully navigate out of the cavern in eight strokes without significant downtime to the operation. The team on site managed to overcome this obstacle about two weeks (see Figure 5). The cavern was not backfilled, but left in place with an entry point for future access if needed.

Figure 5 Wall of concrete erected to provide gripper support for TBM

2.3 A Second Cavern

Back on track and in a continuation of the professional performance on site, the Eiffage team with "Augustine" delivered advances rates averaging 20 to 22 m per day and over 400 m a month. The shift organization included two shifts per day as well as a dedicated night shift for maintenance. Thus, the machine was at all times kept at its best level of service and availability.

The crew enjoyed good performance but was always alert and took measures to detect the ground ahead. At mark 2,157m, the machine grazed the top of an unknown cavity that extended deep below the tunnel path. This structure measured 22 m long, 15 m wide, and 14 m deep, or about 4,500 cubic meters of open space. So, about half the size of Grotte Marie Lesimple when considering its volume but far more critical with respect to its location – beneath the machine's alignment (see Figure 6).

The action plan on site included probing in front of the cutterhead and stabilizing the cavity with foam and concrete. Since access to the cavity across the cutterhead was very much limited due to the machine's size and diameter (3,50m), bypass galleries were built to get access.

After filling much of the cavity (1,500 m^3), the biggest difficulty was to ensure the gripping of the machine. In total, six bypass galleries and four months of work were necessary to reach the end of this challenge. The cavern was closed off after passing through it.

The remaining 600 m of tunneling presented good rock and Augustine performed at rates mentioned above. The best performance rate was noted at 25 m per day. Final breakthrough occurred in April 2019 (see Figure 7).

Figure 6 Second cavity encountered

Figure 7 Machine breakthrough in April 2019

3. CONCLUSION

Tunneling and work in the underground always holds surprises and although the quality of geological investigation and reports over the years has substantially improved, tunnellers need to be prepared.

In the Galerie de Janots Project, it was expected that the TBM may run into cavities and the team was aware of this. Professional employment of the machine and experienced workforce on site overcame two major caverns and managed to complete the project with success and without injury or serious consequences.

This was a tunnel full of obstacles and the lessons learned have been invaluable. The crew were able to pick up on anomalies around the TBM in time to deal with them safely, and they successfully put to the test methods to extract a TBM after encountering caverns and karsts, getting the operation moving again.

Eiffage, together with the Robbins Field service team on site worked together very well and the project success is the result of this cooperation.