Karst and tunnelling: a reverse impact case history

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Abstract. In this paper we present a case history in which tunneling heavily impacted onto a karst system. This paper deal with a hydraulic tunnel under pressure crossing a mountain ridge constituted by calcareous and gypsum units, karstified in recent geological time. The tunnel was driven right above the water table, and above the base level of karstification, in the transfer zone. During time, the concrete lining suffered deterioration mainly due to cavitation processes that led to pierce the lining and the water flowing from the tunnel into the surrounding rockmass. The water pressure into the tunnel changes daily, according to the needs, from 400 to 600 kPa. That led to inflowing water into the karstified rock-mass creating a bub-bile of water infilling the karst system tubes and conduits above the tunnel for a highness of 40 m to 60 m and asymmetric shaped to the lower end of the moun-tain ridge and its sides. Therefore, many springs at higher level of the natural wa-ter table were activated and the base water flow in the karst emerging springs largely improved. When for the execution of the remedial works the tunnel was empty a surplus of water flow of about 6 Mm3 was recorded, all this water was drained from the water bubble created into the karst system. Once the tunnel had been cladded by a steel tube and the water flow reopened no more water losses occurred.

1. Introduction

Karst is a common geo-morphological feature widespread in the nature and develops in the presence of well-defined lithological and environmental conditions.

In tunnel projects, the hazard for affecting the local groundwater resources and the safety in execution must be mandatory considered at any stage of the project development, failing in that can result into unexpected incidents, with delay of timing, increase of the costs and also possible injuries and casualties and environmental impacts.

Karst deeply impacts tunneling during execution, in some instance the presence of a karst system along the tunnel alignment can lead to a substantial changing the detailed design in order to solve major difficulties related to the type of the expected karst features; this topic had been addressed by [1, 2].

In this paper, we present a reverse case history, where is the tunnel to heavily impact onto the crossed karst system.

We are sorry but due to permit constrains we are not allowed to specify the location of the tunnel.

2. The context

2.1. Geology
The tunnel into consideration crosses a metasedimentary sequence constituted by Late Triassic dolomite with gypsum, Jurassic micritic limestones, Cretaceous marly-limestones and sandstones (Figure 1), poly-phased deformed by Tertiary tectono-metamorphic events.

At present, recent alluvial deposits fill the glacial deep valleys, which datum is about 200-300 m above the bedrock.

Figure 1. Geological sketch map of the area with the trace of the hydraulic tunnel. T: Triassic dolomite and gypsum, J: Jurassic limestone, K: Cretaceous marly-limestone and sandstones, Q: Quaternary glacial and fluvial deposits.
The first Tertiary tectono-metamorphic phase assembled these units into tight anticlines and synclines, later refolded by the second phase into large gentle recumbent folds, with B2 axes almost N-S trending (Figure 2); the tunnel runs along the B2 axial plane.

**Figure 2.** Geological cross section along tunnel alignment. T: Triassic dolomite and gypsum, J: Jurassic limestone, K: Cretaceous marly limestone and sandstones. Red lines: B1 and B2 anticline and syncline axial planes; blue lines: continuous water table during water loss, dashed natural water table.

Carbonate units are deeply affected by fracturing, especially by long persistent N-S neotectonic sub-vertical fractures, grouped into bands a few meters wide, tenths of a meter spaced; which present large to very large aperture (up to 20 cm) (Figure 3).

This fracture network resulted into a high permeability of the rock-mass, enhanced by the neotectonic fracture bands.

**Figure 3.** View of the dolomite unit deeply affected by the long persistent neotectonic sub-vertical fractures, which had been preferential site for karstification.
2.2. The karst system
The Late Triassic dolomite with gypsum and Jurassic limestone, had been karstified, most along the long persistent neotectonic sub-vertical fractures and following the ubiquitous discontinuities network, constituted by bedding and joints. Karst system had been developing from top of the mountains down to the datum of the bedrock of the main valley where the base level of karstification is. The karst system developed with main vertical conduits enlarging the fractures in the fracture bands and a minor network on charge of the ubiquitous discontinuities. At present, a sub horizontal cave system is present at the datum of the main valley and represent the collector of the karst water and the base level of the water table; above the water table, there is the transfer zone, where meteoric water flows through preferential karst tubes and conduits (Figure 4).

Figure 4. Sketch of the karst system in the studied area, with the location of the hydraulic tunnel.

Karst system aquifer feeds minor springs along the lower slopes of the lateral valleys and has its main natural outflow of about 600 l/s in the main northern valley (Fig 1).
Permeability of the karst-rock mass is equal to 100m/s, a simple computation led to estimate the ratio of the karst void to be at least the 5% of the volume.

2.3. The tunnel
In the late 1960s, within the frame of a major hydroelectric project, a pressurized hydraulic tunnel (6 km long, 4 m in diameter and going from 900 to 850 m a.s.l.) was built, using drill & blast method. The tunnel supplies water from a mountain dam basin to a hydroelectric power plant, with a power of 150 GWh.
According to needs, the water pressure into the tunnel ranges daily from 400 to 600 kPa (40 to 60 m, or 4 to 6 atm).
This hydraulic tunnel runs almost normal to the second phase fold axe and neotectonic fractures bands, at the level of a B2 axial plane (Fig.3).
It is well known that neotectonics opens and detensionate fracture bands acts as a main path for under-ground water [2].
Correctly, the tunnel was driven in the transfer zone, right above the water table, where meteoric waters flow through preferential karst tubes and conduits.
The tunnel was lined with about 30 cm of concrete as definitive support for the rock-mass and for allowing a fluent water flow, due to the presence of the gypsum in the rocks the concrete was sulphates resistant; according to the rules in force at that time.
3. The impact
A few years after the tunnel had been put onto operation, the water flow at the power plant downstream resulted less than the water inflow upstream from the dam; this lost was estimated in about 2,000 l/s; contemporary, water flow in the springs along the lateral valleys increased, new springs outflow at higher datum, and the water outflow of the base spring of the local karst system increased too.

Some years later, during the day, in the valleys occurred rumbles and sudden rumors of waterfall; it was noted that these events occurred a bit after the main changes of the water pressure into the tunnel, which daily changes according to the needs, from 4 to 6 atm; because the tunnel is right above the water table that means the piezometric level of the water in the tunnel was between 40 m and 60 m above the natural water table.

Therefore, the production was suspended, with severe economic damage, and the tunnel emptied for site inspection.

A surplus of water of about 6 Mm³ was recorded downstream the tunnel after the closing of the water flow from upstream the tunnel;

Analysis and coring of the lining evidenced the concrete was affected by abrasion and cavitation and by dissolution of the cement matrix and calcareous aggregates due to cavitation processes and sulphates attack; this last related to the presence of gypsum in the Late Triassic dolomite (Figure 5).

![Figure 5. Tunnel line pierced by cavitation processes and water flowing back inside the tunnel by the surrounding rock-mass.](image)

The inspection outlined the presence in the lining of longitudinal cracks due to the water pressure inside the tunnel; the lining had been forced against the surrounding rock-mass, as well evidenced by georadar surveys.

Chemical analysis of the natural in situ water pointed out a Langelier index ranging between -0.2 and -1.2 that classified the water as aggressive to highly aggressive for concrete.

The rules in force at the time of the execution did not completely guaranty concrete from aggressive sulphates water attack and therefore new rules more guaranty-ing against sulphates attack were emitted years later.

That led to pierce the lining and the water flowing in pressure from the tunnel into the surrounding rock-mass, especially in the stretch crossing karstfied Triassic dolomite with gypsum and Jurassic limestone. Plus, the water outflow through the longitudinal cracks opened due to the inner pressure of the water in the lining.

That inflow of water into the karstfied rock-mass created a bubble of water infilling the karst system tubes and conduits above the tunnel for a height of 40 m to 60 m (Figure 6).
This event activated new springs at level higher than the natural water table and largely increased the flow of the previous natural springs and the base water flow in the karst emerging springs.

This about 6 Mm3 of water drained back by the emptying of the tunnel represents the drainage of the water bubble developed into the rock-mass, which had been feeding the new springs and the increase of water flow in the others; in total it was estimated a total extra water discharge in the order of 2.5*E+09 cubic meters of water.

Considering the void of the karst system about the 5% of the rock-mass volume, a roughly estimation led to evaluate the volume of the rock-mass saturate by the water flowing out from the tunnel into hundreds of Mm3 allocated into the karstfied unit.

Once the tunnel was empty, the springs above the original water table dried, the previous natural springs got back to their natural flux and the karst base flux returned to its previous natural values of about 600 l/s.

4. The remedial works
In order to overcome the damages in the tunnel and avoiding further environmental issues and impacts onto the karst system and its natural regime, it was decided to proceed to a total new lining of the tunnel.

The first proposal was to destroy the existing lining and made up a new one sulphates attack resistant and in reinforce concrete for containing the outward water pressure.
After a detailed costs-benefits analysis it resulted that the best solution was to insert inside the existing tunnel, for all the tunnel length, a still-tube (Figure 7), resistant to pressure, cavitation and sulfate attack. This solution also had the benefit do not operate any intervention in the existing lining.

Once the tunnel has been cladded and the water flow reopened no more water losses have been recorded, neither anomalies in the springs and karst water flows, or rumbles in the valleys (Figure 8).

**Figure 7.** Cavitation, sulphate attack and out-thrust pressure damaged the original concrete tunnel lining; the insertion of a still tube (black) inside overcome all these features occurrence.

**Figure 8.** Works in progress for the insertion of the still-tube inside the hydraulic tunnel
5. Final remarks
This paper presents a peculiar case history, where despite any effort for environmental respect a tunnel deeply impacted onto the karst system.

During the design process, the environmental aspects were taken into account, and in particular the presence of sulphates rock and aggressive water, by using sulphates resistant concrete (according to the rules in force at that time), and the respect of the karst system, by staying above its base level and the water table.

However, an unforeseen degradation of the final lining, due both to no fully guaranty rules in force at that time for concrete resistant to sulphates attack, outward pressure and cavitation processes, led to a not imaginable impact of the tunnel onto the karst system.

That resulted into large flow of water in pressure from the tunnel into the karst system, with severe environmental noise and high remedial costs for both the production and the works.

The case history, of the negative experience here presented, represents a lesson to be learned and taken into account when planning and designing new tunnel projects across karsts system in order to avoid the issues on damaging the environment by a possible reverse impact.

References
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