Tunnelling Through Karstic Rocks

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1. Introduction

Groundwater is a main source of problems in tunnel construction associated with stability and safety issues. Groundwater control during both construction and operation of the tunnel is one of the most challenging problems faced by tunnel designers and contractors. Seepages, or leakages, into underground works from the surrounding aquifer can also affect the surrounding ground and adjacent facilities. Depending on local geology, hydrogeology and geotechnical parameters of the material, a severe environmental impact may be expected. Temporary but severe depletion of ground water resources during construction may also take place. In the opposite case, i.e. when leakages from underground works to an underlying aquifer are possible, the hazard of groundwater contamination has to be considered. The crossing of voids and caverns, whether empty, aquiferous or filled with weak and/or erodable material causes difficulties and the solutions that should be engineered are often site specific. Hence, although limestone and carbonate rocks in general exhibit good geotechnical behaviour, when karstic, they may induce all the aforementioned problems in tunnelling operations.

2. Interaction with groundwater; general considerations

The interaction of tunnelling works with groundwater can be summarized as follows:

During construction:
- Inflows of water in the underground space, affecting normal construction procedures and possibly induce face and roof stability. Minimize the water heads by drainage is essential.
- Sudden inflows occurring with the crossing of specific and localized aquiferous features, e.g. faults, crushed zones, big karstic conduits etc. This is a serious hazard during construction and can be sudden and violent. Loose filling sediments may be associated with this blow out.
- Decline in yields of springs, decrease of groundwater discharge to wells.
- Development of sinkholes in susceptible areas due to piping or internal erosion. This risk is mainly present in shallow tunnels but collapses to the surface have been reported for depths of at least 100m [1].
- Unacceptable settlements, where compressible fine-grained soils or heavily fractured rock masses are present, due to the increase of effective stresses by lowering of the groundwater table. This risk is particularly high for shallow tunnels in covered karst with a confined ground water table. The drainage and deconfinement of the karstic aquifer may induce lowering of the piezometric surface of the perched aquifer developed in the cover sediments.
- Temporary contamination of groundwater occurring at lower elevations, by infiltration of polluting substances used for the construction.

In the following text the term limestone often refers also to all carbonate rocks that undergo karstification.
During operation:
- Infiltration of used chemically and organically contaminated waters from road or rail tunnels, which affect the quality of the groundwater if the tunnels are crossing the non-saturated zone and the lining is not appropriately sealed.
- Rise of piezometric levels by the obstruction of groundwater flow by lined tunnels; the rise is effective when the tunnel is located at a shallow depth under a shallow water table, normal to the direction of flow and can affect the built environment (foundation, basements) and/or mobilize contaminants in case of saturation.
- Influence of the hydrostatic head on the lining of the tunnel.
- Tunnel collapse by wide fluctuation in hydrostatic pressure associated with normal operation of hydraulic unlined tunnels.
- In the case of water conveyance tunnels with lining deficiencies, the relation between the head of the waters flowing in the tunnel and the head of the surrounding aquifer can cause:
  - Inflow of eventually polluted waters in the tunnel and/or development of all the related and abovementioned risks (internal head lower than the head of the aquifer).
  - Leakages from sewer tunnels can contaminate the surrounding aquifer (interior head higher than head of the aquifer); leakage is a major concern when tunnels carry high-pressure water with toxic ingredients. Such fluids must be contained by a high quality impervious liner.

3. Investigation

3.1. General considerations

It is essential to have accurate preconstruction assessment of groundwater conditions. No major underground engineering operation should be initiated before a comprehensive knowledge about the heads and flow regime of groundwater is established.
In the case of a tunnelling project close to the surface or in urban areas a good number of investigation techniques suitable to provide direct information and measurements are available (on piezometric heads, permeabilities, discharges). Geophysical investigation is often of great assistance. Unforeseeable conditions are thus very constrained.
In case of long tunnels at greater depths (in mountainous areas) the investigation possibilities are rather limited either physically or due to high cost. In such areas the investigation is mainly based on classical hydrogeological studies, procedures and techniques and should cover a broader area for getting all necessary data and all geological boundary conditions. A study of this calibre must be based also on some kind of geological judgment. This procedure must include:
  - identification and classification of aquifer media (lithological and structural mapping)
  - distinction of hydrogeological units and water tables
  - definition of hydrogeological basins (underground catchment areas) and of the discharge areas
  - delineation of water budgets
  - study of springs: location, elevation, flow dynamics and discharge rates
  - compilation of piezometric maps
  - evaluation of hydraulic parameters both locally around the tunnel and in the broader area.
  - conclusions in the form of a report on the hydrogeological and geometrical boundary conditions for each aquifer and evaluation of heads and inflows relative to the underground construction. The report must provide also approaches for likely zones of sudden inrush hazard.

3.2. Particularities in karstic rock masses

The particular or even unique hydrogeological features in a karstic environment demand special attention, owing to the:
  - high coefficient of infiltration from meteoric water.
  - very high permeability and often non-linear underground flow.
  - preservation of high values of permeability at greater depths.
- potential of development of large hydrogeological basins, which may extend far beyond the boundaries of the corresponding geographic - hydrological basins of the considered area, involving, thus, greater quantities of groundwater.
- development of a non uniform, heterogeneous pattern of flow paths; depending on the post-
tectonic and paleogeographic evolution of the area, preferential flow conduits and karstic tubes could be developed with a capacity to transmit water at large discharge rates; these conduits drain the surrounding jointed or finely fractured rock mass of low or medium permeability.
- natural groundwater flow in a flooding manner throughout the transfer ("unsaturated") zone.
- potential crossing of large underground cavities filled eventually with earth materials, with the possibility also to carry a column of perched ground water.

Given this unique environment the detection and characterization of the karstified zones and features ahead of the advancing face is vital.

4. Potential hydrogeological models to be encountered

During the first stage of investigation in a limestone terrain it is crucial to understand the karstic pattern around the tunnel by means of a detailed hydrogeological study*. Such hydrogeological study should include a paleogeographic evaluation of vertical movements and changes of the geographic base level related to past locations of springs, in order to assess the depth of karstification inside the limestone mountain and the geometry of the karstic base level. This level is not necessarily restricted at the present elevation of the springs. Thus, the geological reconnaissance in a broader area is a prerequisite for the investigation regarding tunnelling in karstic ground.

Dye tracing testing and follow up of the route of major underground flow axes, i.e. between sinkholes and springs, greatly assists the understanding of the delay of underground flow and is thus elucidating as to the presence of potential branching of the large karstic conduits or of a general dispersion of flow to several directions. In this same rationale, the study of the distribution and the hydrographs of springs is always the most reliable tool for understanding the internal structure and geometry of a karstic aquifer, since it reflects the hydrodynamics of the whole mass.

The question of whether concentrated or dispersed inflows are to be expected is of great concern since the former may dramatically threaten tunnelling operations. A detailed structural analysis of the hydrogeological basin will define zones of possibly very high permeability (i.e. faults, or systematic zones of bends in folds). The distribution of springs in the lower geographic levels gives good indications. In well-developed karst, springs are to be found in lower geographical elevations of the outcrops. In these locations, the existence of long linear front of springs reflects on more dispersed flow inside the karstic mass.

The position of groundwater levels and fluctuations in the investigation boreholes must be recorded at all times since they reflect the transmissivity and the drainage capacity of the overall fundamental karstic mass. They cannot however give information for the transmissivity of particular karstic conduits of sizeable cross-sections, in case such a karstic model exists.

In the case of tunnelling in mountainous areas, pumping tests from wells, even if feasible, are not as helpful as for tunnels in low relief terrain. In those cases, packer tests restricted in the zone around the tunnel controlling the inflows are a common practice. In big and high mountainous areas, where boreholes and geophysical methods are physically constrained, the understanding from geological and hydrogeological surface mapping can provide a reasonable frame of guess for the conditions to be encountered. This has to be continuously checked by probing ahead the face investigations, during construction of the tunnel.

Table 1 intends to provide the main hydrogeological models in a limestone environment. The answer on the most probable model to be crossed will facilitate the appropriate design of the tunnel and the provision of the methods and equipment necessary to face the hazards associated with the karstic conditions to be encountered.

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* The reader can get insight on karstic processes in some excellent publications ([2], [3], [4], [5] and [6]).
Table 1. Potential hydrogeological models in limestone environment. Note that in some cases (e.g. platform karst) the inundation zone may be insignificant or transient. Carbonate rocks with substantial primary porosity can be considered in the fine jointed type model presented in this table. Few climatic type of karstification may produce patterns different from those above. In the case 2.2 the lower part of the karst over an old base level may be fossilized and filled ([7] with modifications).

**Case 1.** Non-karstic limestones: Groundwater issues are considered as for a jointed or fractured strong rock mass. Permeability is generally low and decreases dramatically with depth. Exceptions may occur in fault zones.
- **Model A. Tunnel in unsaturated zone:** Tunnel will cross a dry limestone; no risk for floods. (fig. 1)
- **Model B. Tunnel below water table:** Tunnel will encounter medium to insignificant flow, depending on the frequency and aperture of joints or fractures. In large depths permeability is practically zero (fig. 2).

![Figure 1. Case 1. Model A. Tunnel in the unsaturated zone of a non-karstic jointed limestone (sketch not to scale)](image1)

![Figure 2. Case 1. Model B. Tunnel below water table for a non-karstic jointed limestone (sketch not to scale)](image2)
Case 2. Karstic limestones. Permeability due to well developed karstic conduits and/or a net of fractures and joints more or less widened by dissolution: Dramatic difference in behaviour compared with other aquiferous media; presence of high permeabilities and high discharges.

Case 2.1. Tunnel below base level of karstification (figure 3): The rock mass surrounding the tunnel has never been in the past exposed to underground erosion due to the paleogeographic-tectonic vertical movements of the area in relation with the present geographic base level or due to its isolation from infiltration and flow to outlets (springs). However in large mountainous masses the interior of the mountain could have escaped karstification and the base level of karst to lie at much higher elevations than the present geographic level (level of the springs, [8]). Tunnels with such conditions will rather comply with model B.

![Figure 3. Case 2.1. Tunnel below base level of karstification (sketch not to scale)](image)

Case 2.2. Tunnel above base level of karstification: The size of the problems and risks depend on the internal geometry of the karstic aquifer. Two options are possible:

- **Case 2.2.1.** The underground flow is mainly concentrated and governed by distinct preferential large karstic tubes and conduits. This is often the case where a continuous downward underground erosion persists as the geographic base level was progressing towards lower elevations or where the lowest geographic level was restricted to a confined zone. The karstic tubes and conduits have a selective orientation to the horizontal when they approach the base level of discharge of the karstic aquifer. More horizons with horizontal tubes may have developed during the paleogeographic evolution of the area.

- **Model C. Tunnel in the transfer zone:** The tunnel is in the transfer zone of a selectively highly karstified mass. It will cross dry karstic conduits but if located at depth the hazard for personnel and equipment from sudden inrushes and flooding will be high when storms occur in the catchment area (fig. 4). Erosion of loose filling material may result to a mudflow into the tunnel. Systematic probing ahead of the face during the tunnel advance should be a common practice.

- **Model D. Tunnel in the inundation zone:** The tunnel will drain either well developed karstic conduits and/or the fundamental mass around them.

  - **Model D₁ (fig. 5):** The tunnel is in the inundation zone and will drain usually moderate quantities of ground water of a limestone mass between karstic conduits. These quantities are fed by water stored in fractures and joints between these conduits. During construction, the tunnel can easily and abruptly enter in the conduits of the system. Upon encounter of the conduits, considerable increase of inflow will be experienced and violent inrush or flooding of the tunnel cannot be excluded. Probing ahead during construction is an absolute need.

  - **Model D₂ (fig. 5):** The tunnel has to face the huge transmissivity of the inundated karstic tubes and conduits. If possible, pre-drainage techniques (if the conduit is not filled with aquifer loose sediments) or isolation methods with site-specific character should be applied in order to assist the crossing of the flooded conduit. Reestablishment of the natural flow is necessary after the crossing of the karstic tube otherwise a quasi-permanent drainage of the karstic aquifer will last almost all of the construction period. In all cases, the water resources of the area will be temporarily affected.
Case 2.2.1. Model C. Tunnel in the transfer zone of a karstic aquifer with distinct preferential karstic tubes and conduits (sketch not to scale)

Figure 4. Case 2.2.1. Model C. Tunnel in the transfer zone of a karstic aquifer with distinct preferential karstic tubes and conduits (sketch not to scale)

Case 2.2.1. Model D. Tunnel in the inundation zone of a karstic aquifer with distinct preferential karstic tubes and conduits (sketch not to scale)

Figure 5. Case 2.2.1. Model D. Tunnel in the inundation zone of a karstic aquifer with distinct preferential karstic tubes and conduits (sketch not to scale)

Case 2.2.2. Flow is guided by a more homogeneous interconnected system of karstified fractures and enlarged joints. This case is usually the case of thin-bedded and well jointed limestone in areas characterized by a long lasting persistence of an extended flat geographic base level.

- Model E. Tunnel in the transfer zone: The tunnel is in the transfer zone of a dense interconnected system of slightly karstified joints and fractures of moderate aperture (fig. 6). Only dripping waters or small amounts of transient water during wet periods. There is no risk for floods as the infiltration is widely dispersed inside the karstic, more homogeneous permeable mass.

Figure 6. Case 2.2.2. Model E. Tunnel in the transfer zone of a well interconnected system of enlarged joints and fractures (not to scale)

Model F. Tunnel in the inundation zone (fig. 7): The tunnel, being in the inundation zone, will continuously drain significant quantities of ground waters during the construction, imposing the need for appropriate equipment. Violent inrushes are usually restricted. A drainage umbrella in front of the face should reduce the head and control inflows during the excavation. Stability problems may occur only if the limestone is brecciated. If ground water resources have to be protected, sealing of the lining will be necessary; this may considerably increase the cost.

Figure 7. Case 2.2.2. Model F. Tunnel in the inundation zone of a well interconnected system of enlarged joints and fractures

5. Confronting the problems

Groundwater in tunnelling can be faced either by drainage, thus reducing both head of water pressure and discharge into the tunnel, or by grouting*.

* Useful information for controlling groundwater can be obtained from [11], [12], [13], [14]
Methods such as freezing or the use of TBMs with a pressurized face cannot be applied in highly permeable limestone with open karstic features. Usually, drainage is more effective and often cheaper than any other operation. Pre-drainage prior to tunnel construction is probably the most commonly used water control method. The technique basically involves the lowering of the water table by drilling a series of wells or boreholes at either side of the projected tunnel. Drainage can be achieved from within the tunnel itself when dewatering from the surface is impossible. This can be done through drain holes from the face or, in case of a generalized important aquiferous medium, from a long systematic drainage umbrella embracing the tunnel, or even though the construction of small side pilot drainage galleries.

In the case of grouting in limestone, the primary goal is to reduce permeability. Full practice is to drill a 360° array of grouting holes forwarded subhorizontally, then blast out and seal a section of the tunnel inside this completed grout curtain. Grouting anyhow is difficult in large openings or under high pressure of water.

Dewatering can have undesired side effects on adjacent properties, the tunnel itself and the environment, such as ground settlement due to consolidation of compressible soils filling big karstic cavities up to the surface or development of sinkholes. Depletion of adjacent groundwater may also occur. In that cases other methods have to be applied or the dewatering to be associated with strengthening of the overlying the karstic limestones weak materials.

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In the case of voids and caverns problems are often difficult to overcome. The solutions consist of:

- bridging or backfilling of the void, if empty
- tunnelling through a geotechnically weak fill material in filled cavities by strengthening or by applying a heavy supporting shell or by using TBM with a pressurized face.

TBMs with pressurized face can be used in tunnels crossing frequent large filled cavities or crossing the irregular interface of an old relief between karstic limestone and its soil cover, in order to avoid settlements or triggering of sinkholes. In this case an open TBM can also be used only after treatment of the infill material. Such treatment can be achieved with grouting, jet grouting or by crossing the void conventionally with forepolling after the stoppage of the machine.

Using a pressurized face TBM in deep tunnelling is meaningless. The crossing of large conduits and caverns can be made with a rock open TBM after treatment of these voids. Probing ahead for their detection is imperative. Treatment of an empty void can be done by backfilling ([4], see also [9]). If backfilling of the karstic cavern should be carried out from within the tunnel care should be given not to obstruct the cutter head with the concrete operations. When naturally filled, the voids have to be crossed conventionally since an open TBM cannot bore safely the fill. Ravelling through the cutter head of the machine may happen and the machine may also suffer from sinking. Crossing a filled cavity may be done by forepolling, grouting, or by jet grouting. In all cases a stoppage of the machine is imposed. The choice greatly depends on the nature of the ground. Loose soil and soft clays respond well to jet grouting. On the contrary, karstic fills of hard clays and consistent soils may be more efficiently faced with a forepolling umbrella. In the later case the umbrella can be assisted with a tube-a-manchette grouting.

Mechanical probing associated with a TBM drive is indeed absolutely necessary when tunnelling in karstic ground and equipment is recommended to be part of the facilities of the machine when ordering it. Various possibilities are possible following the geological particularities [10]:

- Short but numerous probing from the front or the whole circumference carried out with the normal drilling equipment of the machine, length up to 20-30m, normally outside the tunnel profile
- Medium long bores with special equipment, mounted for this purpose, length around 80-120m, destructive or core drillings with or without preventers. TBM advancing by alternate steps.
- Long bores executed from especially excavated side cavers; length from 500, up to 1500m.

results allow to adapt the tunnel route to a certain extent. TBM can go on while drilling.

When encountering a karst channel, which can be a common case in the transfer zone of the aquifer of the model C in Table 1, unpredictable concentrated water pressure may load the tunnel lining during floods. In order to prevent possible damage, forced drainage of the channel towards lower elevations has to be secured.
6. Conclusions

Tunnelling in karstic ground require a thorough hydrogeological knowledge over a broader area. Lack of this knowledge may result to a design, which will not be able to face problems or hazards that may occur during construction, with probably dramatic consequences on safety and in the completion of the operation. Judgment and engineered solutions, often site specific, should always assist decisions at all stages during design and construction. Probing ahead of the tunnel face, based upon a sound hydrogeological model, is an essential tool for the investigation of either the groundwater conditions in terms of pressures and discharges, or the occurrence of cavities.

7. References