Δελτίο της Ελληνικής Γεωλογικής Εταιρίας, Τομ. XXXIV/5, 1755-1764, 2001 Bulletin of the Geological Society of Greece, Vol. XXXIV/5, 1755-1764, 2001
Πρακτικά 9ου Διεθνούς Συνεδρίου, Αθήνα, Σεπτέμβριος 2001 Proceedings of the 9th International Congress, Athens, September 2001

TUNNELLING IN LIMESTONE TERRAIN: THE NEED OF THE KNOWLEDGE OF THE HYDROGEOLOGICAL MODEL

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ABSTRACT

Although limestone and most carbonate rocks exhibit good geotechnical behavior, when karstic, they may induce hazards during tunnelling operations, which may evolve into huge problems. Groundwater is the main source of problems and so is the crossing of voids and caverns, empty, aquiferous or filled. In order to estimate the probability of encountering such conditions and be prepared to face them, a thorough hydrogeological study should complement the traditional site investigation. This study has to consider a broader area embracing the whole hydrogeological basin of the karstic aquifer with background knowledge of the tectonic and paleogeographic evolution. In this paper a series of hydrogeological models are discussed depending on the internal karstic geometry of the aquifer and the position of the tunnel, either in the transfer or the inundation zone. Each model is associated with its own tunnelling particularities in terms of hazards and countermeasures. A discussion on the solutions to be engineered in order to cross big karstic cavities is presented.

KEY WORDS: Tunnels, limestone, karst, hydrogeological model.

1. INTRODUCTION

Groundwater is often the 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. Drainage facilities from the headings may be required and when the necessary invert grades are not available, the additional trouble and expense of pumping are unavoidable. Water can affect roof and face stability and in appreciable quantity will impede construction. If the host ground is soft and prone to erosion the risk is further increased.

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. In the opposite case, i.e. when leakages from underground works to the aquifer are possible, the hazard of groundwater contamination has to be considered.

The crossing of voids and caverns, empty, aquiferous or filled with erodable material causes difficulties and the solutions that should be engineered, are often site specific.

Hence, although limestone and carbonate rocks in general exhibit a good geotechnical behavior, when karstic, they may induce all the aforementioned problems in tunnelling operations . Many large engineering projects involving tunnels are currently under construction in countries where limestones are a very common geological formation. The design of underground excavations in these materials requires knowledge of the geological and hydrogeologic model in which these excavations are carried out.

2. INTERACTION WITH GROUNDWATER; GENERAL CONSIDERATIONS

The interaction of tunnelling 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.
- Sudden inflows associated with specific and localized geological features, e.g. faults, crushed zones, big karstic conduits etc.
- Decline in yields of springs, decrease of groundwater discharge to wells.
- Development of sinkholes in susceptible areas due to piping or internal erosion.

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* IN THE FOLLOWING TEXT THE TERM LIMESTONE REFERS ALSO TO ALL CARBONATE ROCKS THAT UNDERGO KARSTIFICATION

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- Acceleration of dissolution of soluble sediments (e.g. gypsum).
- 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.
- Temporary contamination of groundwater occurring at lower elevations, by infiltration of polluting substances used for the construction.

During operation

- Infiltration of used chemically and organically contaminated waters from road or rail tunnels can affect the quality of the groundwater if the tunnels are crossing the unsaturated zone.
- 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 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). Underground excavations containing fluids such as petroleum products at near-atmospheric pressures can be left unlined if the rock quality is high and if the excavation is below the water table since the fluids are contained by inward seepage of groundwater
- 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 an impervious liner.

3. INVESTIGATION

Particularities in karstic rock masses

The particular or even unique hydrogeological features in a karstic environment demand special attention, as there is an increased risk for water inflows and for environmental problems. Tunnelling in limestone terrain may thus be a challenge for both geologists and engineers owing to:

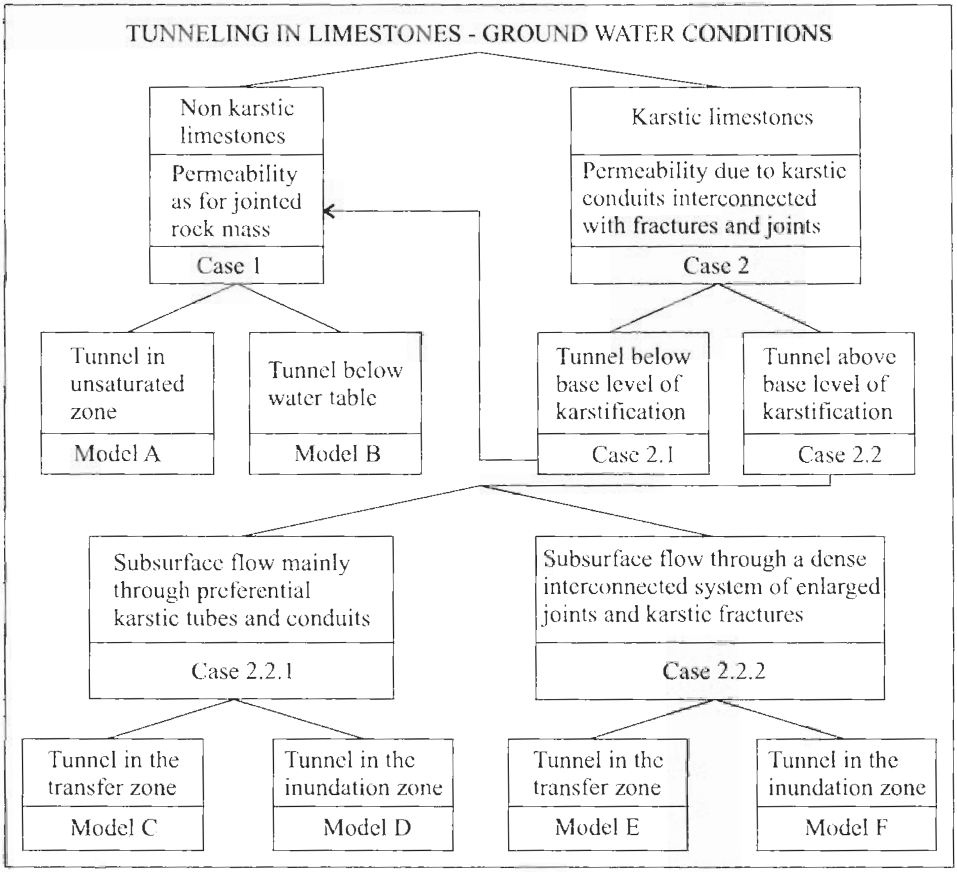
- high coefficient of infiltration from meteoric water.
- very high permeability; often non linear underground flow.
- preservation of high values of permeability at greater depths.
- potential of development of large hydrogeological basins, which may extend far beyond the boundaries of the corresponding 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.
- 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.

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 surficial springs. Thus, the geological reconnaissance in a broader area is a prerequisite for the investigation regarding tunnelling in karstic terrain.

Dye tracing testing and follow up of the route of major underground flow axes, i.e. between sinkholes (ponors) 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 a general dispersion of flow to several directions.

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 of the finely jointed type presented in this table. Few climatic type of karstification may produce patterns different from those above.***



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 interior of the karstic mass.

The question of whether concentrated or dispersed inflows are to be expected is of great concern since the former may threaten tunnelling operations. A detailed structural analysis of the hydrogeologic basin will define zones of possibly very high permeability (i.e. faults, or systematic bending zones).

Finally, the position of groundwater levels and fluctuations in the investigative boreholes, must be recorded at all times since they reflect the thansmissivity of the whole karstic mass. 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, is a common practice.

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 (Marinos, 2001).

Case 1: Groundwater issues are considered as for a jointed or fractured rock mass. Permeability is generally low and decreases dramatically with depth. Exceptions may occur in fault zones.

- **Model A:** Tunnel will cross a completely dry limestone mass; no risk for floods

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* The reader can get insight on karstic processes in some excellent recent review publications (Breznik, 1998, Milanoviç, 2000 and White, 1999).

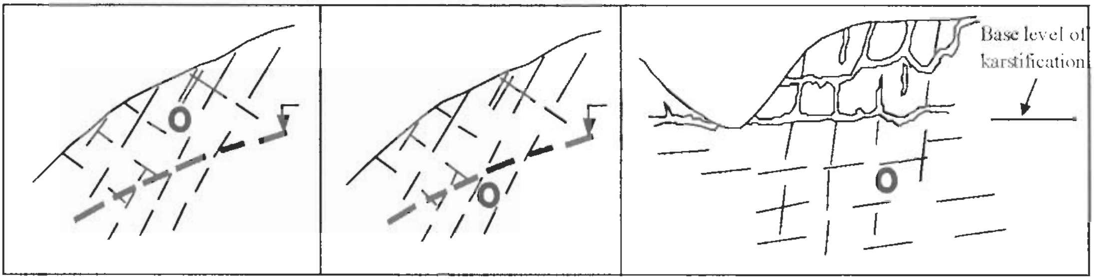


Fig.1 Case 1 and Case 2.1. G.W. Groundwater piezometric level surface

- **Model B:** Tunnel will encounter medium to insignificant flow, depending on the frequency and aperture of joints or fractures.

Case 2: Dramatic difference in behavior compared with other aquiferous media; presence of high permeabilities, large discharges.

- *Case 2.1:* The rock mass surrounding the tunnel has never been exposed to underground erosion due to the paleogeographic evolution of the area or its isolation from infiltration and flow to outlets. In low relief morphology, the past geographic base level of the area to be crossed has never been lower than that of the tunnel. However in large mountainous masses the interior of the mountain could have escaped karstification and the base level of karst lies at much higher elevations than the present level of the springs. Tunnels with such conditions will comply with either model A or B (Fig.1).

- *Case 2.2:* The size of the problems and risks depend on the internal geometry of the karstic system. Two options are possible:

- *Case 2.2.1* when the underground flow is mainly concentrated and governed by distinct preferential large karstic tubes and conduits or,

- *Case 2.2.2:* when flow is guided by a more homogeneous interconnected system of karstic fractures and enlarged joints. The latter is usually the case of well-bedded limestone in areas characterized by a long lasting persistence of an extended flat geographic base level. The former is often the case where 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.

Model C: The tunnel is in the transfer zone of a selectively highly karstified mass. It will cross dry limestones 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. The stability of the tunnel might also be endangered. Erosion of loose filling material may result to a mudflow into the tunnel. Probing ahead should be a common practice. Contamination of the underlying "water table" is a real risk (Fig. 2).

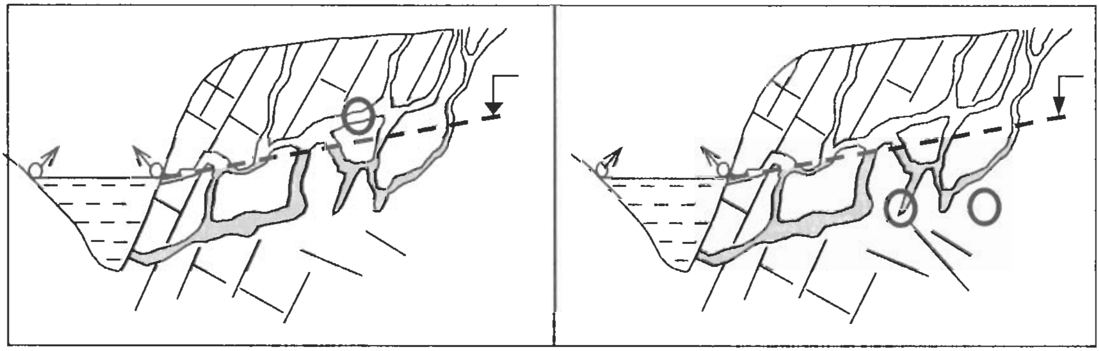


Fig. 2 Case 2.2.1. (Model C) *Case 2.2.1. (Model D)*

Model D: The tunnel is in the inundation zone and will drain moderate quantities of ground water between karstic conduits (D1). These quantities are fed by water stored in fractures between these conduits. Upon encounter of the conduits (D2), 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 (Fig.2). Predrainage

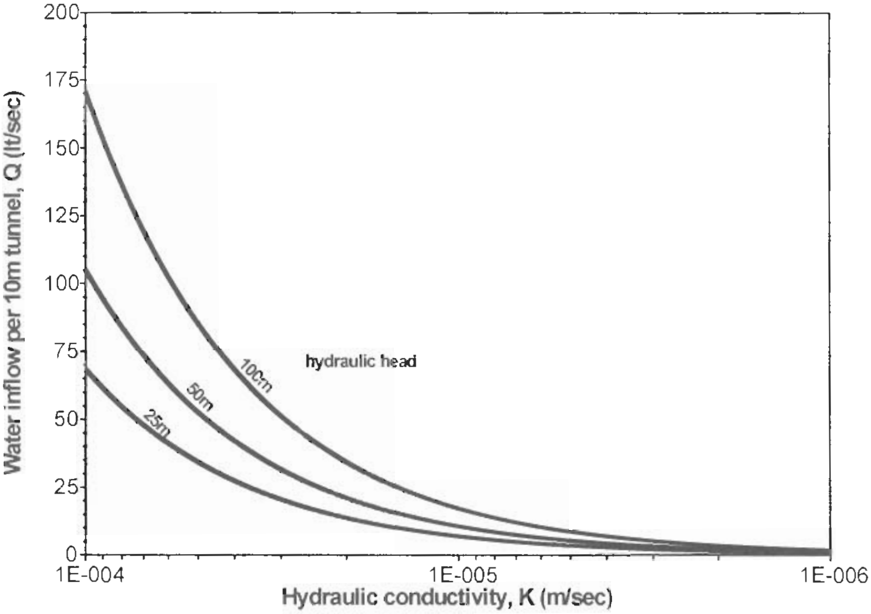


Figure 3: Estimation of water inflow in a 10 m diameter tunnel for steady flow condition. This graph can be applied in the inundation zone of a limestone aquifer for estimating maximum values before transient flow is established and in sections between two main karstic conduits. It does not apply to discharges through the conduits themselves. These conduits may recharge their fractured-jointed limestone environment simulating steady flow conditions.

techniques with site-specific character should be applied in order to assist the crossing of the conduit. A quasi-permanent drainage of the karstic aquifer will last almost all of the construction period. The water resources of the area will be affected. Ground water discharges from the limestone mass between karstic conduits can be approached by the graph of Fig. 3. This estimation does not apply for the discharges of the conduits themselves.

Model E: The tunnel is in the transfer zone of a dense interconnected system of slightly karstified joints and fractures of moderate aperture (Fig.4). It will cross a mass with 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 mass.

Model F: The tunnel, being in the inundation zone, will drain, almost permanently significant or very significant quantities of ground waters during the construction, imposing the need for appropriate draining equipment. Violent inrushes should be restricted (Fig.4). An estimation of the transient discharge is given in Fig 5. Special design arrangements are to be implemented (i.e. diversion of waters to the sides of the tunnel). A drainage umbrella in front of the face should_reduce the head and control inflows during the excavation (Fig. 6). Stability problems may occur only if the limestone is brecciated. Groundwater resources can be seriously affected.

5. CONFRONTING THE PROBLEM OF WATERS

Groundwater in tunnelling can be faced mainly with the following generally regarded operations (general information can be obtained from Anonymous, 1992 and Bauer, 1994):

- lowering groundwater level by controlled drainage or dewatering via pumping, thus reducing both head of water pressure and discharge into the tunnel
- grouting

Methods such as freezing, ground control by slurry, compressed air or earth pressure balance boring machines cannot be applied in highly permeable karstic limestone. 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 from a long

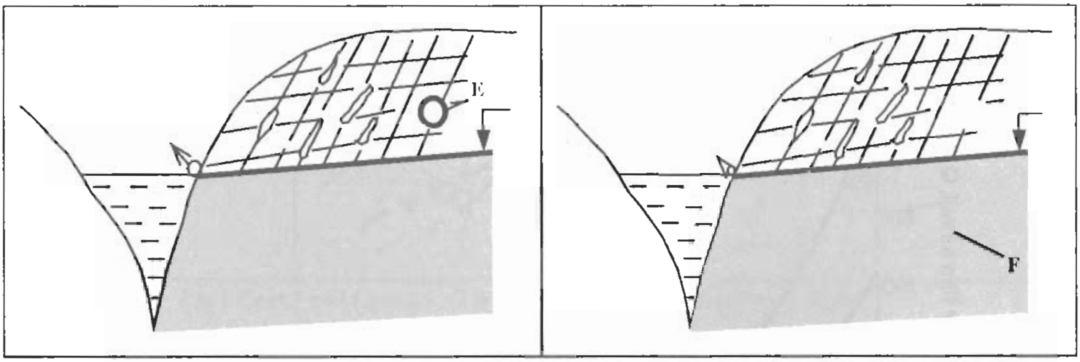
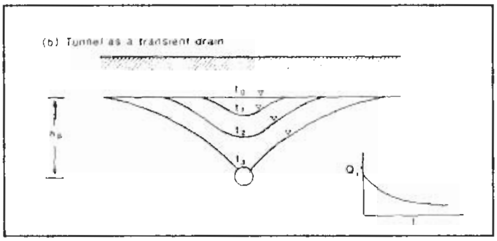


Fig. 4 Case 2.2.2. (Model E)

Case 2.2.2. (Model F)

systematic drainage umbrella embracing the tunnel (Fig. 6), or even though the construction of small side pilot rainage galleries.

In the case of grouting in limestone, the primary goal is to reduce permeability. Modern practice is to drill a 360° array of grouting holes forwarded sub horizontally, then last out and seal a section of tunnel inside this completed grout curtain. This also largely deals with the hazard of catastrophic inrush, i.e. a flooded cavity should be first encountered by a narrow bore drill hole that can be sealed off quickly. Grouting anyhow is difficult in large openings or under high pressure of water.



$$Q = \frac{k(h^2 - D^2)}{R}$$

where

$$R = 1.50\sqrt{\frac{(k)\,t}{S}}$$

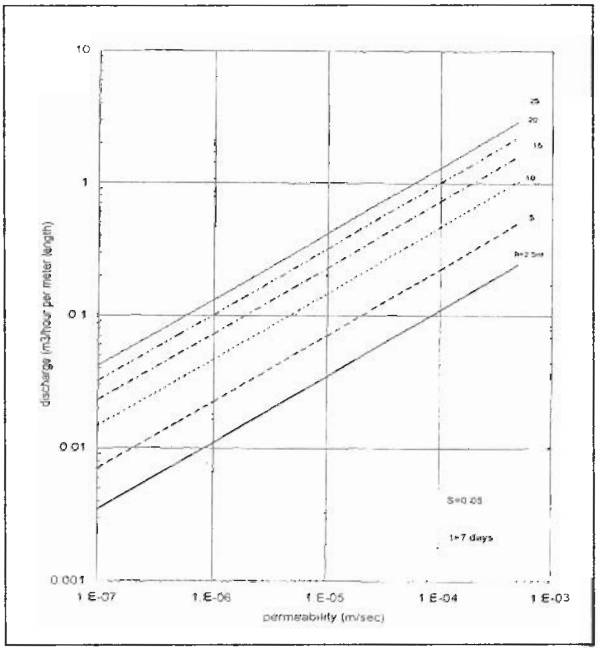


Fig. 5 Estimation of transient discharge

Dewatering can have undesired side effects on adjacent properties, the tunnel itself and the environment, such as (see also Powers, 1985):

- ground settlement due to consolidation of compressible soils filling big karstic cavities up to the surface as an effect of increased effective stresses from water table lowering. Fortunately, such ground settlement cannot take place when limestones cover the ground as the rock is not compressible

development of sinkholes

depletion of adjacent groundwater and/or surface water supplies

salt water intrusion

expansion of contaminant plumes

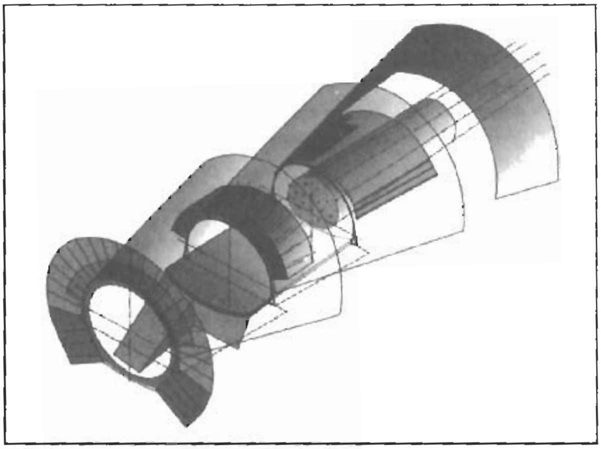


Figure 6: Driving a tunnel through an important water bearing zone with predrainage through embracing drainage umbrellas (sketch from "Geodata", Torino, personal communication).

- release of contaminated water into the environment

6. GEOTECHNICAL ISSUES WHEN TUNNELLING IN LIMESTONE ROCK MASS

The rock mass itself

With the exception of the problem associated with the karstic characteristics, limestone and all other carbonate rocks in general, exhibit a good geotechnical behavior and a friendly tunnelling response. They exhibit reasonably good resistance to drilling or boring with reduced wear of excavation tools. The strength of a limestone rockmass can never reach low levels such as those of a squeezing ground, even when brecciated. Limestone breccias always exhibit good frictional values; however, support is sometime necessary with light steel sets or lattice girders, beyond rock_bolts and shotcrete.

From another point of view, when the rock is at great depths or under high horizontal stresses, it cannot generate typical bursting instability, as is the case of hard rocks, since it is not a brittle material*. Any mild spalling problems in tunnels can be satisfactorily coped with rock bolting and reinforced shotcrete.

Figure 7: Typical appearance of a small karstic void partially filled with clay and silt; Dodoni tunnel, northwestern Greece, 2000.

The case of voids and karstic caverns

The meeting of caverns and big karstic conduits may be associated with the following problems,_often very difficult to overcome:

- bridging the void, if empty
- tunnelling through a geotechnically weak fill material
- confronting water inrush associated with mud flow if the void is water bearing and filled partially or totally with earth materials (as discussed earlier).

In the case of urban tunnels with a thin cover, the occurrence of these voids can effectively be investigated with a drilling program assisted by geophysical testing. In most shallow depths the georadar can give reliable information. In deeper levels cross-hole tomography could be the best choice. In tunnels close to the surface an associated risk is the collapse of an adjacent cavern after an earthquake; filling these voids prior to the comple-

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* In terms of mechanical properties typical bursting situation can usually be met in hard, strong and brittle rock, e.g. having an unconfined compressive strength higher than 100 MPa and a modulus of deformation greater than 4 GPa.

tion of the tunnel is an additional task to be undertaken. In the case of deep tunnel through a mountain and given there are clear indications that such cavities are present, the only reliable method is probing ahead, as was previously mentioned.

The Dodoni tunnel in northern Greece, with a length of 3.3 km and 12 m in diameter, is currently (fall – winter 2000) being driven in a limestone sequence with well developed bedding and possible local intercalations of siltstones or cherts a few cm or dm of thickness. The limestone encountered so far has behaved well and this behavior is expected to continue. However, significant overbreaks have occurred at some locations and these overbreaks were due to instability of the fill in karstic cavities (Fig. 7). Karstic solution features may indeed be observed in outcrops on the surface of the mountain ridge crossed by the tunnel under a cover of at least 100 m. These features indicate that karstic processes were active inside the limestone ridge.

Two major collapses occurred related to the presence of sinkholes at the surface with outcropping chimneys almost 100 m of height. The voids were filled with clayey material and pieces of broken rock and were prominently wet. The main collapse had a diameter of approximately 1.5 m in the tunnel and 3 m on the surface (Fig. 8), leading to 1200 m^3 of material falling into the tunnel.

In order to detect karstic cavities, pockets filled with soft and broken material, shear zones and gouge-filled faults, it was recommended that routine probe drilling ahead of the tunnel face should be carried out (Hoek and Marinos, 2000, experts' unpublished report to "Egnatia Highway S.A."). Typically, such probe holes are percussion drilled using the normal jumbo. Ideally, the probe hole should always be kept one tunnel diameter ahead of the advancing face and the most convenient way to achieve this is by drilling long holes (30 to 50 m) during maintenance shifts or at weekends. As in all karstic voids, because of the irregular and unpredictable shape and location of weak zones, it is recommended that at least three probe holes should be drilled from the face at 10, 12 and 2 o'clock positions. These holes are believed to have the highest probability of detecting the most dangerous zones. During drilling, a supervising geologist or engineer should be present and, together with the driller, should watch for rapid changes in drill penetration rates, nature of the chippings and color of the return drilling water. An experienced driller will usually be able to detect changes in the drill performance and to give a reliable prediction of the nature of the ground ahead of the face.

Figure 8: Collapse of the filling of a karstic chimney crossed by Dodoni Tunnel. The collapse outcropped on the surface about 100 m. over the tunnel.

When a significant weak zone is detected additional probe holes should be drilled to define the extent and shape of the zone as accurately as possible. In exceptional cases, one or two cored holes may be required to determine the nature of the filling material.

As a general rule grouting of the filling material within the cavity is a primary consideration in order to improve its cohesive strength. However, it has to be realized that the effects of such grouting are highly unpredictable, depending on the nature of the filling materials.

The support measures to be used depend upon the nature and the extent of the weak zone. When a weak zone (e.g. a karstic cavity or a filled pocket of limited extent) is to be dealt with, the use of forepoles to bridge the cavity should be considered. These forepoles play an entirely different role from those used to pre-support the face in squeezing ground. Their function is to form a roof over the tunnel through which the weak filling material of the cavity cannot pass. Hence, depending on the volume of material to be supported, the forepoles should be reasonably light (say 75 mm diameter tubes) and they should be as closely spaced as possible. They should also be long enough to ensure that they are securely socketted in good limestone on either side of the cavity. The number of forepoles to be installed should be limited to the number required to form an effective barrier under the cavity. It is not necessary to implement a complete support system, with an extensive forepole umbrella and additional support measures, such as that used in squeezing ground.

When the probe drilling detects a continuous feature of significant size, the approach has to be quite different from that described above. In such a case, the rock mass on either side of the cavity will be most probably weaker than the surrounding limestone and the zone may be 10 m thick or more, depending on the orientation of the void. In such a case, it is prudent to implement the full forepoling solution, similar to that used in squeez-

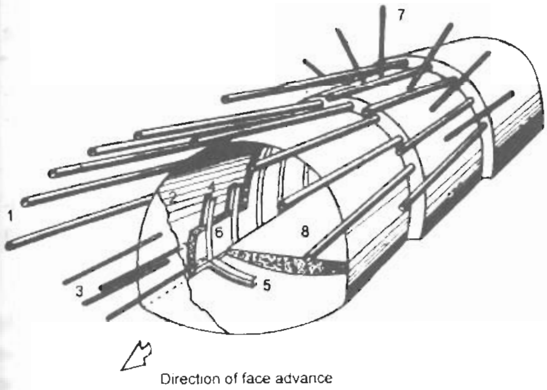

Figure 9: Full-face excavation through weak ground under the protection of a forepole umbrella. The final concrete lining is not included in this figure (Hoek, 2000). The method can be applied in cases of large karstic caverns or large chimneys filled with cohesive soil under substantial load. Note that it is not always necessary to implement all the components shown in this figure.

1. Forepoles typically 75 or 114 mm diameter pipes, 12 m long installed every 8 m to create a 4 m overlap between successive forepole umbrellas.
2. Shotcrete - applied immediately behind the face and to the face, in cases where face stability is a problem. Typically, this initial coat is 25 to 50 mm thick.
3. Grouted fiberglass dowels – Installed to reinforce the rock immediately ahead of the face. These dowels are usually 6 to 12 m long and are spaced on a 1 m x 1 m grid.
4. Steel sets - Installed as close to the face as possible and designed to support the forepole umbrella and the stresses acting on the tunnel.
5. Invert struts Installed to control floor heave and to provide a footing for the steel sets.
6. Shotcrete - Typically steel fiber reinforced shotcrete applied as soon as possible to embed the steel sets to improve their lateral stability and also to create a structural lining.
7. Rockbolts as required. In very poor quality ground it may be necessary to use self-drilling rockbolts in which a disposable bit is used and is grouted into place with the bolt.
8. Invert lining Either shotcrete or concrete can be used, depending upon the end use of the tunnel

ing ground (Fig. 9).

One further possibility needs to be considered and that is the case of a large empty karstic void. Such a void will generally require bridging and backfilling. The nature of the backfill will depend on the location of the void relative to perimeter of the tunnel. If water is associated with the void, drainage holes have to be foreseen as described earlier (see also Fig. 6)

Encountering a vertical karst channel, which is the most common case in the transfer zone of the aquifer (model C in Table 1), unpredictable concentrated water pressure may load the tunnel lining. In order to prevent possible damage, forced drainage of the channel towards lower elevations has to be secured.

When tunnel boring machines (TBM) are to be used, local realignment of the tunnel axis in order to avoid voids is not an option and usually a stoppage is imposed in order to backfill or bridge the void. 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 (Milanovic, 1996 and Marinos 2001). When naturally filled, the voids have to be crossed by conventional tunnelling since the TBM, being usually of an open type, cannot bore the fill that could ravel through the cutter head of the machine.

7.CONCLUSIONS

Tunnelling in karst terrain requires 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 the completion of the operation. Judgment and engineered solutions should always assist any decision at all stages during design and construction.

ACKNOWLEDGMENTS

Particular acknowledgments are due to Harry Saroglou for his assistance in editing this paper.

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