Karst-related engineering geological hazards, a comparative study of Hungary and Greece.

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Abstract: The karstic rock covers 4.4 % of Hungary but there are large cities such as Budapest, where carbonate rocks are widespread on the surface and in the subsurface. Karst areas are more widespread in Greece having a surface cover of nearly one third of the country, and karstic rocks are commonly found in cities and towns, such as Athens. The comparative study of karstic territories in Hungary and Greece enabled us to summarise the engineering geological and environmental geological risks of karst areas for covered and uncovered karst environments.

In Greece the major engineering geological risks are related to subsurface karst system in the form of karst water intrusion into foundation sites and tunnels. In Hungary the mining related intense karst water table draw down caused severe problems in the Transdanubian Central Range resulting in a shortage in urban karst water supply and drying of springs. The collapse of cold water related karstic cavities endanger tunnelling works in Greece while cave passage collapse cause engineering hazards in urban areas of Budapest. Further environmental risks are related to groundwater pollution of thermal karst system of Budapest and the contamination of famous spas.

Résumé: Les couvertures karstiques de roche 4.4 % de la Hongrie mais là sont de grandes villes telles que Budapest, où les roches de carbonate sont répandues sur la surface et dans la sous-surface. Les régions de Karst sont plus répandues en Grèce ayant une couverture extérieure presque d'un tiers du pays, et des roches karstiques sont généralement trouvées dans les villes et les villes, telles qu'Athènes. L'étude comparative des territoires karstiques en Hongrie et en Grèce nous a permise de récapituler les risques géologiques géologiques et environnementaux de technologie des secteurs de karst pour les environnements couverts et découverts de karst.

En Grèce les risques géologiques de technologie principale sont liés au système à fleur de terre de karst sous forme d'intrusion de l'eau de karst dans des emplacements et des tunnels de base. En Hongrie l'exploitation a relié des problèmes graves vers le bas posés intenses d'aspiration de table de l'eau de karst dans la chaîne centrale de Transdanubian ayant pour résultat un manque dans l'approvisionnement en eau de karst et le séchage urbains des ressorts. L'effondrement des cavités karstiques reliées d'eau froide mettent en danger des travaux de perçage d'un tunnel en Grèce tandis que cause d'effondrement de passage de caverne machinant des risques dans des régions urbaines de Budapest. Encore d'autres risques environnementaux sont liés à la pollution d'eaux souterraines du système thermique de karst de Budapest et de la contamination des stations thermales célèbres.

Keywords: limestone, geological hazards, hydrogeology, fractures, caverns, tunnels.

INTRODUCTION

The karst system is a very delicate geological formation often associated with engineering geological (Waltham & Fookes 2003) and environmental geological hazards. It is estimated that karst landscapes occupy up to 10% of the Earth's land surface and thus more than 25 percent of the world's population either lives on or obtains its water from karstic aquifers (Ford & Williams 1989). The karst has an important role in the environment, economy and engineering practice of Greece and Hungary, since about 30% of Greece and 4.4 % of Hungary belongs to karstic area.

Engineering geological hazards associated to karst systems are discussed in this paper by using examples from Greece and Hungary. The case studies shown here are focusing on tunnelling in karst, karst water supply and mining induced karst water drawdown, instability of cave passage systems and bedrock collapse. The scale of engineering works is different in the two countries since large linear structures such as tunnels and highways are constructed in Greece while smaller scale urban developments are found in karstic terrains, in Hungary. Thus, a comparison of site surveying methods and engineering geological approaches of handling karst-related hazards are discussed here partly focusing on scale problems.

KARSTIC ROCKS IN GREECE AND IN HUNGARY

Greece

In Greece, karstic features, phenomena and engaged problems are associated with carbonate rocks, mainly limestones and marbles and in some cases, dolomites and dolomitic limestones. In Greece engineers face karst geohazards during large-scale design and construction works, such as roads, railway lines, reservoirs and dams.

Limestone

Limestone, which represents the vast majority of carbonate rocks, covers about the 30% of the Greek territory. These rocks being products of the Alpine orogenic process are mainly of Mesozoic age and are situated under the upper Cretaceous flysch formations in Eastern Greece or Miocene flysch in Western Greece. There also exist limestones of Neocene age, which occur within the post-alpine rock series. The soft and porous Neogene limestones are commonly used as ashlars and building blocks at some islands such as Rhodes.

In some thick limestone bed sequences in mountainous coastal regions of Central Greece and Peloponnesus, karstification has affected only the top few hundred meters forming a zone running parallel to the slopes of the mountain in a stage pattern, while the core of the mountain is left intact. Large karstic conduits occur in limestone and marble areas where caves are present (Marinos et al. 1987)

Marble

Marbles of large aerial exposure are found within the metamorphic zones in Attica, Cyclades and parts of Macedonia and Trace regions, where they generally exhibit lesser area and volume than the other metamorphic rock-members of the above zones, being gneisses and schists. Both calcitic and dolomitic marbles are known.

Hungary

69% of Hungarian territory is covered by soft sediments. Nearly the half of the remaining areas (15% out of the 31%) is low lying with an elevation of less than 200m. The mountains with elevation of more than 400 m represent only 2% of the country area. Karstic rocks limestones and dolomites are more typical for elevated hilly regions. Palaeozoic, Mesozoic and Cenozoic carbonates are found in very limited areas with a lateral extent of 4.4% (Fodor & Kleb 1986).

Carbonates are the major mountain forming rocks besides volcanites in Hungary. Their lateral distribution is well documented since many of the Hungarian mid-mountains are formed from dolomites or limestones. Although the spatial extent of karst terrain is mostly limited to sparse mountainous areas the importance of karst in Hungary is related to the fact that many of our largest cities are found in karstic region. Consequently, the engineering geological hazards of karsts are mostly hampering the urban planning and development in Hungary.

Karstic formations are classified according to their origin and engineering geological properties in Hungary. From an engineering geological point of view six major karstic rock types can be distinguished.

Marble

The occurrence of metamorphosed carbonates within the present territory of Hungary is very limited. Marbles are sparse, but strongly recrystallized limestones which have physical properties similar to marbles occur and are quarried. These rocks are Palaeozoic carbonates (e.g. Rakaca “marble”, Polgárdi Limestone).

Compact, dense limestone

Recrystallized but fine crystalline limestones of Plaaeozoic, Mesozoic and Eocene age belongs to this group of rocks. These limestones have a relatively high compressive strength and low water absorption capacity (less than 1% with a maximum of 2 to 2.5%). This type of limestone is the primary mountain forming carbonate of Hungary.

Porous, soft limestone

Soft, but slightly cemented porous limestones of Tertiary age (prevailingly Miocene) and oolithic limestones represent this group of carbonates. Their surface occurrence is limited although in and near Budapest (Kőbánya, Budafok) they can cover larger areas of few tens or rarely hundred of square kilometres.

Freshwater limestone (travertine)

Highly porous but strongly cemented travertines were formed form Quaternary springs in a various subenvironments such as lakes or cascades or stream deposits. The rigid varieties of these carbonates are used as polished slabs and are popular building stones of Budapest (Budakalász, Süttő).

Dolomites

Mesozoic dolomites are important in Hungary partly as mountain forming carbonates besides compact limestones and as karst water reservoirs. Most of the dolomites are of Triassic age and are extensively used as raw material in the construction industry (aggregates, paints etc.).

Marl and calcareous marl

No large karstic forms and terrain are associated to marl covered areas in Hungary since marls are less soluble than limestones and their lateral extent is very limited. Nevertheless parts of the most spectacular thermal caves of Budapest are found in Eocene marl.

KARST WATER TABLE, TUNNELING AND MINING

Giona tunnel, Greece

The Giona tunnel forms a part of Mornos-Athens water-supplying aqueduct system. It crosses an extended karstic mountain at great depth in central Greece. The tunnel has a length of 14.6 km; it is parallel to the coast, at an altitude of 377 m, beneath a cover of 1700 m, and with the central section 14-20 km from the coast of the Corinthian Gulf, where the groundwater of the mountain is discharged through coastal springs.

At the beginning of the tunnelling project, the intense karstification of the surface of the mountain and the drainage towards the low points of the coastline led the designers to a first hasty hypothesis that the tunnel would pass through karstic limestone, but more or less above the karstic water table due to the gentle hydraulic gradient expected for such a karstic environment. The tunnel was thus expected to be within the transfer (or conveyance) zone of subsurface waters with high risk for sudden inflows during floods but with no permanent underground water. This water table would be considerably lower in areas of high permeability and of unobstructed discharge to the coast.

A few investigative boreholes, although not deep enough, provided some indications that the limestone was not karstified at depth, but merely finely fissured. In such a case, the water table could lie considerably above the level of the tunnel and obviously with low-yield inflows in the tunnel.

Finally the karstic and hydrogeological conditions of the interior of the mountain appear more composite, since the interior of the carbonate mountain does not appear karstified; and karstification seems to penetrate at a depth of a few hundred meters and creates a karstic zone, which proceeds in stages parallel to the surface of the mountain (Marinos 2001). The paleogeographic development of the area, with gradual surface erosion and levelling due to successive faulting and changes of sea level, contributes to the formation of such an underground karstic geometry. Beneath the karstic zone, the limestone is not karstified but appears finely and tightly jointed, hence leading to low permeability.

The water table exhibits low gradients only at the karstic zone (in the lateral envelop of the mountain and behind the springs) but the gradients become steeper towards the low permeability interior of the mountain. The classical concept of the karst base level does not apply except for the areas below these peripheral parts of the mountain and evidently the mountain remains not karstified in its central part.

The water table in the outer karstified parts of the mountain is below the position of the tunnel and rises above it in the non-karstified central areas. In these areas, the limestone is of low to very low permeability and the flow can be thought of as that in a poor porous medium. Drainage in the tunnel is barely perceptible mainly in the form of “transpiration”, wet sidewalls or drip flows.

However, a few deviations from the general regime of the mountain’s interior were found in the form of very limited zones of high permeability. Throughout its length, for more than 11 km in the interior of the mountain, the tunnel crossed just two karstic conduits, which were developed most probably in fault zones (Figure 1). These conduits constitute no more than an exception and do not change the general non-karstic characteristics of the interior of the mountain. These barely wide conduits were crossed at 9.8 and 6.5 km from the western entrance of the tunnel. The voids were bridged by fill and concrete slabs to allow boring by the Tunnel Boring Machine. When the first conduit was crossed, water was released under pressure but then the discharge quickly declined to small amounts. The second conduit was partially filled with clay, sand and gravel without water, but with clear indications of underground flow. Following a heavy storm, a flood reached the tunnel with a delay of only 8 hours. The water drained away from the tunnel within about a week. The active hydrogeological role of these conduits as a zone of transfer of infiltrated waters to an underlying inundated section was verified when they could not drain the water discharged into them by the tunnel; given that it was the season of high rainfall, the water table was elevated close to the level of the tunnel in that area.

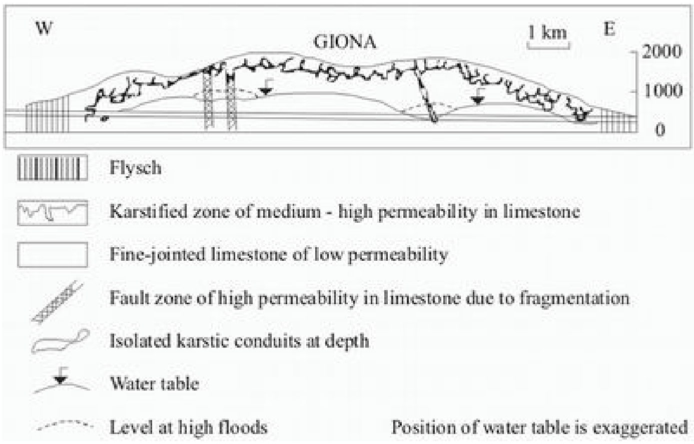

Figure 1. The underground hydraulic regime at the Giona mountain tunnel showing major fault zones.

These karstic tubes comprise axes of preferential isolated drainage according to a model with a restricted extension inside the mountain. An additional result of their presence is a local significant lowering of the high, but low-yield water table prevailing inside the massif.

Given the information gathered during the tunnel construction, the hydrogeological description of the interior of the mountain is only complete if one takes also into account the presence and role of faults with or without a mylonitic zone. These fault zones do not bear karstic features or voids along their discontinuities, but few of them caused water problems, especially in the sections between 9.3 and 10 km from the East side. In total, more than 400 l/sec of water entered the tunnel, 150 l/sec of which were contributed by a single fault through its fairly narrow mylonitic zone.

The water-bearing faults increase the underground hydraulic heterogeneity of the interior of the mountain. These faults are fed by the karstic and highly permeable portions of the surface of the mountain. Hence, according to the geometry of the faults and their discharge capacity, the resulting water column can maintain a significantly raised water table despite the high permeability of these zones. This column recharges the surrounding finely-jointed limestone during wet periods and drains it during the dry periods.

Leakage from this hydraulic tunnel (piezometric head of 80 m) was impossible for most part of the mountain and the water table applies a high hydrostatic load that the lining was designed to withstand. On the contrary, leakage from the tunnel was possible at the endmost parts the tunnel, where the karstic zone was crossed. In these parts, a tighter grouting program had to be applied, as the karstic water level lied lower than the tunnel.

Karst water drawdown due to mining, Hungary

The karstic water has a very high practical importance in Hungary since the cold and hot springs as well as thermal and balneological waters are mostly of karstic origin. The largest near surface karst water system belongs to the karst of Transdanubian Central Range in Central Western Hungary. Mineral resources such as bauxite (Figure 2) or brown coal are also found in that region. The mining activity of raw materials caused an intervention into the karst system and adhered severe problems in karst water balance.

Karst water is found in the Triassic carbonate sequence mostly in Main Dolomite and Dachstein Limestone. These two formations extend in an approximately 150 km-long and 50 km-wide zone from the west ending in the East at Buda Mountains in Budapest. The vertical extent of this unique, but very sensitive karst formation, is in the order of 2 km.

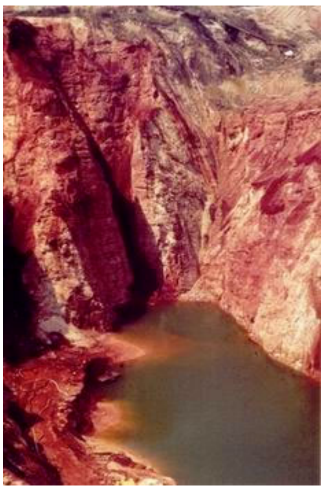

Figure 2. Open bauxite mine partly filled with karst water, Iharkút, Hungary.

The karst hydrogeological research has begun in the fifties with the exploration of karst springs. In that period the karst water system was intact and karst water pumping did not modify significantly the dynamic water balance.

In the period of the 1960's major mining centres were developed and water draw down extended for the entire area of the Transdanubian Central Range. Increased pumping of karst water and uncontrolled karst water exploitation was typical. From the early 70's a new period began when karst water of the "active protection of mines" (i.e. lowering of karst water table) was used in water supply. The pumped karst water was diverted mostly into closed pipe systems and not to surface streams. The monitoring of karst water table started between 1967 and 1970 by establishing an observation well network. From that period onward karst water maps with well data were annually published.

Due to the improper design of "active water protection" of mines the karst water pumping affected a much larger area than it had been required and as a consequence caused a significant damage in the natural karst system and in karstic springs. When mining activity was in progress a maximum of 100 m karst water table draw down was recorded at some areas (Figure 3). The most severely affected ones were in the regions of Nyírád, Ajka, Kincsesbánya and Tatabánya.

The mining-related karst table drawdown lead to the closure of the coal mines in the second half of the 80's. It was followed by the termination of bauxite mining in Nyírád area in 1990. By closing the mines the karst water table drop stopped and the recuperation of the karst system began. The termination of mining activity had other less positive effects as well. The mining-related karst water pumping significantly contributed to the water supply of the region and thus it was necessary to redesign parts of the water supply. The flooding of abandoned mining galleries and shafts produce a risk of environmental pollution. In other areas the rising karst water could endanger areas that were constructed when the water table was lowered by pumping.

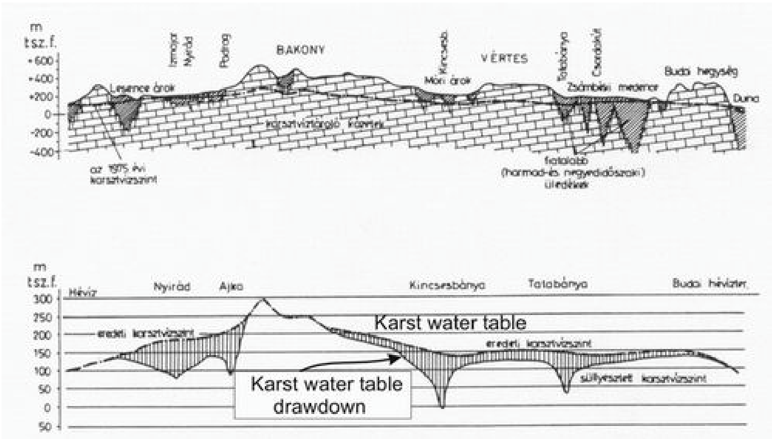

Figure 3. Drop in karstic water table in the Transdanubian Central Range due to mining activities (top: geological profile, bottom: karst water level, after Fodor and Kleb 1986)

OVERBREAKS AND COLLAPSE IN KARSTIC ROCKS

Dodoni tunnel, Greece

The Dodoni tunnel is located in north-western Greece. With a length of 3.3 km and 12 m in diameter, it was driven in a limestone sequence with well developed bedding and possible local intercalations of siltstones or cherts a few cm or dm in 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 (Figure 4). 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.

Figure 4. Typical appearance of a small karstic void partially filled with clay and silt; Dodoni tunnel, northwestern Greece, 2000.

Two major collapses occurred and caused 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 (Marinos 2001). The main collapse had a diameter of approximately 1.5 m in the tunnel and 3 m on the surface (Figure 5), 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. 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). 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.

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.

Figure 5. Collapse of the filling of a karstic chimney crossed by Dodoni Tunnel. The collapse outcropped on the surface at about 100 m. over the tunnel

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 encountered, 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 infill material of the cavity cannot pass. Hence, depending on the volume of material to be supported, the forepoles should be reasonably light 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 construction approach has to be quite different from that described above. In this 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 cases it is prudent to implement the full forepoling solution, similar to that used in squeezing ground.

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.

Encountering a vertical karst channel, which is the most common case in the transfer zone of the aquifer, 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.

Cave collapse in Budapest, Hungary

There are several caves in Hungary which have speleothemes and minerals that can not be explained by formation from descending cold karst waters or cold karstic water flow (Takács Bolner & Kraus 1989). The formation of these caves is related to thermal waters. Many and mostly the largest thermal karstic caves are found in Buda Mountains in Triassic and mostly in Eocene limestones or marls below valuable urban areas of Budapest.

A detailed survey of these thermal caves was performed in Józsefhegy region (Rózsadomb) (Kleb et al. 1993). Józsefhegy "crystal cave" was found by accident in 1984 during the construction works of a housing estate. An excavator fell to a cave passage due to the roof collapse of an unknown cave. This cave is 4800 m-long and its upper levels are in Upper Eocene marl and limestone while its lower levels are in Triassic cherty limestone. The largest hall, "Kinizsi railway station", with its 70 m length, 15 m width and 20 m height is one of the largest thermal karst halls in the Word. The cave is richly decorated by mineral precipitates. Large gypsum crystals, aragonite needles and popcorns and barite crystals cover the walls. It is located in Rózsadomb area, which is the most valuable real estate area of Budapest. The existing and unexplored caves bear a potential risk of collapse and thus endanger properties and buildings (Figure 6).

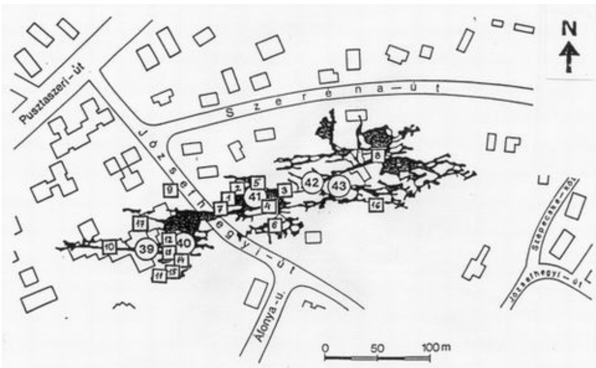

Figure 6. Cave passages (in black) and street map showing the location of buildings near Józsefhegy thermal karstic cave, Budapest

The upper cave passages are in thin bedded and fractured Eocene marl often with very thin cover (Figure 7). The roof collapse was related to a dissolution cavity of thermal water origin (Figure 8). Consequently, outbreak of cave passages or unknown thermal karstic cavities brings an unpredictable risk, since thermal karstic activity does not have a surface sign and no sinkholes or dolines are present.

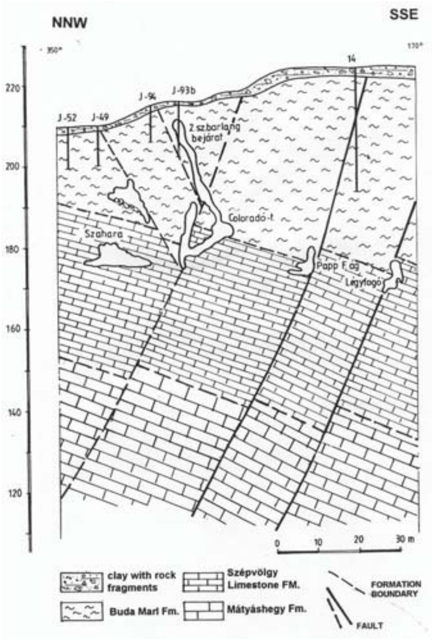

Figure 7. Cross section of Józsefhegy thermal karstic cave with cave passages extending into the marl near to the surface

Figure 8. The collapse of a cave passage was the first indication of the existence of Józsefhegy thermal cave.

CONCLUSIONS

The karstic rock cover in Hungary is only 4.4 % while in Greece it is about 30%. Despite these differences in surface cover similar karst related engineering geological hazards occur in both countries. The scale of engineering works differs in the two countries. In Greece large-scale works and construction sites (dams, highways and tunnels) while in Hungary settlements related small-scale foundation sites or subsurface mining activities are reported.

The deep-seated tunnels in carbonates might induce a risk of karst water inundation and it has been proved for selected Greek cases that karstification seems to penetrate at a depth of a few hundred meters and creates a karstic zone, which proceeds in stages parallel to the surface of the mountain. It has been documented that not necessarily the karstic formation but the fault zones within the karst are causing potential hazards. The water-bearing faults increase the underground hydraulic heterogeneity of the interior of the mountain, since these are fed by the karstic and highly permeable portions of the surface of the mountain. Therefore, according to the geometry of the faults and their discharge capacity, the resulting water column can maintain a significantly raised water table despite the high permeability of these zones and thus when it is cut can cause inundation.

The mining activity of Hungary and related karst water pumping caused other hazards. Namely the drawdown of karstic water leads to a dramatic drop in water table and initiated water supply problems and the cessation of spring activity of thermal spas. Hence, it generated engineering geological and environmental problems.

In Greece the tunnelling in karst formations brings another major engineering geological hazard. The overbreak of tunnels is mostly caused by undetected sinkholes and karstic chimneys. To avoid major collapses a method of karstic voids detection is suggested. Due to the irregular and unpredictable shape and location of weak zones, it is recommended that at least three probe holes should be drilled from the tunnel face at 10, 12 and 2 o'clock positions.

The thermal karstic caves present an engineering geological hazard in the development of urban areas in Budapest. The collapse of cave passages mostly occurs when foundation works are in progress. The prediction of such passages is even more difficult than that of the cold karst caves since these chimneys are forming by the dissolution of upward migrating hot fluids rather than the dissolution of infiltrating waters.

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