Hydraulic Properties of Karst Groundwater and Its Impacts on Large Structures

Petar Milanović

Abstract A karst environment is a particularly sensitive and risky geological formation for the infrastructure construction from the micro to the mega scale. The hydraulic properties and specific regime of groundwater in karst are, in many cases, the source of catastrophic failures. The most common destructive influence of groundwater is the consequence of: massive turbulent flows; the fast erosion of unconsolidated deposits in caverns and joints; the great kinetic energy of underground flows; propagation of hydraulic pressure at large distances (piston effect); and the enormous hydraulic pressures created in periods of full aquifer saturation, including water-hammer and air-hammer effects due to rapid fluctuation of the water levels. Despite extensive investigations, the destructive impacts are mostly unpredictable in space and time. In many cases these destructive processes take time to become established but final effects appear abruptly, causing considerable damages or failures. The most common consequences of these impacts are subsidence at the urban areas, along the roads and railways, as well as at the bottom of reservoirs; water seepage from reservoirs; break-in of groundwater under high pressure during underground excavation; destruction of surface remediation structures; destruction of tunnel lining; degradation of grout curtains, induced seismicity; decreasing of downstream spring discharges; endangerment of underground species; and the creation of many other unpredictable and unexpected problems. Some dam failures (empty reservoirs) or collapses (entire buildings and factories sinks) were catastrophic. Successful remediation solutions require serious and comprehensive investigations including long period monitoring of groundwater regimes and (in many cases) remedial works during the lifetime of the structure. During construction modifications and adaptations of structures are very common in karst. Persistent, time-consuming and expensive remedial works during the lifetime of the structure are no exception, but, rather, they are the rule.

P. Milanović (✉)
Belgarde, Serbia
e-mail: petar.mi@EUnet.rs

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1 Introduction

Karstification is a specific exogenetic process in which the hydrogeological properties of soluble rock masses are changed by solution in vertical and horizontal extension. The principal conditions for karstification are soluble rocks, a large quantity of water and the presence of discontinuities mostly of endogenetic origin. Karstification starts with the chemical action of water (solution) and after flows becomes an important process of turbulent erosion. Both processes (solution and erosion) occurred simultaneously. Mostly the intensity of karstification is not continuous on a geological time scale. Karstification is connected to an emergence phase. Each phase of emergence was in some time followed by the process of karstification of upraised carbonate rocks above the sea level.

As a result of the dynamic neotectonic movement and karst aquifer evolution process, the transformation processes from several karst aquifers into a single aquifer or decomposition of a single aquifer into a few independent aquifers are common. Consequences of these processes bifurcation zones are common in karst, also.

Intensity of karstification increases gradually from initial to the mature stage. In contrast with other natural exodynamic processes, which are mainly limited to the shallow surface zone, the karstification process penetrates into the deeper rock masses mostly along the deep discontinuities. In some cases upraised water (thermal or cold) plays an important role in karstification—hypogene karstification.

In a number of deep and high developed karst aquifers the role of some conduits has been changed during the karst aquifer evolution process. After the aquifer discharge point has been accommodating to the lower erosion base level, the upper channels lose the activity of base flows and stay permanently above the saturated zone. These channels become the cave systems with temporary flows, and, sometimes, are partially filled or completely plugged with cave deposits and sediments.

In Fig. 1 the simplified cross-sections are presented as piezometric lines at different stages of karst aquifer depletion. Concentrated karst flows mean that karst conduits very rarely are continuously inclined. Mostly its horizontal and vertical conduit direction changes frequently. As a consequence, the karst channels in the form of siphons are common and frequent. During dry periods these sections are permanently full of water. Thousands of underground lakes exist in a number of karst aquifers. The large concentration of cave-dwelling aquatic endemic species settled in underground karst lakes all over the world. The exit part of the majority of large karst springs (permanent or temporary) has a form of deep siphons.

As a consequence of the karst evolution process the hydrogeological hierarchy of karst conduits (hydrogeological singularities) is created as one of the

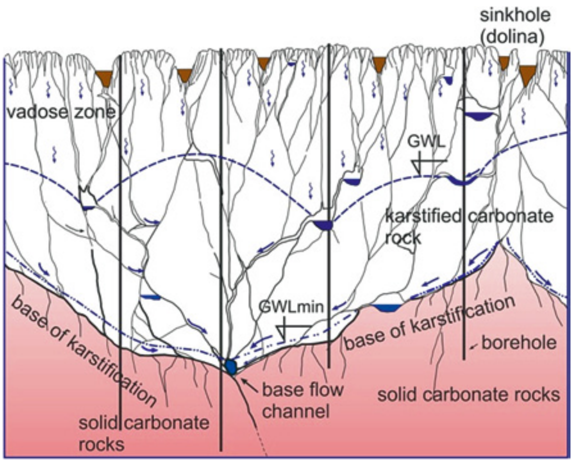


Fig. 1 Simplified cross-section of karst aquifer perpendicular to main flow direction

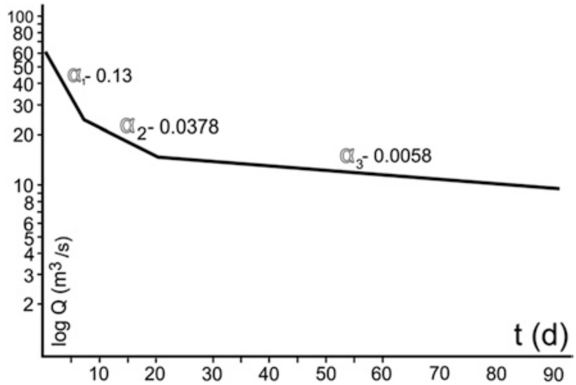


Fig. 2 Ombla Spring recession curve

main properties of a karst aquifer. The top ranking conduits in hydrogeological hierarchy (base flows) represent the base level for the entire karst aquifer. To simplify the explanation of karst aquifer hydrogeological hierarchy, the recession curve of karst springs discharge can be used. The recession curve is a complex function which represents the discharge regime of the aquifer, i.e., the hierarchy of the active karst conduits.

Different inclinations of recession curve correspond to the different discharge coefficients, i.e., to the different hierarchy levels of karst flows. In particular, the case presented in the Fig. 2 part of recession curve with $\alpha_1 - 0.13$ represents the flow in the largest channels, i.e., the top hierarchy channels and flows. The next two sections of recession curve (α_2 and α_3) represent joints enlarged by the dissolution process, and fractures and caverns filled with cave sediments, means secondary and tertiary flows in hierarchy.

1.1 Groundwater Regime of High Developed Karst

The main characteristics of groundwater regime in karst are: extreme fast aquifer saturation, concentrated and fast underground flows, rapid groundwater level fluctuation, kinetic energy of underground flows, piston effect and fast empting of the karst aquifer.

Saturation of karst aquifers is very fast, particularly in bare karst. Saturation occurred mostly through the extremely pervious epikarst zone, but also, in the form of concentrated infiltration through the swallow-holes (ponors), with a swallowing capacity of up to 120 m^3/s.

Mostly the epikarst zone exposed at the surface without any soil cover (bare karstified rock) is the groundwater free zone. The approximate thickness (depth) ranges between 10–20 m, only locally deeper. Most of the openings (karst channels), dolines (sinkholes), karrens and fissures drain the water immediately down to the saturated zone. In many cases 90 % of the water (in spite of the precipitation at 100 mm/10 h) immediately percolate through the epikarst zone and after a few hours reach the aquifer level at a depth of 1,000 or more meters. The negligible part of water can be retarded in the unconsolidated sediments deposited in the karrens, features or bottom of dolines (sinkholes). The thickness of epikarst cover can be from a few meters, up to hundreds of meters. Depending on the cover thickness the epikarst zone can be temporarily saturated, or can be permanently saturated. In some cases the groundwater level is permanently a few meters, or a few tens of meters above the epikarst zone.

Symbolic features in karst hydrogeology are ponors and estavelles, i.e., the features of concentration infiltration. Often ponors are located along the periphery of karst poljes and alongside river beds and river banks. Usually the recharge capacity varies in range of a few m^3/s; however, in a number of cases recharge is a few 10 m^3/s. The capacity of the Ponor Biograd in Nevesinje Polje (Herzegovina) is about 110 m^3/s, and recharge of the Slivlje Ponor in Nikšićko polje (Montenegro) is about 120 m^3/s. From a reservoir integrity point of view, estavelles are particularly dangerous because of double function and ponors cowered (masked) by unconsolidated or low consolidated sediments.

Very fast concentrated underground flows (between 0.5 and 14.0 cm/s, locally up to 50.0 cm/s) with a huge amount of flowing water (10 m^3/s up to the more than 200 m^3/s) have as a consequence large kinetic energy. In some cases the measured exit velocity at the end of the karst channel (spring outlet) was 16 m/s. If the spring outlet is plugged the measured pressure in the channel behind the outlet was between 10 and 11 bars. Another experiment by intensive pumping from syphonic karst spring, in a dry period, shows that the flowing groundwater mass in karst channels has considerable kinetic energy. Explanation of this phenomenon is documented in the graph of the pumping test in Fig. 3.

During the recovery period, due to kinetic energy of underground flow, the water level continued to rise to 130 cm above the starting position of the groundwater level.

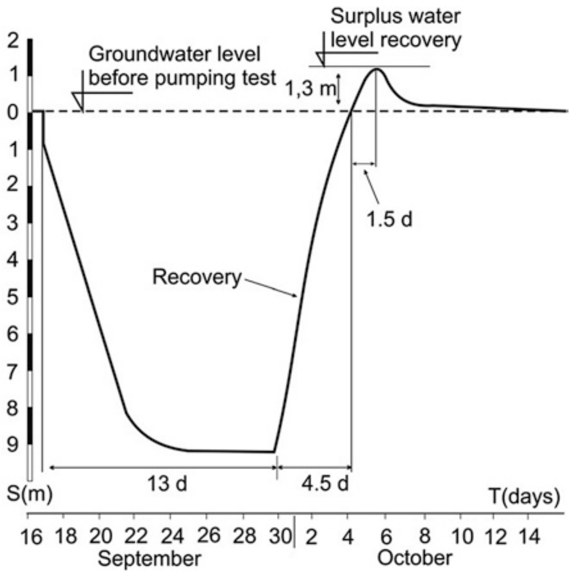


Fig. 3 Graph of pumping test. Jama Spring, Nevesinjsko Polje

As a consequence of fast and turbulent groundwater flows, a very intensive erosion and flushing of clayey deposits from cracks; and cavities frequently occur beneath the dam foundation or along the reservoir banks. It is confirmed that the grouting procedure is an extremely complex task if the water velocity is 10 cm/s or more.

In case of an earthquake, the seismic waves multiply the magnitude of erosion and clay flushing from caves and joints at the dam site. In 1979, after the earthquake in Montenegro (IX^{o} MCS), some consequences were registered at the Gorica dam site (Herzegovina). The distance from the epicenter is about 100 km. In the tailing water, downstream from the dam, the content of eroded clay increased tremendously. Together with thick clay-flow and intensive bubbling the compact clay pieces (0.2–1 kg) were taken out.

Saturated karst aquifers have properties of the hydraulic system under pressure. The piston effect was confirmed by large-scale experiments and analysis of the relationship between the spring discharge and water level in boreholes 4–6 km behind the spring. Between 22 and 78 m^3/s of water was injected into the ponor zone at a distance of 16.5 km away from the spring (Ombla). At the same time, in the ponor zone was injected dye tracer (Fig. 4).

Due to the piston effect the response of the system was much faster than the velocity of underground flow. The spring discharge increased 35 h after water injection. The labeled wave travel time from the same injection point to the spring was nearly four times longer. A very strong correlation between the discharge of the spring and water level in piezometers (r = 0.976) confirms also a very strong hydraulic connection along the saturated karst system.

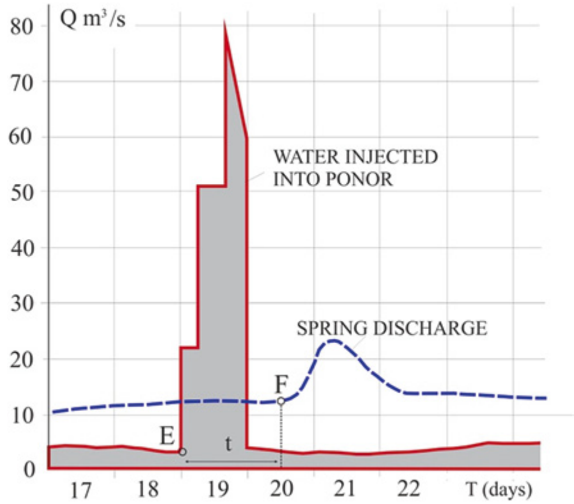


Fig. 4 Comparative graph of water injected into the ponor and the discharge graph in the spring

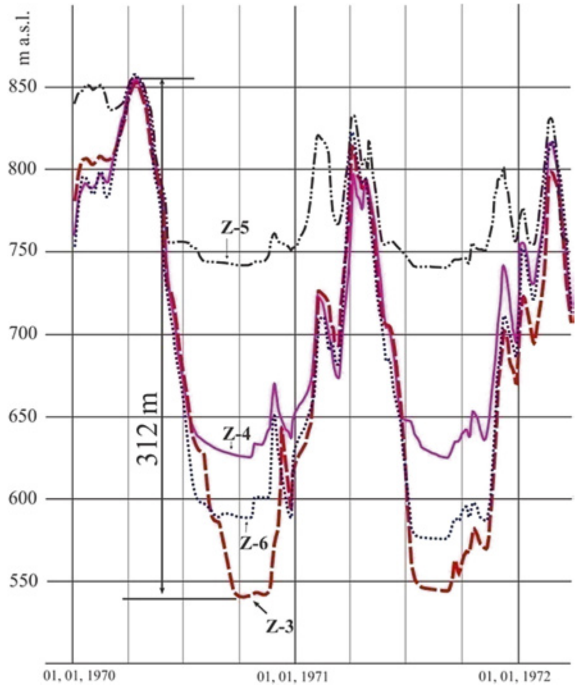


Fig. 5 Groundwater level fluctuations (Nevesinjsko Polje, Herzegovina)

In highly developed karst the groundwater fluctuation is rapid (up to 80 m/24 h) and with huge amplitudes (up to 312 m difference between minimum and maximum) (Fig. 5).

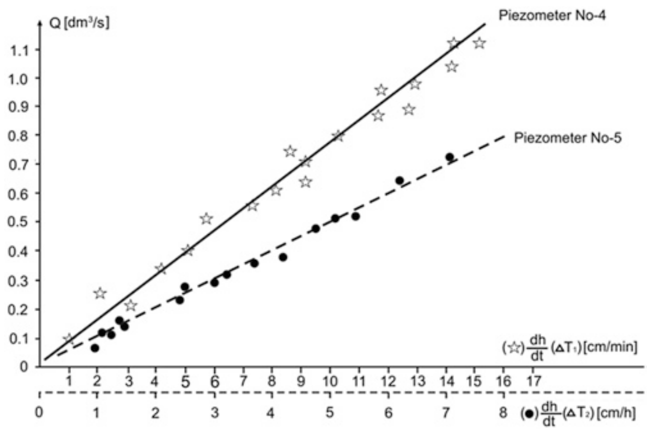


Fig. 6 Relation of air amount (Q) and velocity of water rising in piezometer (Kesić and Kovačina 1978)

The karst aquifer water level graphs are among the most diagnostic sources of hydrogeological information. As a consequence of hydrogeological properties created by karst evolution process and karst aquifer groundwater regime, it is obvious that simple stand pipe piezometers are the best monitoring devices in karst. Double stand pipe piezometers have to be used also if hydrogeological properties require its application only. Systematic use of multi-level piezometers in karst is not justifiable. It is in collision with hydrogeological properties of the nature of the karst aquifer and can be the source of improper design, and, in some cases, may lead to erroneous conclusions.

As a consequence of extremely fast aquifer saturation, the water table rises quickly and removes the air from cavities in the aeration zone. Measurements of air stream velocity from the piezometric pipes confirm good correlation between velocity of water level rising and the amount of air squeezed out. Depending on the volume of the local karst porosity relation between water level rising and the amount of squized air, it is different in separate boreholes; even these boreholes are closely spaced (Fig. 6).

The air stream from some of the piezometric pipes sometimes reaches a velocity of 15 m/s. If karstified rocks are covered with low consolidated sandy-clayey sediments, the fast water table fluctuation provokes strong bottom–up erosion and collapse at the surface of the terrain or at the reservoir bottoms.

One of the most visible aspects in the evolution of karst processes is the existence of well-defined karst horizons. As a consequence, the steady level hydrographs of piezometric boreholes located in such zones are some of the well known characteristics of karst aquifer (Fig. 7).

Discharge of karst springs changes rapidly with enormous difference between minimum and maximum. In some cases, the difference is between 2 and 380 m^3/s (Fig. 8). Discharge of temporary karst springs can vary between 0 and 200 m^3/s.

A karst spring with a pulsation of discharge (intermittent springs) is one of the hydraulic specificities of karst flows.

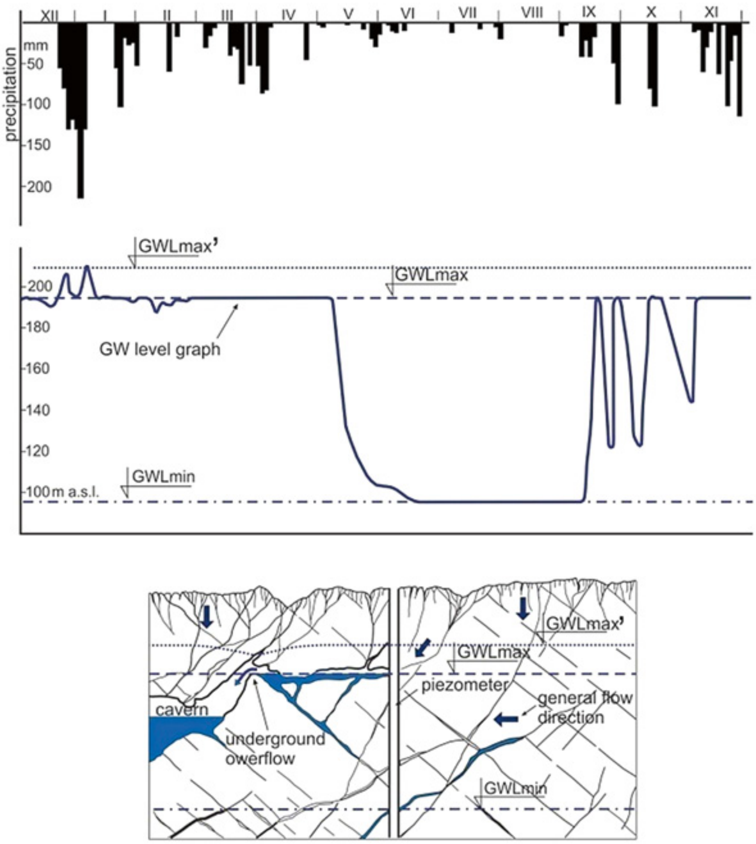
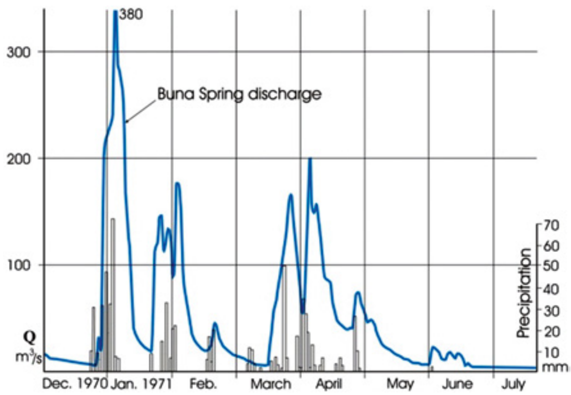


Fig. 7 Steady water level graph indicates presence of karst channel with great flowing capacity

Fig. 8 Buna spring discharge graph (Herzegovina)



2 Permeability of Karstified Rock Masses

Permeability of rock masses is commonly expressed by hydraulic conductivity, Lugeon units or specific permeability. A water pressure test (Lugeon test) still appears to be one of the most commonly applied methods in the framework of hydrogeological investigations. The number of results and long time experience of many specialists raise doubt about the reliability of the Lugeon criteria, particularly for karstified rock masses. Other methods are pumping tests, air pressure tests and tracer tests methods that utilize dye or radioactive tracers.

Analyzing the relationship of the consumption of grouting mixture and the basic permeability (results of WPT), no correlation was established. By comparing the results of WPT (Lugeon test) and grout consumption that were obtained from many examples in karst, it can be concluded that, according to the average permeability, a sound estimation of a possible consumption of grouting mass in the grout curtain cannot be made.

One of the very important reasons for the absence of correlation between Lugeon values and grout consumption is the difference of fluids characteristics. The Newtonian fluid, such as water, used in the case of a Lugeon test, can be characterized by only one parameter—viscosity. The grout mass behaves as a Bingham fluid possessing both viscosity and cohesion.

In spite of its limited practical value, the conclusion of the General report Q58 of the International Commission for Large Dams (Božović 1985) indicates that the Lugeon test remains the main engineering tool in assessing permeability of the dam foundations and in evaluating the achieved efficiency of the grouting treatment.

Lu physically means approximately one joint (aperture 0.2 mm) at each 10 cm of the borehole wall. Results of the WPT test contain also information related to erodability, groutabilty and drainability of rock mass.

If the water pressure test encounters a cavern the double packer method has to be used. The length of the test section, instead of 5 m, should be reduced, i.e., the cavern has to be separated by two packers. That section can be considered as having infinite permeability (unspecified high permeability). Usually it is defined as permeability >100 Lu. A precise location of caverns along the grout curtain route is very important to select the proper water-tightness treatment.

3 Hydrogeological Role of the Base of Karstification

The ***base of karstification*** which represents the transition zone below in which there is no intensive karstification or karstic features are very rare. In general, the base of karstification and the minimum water level coincide. On a regional scale, the base of karstification plays important role from a geological engineering, particularly hydrogeological, point of view.

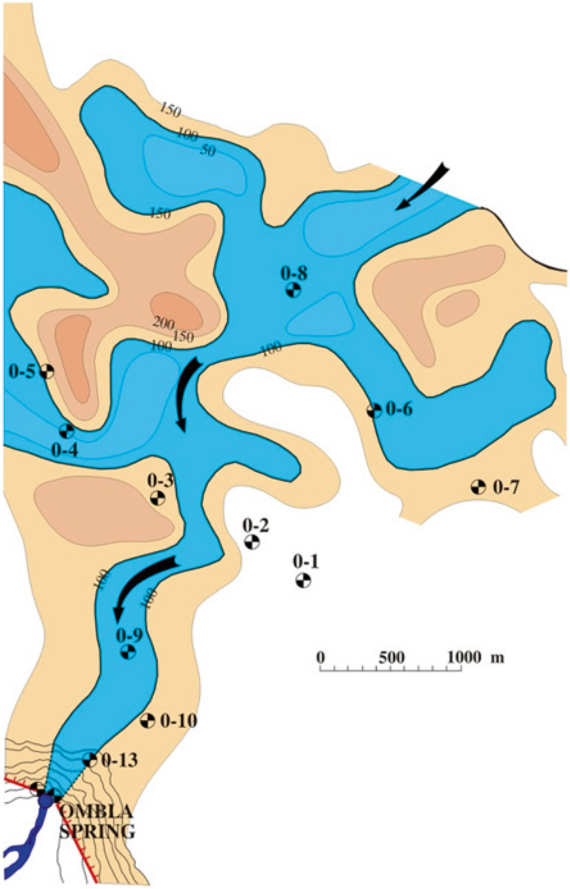


Fig. 9 Contour map for the base of karstification according to results of jointly used electrical profiling and electrical sounding. *Arrows* indicate base flow zone

In many cases the high position of the base of karstification has a role of underground watershed zones. High position of the base of karstification prevents the leakage from Bileća Reservoir (Bosnia and Herzegovina) toward the Bregava River catchment area, as well as the leakage from Piva Reservoir (Montenegro) toward the Tara River erosion base level. The high base of karstification prevents leakage from the Geheyan Reservoir toward the Qingjiang River, China (Ruichun and Fuzhang 2004). A similar situation was found between Cerkničko Polje and Pivka valley in Slovenia (Breznik 1985).

In the opposite deep and narrow base of karstification, a position of concentrated underground flows is indicated. The narrow and deep corridor of the base of karstification, with huge underground flows, was detected by geoelectrical investigations in the catchment area of the Ombla Spring (Fig. 9).

4 Role of Geological Structure on the Groundwater Regime

The number of dams and reservoirs operate successfully because the foundation places were carefully selected on the basis of a superb understanding of a geological structure, its position and groundwater regime. In the opposite, the dam failures attributed to geological causes which mostly occurred due to adverse geological structure and poor hydrogeological data.

The starting point in geological engineering is based on a good and reliable geological data base. A good geological map is needed as a basis from which an analysis of geological structure can be made. Results of such analysis provide the basis for solving any of the engineering problems related to the reservoir watertightness, dam stability, selection of grout curtain geometry, geotechnical treatment of rock mass, tunnel driving, as well as for additional mitigation measures of possible damages during the hydraulic structure operation.

Structural characteristics of the rock mass are, mostly, the consequence of tectonic activities; however, they are also the consequence of exogenetic factors (release discontinuities). Structural relationships play an important role in regional and local directions of groundwater circulation and rock mass quality. Position of impervious lithological units with dominating marly, shaly or clayey component; position of regional and local faults, including mylonite zones; and position of discontinuities (including dip direction, aperture, kind of infilling) govern the groundwater circulation. Wide fault zones, with prevailing mylonite component, are not the proper environment for karstification. In some cases karstification is developed along the secondary joints along the perimeter of the main crushed zone.

Folding structures, especially the compressed anticline cores, are more resistant to karst processes than horizontal and monocline structures. They reduce circulation that is perpendicular to the strike and increase it in the direction of the strike. This conclusion was carried out on the basis of number of case studies in China, Herzegovina, Iran, Tasmania and many other karst regions.

By construction of any large structure the hydrogeological conditions and hydraulic fields in rock mass are drastically changed. Grout curtains become barriers for groundwater filtration and tunnels become huge drains. In both cases the natural groundwater regime is completely changed, sometimes with considerable influence on the surrounding environment.

5 Hypogene Karstification at Dam Sites

An important and quite special problem is the presence of hot or cold up-razed water flows at the areas of some dam sites: Višegrad Dam (BiH), Salman Farsi Dam (Iran), Hammam Grouz Dam (Algeria), Chichik Dam (Uzbekistan), Zhaiziangkou and Pengshui dams, China. According to origin, approximately 10 % of known caves can be classified as hydrothermal or hypogene (Ford and Williams 2007).

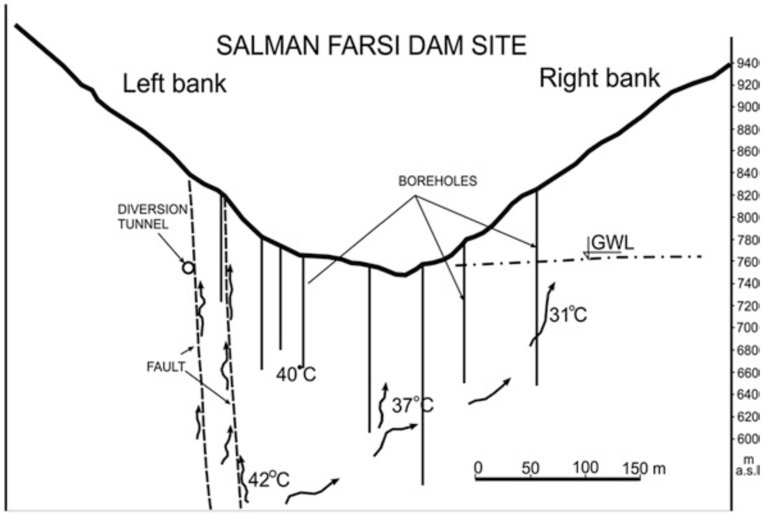


Fig. 10 Deep upward circulation, source for karsification

Mostly the location of the thermal source is very deep with the possibility to be exactly defined as low. However, deep karstification in these cases is obviously the consequence of hypogene flows and, in many cases, requires adaptation of grout curtain route and lower contours. The presence of hot water, particularly if it contains salt, requires particular analysis of possible degradation influence on grout curtains.

Karst features at the Salman Farsi dam site (Iran) are developed as a consequence of hypogene water at depth and simultaneous influence of hypogenic and meteoric water close to the surface (Fig. 10). The number of detected caverns was situated along the grout curtain route at different depths.

In the case of the Salanfe Dam (Switzerland) the leakage from the reservoir has been registered during the first reservoir filling (1953). When the leakage reached its maximum (>1 m^3/s), the new thermal springs (20 l/s) appear in the valley at a distance of 8 km and simultaneously induced earthquakes were registered (Biancchetti et al. 1992).

6 Consequences of Karst Features and Underground Water Regime on Large Structures

As a consequence of the above-mentioned properties, construction of large structures in karst is a risky task. The most common consequences of the listed hydrogeological properties are subsidence at the ground surface as well as at the bottom of reservoirs; water seepage from reservoirs; seepage of highly polluted water from tailings; break-in of groundwater under high pressure during underground excavation and tunnel operation; washing out of clayey/sandy filling from the rock

Fig. 11 Hutovo Reservoir, BiH. Ponors and large cracks created during the first reservoir filling

discontinuities and cavities; destruction of surface protective structures (air-hammer and water-hammer effect); destruction of tunnel lining; progressive degradation of grout curtains by erosion; induced seismicity and specific consequences of natural earthquakes; instability of dam structures due to intensive solution process of evaporates in the foundation rocks; decreasing of downstream spring discharges; endangerment of underground species; other various environmental consequences, and the creation of many other unpredictable and unexpected problems.

6.1 Collapses as a Consequence of Reservoirs Operation

Induced collapses (swallow holes) at the reservoir bottom in karst are spatially independent random events created by reservoir operation. Formation of induced collapses in such a manner is very harmful because their development is unpredictable and practically instantaneous. Collapse at the reservoir bottom is one of the common failures that provoke leakage from the reservoir. Permanent reservoir fluctuations caused the groundwater level fluctuation and washing out of the unconsolidated sediments or cave filled deposits. It provokes collapses in alluvial coverage, as a consequence of ponors in the limestone bedrock and leakage from the reservoir. An inevitable effect is concentrated seepage from the reservoir.

Well-known incidents related to this kind of reservoir leakage are: Lar Reservoir (Iran), May and Cevizli (Turkey), Perdika (Greece), Vrtac and Slano (Montenegro), Angara (Russia), Hutovo (BiH, Fig. 11), Mavrovo (FYUR Macedonia, Fig. 12), Kamskaya (Russia), Huoshipo (China) and North Dike (Florida). In some of them (May, Cevizli, Vrtac) all water quickly leaks out of the reservoir as soon as the rains subside.

Some collapses are extremely voluminous. Among the many collapses which have occurred during the Angara Reservoir operation, the largest collapse has a volume of 7,000 m^3 (Trzhtsinsky and Filipov 1981).

Fig. 12 Mavrovo Reservoir (FYUR Macedonia). Collapses as a consequence of reservoir operation

Fig. 13 Demolished shotcrete at the reservoir bank

The integrity of reservoirs in karst is seriously endangered by water table fluctuation up to the reservoir bottom (presence of estavelles at reservoir bottom). Sudden, abrupt, significant and rapid rise in the water table could cause strong uplift, including air-hammer and water-hammer effects. Another phenomenon, danger for reservoir watertightness, is also related to an increase in the water table. In some piezometers at the Hutovo Reservoir a “breathing” phenomena was registered: air would first rush out (the borehole would “exhale”) to be followed with air rushing in (the borehole would “inhale”) with each stage lasting for up to 30 min and the cycle could be repeated many times. The air current velocities vary between 0.5 and 1.5 m/s. However, the fastest air current circulation from the aeration pipe can be about 15 m/s (Milanović 2006).

During 2 years of operation of the Hutovo Reservoir (Herzegovina) a number of damages at the reservoir bottom have been recorded: 74 newly created collapses, 1,300 m of fissures (width 2–15 cm), explosion of geomembranes and destruction of shotcrete in a few places (Fig. 13).

After two remedial phases (sealing of collapses and fissures), including construction of aeration tubes to release pressure, the seepage rate was reduced from 3–5 to 1.0 m^3/s (Milanović 2000).

6.2 Water Seepage From Reservoirs

Leakage beneath the dam foundation or through the reservoir banks occurred after the first filling at almost 80 % of analyzed case studies. In such cases the sealing solution requires much patience and perseverance, as well as adequate funds. As a result of a persistent, time-consuming and step-by-step sealing treatment, in some cases the results justify the invested money.

After the sealing treatment, the leakage from Keban Reservoir (Turkey) was reduced from 26 to less than 10 m^3/s; in Camarasa (Spain) from 11.2 to 2.6 m^3/s; in the case of Marun dam site (Iran) the leakage of 10 m^3/s was reduced to the negligible amount; in the example of the Great Falls (USA) from 9.5 to 0.2 m^3/s; in Canelles Reservoir (Spain) from 8 m^3/s to a negligible amount; in Mavrovo reservoir (FYUR Macedonia) a leakage of 9.5 m^3/s was considerably reduced; Buško Blato (BiH) from 40 m^3/s in natural conditions to 5 m^3/s; and in the case of Hutovo Reservoir (BiH) from 10 m^3/s in natural conditions to approximately 1 m^3/s.

In the case of El Cajon Dam (Honduras), the sealing treatment was successful in spite of very deep karst flow. The large karst cave situated 176 m below the gallery had to be grouted under an extremely high head. To reach deep cavities at this dam site the maximum borehole length of 250 m was applied (H. Kreuzer, Personal Communication).

However, in some cases, despite an extensive investigation program and sealing treatment, the results were inadequate to justify the time and money because the hydrogeological conditions, as a consequence of karstification, were too complex. After the first filling of Hails Bar reservoir in USA the leakage was enormous, 54 m^3/s. Corrective treatments started in January 1919. The dam was acquired by Tennessee Valley Authority in 1939. Unable to overcome the continual problems with foundation and leakage, TVA replaced Hales Bar in 1968 with Nickajack Dam 10.3 km downstream. Montejaque Dam (Spain) is abandoned because of unacceptable high leakage—4 m^3/s (Fig. 14).

In the case of Vrtac Reservoir (Montenegro), leakage reached 25 m^3/s; Višegrad Dam (Bosnia), 14 m^3/s; Iliki (Greece), 13 m^3/s; Salakovac (BiH), >10 m^3/s; Lar Dam (Iran), 10.8 m^3/s; Ataturk (Turkey), >11 m^3/s; Samanalawewa (Sri Lanka), 2 m^3/s; Perdikas (Greece); Mosul (Iraq) and May (Turkey) the water-tightness treatment was unsuccessful.

In a karstic environment with a highly random distribution of karstic features some uncertainties always remain. In karst *modifications during grout curtain or tunnel construction are therefore the rule and not the exception.* Re-design of anti-seepage structures has been applied in the case of Salman Farsi, Seimareh and Kavar dams in Iran, as well as in the cases of Frimen Dam (USA) and Sklope Dam

Fig. 14 Abandoned Montejaque Dam, Spain

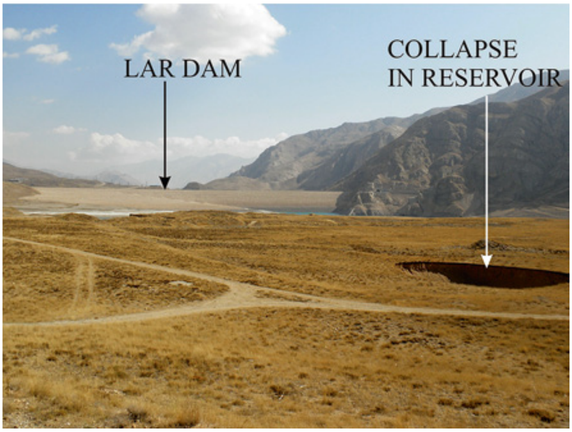


Figure. 15 Lar Dam, Iran. One of the collapses induced by reservoir operation

(Croatia). In many other cases the number of local modifications (re-routing, extensions, increasing the number of rows, increasing of curtain depth) were applied.

Problems related to the progressive erosion of clayey/sandy deposits from faults, joints and caverns have as a consequence increased leakage from reservoirs after many years of operation: Mavrovo Reservoir (FYUR Macedonia), after 25 years of operation; and Hammam Grouz (Algeria), after 17 years of operation. In the case of Višegrad Dam (Bosnia), during 20 years of operation, leakage gradually increased from 1.2 to 14 m^3/s (roughly 0.7 $m^3/s/year$).

Deep and fast flows—doubtful treatment. In the case of some reservoirs or tunnels, very deep underground flows had caused partial or total failure of the project. In the case of Lar Dam (Iran) the leakage problem is one of the most complicated and extremely difficult problems to be solved using the common geotechnology (Fig. 15).

The deepest karst leakage flows (10.8 m^3/s) from the Lar reservoir have been discovered down to 430 m below the riverbed. However, fractured karstic limestone is extended to at least 700 m below the river bed. At 210 m below the river bed a large cavern was found and plugged (23 m high and 67 m wide, i.e., more than 90,000 m^3). Few other caverns have been discovered at the depth of 250 m down to 430 m below the river bed. In spite of the extensive grouting and cavern filling, the reservoir losses are still almost the same as before treatment (Djalaly 1988).

The main grout curtain at Ataturk dam site is 175–300 m deep below the river level. The grout curtain bottom is high above the base of karstification. The total leakage through the dam foundation in May 1996 was 11–14 m^3/s for reservoir level 6 m below the normal storage level (Riemer et al. 1997).

In the case of Špilje Dam (FYR Macedonia) the main portion of water losses (2 m^3/s) occurs through the deep karst conduits. The deepest conduits are indicated more than 250 below the dam foundation.

In another case, Višegrad Dam (Bosnia and Herzegovina), the main leakage conduits are encountered at the depth of more than 130 m below the dam foundation (14 m^3/s).

However, in some cases the deep sealing works are successful. There are some examples of very deep but successful grout curtains. In those cases the velocity and capacity of underground flows was limited, or filtration occurs through the tight joints. It was the technical prerequisite for successful deep grouting.

In the case of Berke Dam (Turkey) the uppermost grouting gallery is at the elevation of 346 m and bottom of deepest grout curtain contour line is at elevation of minus 50 m. It is one of the most complicated grout curtains in the world (Altug and Saticioglu 2000).

6.3 Underground Treatment

To prevent underground filtration beneath the dams and leakage from reservoirs in karstified rocks the commonly applied underground geotechnical measures are: grout curtain, positive cut-off, diaphragm wall, bath-tub structure and karst cavern sealing.

6.3.1 Grout Curtains and Cavern Sealing

To define extension and lower contour of the suspended curtain, the rock mass permeability is common criteria. The question of target permeability in karst is still open. The prevailing opinion is that permeability less than 5 Lu indicates sufficiently impervious and practically ungroutable rock.

To construct a successful grout curtain in karst the closely spaced grouting galleries are required (less than 30 m between galleries). The following grouting materials are commonly applied: cement with different additives, cement/clay, clay/cement, polyurethane foam, asphalt or hot bitumen and different types of cement mortar.

Almost always grout curtains in karst are combined with plugging of concentrated underground flows or caverns. Surfaces of some important grout curtains in karst are presented below:

Ataturk (Turkey)	1,200,000 m^2, length 5.5 km, depth up to 300 m
El Cajon (Honduras)	610,000 m^2
Limmernboden (Swiss)	544,740 m^2
Berke (Turkey)	533,000 m^2, depth up to 235 m
Buško Blato (Bosnia)	475,000 m^2
Dokan (Iraq)	471,000 m^2
Khao Laem Dam (Thailand)	437,000 m^2
Slano (Montenegro)	404,224 m^2, length 7.011 m
Keban (Turkey)	338,000 m^2
Salman Farsi (Iran)	261,000 m^2

Extreme inhomogeneity of karst porosity leads to great variability of grout mix consumption along the grouting hole. For instance, in the case of Salman Farsi (Iran) the average consumption of grout curtain is 79 kg/m; however, the consumption range varies between 6 and 234.048 kg/m. A consumption rate less than 100 kg/m in karst is rare (only 17 % of analyzed cases). The consumption rates vary mostly between 100 and 600 kg/m (in almost 70 %).

The term "***karst cavern sealing***" along the grout curtain or at reservoir banks means: the geotechnical operation needed to block the groundwater circulation along any karst singularity (channels or caverns) which cannot be treated by applying a conventional grouting technology. This term also includes the treatment of potential leakage paths along the heavily tectonized and wide zones filled with mylonite or re-deposited clay/sandy material.

Plugging of large and accessible cavities along the grout curtain route requires different technologies, including speleological investigations, excavation of access shafts and adits, large diameter boreholes, and, sometimes, re-routing the weak places at the grout curtain. If caverns are situated below the water table the first step is definition of cavern size. If a cavern is detected by a borehole, one of the best methods to establish cavern contours is echo logging. The cavern walls are recorded by horizontally and vertically oriented ultrasonic transducer. Good results were also provided by borehole TV camera.

For access and filling of the cavern by aggregate, large diameter boreholes should be used. The next step is consolidation grouting of the aggregate and finally grouting the contact between the concrete plug and cavern walls.

Volume of some large caverns at different dam sites is presented below:

Keban (Turkey)	600,000 m^3 Petek Cavern 150,000 m^3 Crab Cavern
Salman Farsi (Iran)	>150,000 m^3 Golshan's Cavern
Lar (Iran)	90,000 m^3
Pueblo Viejo (Guatemala)	60,000 m^3
Sklope (Croatia)	25,000 m^3
Canelles (France)	10,000 m^3
Slano (Montenegro)	6,000 m^3
Dokan (Iraq)	5,000 m^3
El Cajon (Honduras)	5,000 m^3

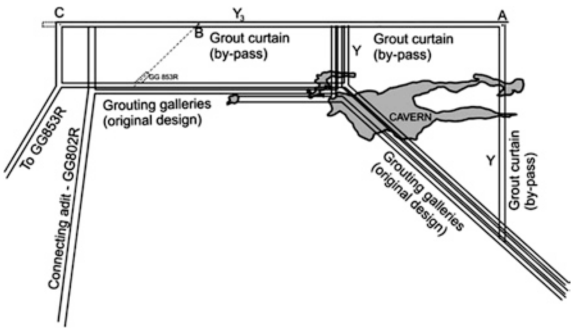


Fig. 16 Salman Farsi Dam (Iran). Grout curtain by-pass around a large cavern

In the case of Keban Dam the Crab Cavern (below the dam foundation and below the groundwater level) was filled with concrete and injected solids. The large Petek Cavern (at the left dam site bank, 150 m from the dam body) has been filled through the shaft 2.5 m in diameter and 13 large diameter boreholes. About 605,000 m^3 of limestone blocks, gravel, sand, and clay were thrown into the cavern. Leakage rate from the Keban Reservoir decreased from 26 to 9 m^3/s.

The problem of Golshan's cavern (Salman Farsi Dam, Iran) has been solved by re-designing the grout curtain in the right abutment to by-pass the cavern from the upstream side (Fig. 16). To plug six large caverns along the grout curtain route at the same dam site 3.125 m^3 of the SCC (Self Compacting Concrete) was used.

One of the largest plugs was constructed as part of the Wulichong underground dam in China. The plug size is: 33.46 m high, 13.9 m wide, and 2–10 m thick, and volume 4,811 m^3 of concrete (Zhang and Wu 2000).

In the case of the cavern at Sklope dam site (Croatia), left bank, the grout curtain route was re-designed and shifted downstream (Pavlin 1970). Presently the large cavern is filled with water.

One of the first treatments of karst channel flows in the Dinaric karst area was performed on the section of Slano Reservoir grout curtain. This channel flow was plugged at depths of 90–100 m below the surface, about 30 m below the lowest level of water table. The successful injection of the grouting mix could be carried out only during the lowest water table time. Under high water table conditions the groundwater flow was too fast and caused instantaneous washing out of the gravel and grout mix. As a consequence plugging which was initiated in 1966 was carried out intermittently over a period of 4 years and 5 months. Through a borehole Ø 146 mm 4,124 m^3 of gravel and 4,500 tons of grout mix (only dry component) have been injected into the karst channel (Vlahović 1983).

The plugging procedure of karst channels with water flows was successfully used in some other cases: Charmine Dam (France), Krupac Reservoir (Montenegro), Buško

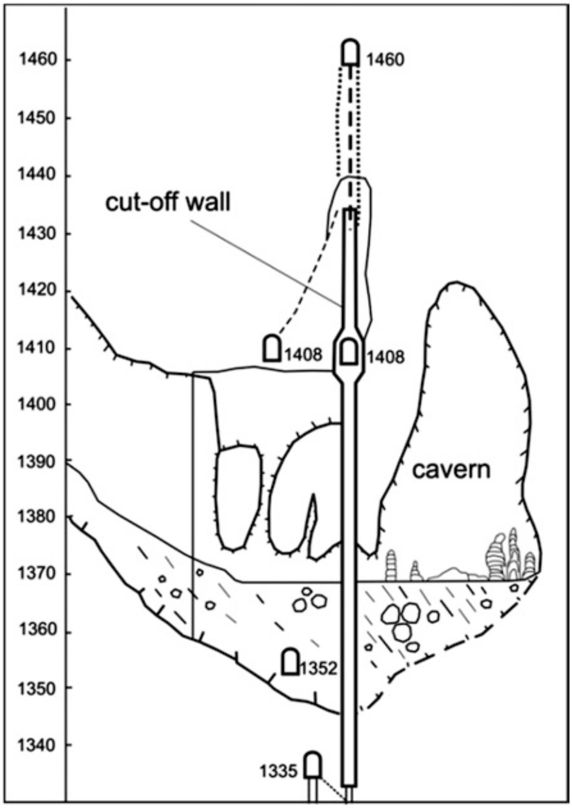


Fig. 17 Wulichong underground dam (China). Concrete cut-off wall (Kang and Zhang 2002)

Blato Reservoir (BiH); Čapljina underground Power Plant (BiH); Guntersville Dam (USA), and Douglas Dam (USA).

Cut-off (Diaphragm) wall is a very effective watertight structure for plugging the highly karstified and wide tectonized zones.

Different technologies are available: deep trenches made by cutters (Gotvand, Iran); overlapping piles (Khao Laem Dam, Thailand; Akkopru Reservoir, Turkey; Pavlovskaya Dam, Russia; Erevan Dam, Armenia; Baipazinskaya Dam, Tajikistan; Wolf Creek Dam, USA); Kamthikhera Dam (India); Khoabin Dam (Vietnam) and a mining method in the form of trenches between the close spaced galleries (Karun I Dam, Iran).

One of the largest cut-offs has been constructed as part of the Wulichong underground dam (Fig. 17). A reinforced concrete cut-off wall is 100.4 m high, 50–30 m wide, and 2.5–2 m thick (Kang and Zhang 2002). For the cut-off foundation, 14,775 m^3 of karstified rock mass and cavern deposits was excavated and replaced with 15,152 m^3 of concrete.

Bath-tub structure means construction of an impervious structure by combination of vertical, inclined or sub-horizontal (Oymopinar Dam, Turkey; El Cajon Dam, Honduras).

Fig. 18 River Trebišnjica, BiH. River bed covered by shotcrete

6.4 Surface Impermeabilization: Structures and Technologies

To reduce water losses from the reservoirs situated in karst the common applied surface structures and technologies are: compacted clayey blankets; different kinds of geomembranes; shotcrete (in the case of exposed rock); plugging of ponors (swallow holes); impermeabilization of ponor zones by grouting blankets; heavy reinforced concrete slabs (in the case of high water pressure); cylindrical dams around the large ponors and estavelles; non-return valves to prevent uplift destruction (in the case of estavelles); construction of rock-filled or earth-filled dikes to amputate sinking zones from reservoir and construction of aeration pipes to prevent air-hammer destruction. In many cases, for a successful water losses reduction strategy, the combination of a few presented approaches is needed.

In the case of Karacaoren II Reservoir (Turkey) three types of protection have been successfully applied: thick concrete, shotcrete and clay blanket (Okay and Soydam Bas 1999).

A few different types of water-tightness protection of the Hutovo Reservoir (BiH) have been applied: compacting of natural alluvial bottom; plugging of individual ponors; grouting of largest ponor zone below the alluvial cover; geomembrane at critical areas; and reinforced shotcrete over the limestone banks.

To prevent leakage along the Trebišnjica lost river (Herzegovina, length of 65 km) 2.2 million m^2 of shotcrete (5 cm thick) have been used (Fig. 18). In natural conditions the river bed was completely dry and the groundwater level was deep below the bed. During the rainy period some sections of river bed are under strong uplift. To prevent destruction of shotcrete the non-return valves were installed.

However, in karst, the risk is never completely eliminated. During reservoir operation any impermeabilization structure is exposed to heavy water pressure and different deterioration processes: piping, erosion, groundwater uplift, and air-hammer and water-hammer effect. Collapses and wide open cracks can occur below the watertight structures (Fig. 19).

To prevent a destructive effect of pressurized air, construction of aeration pipes is necessary (Fig. 20).

Fig. 19 Reservoir bottom (Hutovo, Herzegovina). Collapse and cracks beneath the geomembrane

Fig. 20 Aeration pipe at the reservoir bottom (Hutovo, Herzegovina)

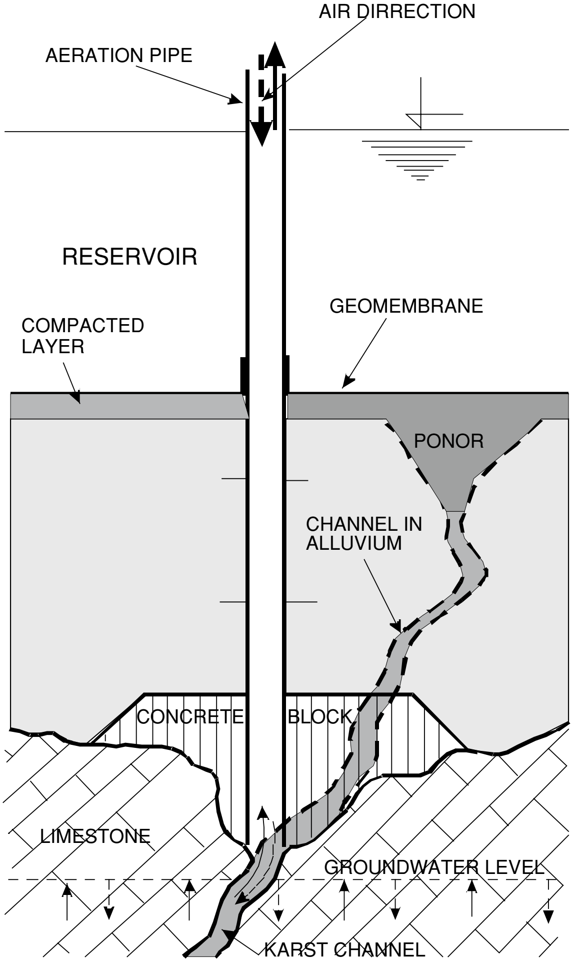


Fig. 21 Nikšić Polje, Montenegro. Cylindrical dam around a large estavelle at the reservoir bank

Fig. 22 China, Guangxi. Gravity concrete dam in front at the entrance of the large underground river

One of the extremely massive structures was constructed to prevent water leakage from the Akkupru Reservoir (Turkey). A 1 km wide stripe of karstified reservoir bottom is protected with one meter of heavily reinforced concrete slab to be resistant against 100 m of water column. The reservoir bank is protected with massive reinforced concrete, also up to the reservoir level of 100 m. To prevent leakage beneath the concrete slab the two rows of cut-off walls (overlapped piles) have been constructed along the reinforced slab, down to the impervious flysch (Günay and Milanović 2005).

To solve the problem of large ponor zones along the perimeter of the reservoir long dikes were used. In some cases to amputate the ponor zone from the reservoir, the dike almost 3 km long has been used (Buško Blato, BiH). In the case of large estavelle or ponor, with a single opening, cylindrical dams were constructed (Fig. 21).

To prevent leakage from the reservoir area in China (Guangxi), the concrete gravity dam was constructed (Fig. 22).

7 Underground Damming

The case studies performed in different regions in the world, particularly in China, provide that an artificial underground storage in karstified rocks may be technically realistic. According to Lu (1986) more than 20 underground reservoirs have been created in different karst regions of China. According to Yuan (1990) in the Xiashi district (Guizhou Province), 16 underground dams have been constructed in karsified rocks. One of largest underground reservoirs was formed on the Linlangdong ground river by construction of a 15 m high dam (Q average is 23.8 m^3/s).

Two underground dams are constructed in the submarine spring karst `channel to mitigate influence of sea water (Port-Miou and Bestouan, France). The first dam is located 2,230 m from the entrance, 147 m below sea level. The other dam (Bestouan) is at a depth of 31 m below sea level and at a distance of 3 km from the channel entrance (Potie et al. 2005).

The project of the Ombla underground dam and reservoir is one of the largest in the world. Location of the underground dam site is proposed about 200 m behind the large Ombla Spring near Dubrovnik (Croatia) at sea level. The average discharge of the spring is $Q = 24.4\ m^3$. The crest of the underground dam is foreseen to be at elevation 100–130 m. Estimated underground operational storage space is about 5 million m^3.

Some dams in China are successfully constructed in front of the large cave to create a reservoir in front of the ponor zone.

8 Problems in Evaporates

More than 60 dams and reservoirs along the world needs rehabilitation because of problems related to the solubility of evaporates, mostly gypsum. A number of cases were reported in the U.S., China, Russia, Iran, Iraq, Argentina, Guatemala, Switzerland, Peru, Venezuela and some other countries (Cooper and Calow 1998).

Some prominent examples are: Mosul Dam (Iraq), Bratsk and Kamskaya (Russia), McMilan Dam (U.S.A.) and Huoshipo Reservoir (China). Grouting in the jointed gypsiferous rock is a questionable and risky task. In many cases, in spite of massive and long-term grouting results, they are not successful (Mosul Dam). According to Maximovich (2006), successful grouting of the gypsiferous foundation rock (Kamskaya Dam) has been done by applying an oxaloaluminosilicate solution.

The salt rocks, which are more soluble than gypsum, are present in the foundation of the Rogunskaya and Nuretskaya dams in Tajikistan. If reservoir water is in touch with salt, the problem of pollution appears as crucial (Gotvand Reservoir, Iran).

The worst was the failure of the St. Francisco Dam (California, US—1929), which killed 450 people. Catastrophic failure of San Juan earth Dam (Spain) occurred during the first filling of the reservoir in 2001. Due to intensive dissolution of gypsum the part of dam collapsed provoking a huge flood in the downstream area (Gutierrez et al. 2003).

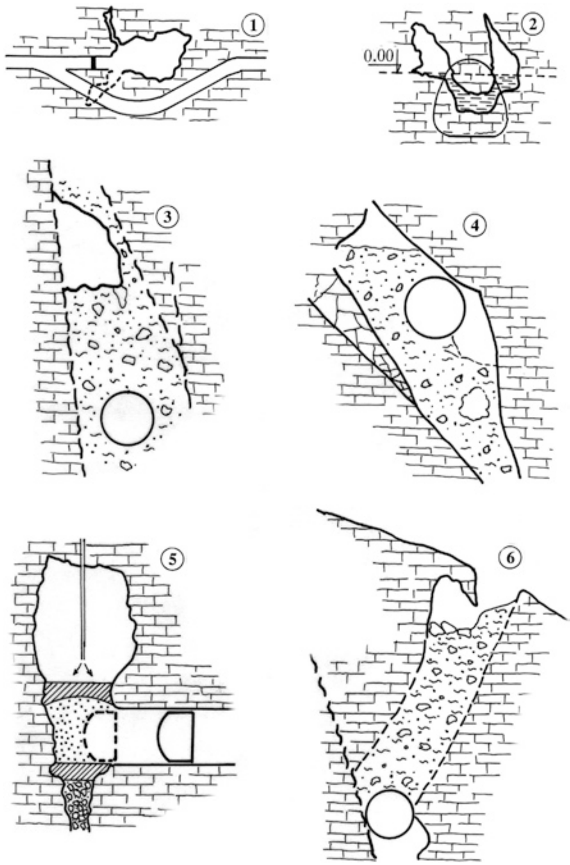


Fig. 23 Different examples of tunnels situated in cavernous rocks

9 Underground Excavations in Karst

Tunnels in karst appear to be the most vulnerable structures. The large caverns and huge inflow of underground water considerably retarded excavation of the derivation tunnels, dewatering tunnels, as well as water transfer and communications tunnels. Some common situations are presented in Fig. 23: (1) excavation of a bypass around a huge cavern; (2) crossing the cavern at sea level; (3) and (4) crossing a cavern filled with unconsolidated deposits; (5) treatment of an empty cavern in front of TBM; (6) collapse at surface provoked by tunnel operation.

From a hydrogeological point of view tunnels are situated: above the maximal groundwater level (GWL); in the zone between minimal and maximal GWL (temporary flooded); and below the zone of minimal GWL (in saturated zone).

Every large sinkhole above the tunnel route is a potential swallow hole during heavy rains. In that case sudden and large water inflow is possible in spite of the fact that the tunnel route is situated high above the GWL.

Particular problems may be encountered during excavation of tunnels below the water table. In this case all karst channels are subject to high pressure, destructive

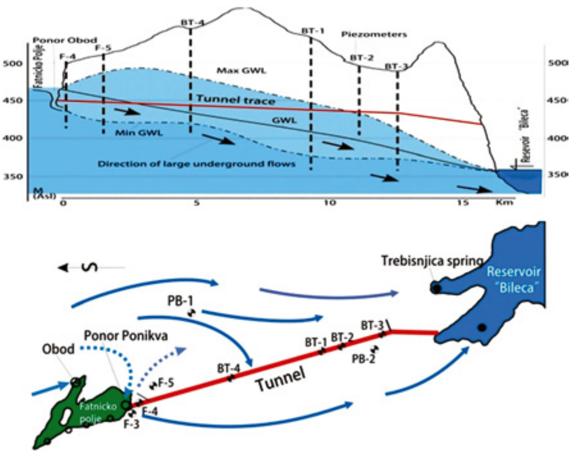


Fig. 24 Tunnel Fatničko Polje—Bileća reservoir

effects of turbulent inflows and an enormous amount of water. Without the possibility of draining the tunnel by gravity, any groundwater intrusion more than 100 l/s is a very serious and dangerous problem. Sometimes consequences are tragic.

Defects during the tunnel operation are very common, particularly in the case of power plant headrace tunnels. These tunnels are under pressure, and failures occurred mostly in the sections where the tunnel intersected large caverns filled with nonconsolidated cave sediments.

The large inflow of underground water considerably retarded excavation of a number of tunnels in different karst regions. Excavation of the Kuhrang III (23 km long tunnel in Iran) had a few years construction delay because of enormous groundwater intrusions (and floods) at a number of sections along the tunnel route situated in limestone. In some sections the pressure of underground flows was 10–11 bars. In the tunnel section with overburden of 1.100 m the karst channel (aperture 1–1.2 m) has been cut by TBM. Discharge of a few liters of muddy water started immediately. After 4 h, discharge increased up to 1 m^3/s. During 24 h, more than 1,000 m^3 of boulders, gravel and sand, including ~500 tons of suspended material in water, was transported from underground into the tunnel. Very complicated drainage structures in front of the TBM head, including a 4 m thick concrete plug, were constructed to allow the plugging of the karst channel, grouting the karstified rock mass in front of the tunnel head and further excavation. In spite of a few horizontal pilot boreholes in front of the tunnel head, the existence of the large karst channel was predicted partially, only.

The intake structure of the water transfer tunnel from the Fatničko Polje to Bileća Reservoir (15.6 km long, BiH) is located at the temporary flooded karst polje at the ponor zone with a swallowing capacity of over 100 m^3/s (Fig. 24). The nine large caverns and a few karstified sections presented a great obstruction for TBM technology. Different unconventional technologies were applied to overcome problems with the cavern. In the dry period, the GWL is below the tunnel level. After heavy rains the groundwater rises above the part of the tunnel in only a few hours. As a consequence of intensively karstified surrounding rock the amount of groundwater intrusion into the tunnel was sudden and large. Beside the direct inflow of sinking water in Fatničko Polje, the large amount from a remote part of the catchment area appears in the middle section of the tunnel.

For optimal excavation planning and to protect people in the tunnel the surrounding catchment area and karst aquifer must be under severe hydrogeological and hydrological monitoring.

According to present experience, TBM technology has a considerable deficiency for application in heavily karstified rocks. Every cavern, empty or filled with clay, with aperture more than 5 m, is a great obstacle for TBM. The problem increases tremendously in the case of a cavity with strong water inflow at the tunnel head. If the cavity is filled with plastic clay, the efficiency of TBM is very low and the possibility for TBM head sinking is very high. In many cases excavation of the by-pass adit around the TBM head for manual cleaning and plugging are the only possibility. This is a time consuming procedure.

To resolve the problem of groundwater burst (6.5 m^3/s) into the 6.17 km long Sozina traffic tunnel (Montenegro) the drainage tunnel (1.75 km long) was excavated below the main tunnel.

Because of the intensive washing process of the clayey/sandy deposits, the tunnel tube of the 8 km long head race tunnel of the Čapljina Reversible Power Plant lost support at a length of 16 m. The leakage of 1 m^3/s was a consequence of lining destruction. Repair works consist of construction of a reinforced arch beneath the tunnel and filling of the empty space by gravel and grout mix. The empty space above the tunnel was left untreated.

Relocation or deviation of the tunnel route because of huge caverns or cavernous zones is common in karst: tunnel for reversible PP Bajina Bašta (Serbia), Čapljina RPP (Herzegovina), Ybing-Gonxian Railroad tunnel, Nunning-Kunming railway tunnel, water intake tunnel in Ontario (U.S.A.) and many others. Due to enormous inflow in the head race tunnel in the case of Seimareh Power Plant the inclination of the tunnel route was changed. In the case of Bajina Bašta head race tunnel the proposed route was changed to avoid the cavernous zone on the base of geophysical investigations (geoelectrical sounding and mapping) from the surface.

Collapses at the surface occurred also as a consequence of tunnel driving through the caverns filled with clayey material, sand and pieces of rocks including pieces 5–50 m^3: head race tunnel for RPP Čapljina (Herzegovina), and Dodoni tunnel (Greece). In the case of Dodoni, tunnel collapses have occurred at the surface, 100 m above the tunnel (Marinos 2005).

Eleven examples of hydrogeological problems during excavation of tunnels in Chinese karst is presented in the book "Prediction and engineering treatment of water gushing and caverns for tunneling in karst "written by Xingrui 2010. The Long Tan traffic Tunnel (8,693 m) crosses the area of the Tanchunguan underground river. More than 770 m of the tunnel route is situated in the huge cavern filled with clay and gravel deposits (Fig. 25).

Two serious problems during construction were successfully solved: foundation in soft clay deposits and inflow of a huge amount of underground water. In the case

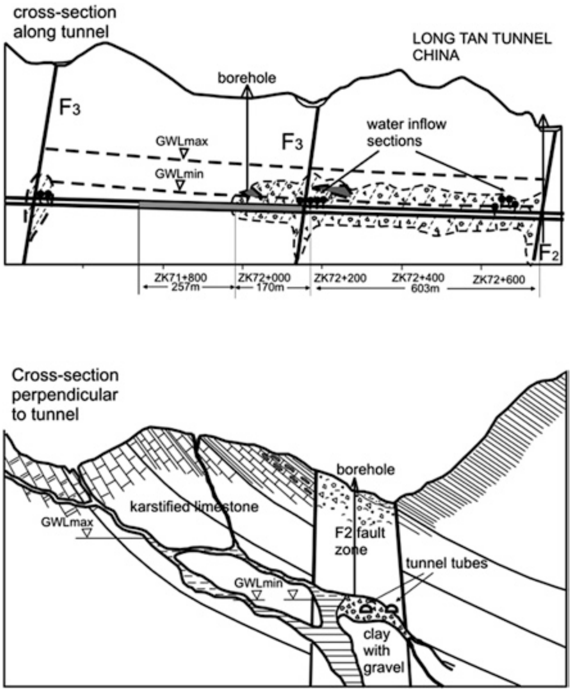


Fig. 25 Ling Tan tunnel near underground river (China) (Xingrui 2010)

of the Zujiayan Tunnel, the problem was the direct connection of the tunnel area with the surface, 200–300 m above, by a few karst channels (shafts). The main water inflow occurred at the tunnel intersection with the karst channel.

10 Induced Seismicity in Karst

In many karst areas local seismic activities are registered during the intensive rainfall when there is abrupt filling of a karst aquifer and rapid rising of groundwater levels. As a consequence of the water table increasing, the pressure of the air in the karst channels and siphons significantly increase. Trapped "air-pillows", including the water in the vapor phase in caverns and fissures, escape the creation of strong explosions that locally can lead to a damaged reservoir bottom and shotcrete lining along the canals. Many times underground air-pillow explosions were recorded by the seismological stations.

One of the earliest documented examples of induced seismicity was registered at 1,837 in an Italian part of Dinaric karst. Explosions of compressed air as a consequence of the fast increasing of water level have been registered by local inhabitants in the Timavo Spring region near the town of Trieste (Galli 1999).

In the other part of the Dinaric karst area (Fatničko Polje, Herzegovina), after heavy precipitation, local inhabitants have noticed strong ground shaking.

Seismic shocks occurred 15–30 h before discharge of the large Obod Spring began (Q_{max} ~ 60 m^3/s). To analyze these events, one seismic station was temporarily installed above the spring (Z-component, 1975). Ground vibrations and shocks, before spring discharge started, were clearly registered by seismograph (Milanović 2000). During abrupt impounding, at the "Bileća" Reservoir (completely situated at extremely karstified rocks) some vibration and shocks were registered by seismograph, which cannot be explained by normal seismic activity or induced seismicity. These vibrations were interpreted as explosions of trapped air and water vapor in karst channels. The sound of escaping air at the surface close to the reservoir and the appearance of colored water (by clayey particles) in the reservoir water were visually observed.

In China, Lu and Duan (1997) distinguished three different types of induced seismicity caused in karstic areas by reservoir water storage: A—loading faulted type (due to reservoir weight); B—pneumatolytic process type (explosions due to uprising of boiling water below the reservoir); and C—cave damaged type (explosions of compressed air mass in caverns).

Similar seismic activity in different karstic regions, related to the fast saturation of a karst aquifer after heavy rainfall, was noticed by authors from China, Italy, Germany and USA.

References

Altug S, Saticioglu Z (2000) Berke arch dam, Turkey: hydrogeology, karstification and treatment of limestone foundation. Present state and future trends of Karst studies. In: Proceedings of the 6th international symposium and field seminar. Marmaris, Turkey

Bianchetti G, Roth P, Vuataz F-D (1992) Deep groundwater circulation in the Alps relation between water infiltration, induced seismicity and thermal springs. The case of Val d'Illieze, Wallis, Switzerland, Eclogae geol. Helv 85(2): 291–305. Birkhauser Verlag, Basel

Bozović A (1985) Foundation treatment for control of seepage, report Q 58. Quinzieme Congres das Grandes Barages, Lausanne

Breznik M (1985) Exploration, design and construction of cut-offs in karstic regions. Quinzieme congres des grandes barrages, Q.58, R.67. Lausanne

Cooper AH, Calow RC (1998) Avoiding gypsum geohazards: guidance for planning and construction. British Geological Survey. Technical report WC/98/5

Djalaly H (1988) Remedial and water tightening Works of Lar Dam. Seizieme Congres das Grandes Barages, San Francisco

Ford D, Williams P (2007) Karst hydrogeology and geomorphology. Willey, NewYork

Galli M (1999) Timavo, Esplorazioni e studi. Suplemento no 23 di Atti e Memorie della Commissione Grotte Eugenio Boegan, Trieste

Günay G, Milanović P (2005) Karst engineering studies at the Akkopru Reservoir area, SW of Turkey. In: International conference water resources and environmental problems in karst, Belgrade and Kotor

Gutierrez F, Desir G, Gutierrez M (2003) Causes of the catastrophic failure of an earth dam built on gypsiferous alluvium and dispersive clays (Altorricon, Huesca Province, NE Spain). Environ Geol 43:842–851

Kang Y, Zhang B (2002) Karst and engineering handling to the karst in Wulichong Reservoir, Yunnan Province. Carsologica Sinica, Institute of Karst Geology, Guilin, China, 21(2): 120–130

Kesić P, Kovačina N (1978) In: Laksiri K, Gunathilake, Iwao Y, Engineering geological evaluation of reservoir leakage problem. 73rd Annual Meeting of ICOLD, 2005 Tehran, Iran, Paper No.: 151–S3
Lu Y (1986) Some problems of subsurface reservoirs constructed in Karst regions of China. Institute of Hydrogeology and Engineering Geology, Beijing
Lu Y, Duan G (1997) Artificially induced hydrogeological effects and their impact of environments on karst of north and south China. In: Proceedings of 30th international geological congress, Beijing, vol. 22, pp 113–120
Marinos P (2005) Experiences in tunneling through katstic rocks. Water resources and environmental problems in Karst. International Conference Belgrade-Kotor
Maximovich NG (2006) Safety of dams on soluble rock (The Kama hydroelectric power station as an example). The Russian Federal Agency for Science and Innovations, Perm
Milanović P (2000) Geological engineering in Karst—Dams, Reservoirs, grouting groundwater protection, water tapping, tunneling. Zebra Publishing Ltd, Belgrade
Milanović P (2006) Karst of Eastern Herzegovina and Dubrovnik Littoral. ASOS, Belgrade in Serbian
Okay G, Soidam Bas A (1999) Experiences on two karstic dam sites. International commission on large dams (ICOLD), Antalia
Pavlin B (1970) Kruščica storage basin in the cavernous Karst Area. Dixieme Congres des Grandes Barages (ICOLD), Montreal
Potie L, Ricour J, Tardieu B (2005) Port-Miou and Bestouan freshwater submarine Springs (Cassis-France) investigations and works (1964–1978). In: Proccedings of water resources and envirnomental problems in Karst. Belgrade-Kotor
Riemer W, Gavard M, Soubrier G, Turfan M (1997) The Seepage at the Atatürk Fill Dam. Dix-Neuvieme Congres des Grands Barrages, Florence
Ruichun X, Fuzhang Y (2004) Karst geology and engineering treatment in the Geheyan project on the Quingjiang River, China. Engineering Geology 76:155–164, Elsevier
Trzhtsinsky Yu B, Filipov VM (1981) Tectogenic activization of Karst in Angara Water Reservoir. International engineering geology symposium, Istanbul
Vlahovic V (1983) Karst Reservoir of Slano. The Montenegrin Academy of Sciences and Arts. Special editions, vol. 14. Titograd (Podgorica)
Xingrui H (2010) Prediction and engineering treatment of water gushing and caves for tunneling in Karst. Guangxi Normal University Press, China
Yuan Daoxian (1990) Construction of underground dams on subterranean streams in South China Karst. Institute of Karst Geology, Guilin
Zhang B, Wu M (2000) Seepage control treatment of Blind Valley Reservoir, Gao Yaoji, China. Hydroelectric Power Construction Engineering Consultant Company, Yunnan Province

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