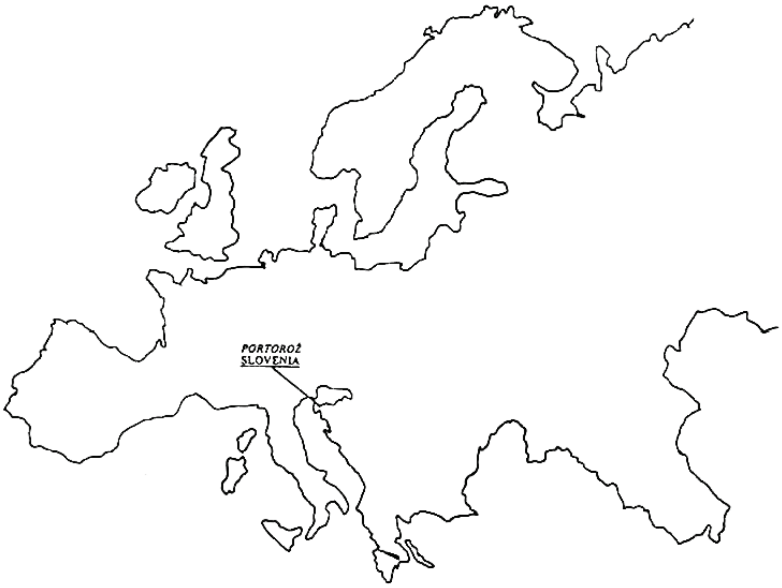
WORKSHOP

ENGINEERING IN KARST



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EXPLORATION, DESIGN AND CONSTRUCTION OF CUT OFFS IN KARSTIC REGIONS (*)

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1. INTRODUCTION

The sealing of porous carbonate rocks under the dam, in its abutments and in the basin represents the biggest problem when undertaking the construction of storage reservoirs in Karst regions. Underground dams and other cut off structures are the most delicate and also the most frequently damaged element of accumulation basins in Karst regions. Therefore the choice of the most appropriate position of the dam and of the most adequate sealing method are very important for the reliability and durability of the dam of the storage reservoir.

This paper does not discuss the use of surface carpets which are reliable on rocky reservoir slope and unreliable on clayey bottom of karstic poljes (Breznik 1979).

2. GEOLOGIC EXPLORATIONS

A geologic map with the description, age and tectonic position of rocks exists already in most of the countries. More detailed maps have to be elaborated for the important parts of the basin. Favourable natural conditions as impervious Eocenic shale and sandstone and semi-impervious Upper Triassic dolomite layers, frequent between limestone in Dinaric Alps, have to be incor-

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(*) *Parafouilles en zones karstiques : reconnaissances, conception et construction.*

porated into the impervious system of a reservoir. In other words a reservoir has to be situated so as to include as much as possible of natural underground barriers. Classification of Karst terrains (Herak, 1977) in accordance with its tecto-genesis indicates already the characteristics known for different Karst types.

Epi-orogenic karst is developed within carbonate deposits laid down in an epicontinental sea or in fresh water conditions. The normal position of rocks is more or less horizontal. Faults have often a regional extension. Impervious rocks form the karst basis. The depth of karstification is clearly defined. Surface and underground flows are frequent. Descending and overflowing springs are predominant.

Orogenic karst is formed in carbonate rocks that were before their karstification subjected to orogenic disturbances with imbricate structures and very often with overthrusts. The thickness of rocks prone to karstification defines the morphological and hydrogeological features of a karst area.

In the Orogenic accumulated karst the great primary thickness of carbonate rocks and also the secondary one (accumulation of karst terrains), karstification below the deepest valleys and in the coastal region below the sea-level are specific features. The real basis of karstification is unknown. All morphological forms are developed comprising polies with complicated hydrogeology and broad karst plains. Karstic springs, ponors (swallow-holes), estavelles (springs in rainy and swallow-holes in dry periods) lost rivers and submarine springs are common. Rock complexes are highly disturbed, and therefore the formation of extensive caves and caverns on one level is reduced in comparison with the varieties of epi-erogenic karst. Surface water sheds are exceptional, subsurface ones not in accordance with the topography are common. The Dinaric High-karst belt in Yugoslavia, the Hellenic karst in Greece, the Tauros Mts. karst in Turkey, the Zagros Mts. karst in Iran and others are of this type.

The described karst types are characterised by specific underground nets of hollows and hence by some hydraulic specifities, too. In any consideration of a karst area it is necessary to determine to which tectogenetic type of karst it belongs.

History of karstification in relation with recent tectonic movements is an important part of geologic explorations.

3. HYDROGEOLOGIC EXPLORATIONS

The region has to be divided into the area with surface runoff and into that one with subsurface runoff. Maps of surface karstic phenomena may already indicate the direction of former or present underground flow. Tracing of water flowing into the ponors and detecting it in karstic springs reveals the direction and the velocity of the underground flow. The average underground-flow velocity varies between 1 and 10 cm/s in the Dinaric Karst.

Observation of the piezometric levels is one of the most important tools in this exploration. A normal fluctuation of the piezometric levels is from 10 to 50 m and the maximum about 100 m in the Dinaric karst. All the boreholes are not good piezometers as some might be situated in impervious isolated blocks. Direction of underground flow and elevation of the lowest piezometric levels are the most important data. The lowest levels might indicate the existence of the relative basis of karstification in a depth of some metres or tens of metres below them. But a downstream-situated underground barrier may have lifted the levels to a higher elevation which might lead to erroneous conclusions. The position of a subsurface watershed of a region drained by two or three main karstic springs is estimated by its water balance. The discharge of springs, the precititation, the infiltration rate and the supposed position of the watershed have to be taken into the calculation. The method is called a backward calculated water balance. Infiltration rates in the Dinaric High-karst belt are high, namely of 0.6 to 0.9.

A multiple tracing test is needed in an advanced stage of explorations in an area with complicated underground-flow conditions (Fig. 1).

Different tracers are introduced in different ponors and all the springs in a larger area observed. A period with a constant flow has to be selected and discharges of water into the ponors and out of the springs have to be measured. The amount of tracers recovered out of different springs has to be measured Underground flow bifurcations, that is a flow from one ponor to different springs, is a rule and not an exemption in regions with deep karst. Such a test requires some years of preparatory works, a numerous skilled staff and large funds. An example is the Tracing test of the Ljubljanica-river karstic catchment area in NW-Yugoslavia in 1975 (Fig. 1).

This test over an area of 1,100 km^2 with a total mean discharge of 38 m^3/s and only two profiles with discharge measurement possibilities has enabled the partition of the region into 8 subcatchment areas. A complete water balance of each area with inflow and outflow was implemented (Fig. 2).

This has made feasible the computation of inflow into 2 possible prospective reservoirs of Cerknica and Planina situated inside this karstic region.

The water test is another very important tool of exploration. In karstic areas the water test has to be done in the downward direction by 5 metre sections throughout the boreholes. Water pressures of 500, 1,000 and 500 kPa have to be applied for 5 or 2 × 5 minutes. The results have to be presented graphically in Lugeons (l/min/m of borehole at a pressure of 1,000 kPa). The permeability coefficient (Darcy) should not be computed from water tests. Such results are always misleading. The reason is the unisotropic nature of karstic aquifers where the flow in channels and drains is not consistent with the uniform Darcy flow in isotropic aquifers. The Lugeon values give an idea on the karstification and permeability of the karstic rock massif. A value of 1 Lu indiccates an "impervious", of 10 Lu a moderately, of 30 Lu a very pervious and from 100 to 1,000 Lu an extremely pervious section of the rock massif. The

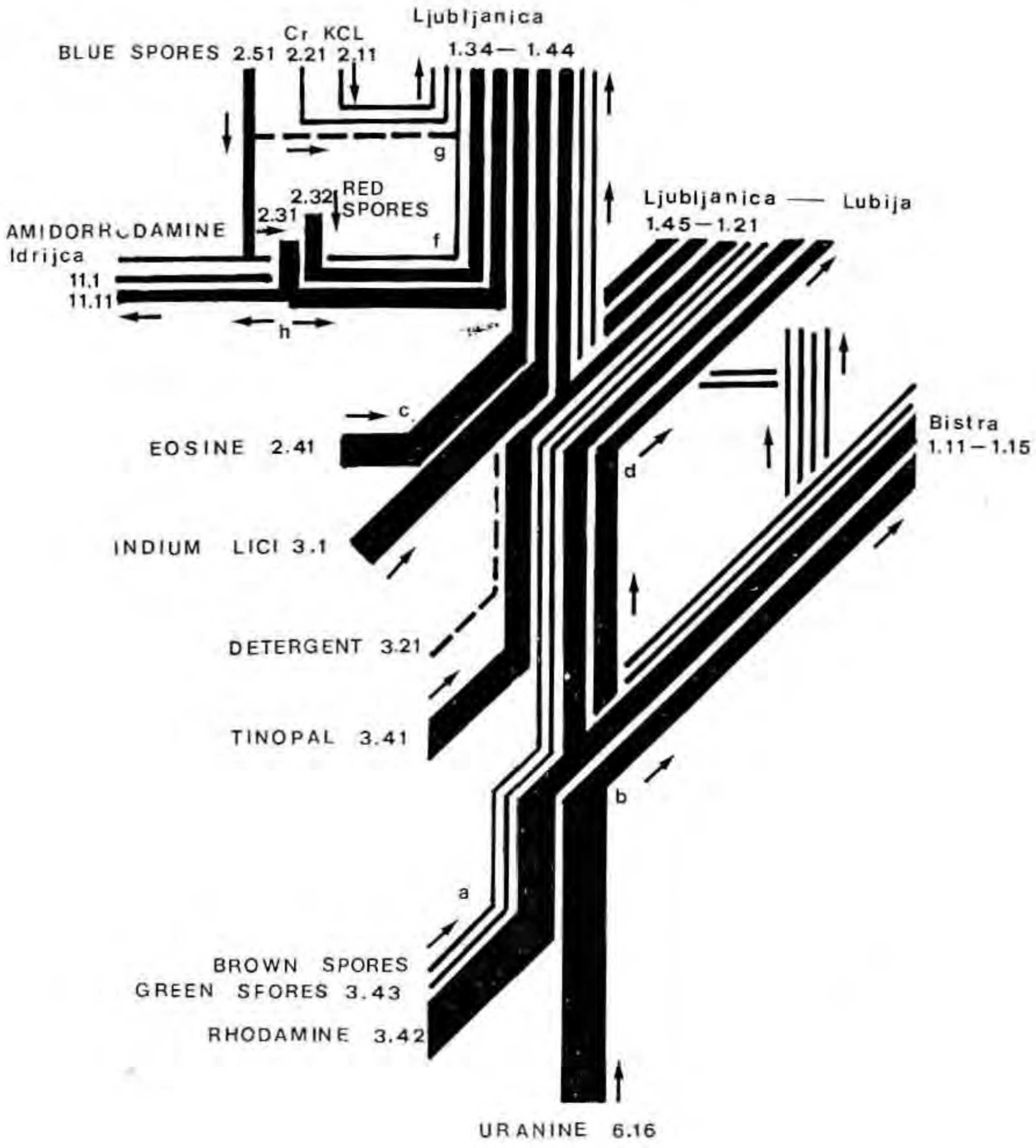

Fig. 1

Underground water connections scheme after the results of water tracing experiment 1975 (after Habič 1976)

Revue des connexions d'eau souterraine d'après les résultats d'essai de traceurs en 1975 (d'après Habič 1976)

a. to h-main critical points in the underground drainage system, where the underground flows are united and dismembered
6.16-2.11 karstic ponors
1.11-1.44 and 11.1-11.11 karstic springs, uranine and others-tracers

a. à h-principaux points critiques dans le système de drainage souterrain où les courants souterrains sont unis ou divisés
6.16-2.11 ponors karstiques
1.11-1.44 et 11.1-11.11 sources karstiques, uranine et autres traceurs

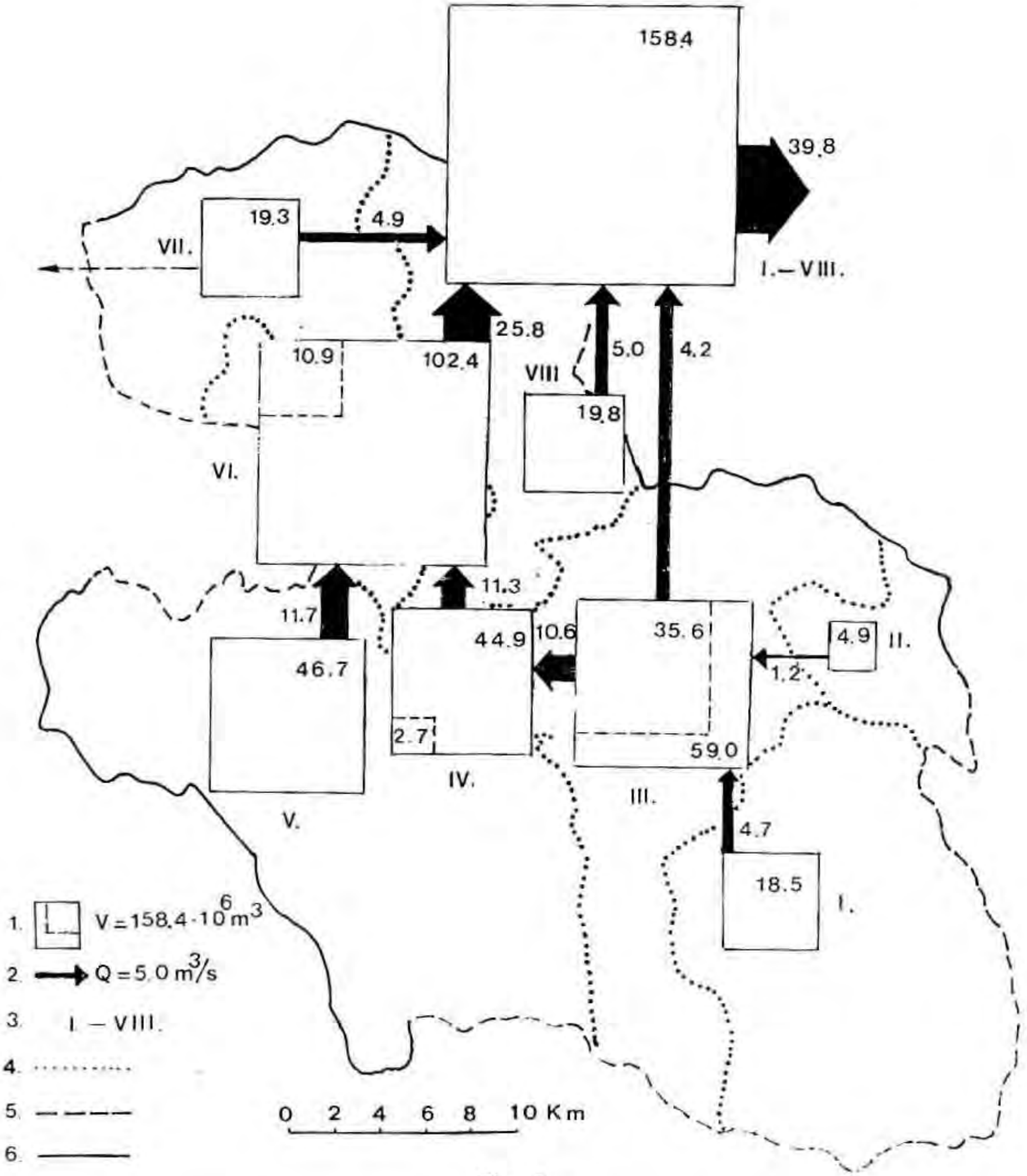

Fig. 2

Waters runoff from the subcatchment areas of the Ljubljanica river karst basin during the tracing test period (May 26th till July 1975) (after Žibrik, Lewicki and Pičinin 1976)

Écoulement total des sous-bassins versants du bassin karstique de la rivière Ljubljanica (d'après Žibrik, Lewicki, Pičinin 1976)

1. Total runoff	*1. Écoulement total*
2. Discharge	*2. Débit*
3. Subcatchment areas, assumed and calculated	*3. Sous-bassin versant, supposé et calculé*
4. Boundary of subcatchment areas	*4. Limite du sous-bassin versant*
5. Karst watershed line, supposed	*5. Limite du bassin versant karstique supposée*
6. Superficial watershed line	*6. Limite superficielle du bassin versant*

same applies to the "indeterminably high" Lu in section where the water pressure cannot build up due to a too small capacity of the pump. In order to avoid such a section a 200 l/s pump has to be used and shorter sections of boreholes tested.

Table I shows the nature of a karstic aquifer with "impervious" rock and an extremely pervious sections in a karstic cavern.

Table I

Water test in borehole V-31 on the slope of Planinsko polje (after Breznik, 1962)

Essai d'eau dans le forage V-31 sur la pente de Planinsko polje (d'après Breznik, 1962)

Section	Water pressure kPa	Consumption of water Litre per minute per metre	Remark
3.4-20.0	1.000	11.6 -31.0	
20.0-30.0	1.000	0.29- 0.9	"impervious" layer
30.0-54.5	1.000	7.5 -26.4	
54.5-60.5	1.000	0.34	"impervious" layer
60.5-65.5	500	25.0	
65.5-70.0	0	29.0	flow without pressure
70.4-90.5			karstic cavern

Very important is the estimation of the present depth of the basis of karstification, i.e. the lowest zone with significant groundwater flow at the present. Below that zone is the zone of semi-impervious carbonate rocks in which the underground water movement is reduced and water losses are small. The method of karstification history is to be used.

A 6 kilometre long left-bank stretch between Goričica and Laze of the Cerkniško polje reservoir is in a very karstified Cretaceous and Jurassic limestone. There are numerous estavelles and the piezometric level falls by 10 or more metre below the surface of the polje in dry periods. Former researchers supposed big losses of water into that stretch and possible outflow into the Pivka river which is at the same elevation and 10 kilometres distant. The construction of a reservoir would not be feasible (Fig. 3).

Yet the study of the history of karstification of the Javornik mountain range that separates the Cerkniško polje and the Pivka valley showed a different picture. The 600 metre higher Javornik mountain is a still raising horst separated by subvertical faults from the Pivka and Cerknica poljes. The infiltrated water flows probably to both sides of the mountain where the main karstic channels are formed along the border faults. Such an underground-water flow pattern requests a rising piezometric level, a rising basis of karstification and a rising semi-impervious rock from both the poljes towards the centre of the Javornik mountain. A semi-impervious rock in the central part of the

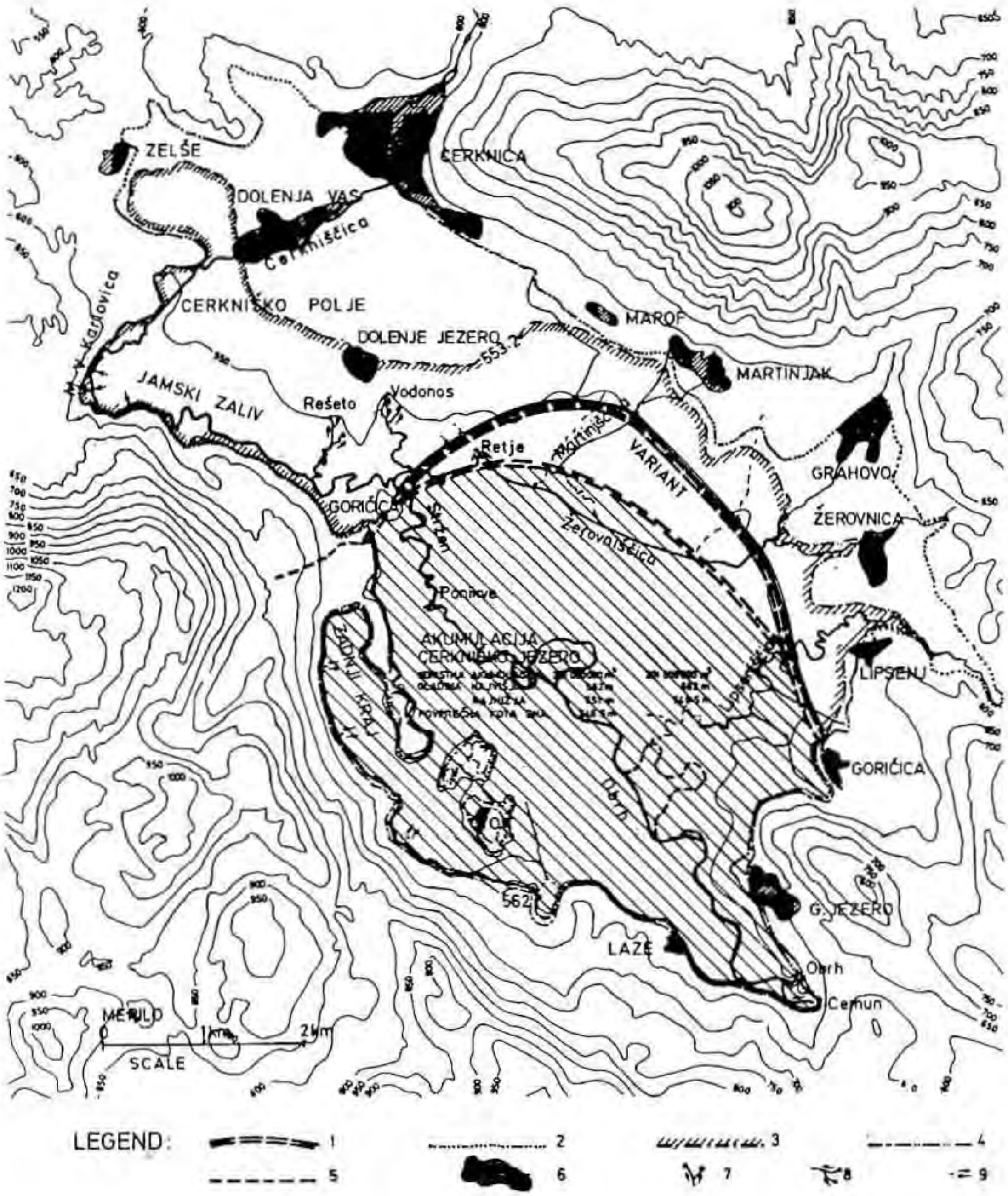

Fig. 3

Site of the Cerkniško polje dam (after Breznik 1983)

Site du barrage de Cerkniško polje (d'après Breznik 1983)

1. Position of dam	*1. Position du barrage*
2. Boundary of polje	*2. Limite du polje*
3. Boundary of highest natural flood	*3. Limite de l'inondation maximale naturelle*
4. Boundary of reservoir	*4. Limite du réservoir*
5. Grout curtain	*5. Voile d'injections*
6. Settlements	*6. Villages*
7. Karstic swallow hole	*7. Ponor karstique*
8. Karstic spring	*8. Source karstique*
9. Karstic estavelle	*9. Estavelle karstique*

mountain situated at a higher elevation than the highest reservoir level prevents water losses out of the Cerknica reservoir toward the Pivka valley. This suposition had to be confirmed by 500 metre deep piezometric boreholes between Cerknica and Pivka.

The supposed main karstic channels along the Cerknica-Javorniki fault had to be sealed by a grout curtain in the rocky abutment of the dam (Fig. 4).

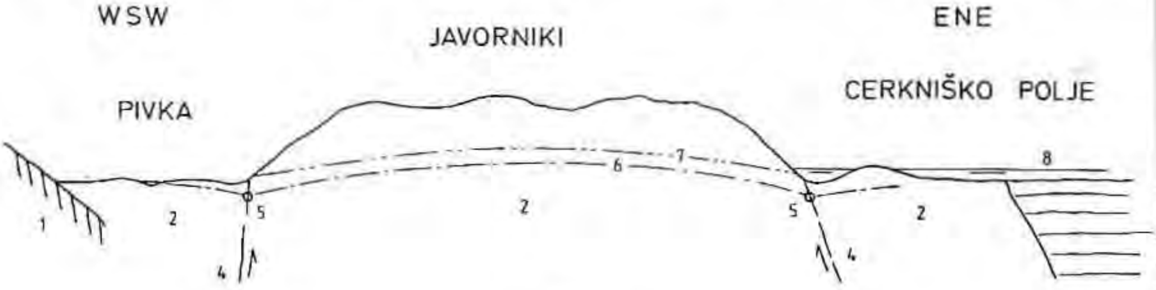

Fig. 4

Supposed hydrogeologic cross section of Javorniki mountain range (after Breznik 1983)
Section hydrogéologique supposée de la chaîne de montagnes Javornik (d'après Breznik 1983)

1. Eocene flysch, impermeable	*1. Flysch d'eocene, imperméable*
2. Limestone, karstic and permeable	*2. Calcaire karstique et perméable*
3. Upper triassic dolomite, semi-impermeable	*3. Dolomie du trias supérieur, semi-imperméable*
4. Fault with raising horst	*4. Faille avec horst élevant*
5. Supposed main karstic channel	*5. Principal chenal karstique, supposé*
6. Supposed lowest piezometric level	*6. Le plus bas niveau piézométrique, supposé*
7. Supposed high piezometric level	*7. Haut niveau piézométrique, supposé*
8. Reservoir level	*8. Niveau de retenue*

A very similar geologic estimation proved correct for the Mratinje reservoir. The Piva and Tara rivers have cut about 1,000 metre deep canyons into the rising Durmitor plateau. The distance between the two rivers is about 10 km at the dam site and their elevations equal. Both rivers are in Mesozoic limestone with a moderate karstification till at river level. The Piva level was raised by 190 m by the 220 metre high Mratinje dam. The responsible geologists estimated that the uplifting of the Durmitor plateau was so quick that the karstification could not follow it except along the river beds. A high basis of karstification between the Piva and Tara rivers prevents water losses out of the Piva reservoir into the Tara river in spite of considerable new gradient. Piezometric boreholes were not proposed for reason of the about 1,000 metre depth and the absence of roads in the montaineous region. A panel of Yugoslav geologists supported that estimation.

The reservoir is in operation since 1975 and no losses into the Tara river were observed.

4. GEOPHYSICAL EXPLORATIONS

The Planina polje in NW-Yugoslavia offers as a natural enclosed basin and due to a large belt of semi-impervious dolomite favorable natural conditions for the project of a storage basin.

Most of karstic poljes have an almost horizontal bottom which was formed by sedimentation of clay and silt during the rainy Pleistocene period when most of the poljes were lakes. On the border site of the Planinsko polje bottom there are active ponors which have washed away some metres of the thick natural clay-silt carpet. No active ponors exist in the main part of the polje bottom. Clogging of existing ponors and opening of old ones with clay and silt being washed away is a continous geologic process.

We are interested in finding possible areas of fossilizet ponors and estimated that the clay-silt carpet shold be thicker in such former outflow areas. The thickness of the carpet was determined by the geophysical method of apparent resistivity in profiles distanced by 30-60 m. The map displaying the thickness of the natural clay-silt carpet clearly indicates the regions of fossilizet ponors.

A geophysical detection of deep large karstic channels which are the main drains of a karstic region would be of the upmost importance. By the geoelectrical Turam method a shallow karstic channel was easily detected. Yet so far, it was not possible to detect any deep large channels.

A floating device of a weight of 10 N and with a delayed-explosion mechanism was inserted into a ponor. The position of the underground explosion was located by means of geophones arrayed as usual for geophysical seismic tests. The explosion was programmed for half an hour after the insertion of the "geophysical bomb" as the device has been dubbed, into the ponor. The position of the explosion was detected at a distance of some hundreds metres from the ponor in a karstic channel which was the outflow of the ponor. This method is not often applied as the device can be inserted into the underground only through a rather large ponor. It is also costly and to some extent dangerous.

A general conclusion is that at the present geophysical measurements cannot detect at a reasonable cost in a karstic massif a large karstic channel at a depth of some tens of metres.

5. POSITION OF CUT OFFS

The dam with cut off, the cut off in the rocky abutments and the cut off in the reservoir slope have to be situated in such a position that the sealing works are at the least difficult and expensive. In karstic regions the cost of cut offs some times exceeds the cost of the dam, therefore the position of the dam is selected in accordance with this fact.

Generally it is necessary to take advantage of possible favourable geologic conditions in a part of the reservoir and to place the sealing structures there. This requires much more explorations regarding the permeability of rocks than in non-karstic regions. A general concept on the possibility of sealing the reservoir has to be formed and in a later stage of explorations confirmed. Cut offs have to be connected with natural impervious barriers or situated in areas of the smallest karstification. Some initial permeability along a fractured zone enhances the initial groundwater flow and the process of karstification. As a consequence the karstification is stronger along main and secondary fault zones.

Hydrogeologically, there are two different situations for the outlay of a reservoir in karstic regions, i.e. :

— a reservoir in a karstified valley, or

— a reservoir in a karstic polje.

If a river which is the main drainage and the present erosional base flows through the valley, a reservoir is formed by blocking the river by a dam. The tributaries of the river are mainly developed as karstic springs along the river. Normally some of their karstic channels are situated below the river bed and sometimes as syphons feed springs on the opposite site of the main catchment area. Karstification exists also below the river bed. The dam and the cut offs have to be situated in an area with few faults and few springs where the karstification is apparently less developed. Cut offs in the abutments have to avoid bigger cavities. With deviations of the grout curtains it is possible to close a karstic channel at its narrowest section.

From 30 to 200 metre high dams with their grout curtains were constructed in Yugoslavia at Peruča, Liverovići, Prančevići, Grančarevo, Globočica, Rama, Špilje, Kruščica, Mratinje, Grabovica, Salakovac and other sites during the last 30 years. All these reservoirs are in operation and a proof of successful constructions in karst regions.

A karstic polje is an enclosed basin with an almost horizontal bottom. On one side of the polje is the springs area and on the other the ponors (swallowholes) area. Many poljes are flooded in rainy periods. After the rainy period a river flows between the springs and ponors areas. In the dry period most of the poljes are without surface flow, all the drainage proceeding underground. On most of the poljes there is an impervious barrier which has forced the underground river to the surface in the springs area. A good solution is the isolation of the ponors area from the main part of the polje by a dam and grout curtain and the connection of the dam to the impervious barrier of the springs area. Another possibility is sealing the outflow area of the polje by a dam and a grout curtain through the slope of the polje. The big reservoirs in operation on the Nikšićko polje and Buško Blato constructed 20 and 10 years ago are evidence of a successfull development. A preliminary design was made for the Planinsko polje and Cerknisko polje (Fig. 3). All these reservoirs are in the Dinaric high-karst zone in Yugoslavia.

6. DEPTH OF CUT OFFS

The upper part of a cut off is either a diaphragm wall or a grout curtain and the lower one a grout curtain. There are two concepts regarding the depth of the grout curtain. Anchored grout curtains should reach into the impervious layer in non-karstic regions. In karst regions we consider as anchored also those grout curtains that reach into semi-imprevious carbonate rock where we accept in advance some loses of water. The thickness of the carbonate rock in the Dinaric high-karst zone is some kilometres and such is the depth of the impervious rocks.

As a semi-impervious rock in karst regions is regarded a stratum :

— in which the fossilized karst forms (channels, caves and cavities) are filled with erosion-resistant sediments (bauxite or sandostone);

— into which the speleologists could not enter or where they did not directly measure the depth of open karst form;

— in which during the course of drilling only smaller or rare karst forms were detected;

— in which the apparent electric resistance is decreased;

— in which the amount of water is smaller at the water tests than the selected seepage expressed in Lugeon units (1-5 Lu). The limit is not fixed and is to be chosen according to the importance of the construction;

— which reaches some tens of metres (about 10 to 50 m) farther down than the lowest level of the underground water;

— in which the expected water losses are small and as such economically acceptable.

In Table 2 some relevant data on Yugoslav dams are given.

Table 2

Depth of anchored grout curtains in Yugoslavia (after Breznik 1979/1)
Profondeur des écrans d'injection ancrés en Yougoslavie (d'après Breznik 1979/1)

Name of curtain	Raise of level above river level or polje bottom (in metres)	Lowest ground below river level or polje bottom (in metres)	Depth of grout curtain bellow river level or polje bottom (in metres)
Peruća dam	55	0	200
Peruća abutment	55	0	30
Grančarevo dam	100	0	40-150
Grančarevo abutment	100		70
Sklope dam	80	0	80
Sklope abutment	80		30
Mratinje dam	185	0	200-132
Mratinje abutment	185		50
Krupačka jama Nikšić	12	8	30
Siroka ulica Nikšić	15	49	75
Planinsko polje (design)	35	10	45

Hanging grout curtains are defined as those which reach down into a rock of strong or medium karstification. This means that their deepest section is above the semi-impervious zone and that under the lowest line of the grout curtain there is still permeable rock.

The profile of the spilje dam is built of medium-permeable cretaceous flysch (marl, marly clay, limestone), semi-impervious Triassic chert, and under this lies highly permeable Triassic limestone of big thickness. The dam is 101 metre high. The grout curtain reached at the dam 90 m and in the abutments 50 m below the river level. Water losses are ca. 2.2 m³/s and exceed the estimated values. The discharge of the biggest springs is more than 0.1 m³/s. The Triassic limestone is probably still highly to medium permeable below the grout curtain.

The Buško Blato polje was flooded in natural conditions for several months every year up to 3 m above the ground. The mean surface inflow was 11.7 m³/s and the mean capacity of ponors estimated at 38.8 m³/s. The biggest water losses were till the depth of 40 m below the surface of the polje during the water tests. The lowest undergroundwater levels were 20 to 60 m in the inflow area and 80 to 100 m in the ponors area below the surface of the polje. The reservoir of 800 hm³ was formed by the 19 metre high and 3 kilometre long Kazaginac dam with a 70 to 120 metre deep grout curtain that isolated the main swallowholes area from the basin. An additional 6.4 kilometre long grout curtain was constructed on the polje slope downstream of the secondary swallowholes area. In the first phase this curtain was designed as a hanging one reaching to a depth of about 50 m below the surface of polje. The aim of this curtain was to block the zone of the main underground channels. The reservoir is in successfull operation since 1972. According to the design water losses of ca. 3 m³/s were to be expected. The actual losses exceed that value.

The 185 metre Keban rockfill dam has a reservoir of 30,600 hm³, the biggest in Turkey. The mean discharge of the Euphrates river is 655 m³/s. The reservoir level is at an elevation of 845 m. The lowest points of the dam grout curtain are at elevations 610 to 570 m and the grout curtain of the left abutment at an elevation of 600 m. In the last phase of construction the Crab cavern was found at an elevation of 510 to 530 m. The cavern was filled with 63,400 m³ of pumped concrete and grout.

The losses from the reservoir, which were initially 8 m³/s greatly increased to 25 m³/s when the maximum level had been reached in June 1976. On the left bank of the reservoir, 200 m from the concrete dam, there opened in the limestone slope, at an elevation of 830 m a new swallow-hole. Under the swallowhole a big karstic cavern was found. The losses of water were reduced to 8 m³/s by a concrete dam around the swallow-hole, a concrete carpet on the limestone slope and the filling of the cavern with alluvial and quarry-waste material. In the spring of 1979 the cavern was not yet filled although 600,000 m³ of material were dumped into it.

At the present the left limestone slope of the dam has two sealing structures : a hanging grout curtain and a surface concrete carpet that are not interconnected. Water losses are reduced. There was never any danger to the safety of the dam (Fig. 5).

Such a deep karstification could be explained by favourable flow conditions in the deep syphons. Marble and limestone which are the upper part of the Paleozoic Keban carbonate formation are highly fissured and cavernous. The medium layer of the Keban formations is represented by semi-impervious carbonate schist 15 to 130 m in thickness. The lower layer of this formation is a hard dolomite, karstified and pervious. The Keban formation is at the top and the bottom side of the dam and all around the dam area overlaid with younger Paleozoic metamorphic schists which are impervious (Fig. 5). Such a "sandwich" structure of highly pervious and impervious rocks is favourable for flow

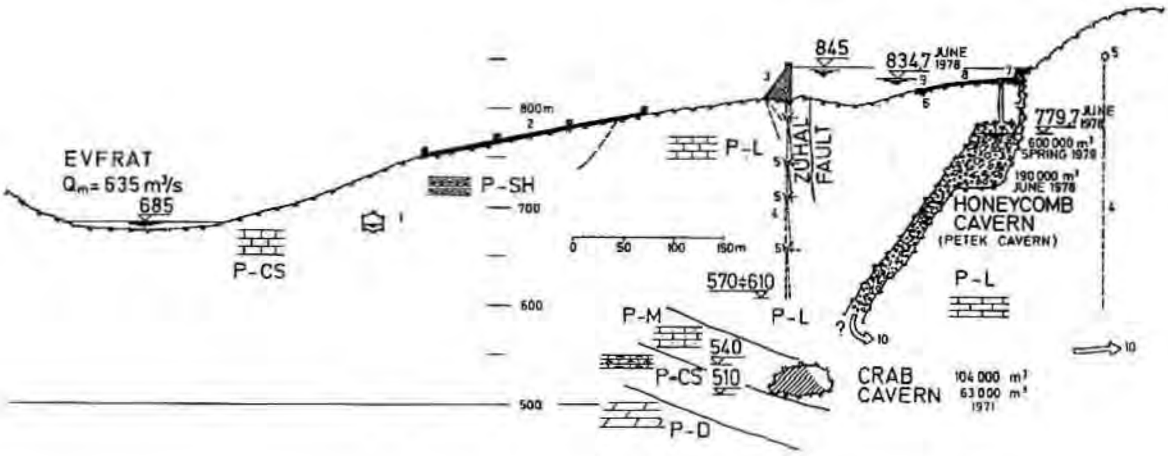

Fig. 5

Cross section of Keban dam and left reservoir slope

Coupe du barrage de Keban et du flanc gauche du réservoir

1. diversion tunnel	*1. galerie de dérivation provisoire*
2. spillway chute	*2. évacuateur à coursier*
3. gravity dam	*3. barrage-poids*
4. grout curtain	*4. voile d'injection*
5. grouting gallery	*5. galerie d'injection*
6. swallow-hole	*6. ponor*
7. swallow-hole plugged by gravity dam	*7. ponor fermé par barrage-poids*
8. concrete carpet	*8. tapis d'étanchéité en béton*
9. dental filling of swallow-hole	*9. bouchon en béton*
10. probable direction of water leakeges	*10. direction probable des pertes d'eau*
P-SH. paleozoic schist, impervious	*P-SH. ardoise paléozoïque, imperméable*
P-L. paleozoic limestone, highly karstic and pervious	*P-L. calcaire paléozoïque, très karstifié et perméable*
P-M. paleozoic marble, highly karstic and pervious	*P-M. marbre paléozoïque, très karstifié et perméable*
P-CS. paleozoic calc-schist, semi-impervious	*P-CS. ardoise-calcaire, semi-imperméable*
P-D. paleozoic dolomite, karstic and pervious	*P-D. dolomie paléozoïque, karstifié et perméable*

in deep syphons. In fact, an underground flow of 1 m³/s was found during the excavation of the diversion tunnel. This flow still infiltrates into the diversion tunnel at the present. At a 20 kilometre distance from the dam is a 25 km² karstic area without surface outflow. This could be the recharge area of the flow which has to follow the limestone and dolomite layers of the Paleozoic (Breznik 1979/2).

Former theories explained the very deep karstification below the Keban dam by a convectional flow of aggressive groundwater induced by postvulcanic processes. A 2 kilometre distant zinc mine should be a proof. Geological features in the underground of the Keban dam do not confirm that theory.

Karstification of small patches of carbonate rocks completely surrounded by impervious rocks is not an exemption. The reservoir Mavrovo of 357 hm³ is located in impervious metamorphic schists. Small patches of marble are included in the schists. After 3 years of operation some ponors opened in the marbles with initial discharges of 10-11 m³/s and which were closed by a surface carpet. In three months 25 hm³ of water were lost. New springs opened in the marble patches 4 km away and at an altitude lower by 320 m. One month after the opening of the swallow-holes the flow of these springs was 0.03 m³/s, a few days after the provisional filling of ponors it reached a maximum of 0.8 m³/s and stopped completely four months after the ponors had been plugged. Less than half of the lost water flowed out in springs. The rest has probably filled lower cavities.

7. DESIGN OF CUT OFFS

A grout curtain can fill only open fissures and cavities. It cannot replace an erodible natural filling of cavern as there are sand and clay. Washing out of this sediments is time consuming and costly. It was successfully done for the consolidation treatment of the rock below the Grančarevo dam. A net of boreholes at distances of 4 m was drilled. Into the outer boreholes water and compressed air were pumped and the rock around the inner open borehole washed. The procedure was effective but time-consuming and costly.

As cavities are mostly filled in the uper part it is advisable to replace a grout curtain in the upper 5-15 metres by a concrete diaphragm wall.

Single-rowed grout curtains with mean distances between boreholes extending from 1 to 2.5 m are mostly used today. In very karstified section a three rows grout curtain, with a distance of 2 m between the rows, offers a possibility of different pressures of grouting fluid to be applied. The outer rows are completed at a smaller pressure and the inner one at a bigger one. The purpose of the outer rows is to prevent long distance losses of grout mix.

The applied pressures correspond to a single or double weight of the rocks covering the grouting section. They range between 500 and 4,000 kPa.

The sequence of grouting is usually from the bottom of the borehole toward its mouth what means in the upward direction.

Cement-bentonite mix, containing 5-15 % of bentonite and for the caverns cement mortar, containing up to 65 % of sand are used for higher dams e.g. Mratinje, Kremasta and Keban.

Grout mix containing 25-30 % of cement, 70-65 % of clay and 5-10 % of bentonite and sometimes with an addition of up to 50 % of sand was used for the construction of dams in strongly karstified regions as Peruča, Grančarevo, Sklope, Krupac, Slano, Buško Blato and other dams in Yugoslavia.

Drainage boreholes are usually not needed thanks to the porous character of the karstified rocks.

8. CONSTRUCTION OF CUT OFFS

Diaphragm walls are constructed in open trenches or as sheet pilings of connected concrete piles if the inflow of water prevents the excavation of a trench.

The grouting of boreholes starts with a grout mix 1:4 (containing 1 part of dry materials and 4 parts of water), continues with a 1:1 mix and is completed with a 1:4 mix when the requested pressure in achieved.

The so-called "final criterium" for the completion of a section of grouted boreholes is usually signalled by the requested injection pressure and decrease in consumption to about 3 litres per minute of a 1:4 grout mix during the last 15 or 30 minutes of grouting. The biggest danger for a pervious grout curtain are "uncompleted sections" in a borehole. That means sections in which the final criterium was not met. These are normally sections with caverns or sections not distant from such ones.

The caverns are filled either by intermittent grouting with sand-enriched grout mix or by filling the cavern with gravel and subsequent grouting or by pumped-concrete filling. The final stage is grouting till the final criterium is met. But this is easier to request than to achieve. Here a constant cooperation of the design engineer, of the constructor, both with large experience, and of the investor is needed. The way how to seal a difficult section of the borehole has to be found on the site.

The consumption of dry grout mix is 1 to 16 kN per 1 metre of borehole or about half of that amount per 1 square metre of curtain. Yet, over 20.000 kN of dry mix were needed to complete some difficult boreholes in Yugoslavia.

Pervious parts of the Buško Blato grout curtain were found and later sealed by temperature logging in boreholes on the downstream side of the curtain. The winter temperature of 4 °C and summer temperature of 17 °C of lost reservoir water clearly differ from the constant temperature of 8.5 °C of underground water (Borić 1980).

9. CONCLUSIONS

Karstification of rocks changes already over small distances. This requires much more explorations than in not-karstic areas.

The tecto-genetic classification of karst terrains and history of karstification are new useful methods which should be applied.

Observation of piezometric levels during some years and water tests in boreholes are the most used hydrogeologic methods. Water tests clearly indicate the degree of karstification. Yet, the value of the permeability coefficient calculated from the results of water tests is dubious. Water losses calculated by such coefficients were misleading. Probably not enough attention was given to the sections where a water test could not be performed due to high losses of water. The second reason is the unconsistence of the flow through karstic channels and the Darcy flow through an isotropic continuum.

Geophysical explorations are useful in borehole logging but could not detect a karstic channel with adequate precision and at a reasonable cost.

Position of the cut offs is very important. Bigger caverns have to be avoided or crossed at the narrowest section. Main swallow-holles areas of karstic poljes have to be isolated from the reservoir.

Determination of the basis of present karstification is of utmost importance. Groundwater circulation below that basis is very small. Grout curtains anchored into semi-impervious carbonate rock, have proved successfull. Water losses of hanging grout curtains exceed expected values. Single-row grout curtains with a distance between boreholes of 1 to 2.5 m are mostly used now.

Drainage boreholes are normally not needed thanks to the pervious character of the rock massif.

In the construction phase it is most important to complete all the sections of boreholes in accordance with the design. This is very difficult in caverneous sections.

A normal consumption of dry grout mix is 5 kN per metre of borehole in strongly karstified rock. Over 20,000 kN of mix was consumed in difficult boreholes.

Some water losses of at least 1 m^3/s have to be expected out of every karstic reservoir.

Sealing by surface carpets which are reliable on rock slopes and unreliable on clayey bottom of karstic poljes is not discussed in this paper.

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SUMMARY

Much more explorations are needed in karstic than in other areas. The Tecto-genetic classification and history of karstification are useful new methods. Observation of piezometric levels and water tests in boreholes are the most used hydrogeological methods. Water tests indicate the degree of karstification but the permeability coefficient and losses of reservoir water calculated from water tests are not correct. Geophysical measurements could not clearly detect a karstic channel with flowing groundwater.

Bigger caverns have to be avoided by cut offs or crossed at the narrowest section. Main swallow-holes areas of karstic poljes have to be isolated. Groundwater circulation is very small below the basis of karstification. Cut offs anchored into semi-impervious rock are reliable. Water losses of hanging cut offs exceed expected values. Drainage boreholes are normally not needed. In the construction phase every section of the borehole has to be completed in accordance sith the design. Some losses of water are expected out of every karstic reservoir.

This paper did not discuss the sealing by surface carpets.

RÉSUMÉ

Il faut exécuter beaucoup plus de recherches dans les régions karstiques que dans les autres régions. La classification tecto-génétique et l'incorporation de l'histoire de la karstification sont de nouvelles méthodes très utiles. L'observation des niveaux piézométriques et les essais d'eau sont les méthodes hydrogéologiques les plus utilisées. L'essai d'eau indique le degré de la karstification mais le coefficient de perméabilité calculé par les essais d'eau et les pertes d'eau de réservoir ne sont pas justes. Les méthodes géophysiques ne peuvent pas clairement déterminer la position d'un conduit karstique avec l'écoulement souterrain.

Les parafouilles doivent éviter les grandes cavernes ou les traverser dans la plus étroite section. Dans les poljes karstiques on doit isoler les régions des avens principaux. L'écoulement est très faible en bas de la base de karstification. Les parafouilles ancrés dans le rocher semi-imperméable sont fiables. Les pertes d'eau des parafouilles suspendus étaient plus grandes que les prévisions. Les forages drainants ne sont pas nécessaires ordinairement. Chaque section du forage doit être terminée en accord avec le projet pendant la construction. Chaque réservoir karstique va subir quelques pertes d'eau.

Ce rapport ne traite pas des tapis d'étanchéité.