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SPECIFIC ENGINEERING GEOLOGICAL AND GEOTECNICAL PROBLEMS OF DAM CONSTRUCTIONS IN KARST TERRAINS

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Sažetak: U radu je, na početku, dan opći prikaz problema izgradnje brana – formiranja akumulacija u krškim terenima, zatim specifičnosti krških terena, specifični inženjerskogeološki problemi i mjerodavni činioci uticaja krškog procesa i njegovih tvorevina na izgradnju brana u njima. Izgradnja brana u krškim terenima predstavlja poseban problem koji zahtjeva dopunske uvjete u odnosu na uvjete u ostalim terenima, te je zbog toga neophodna posebna opreznost tokom inženjerskogeoloških istraživanja, ali i izgradnje i eksploatacije. U krškim terenima postoje brojni, složeni, raznovrsni pa i specifični inženjerskogeološki problemi, skoro uvijek nešto drugačiji, na svakoj novoj lokaciji, koji se moraju uzeti u obzir pri izgradnji brana. Na kraju rada daju se karakteristični primjeri inženjerskogeološkog rizika izgradnje brana u krškim terenima, iz inozemne i domaće prakse, gdje su sanacioni radovi dali pozitivna rješenja, ali i primjeri gdje ni obimni i dugotrajni sanacioni radovi sa velikim financijskim sredstvima, nisu dali zadovoljavajuće rezultate. Posebna pažnja posvećena je riziku proviranja vode iz akumulacije.

Ključne riječi: inženjersko-geološki i geotehnički problemi, izgradnja brana, krški tereni.

Abstract: The paper first presents a general overview of the problem of dam construction - the formation of reservoirs in karst terrains, followed by the overview of the karst terrains specificities, specificities of engineering geological problems, and the relevant influence factors of the karst process and its forms on dam construction in karst. The construction of dams in karst terrains is a special problem that requires additional conditions in relation to the conditions in other terrains, which is why special care is needed during engineering geological research, as well as construction and operation. There are numerous, complex, diverse and specific engineering geological problems in karst terrains, almost always somewhat different, at each new location, which must be taken into account when constructing dams. Typical examples of the engineering geological risk of constructing dams in karst terrains, from foreign and domestic practices, are presented at the end of this paper, including both, remediation works that have given positive solutions, and cases where extensive and long-term remediation works with high financial resources have not given satisfactory results. Special attention is given to the risk of water seepage from the accumulation.

Keywords: engineering geological and geotechnical problems, dam construction, karst terrains

1. General information about construction of dams and formation of reservoirs in karst terrains

Numerous reservoirs are formed by constructing dams in karst terrains, some of them with exceptionally large water mass volumes, even in terrains that seemed quite problematic in terms of water retentivity. However, there are also examples of unfulfilled desires, or constructed dams butnot formed reservoirs. They are usually a consequence of different factors, especially geological ones. *This is best illustrated by the example of the Montejaque reservoir in Andalusia, which cannot be filled in any way (Coyne, A, 1955).* In spite of the large number of dams and reservoirs formed in karst terrains, *the problems of providing bedrock stability and reducing permeability* (water loss from reservoir) *have not been fully resolved yet.*

These problems are caused by the complexity of the karst process, which is manifested in the entirety of geological phenomena occurring in rock mass. Karst terrains are characterized by a specific relief and hydrographic network and surface water and groundwater regime of its own kind. Karst aquifers are characterized by high fluctuation in levels. The amplitude of aquifer fluctuation levels in Herzegovinian karst is about 300 m. In the rainy season, aquifer levels increase by about 100 m in just 24 hours. Groundwater flow velocities in karst are high. Groundwater passes a distance of 35 km in only five days, while it needs twenty three years to pass the same distance in coarse-grained sands (Milanović, P. 1979).

We will mention some examples of dams built in karst that faced the problem of losing water from reservoirs, immediately after being filled: Keban (Turkey) 26m^3/s; Višegrad (BiH, Republic of Srpska) 24m^3/s; Vrtac (Montenegro) 14.8m^3/s; Camarasa (Spain) 11.2m^3/s; Mavrovo (Macedonia) 9-12m^3/s; Salakovac (BiH) more than 10m^3/s; Ataturk (Turkey) more than 10m^3/s; Lar (Iran) 10.8m^3/s; Canelles (Spain) 8m^3/s; Slano (Montenegro) 8m^3/s; Buško Blato (BiH) 5m^3/s; Gorica (BiH, Republic of Srpska) 2-3m^3/s (P. Milanović, 1996) – according to the most recent data (2003) the losses in the right side of the dam near the grout curtain are about 4m^3/s.

There are numerous examples where reducing water losses and ensuring the stability of facilities required large-scale sealing works which in most cases produced satisfactory results, i.e. water losses were significantly reduced (Keban, Camarasa, Mavrovo), or reduced to a negligibly small amount (Krupac, Canelles). There are also examples, as is the case of the Lar hydropower structure, showing that even long-term repairs with large financial resources have not produced satisfactory results. This experience causes dam constructors to be cautious when building in karst terrains, and geologists/engineers to take a systematic approach to research aimed at determining all factors affecting the definition of engineering geological and hydrogeological conditions for dam construction and reservoir formation in karst terrains.

In addition to the loss of water from reservoirs, there are also numerous examples of dam failures, where the causes were usually geological in nature. Statistical data indicate that about 1% of a total of 9000 large dams in the world collapsed and about 2% were seriously deformed or damaged during the 20th century (Zolotarev, S. G., 1990). According to L. Miller, one third to one half of the failures were due to geological problems - insufficient geological data, their improper interpretation, insufficiently reliable geological predictions and so on.

Construction of dams and formation of reservoirs in highly karstified carbonate rock masses is exceptionally complex and requires the most detailed research. The requirements regarding engineering geological and hydrogeological documentation increase, and therefore more complex and extensive engineering geological and hydrogeological investigations are carried out. It is known in advance that they are related to the risk of high water losses. This risk can always be overlooked, and in most cases it can be reduced, and less often eliminated, with the help of more or less expensive improvement - sealing measures. The circulation of groundwater in limestone can lead to washout of cracks, but does not cause reduction in rock mass stiffness, as is the case with the rock masses containing a clayey component. For this reason, engineering geological and hydrogeological investigations in these terrains have specific tasks and realization methods.

In spite of these difficulties and risks of dam construction and reservoir formation in karst, they will continue to be built. The question now is, but why will they be built? Why almost 50% of water engineering facilities in former Yugoslavia were constructed or designed for construction in karst terrains (for example, the entire Trebišnjica hydrosystem), and precisely in exposed karst so.

In karst terrains dams are built primarily for the following reasons:

- In karst terrains, river valleys are usually gorge- or canyon-like in shape, and in morphological terms these are the most favorable locations for a concrete arch and gravity dam profile.
- River valleys in karst terrains have steep slopes and their hydropower potential is high. According to some estimates, 1m^3/s of water at a head of about 650 m produces about 32 million kWh per year.
- These are the areas in former Yugoslavia with the highest average annual precipitation, or areas with unusually favorable conditions for hydropower use of water potential, which is one of the reasons for construction and design of almost 50% of hydropower structures in the Dinarides area.

The construction of dams and formation of reservoirs in karst terrains is a special problem requiring additional conditions in relation to the conditions in other terrains, and therefore special caution is advised.

The high caution, which is positive and highly recommended, often turned into a negative extreme of eliminating any risk in dam construction and reservoir formation in karst. Such a perception does not lead to any progress in dam construction and reservoir formation in karst, but on the contrary, it leads to engineering conservatism.

Faced with the problems of dam construction and reservoir formation in karst terrains, without false modesty, we can say that experts of former Yugoslavia were often ahead of world experiences with their research.

2. Specifics of karst terrains

What actually is karst? Of the many explanations and definitions existing in the world, we will mention only two, one older, local Cvijić's one and one foreign one, given by Russian karstologist.

Cvijić, the world pioneer in the exploration of karst, gave this explanation: *"Limestone terrains are characterized by closed depressions on the surface, and interconnected tangle of caves and cracks under the surface; groundwater flows run through these voids, arranged below each other, between the ground surface and the impermeable layer".* Cvijić wrote that a karst area looks like *"petrified rough seas"*, which is the most faithful geomorphological description of these terrains, *whose interior or subsurface is even more complicated and undefined*. It is difficult to give a full description or characteristics of karst underground. *Porosity, and thereby permeability of karst underground, is comparable only to sieves or bee honeycomb structures.*

The definition of karst, given by Russian karstologists, and which was adopted at the symposium of karstologists in Moscow in 1956, reads as follows: *"Karst means the totality of the geological phenomena in the earth's crust and on its surface, caused by the chemical dissolution of rocks and manifested in the formation of voids in the earth's crust, in the disintegration and alteration of the structure and composition of rock, in the formation of the groundwater circulation and regime of a special character, of the special relief of the area and especially of the hydrographic network regime".*

The logical question: Why is karst complex and still puzzling for researchers and constructors, is best answered by the above definitions of karst.

Both definitions of karst imply: ***"groundwater circulation is the essence of karst"***. Occurrences of springs with discharges up to several m^3/s, but also ponors (swallow holes) with the same capacity and loss of water from reservoirs, as well as catastrophic intrusions of huge quantities of water in tunnels and other underground structures, are only possible in karst terrains.

Karst is of significance for civil engineers and especially hydraulic engineers who design and build in it large construction facilities (dams, tunnels and underground hydropower halls, channels) in order to impound and use karst waters for different purposes. They face the kind of problems that they do not have in non-karst terrains.

The above definitions of karst also provide the answer as to why there are many, complex, diverse and also specific engineering geological problems for dam construction and reservoir formation in karst terrains, almost always different at every new site.

Experiences gained in former Yugoslavia in construction of dams and reservoirs, tunnels, channels and other facilities, in typical holokarst terrains, indicate that there is a whole range of other karst problems that still remain open. Geological studies should include everything that they include when studying non-karst terrains, but paying particular attention to studying tectonic structure in doing so. Tectonic structure is particularly important not only for identification and clarification of the karst process but also for rational design and construction of hydraulic structures and geotechnical ameliorations.

When studying the lithological composition in karst terrains, it is necessary to go into such details as are rarely gone into in non-karst terrains. And the smallest lithofacial, even almost invisible, marly and clayey coatings on bedding surfaces have significance in the karstification process. When exploring karst terrains, it is of exceptional importance to establish underground karst forms and hydrogeological phenomena.

In karst there is a large number of specific surface and underground morphological phenomena. They are considerably more numerous and diverse underground, but for the time being they are studied in detail rather infrequently and are less known. With the exceptions of cracks and joints, all hollows in karst are still called caverns.

In morphological terms, caverns are usually isometric hollows formed by karst processes in limestones and other rocks susceptible to karstification. By the relationships between axes and diameters, caverns are different from tabular voids—cracks and joints—and linear voids—channels, karst conduits, siphons and shafts. In most cases, *caves* are complex forms, combined in a wide variety of ways from caverns, karst channels and conduits. Thus, considering their shape and less frequent interconnection, especially in deeper parts of karstified masses, caverns usually have the function of groundwater reservoirs, while in higher parts of karstified masses, where their connection with other forms of voids is more frequent, they have the function of reservoir conduits.

In contrast to caverns, karst channels, conduits and joints mainly have the function of hydrogeological conductors both in shallower and deeper parts of karstified masses. For this reason, such hollows in karst make the basic communications for movement of sometimes even very strong underground watercourses. These facts give us the right to attach decisive hydrogeological significance to karst channels, conduits and joints, rather than caverns, when solving hydraulic engineering problems in order to either examine the possibility of forming reservoirs or perform amelioration (irrigation and drainage) of ground in karst.

Finally, let us just point out that, when assessing the hydrogeological function of karst channels, conduits and joints, one should not overlook their narrowings - bottlenecks, as well as the total vertical dimension of the system of hollows, or more exactly the hydrostatic column, of which the groundwater speed and flow rate in karst undoubtedly significantly depend. For the purposes of dam construction and reservoir formation in karst terrains, geological investigations (structural, engineering geological, hydrogeological and geophysical investigations) *should determine the shape of caverns, their size, spatial position, mode of formation and hydrogeological functions.*

3. Specific engineering geological problems of dam construction - reservoir formation in karst terrains

Two environments are significant in geological terms for the analysis dam construction and reservoir formation conditions in karst terrains. The first environment consists of the ***bedrock mass in the dam base***, and the other one is the ***surface cover - Quaternary formations***. When it comes to the first environment, it is necessary to determine the following: the types of rock masses, homogeneity and heterogeneity, occurrence types, folding, faulting and jointing. For the second environment, it is necessary to determine the type and thickness of surface formations and their influence on stability and water filtration.

If possible, it should always be aimed to place the dam on bedrock masses. This condition is mandatory for arch-type dams.

When building dams in terrains made of carbonate rock masses, there are almost no difficulties other than those created by karst. Carbonate rock masses are characterized by very different conditions for construction of dams. Compact, very thick and weakly karstified limestones are a favorable environment for dam construction. Significant difficulties are caused by tectonically damaged and karstified limestones. They are subjected to intensive water filtration through bedding surfaces, faults, cracks and caverns. Carbonate rock masses are almost always a statically safe base, but on the other hand, extensive mechanical damage and cavernosity put into question the possibility of economical dam construction or formation of reservoirs on them. Past local and international experiences have shown that it is not possible to build dams and form reservoirs anywhere in karst, but only on the places where economical technical measures can still achieve satisfactory impermeability of the reservoir basin. Narrowed valleys (gorges and canyons) in carbonate rock masses often provide topographically very attractive profiles for construction of arch dams. The question of impermeability is very significant among the numerous questions to be answered by explorations when positioning a dam on highly karstified limestones. Karstification zones can be found at depths of even more than 100 m below the riverbed. That is why the zones with large and numerous karst hollows developed at considerable depths should be avoided when selecting the location.

When it comes to the specifics of engineering geological problems arising in dam construction and reservoir formation in karst terrains, then they can be roughly categorized primarily into the problems of:

- filtration properties of rock masses - water retentivity of the reservoir basin, or water loss at the bottom and edge of the reservoir basin and below and around the dam wall,
- nonuniform deformation properties and
- complex stress states.

Other problems such as shear of the dam wall on the base and sides, seismicity of the area, presence and usability of local geological construction materials etc. are the same or slightly different from these problems in other terrains made of other types of rock masses.

Filtration properties of karst terrains cause considerable difficulties due to the complex and specific porosity of karstified rock masses, or heterogeneous relationships between caverns, caves, karst channels, ponors and other underground forms in karstified rock masses. Hence, the filtration properties are a crucial factor for macro and micro location of the dam site and even the size of the structure. Water filtration can take place through surface cover rock masses and through the underlying rock masses.

Water filtration through surface cover rock masses is possible near the dam (below or around it, or on the sides supporting the dam) and from the reservoir area. There are only two cases of water filtration through surface cover in the reservoir area, namely: water filtration through taluses into deeper groundwater horizons or through alluvial deposits.

Water filtration through the underlying rock masses in the dam base takes place only through the rocks susceptible to dissolution, i.e. through carbonate, sulphate and chloride rocks. The occurrences of gypsum and anhydrite are particularly unfavorable, because the dissolution and suffosion processes in them are more intense than in limestones and dolomites. However, deposits or lenses of gypsum and anhydrite are usually intercalated or surrounded by impermeable marls that "preserve" them from dissolving and allow their long duration. Such marly-gypseous complexes are usually not dangerous in contact with water because water cannot come out of the marl deposits.

Limestones are the most unrewarding environment for dam construction of reservoir formation of all the carbonate rock masses. They are more permeable if they are cracked and more deeply karstified. When limestones are found only in the dam base, and if they are cracked and fragmented, the water loss problem can be solved by constructing a cut-off wall. However, if limestones are found at the bottom of the reservoir, not far from the dam, the antifiltration works get considerably more comprehensive and expensive.

The important factors for dam construction and reservoir formation in karst terrains also include the **hydrogeological properties of karst terrains**, such as: the *type, shape and size of aquifer, hydraulic mechanism, recharging, discharging, capacity, river and lake water connections, direction and interconnection of groundwater flows, water chemistry*, etc.

The deformation properties of rock masses in karst are specific in that karstified masses can cave in if the caverns located shallow below the bottom of the foundation pit remain undetected by the surveys. Other problems related to the deformation properties of karstified rock masses are similar to these problems in other terrains made of stone masses.

In terms of **rock bearing capacity and structural stability**, it can be generally said that the kind of problems found in non-karst terrains can rarely be found in karst terrains. Our karst areas are mostly made of Mesozoic limestone and dolomite that are sufficiently strong and that have elastic and other properties to provide an environment where structures can be built without major difficulties and complications, even if tectonically heavily damaged.

In karst terrains the problem of **stress state** can become important because of possible major defects of karstified rock mass and because these can lead to their failure, especially due to unfavorably oriented filtration and other pressures.

River valleys in karst terrains almost regularly form gorges or canyons, thus providing favorable conditions to position the dam site. However, one should be cautious with the conclusion on the appropriateness of the dam profile, especially in tectonically and mechanically damaged and heavily karstified rock masses. In addition, in karst terrains it is very important to determine the **thickness of fluvial deposit and the character of present and old river erosion** of the old fossil river valley.

Formation and age of river valleys in karst terrains is a very important factor in the construction of dams in deep valleys. Namely, geologically younger and deep valleys formed by fluting predominantly in the Quaternary are observed to have greater instability of slopes and more frequent rockfalls than geologically older valleys of the same depth. This fact is established in karstified limestones of Montenegro, where depths of gorges reach up to 1000 m.

Yet another problem should be emphasized, and that is the **difference in the karstification of limestone and dolomite**. Sometimes it can be so big at the same locality that, in reservoir formation, dolomites behave as hydrogeological insulators that allow reservoir formation in limestone masses above them or beside them. For example, a decisive factor for formation of the Bileća reservoir on the Trebišnjica River, the largest sinking river in former Yugoslavia, was the dolomitic core in the Lastva anticline of the Dinaric strike NW-SE, which separates the Adriatic Sea and the bottom and the edge of the artificial lake. The Grahovo dam in Montenegro was built on bedded to massive Upper Triassic dolomites, which are cracked but not highly karstified. Since these dolomites are strong, highly load-bearing and poorly permeable rocks, these engineering-geological conditions for dam construction and reservoir formation were relatively favorable. So, there was no problem of permeability, and neither were there other geological problems in the construction of this dam.

It should be noted that Bilećko Lake has submerged the karst spring of Trebišnjica, which, after filling the reservoir, was found at 70m below the maximum level of the lake, which has a volume of over 1.2 billion m^3. A large part of the underground reservoir was created in this way. Detailed engineering geological investigations consisting of structural drilling, piezometer observations in the wider area between the lake and the Adriatic Sea, as well as geophysical surveys were carried out for consideration of the—today already realized—possibilities. The base of karstification was established based on the obtained electrical sounding curves. Based on the analysis of results of all conducted works, especially exploratory drilling and electrical sounding, a two-row grout curtain was designed and constructed 150m in depth and with an area of 60.000m^2. 44,000m′ of boreholes were drilled for the purposes of grout curtain.

4. Relevant influence factors of the karst process and its formations on dam construction - reservoir formation

For an effective consideration of the influence of karst, or the process of karstification and its formations, on dam construction and reservoir formation, systematic analysis of numerous factors must be approached. The most significant among them are: the type, genesis and age of karst, karstification depth, the development stage of karst, surface and underground formations of karst, spatial position and distribution regularity of karst phenomena, karst activity and karstification intensity, karst covering, connection of karst with other processes, filling of karst voids, terrain stability and caving in, hydrological and hydrogeological properties of the terrain.

The depth of karstification is of exceptional significance for making a decision on dam construction. For example, when forming the Maifedoum reservoir in Lebanon, a 4 km long and up to 270 m deep curtain was designed because of the deep karstification of bedded and cracked Eocene limestones. This was confirmed by constructing two test grouting fields with grouting down to these depths. We will mention several more examples from international and local engineering practice of the influence of karstification depth on dam construction conditions, or grout curtain depth.

The Keban (Keban Baraji) dam, on the Firat (Euphrates) River in Turkey was found to need grouting down to a depth of 250 m, although it was previously estimated that karstification was shallower and that sealing works could be shallower. The dam was constructed on highly karstified marbles and limestones with intercalations of dolomite and carbonate shales of Paleozoic age. The height of the dam is 211m with a reservoir volume of $30.6\times10^9 m^3$. For the purposes of exploring the dam profile, 11 km of exploratory adits were excavated at five levels and 36,000m′ of exploratory boreholes were drilled. A large number of caverns was subsequently observed in the reservoir base. During the final works on the dam in 1971, a large cavern with a volume of 105,000m^3, which was named "Krab," was discovered on the left side of the dam. The bottom of the cavern was at an elevation of 500m, and the ceiling at an elevation of 539m. About 64,000m^3 of concrete and grouting materials were used to fill it. As the reservoir was being filled in 1975, when the water level in the reservoir rose above the level of 825.5m for the first time, weak turbulent flows appeared on the reservoir surface at different points along the left bank, about 150m upstream from the dam profile. In this area, in 1976, when the level of water in the reservoir reached the level of 838.5m (designed operating level is at 845m), strong turbulent flows developed with a sudden "burst" near the bank line. Filtration losses suddenly increased from 7.5m^3/s to 26m^3/s, which required subsequent complex investigations. After the reservoir was drained below the level of 838.5 m, during the same year, it was established that the previously mentioned swirling movements caused washout of the material filling the cavern entrance. Presence of a large cavern, which was named Petek, was established based on results of subsequent investigations, which included exploratory drilling, echo sounding and speleological explorations. The bottom of the cavern is at an elevation of 730m, and the ceiling at an elevation of 780m. The cavern width in plan is 30m, and length 90m, with extension in the east-west direction. The cavern is connected with the surface with a karst channel of a large diameter through which water was being lost. It was found that a large amount of water rapidly flows into the cavern along the existing cracks in the rock mass. A shaft with a diameter of 2.5 m and 13 boreholes with diameters from 35.56 to 43.18cm were made in order to fill the cavern. 605,000m^3 of limestone from finest fraction to blocks were inserted into the cavern. A total of 30 caverns were repaired. In addition to repairing the caverns, a long concrete diaphragm and cement curtain were also constructed and the power plant building was relocated. The construction lasted several years, and the additional costs for repair works amounted to 40% of the price of the hydraulic power system. The outflow of water in the Keban Stream, at a distance of 2.5km south of the sinking place, was reduced to 8-9m^3/s, which is considered acceptable in comparison with the mean flow of Euphrates (635m^3/s).

The arch dam Dokan (Dokan) in Iraq, with a height of 116m, was constructed in the canyon of the Lesser Zab River. The dam site is located on an anticline limb. The anticline core consists of karstified dolomites, overlain by thin-bedded limestones. The dam rests on two ridges made of highly karstified limestones. In the period 1955-1957, a single-row antifiltration curtain (left and right) was constructed with a total length of 2,541m. When the water level in the reservoir reached 2/3 of the maximum level, losses of 6m^3/s were registered. It was established that water sank in karstified limestones in the left side of the reservoir about 1.8 km from the dam. The sinking zone was formed on the contact between limestone and dolomite. Considering that this water bypasses the grout curtain, its elongation by 336m was carried out with a grouting depth of 150-160m. Grouting works on renewal of the curtain are performed periodically every 10-15 years.

Similar problems were encountered in construction of the dams in Dinaric holokarst in the territory of former Yugoslavia:

- the Sklope dam on the Lika River in the Republic of Croatia,
- the Buško Blato reservoir in the Cetina basin in Bosnia and Herzegovina, which impounds groundwater from poljes of the southwest Bosnia and Herzegovina (Kupreško, Glamočko, Duvanjsko and Livanjsko polje with Buško Blato),
- Salakovac and Grabovica dams on the Neretva River in Bosnia and Herzegovina,
- the Višegrad dam on the Drina River in Bosnia and Herzegovina (the Republic of Srpska),
- the Mratinje dam on the Piva River in Montenegro,
- dams and reservoirs: Slap Zete, Glava Zete and Krupac etc.

The concrete gravity dam Višegrad on Drina in the Republic of Srpska, is founded in karstified limestones and dolomites overlying a complex of marly limestones, sandstones and claystones. At the study stage for defining the dam site, cavernosity was established by boreholes at a low degree. Karstification was subsequently established in sides (in exploratory adits), while in the riverbed presence of large karst channels was determined during excavation of the foundation pit. Some of them were filled with calcite or terra rossa. On an insufficiently studied problem of karstification and assessment of its impact on safe operation, the concrete gravity dam was constructed with a height of 50m, and width 280m at the crest. Grout curtain was constructed 50m in depth and locally also 60m. Construction of the grout curtain for the Višegrad dam was begun by the company Geoinženjering Sarajevo in 1988, and by January 1989 the works on the left side and central part were completed and the works on the right side were begun.

When the reservoir was being filled, at a level of 4.0m below the maximum specified reservoir level, occurrences of springs were registered in the riverbed downstream of the dam - at the site of stilling pool. The spring water was clear, but with higher temperature relative to the surrounding water (14.4-18.7°C). Diver teams established that water with high content of clayey suspended particles was flowing out of karstified rock masses at the bottom of the bed. When this was registered, grout curtain was repaired in the zone of block number 5, in a width of 30m and depth of 110m. After first negative results on test boreholes, grouting work was continued by the company Geosonda from Belgrade. The first stage of repair grouting was carried out to a depth of 100m, but not deeper because of the very rapid filtration. There were major problems when grout curtain was performed in 1990. Drilling of grouting holes resulted in water loss, rig falling through, while consumption of grouting mass was also increased during grouting (even more than 10,000kg/m′). This required a change in grouting design, i.e. a reduction in spacing between grouting holes from 1.5m to 0.7m and deepening of boreholes in some sectors by one to two levels. 6,400t of dry mass was used for grouting.

In spite of the conducted repair works, the outflow of water at the springs downstream of the dam did not stop, but increased from initial 1.4m^3/s (1990) to 14.68m^3/s (December 2012), Fig. 1.

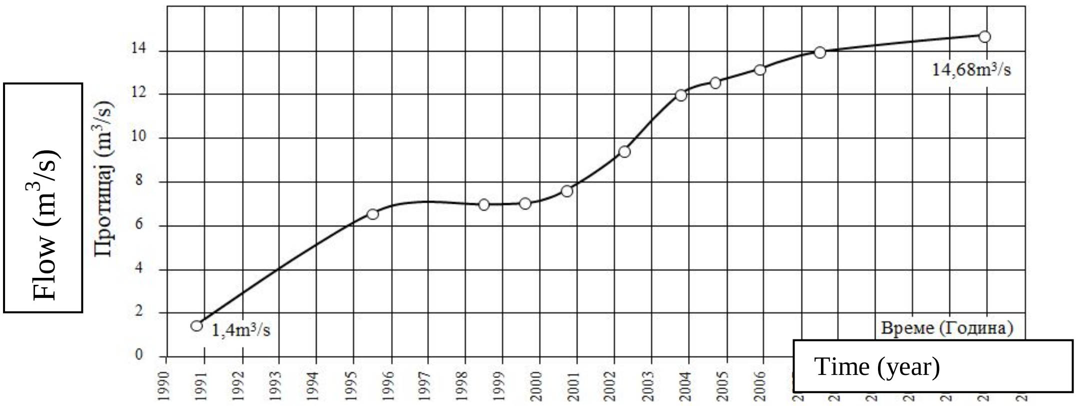

Figure 1. The combined flow at the springs in Drina riverbed under the dam (Institute for Water Resources "Jaroslav Černi" Belgrade and "Stucky Ltd.").

Over a period of five years (1991-1996), the capacity of the springs increased from 1.4m^3/s (which accounts for 0.41% of the average Drina flow of 342m^3/s on the dam profile) to 6.5m^3/s (1.90% of the average flow of Drina on the dam profile).

Five spring capacity measurements were carried out after 1996 and the following results were obtained: 7.18m^3/s (1999), 7.01m^3/s (2000), 7.56m^3/s (2001) and 9.41m^3/s (2003). As evident, in the period 2000-2003, the discharge assumed a radical growth trend in relation to the previous period and accounted for 2.75% of the average flow of Drina on the dam profile.

In order to determine the spatial position of filtration zones, numerous investigations were carried out, on the basis of which the following conclusions were drawn:

- spring water is a mixture of thermal waters coming from greater depths (Višegrad thermal resort is nearby) and water from the reservoir;
- the greatest losses of water from the reservoir are under the central part of the curtain along a zone about 30m in width and about 60-100m in depth;
- filtration takes place along two karstified fracture zones. One of them stretches along the riverbed, and the other is diagonal in relation to the river. The main filtration flows are at a depth of about 108m but should also be expected at depths below 110m.

The main reason of the serious problems accompanying construction of the grout curtain is insufficient knowledge of the karstification process. None of the types of geological investigations, nor those during construction of the grouting curtain, gave reliable answers to the primary questions of the genesis of karstification, of the depth, size and characteristics of karst forms and of the regularity of their spatial occurrence. Predicting the behavior of karstified rock masses in the conditions of backwater formation remained as an open question. Additional studies, conducted in 1996, and subsequently in 1999, have shown that further uncontrolled leakage under the dam could cause serious damage, not only because of the water loss from the reservoir, but rather because of the impact on the safety of the facility itself.

For this reason, the Institute Jaroslav Černi from Belgrade (during 2008 - 2009) was entrusted with detailed investigations, which established general directions of water movement through the underground in the dam zone. The "Project of repair of water leakage under the HPP Višegrad dam" was developed in 2010 based on the results of these investigations.

As required for the implementation of the phase I repair works in the reservoir perimeter, 10 exploratory marker holes (with a total depth of 1733m) were drilled, in which monitoring equipment was installed. Then, four more boreholes (with a total depth of 697m) in the dam crest and three piezometer boreholes from the grouting adit were drilled. In order to monitor the springs in the Drina riverbed, cantilever beams carrying water velocity meters, electric resistance measurement probes and underwater video cameras were installed downstream of the dam.

The sealing was initially attempted by grouting, in which process the following was used: about 2.503,251t of cement, 541,784t of sand, 91,891t of bentonite and 24,638t of additives, or a total of 2.392,842l (dm^3) of grouting mass. Since the results of the sealing were negligible, an intervention in the area of the ponor itself was carried out by manual insertion of granular material. After inserting only 177m^3 of aggregate, the entrance area of the ponor was found to be clogged. That is why further work at this location was stopped, and then material was inserted through exploration marker holes (located in the reservoir). For this operation, boreholes were widened to a diameter ∅500mm, which made it possible to insert the granulated material mechanically (using a rubber conveyor belt). A total of about 37,000m^3 were incorporated (about 20,422m^3 in RB-10; about 23m^3 in RB-4; about 15,027m^3 in B-15 and 1,524m^3 in the ponor). This material was limestone chippings of the following fractions: 0-4mm, 4-8 mm, 8-16mm, and 16-32mm.

As the available financial resources were spent, it was decided to suspend the works and carry out conservation of boreholes, in order to make it possible to resume the repair works at a later stage. The performed repair works, which are presented in a nutshell, achieved a significant success in reducing the leakage (from about 14.68m^3/s to about 4.5m^3/s), as evident in Fig. 2.

Based on the several aforementioned examples, it can be concluded that, in order to select a dam site in karst terrains, among other tasks it is necessary to analyze the history of the river valley formation and different stages of karstification.

Analyzing the results of WPT tests in 150 deep boreholes in eastern Herzegovina with 398 levels of 5 meters each, presence of karst voids was established at 138 levels. In this process, most open caverns (57%) were at depths between 50 and 150m, while the most karstified zone was 0-15m. At depths greater than 270m there is no evidence of permeability greater than 30Lu, which could be attributed to a more significant karstification, and therefore regionally considered this depth is considered the basis of karstification for this area.

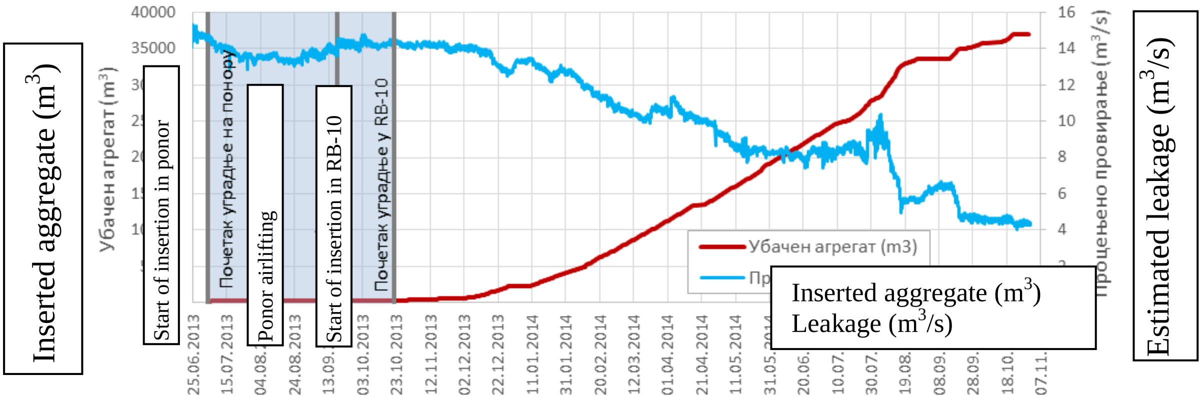

Figure 2. Diagram of repair effects: granulated material (red line) and water leakage (blue) - (Institute "Jaroslav Černi" Belgrade and "Stucky Ltd.").

In deep exploratory boreholes in the Montenegrin seaside, karstification in the Mesozoic limestone was established even at depths of over 2,000m below the sea surface. Still, the Neogene and Quaternary karst, and especially the active karst that is still being developed, has the highest significance for dam construction and reservoir formation.

The **stability of slopes and bedrock** on which facilities will be founded is also tested in karst terrains. This is carried out for the intact terrain conditions, then in the excavation conditions, and also later during operation. As a specific problem there is also the possibility of caving-in above large karst hollows, or caverns and caves in the zone above the foundation of the structure. For example, during construction of the rockfill dam Slano in the Nikšićko polje, in the left side when the quarry was being opened to fill the dam wall, a huge cave was encountered below the dam support, through which 2-3m^3/s of water was lost to the sinkhole storage before grouting.

It is interesting to note that the wall of the Grabovica dam on the Neretva River in Bosnia and Herzegovina, with turbine hall, is located above a cavern filled with clayey-sandy-gravely material. Namely, a fault, along which the cavern was formed, was found in the watercourse closer to the right bank. The cavern was established still at the stage of first engineering geological investigations in 1958. The actual dimensions of the cavern were not determined until the construction stage, and so only in the base of the turbine hall, while the knowledge of its spatial position below the dam foundation is based only on the exploratory drilling data.

Particular attention is paid to establishing *stability at the dam site and within the scope of the reservoir*. Since a dam site in karst terrains is largely chosen so as to be in canyons and gorges, it is in these areas that *falling of rock masses* usually occurs. For example, during construction of the Mratinje dam on the Piva River, preventive removal of unstable stone blocks above the dam was carried out on a massive scale so that they would not jeopardize constructors, and subsequently operation of the facility too. Unfortunately, even some forty years after the beginning of operation, rockfall problems exist. Falling of rock masses in the reservoir near the dam site can cause the occurrence of overflow surges, and it can cause the reservoir itself to fill up.

In addition, in karst terrains *underground impacts occur and water abruptly breaks through into previously isolated caverns*, during deformations occurring at the bottom or less frequently over the edge of the underground part of the reservoir. Such deformations occur during filling, immediately after filling of the reservoir, but also one to two years afterwards. Seismological instruments register these earthquakes as weaker, local earthquakes. In literature, these phenomena are called *triggered or induced seismicity*. In our area, the problem of triggered or induced seismicity was the subject of research for the first time at the Bileća reservoir in Bosnia and Herzegovina (Republic of Srpska). Since the beginning of the reservoir filling from 1 November 1967 to 31 October 1980, 11,413 earthquakes were registered, releasing an energy of $1,392 \cdot 10^{17}$ erg. The largest number of earthquakes took place at the maximum level of water in the reservoir (1968/69 and 1969/70). Similar occurrences were also registered during filling of the Piva reservoir in Montenegro. Immediately after filling of the reservoir, intensification of seismic activity was observed in the entire region of the reservoir lake. Intense seismic activity was in the period 1977-1979, when more than 500 earthquakes with magnitudes from 1.5 to 4.1 were registered. The strongest registered earthquake in the dam and reservoir area since the beginning of filling so far had a magnitude of 4.2, or 6 units on the Mercalli scale, while earthquakes of weaker intensities are still registered today.

Many things about the development of the phenomenon of triggered or induced seismicity so far remain unclear. It can be assumed that the formation of a reservoir creates pressure that causes redistribution of the existing stress state in the reservoir area and wider, and also additionally leads to a change in the dynamics of deep underground water and gases and disturbance of the thermal field. All this together influences the genesis of technogenic earthquakes.

5. Brief reference to the possibility of dam construction and reservoir formation in karst

Construction of dams and formation of reservoirs in karst terrains would be a futile attempt and waste of financial resources if we tried to do that anywhere in karst without the special geological conditions that would make it possible. The first attempt to build a dam in karst was made before World War II on the Zeta River, near Slap in Montenegro. The dam construction was begun in 1938, and was completed in the first postwar years 1949-1951, when the works on the dam, head race channel and turbine hall were completed. The dam is a concrete gravity type dam with a height of 10m and it was built in karstified rudist limestone of the Upper Cretaceous age. The reservoir is formed in the riverbed made of gravel, sand and clay. The karst was shallow, immediately below the alluvium. Ponors were found on the left and right valley sides - Zeta River banks. Dyed water from one ponor regularly appeared in many springs downstream of Slap and in Slap itself, which suggests that the underground karst channels are connected and branched. The velocity of water in karst channels was 5cm/s. Ponors in the riverbed prevented the reservoir from being formed although the dam is low. It was necessary to take a number of technical measures to close the ponors. That was attempted by filling the ponors and covering them with impermeable clay carpet. That did not work. Two months later, deformations appeared in the clay carpet, and later on also ponor openings, which still function today. That was a warning to professionals dealing with these problems that it is necessary to approach cautiously, and adapt the method of solving water retentivity, to hydrogeological conditions when constructing dams in karst.

A number of dams have been constructed in former Yugoslavia until present days, very large ones with backwater of tens of meters and even over 100 in height, forming reservoirs in highly karstified terrains, but there were special - specific geological conditions for that. We will mention just some of them:

- As a first example, we note the observation of Prof. M. T. Luković in the long-past 1954 (before construction of the Grančarevo dam and formation of the Bileća reservoir): "In the Trebišnjica valley it was found that a larger reservoir could be formed in the scope of the great dolomite anticline Lastva, which Trebišnjica transversely intersects. The dolomites are competent and are not karstified." In this case, the special geological condition consists of less permeable dolomites and their spatial position.
- As a second example, we note several reservoirs formed in the Nikšićko polje, whose limestone bottom is covered with a sufficiently thick carpet of impermeable clays, which was the special and sufficient condition for the formation of the reservoirs: Slap Zete, Glava Zete and Krupac.
- As a third example, we mention the Cetina valley where the Peruča dam was constructed: *"The research of the Cetina valley found that a significant water reservoir could be formed near Peruča, because on the right side the valley is closed with Werfen, dolomite and Lemeš beds, and on the other side underground drainage is directed to the valley. The piezometer levels in the karstified Cretaceous limestone on the valley sides rise considerably above the height of the imagined backwater of about 80m in height" (Luković, T. M., 1954).*

Every area in karst is characterized by specific geological conditions that need to be established by explorations. *A hydraulic structure should be constructed in harmony with natural conditions, and especially with specific geological conditions of the locality, so that in the future it can coexist with the nature or geological environment, i.e. so that changes of natural processes are in an essential, minimum extent.* In order to reduce risks in construction of hydraulic structures in karst, it is necessary to develop detailed geological maps (structural geological, engineering geological and hydrogeological maps at a large scale) by combining different investigation methods: field mapping method, remote detection method, neotectonic analysis, geophysical (geoelectrical, seismic) methods, tracing methods for determining groundwater directions and flows with maximum use of data of exploratory drilling and field tests in boreholes and exploratory excavations. Striving to completely reduce

the risks in karst terrains is impossible, it is only possible to reduce the risks to a reasonable measure. This is illustrated by the example of the Keban dam in Turkey.
A complete elimination of risks in dam construction and reservoir formation in karst requires an enormous increase in scale of investigation works, which would not be feasible in professional and economic terms.

6. Conclusions

In studying karst and its effects on construction of various facilities, primarily dams, and formation of reservoirs, significant results have been achieved in our hydraulic engineering practice:

1. Karst is no longer considered as a terrain with many unknowns and unpredictable difficulties which should be avoided and on which it is not possible to build dams or to form reservoirs. On the contrary, karst terrains can also be used for construction of such facilities. This is borne out by one of the first in the world, 123m high, hollow arch dam Grančarevo, built in the Dinaric holokarst.
2. However, the past research has confirmed that karst terrains have many specificities that can and must be well known for proper evaluation of construction conditions, or for selection of construction site, and type and size of the facility. Failure to address only one of these factors can undermine the correctness of the conclusions drawn.
3. Analysis of solidly collected facts resulted in the view that conclusions about karst terrains can be made, but generalizations cannot, especially if doing so with a small number of factors and few examples. However, the results achieved so far give the right to point out the gained experiences and to make some judgments, acknowledging also the results of earlier studies, and especially of Prof. M. T. Luković.

- The basic feature of the modern karstification in our region is the deepening of the karst erosion, usually only to the bottom of erosional basis, and less frequently below it, but in places also very deep.
- In the terrains where post-Pliocene and Quaternary as well as recent uplifts are greater, karstification have not spread to a greater extent along side cracks and interstratal discontinuities. Therefore, there are a number of examples where satisfactory results in reservoir formation in karst are achieved only by closing or isolating ponors (for example, Buško Blato in the Cetina River basin). But there are also many examples where this was done with considerable effort (ponor Krupac in the Nikšićko polje).
- In most karst terrains of former Yugoslavia, deep karst hollows (channels, caverns, caves, etc.) are not spread over huge or even large spaces and they mostly have large volumes. This is essentially the karstification of tectonic zones more strongly manifested in only two dimensions.
- In the continental part of the Dinaric karst, concentrated groundwater in varying degrees flows through independent channels, while other limestone and especially dolomite masses are less permeable or virtually impermeable.
- By comparing the degree of karstification over depth, on several localities karstification of masses was found to be 2-3 times greater over depth of the minimum level of aquifer than below that level (Nikšićko polje etc.).

4. For sealing dams and forming reservoirs in karst terrains, due to the complexity of karst it is necessary to count on the occurrence of many problems and difficulties, but mostly those that can be successfully overcome. After all, this is confirmed by the results achieved so far, since of about 80 high dams in the territory of former Yugoslavia, more than 50% are constructed in karst terrains, and completely successfully so.
5. When studying characteristics of karst terrains, it is necessary to use different methods in combination, because satisfactory results can be achieved only in that way. Namely, in addition to morphological, hydrogeological and geotechnical methods, for this purpose it is also necessary to use geophysical methods, and primarily electrical sounding and

refraction seismics, especially when assessing the overall porosity and depth of karstification of rock masses.

"If we tried to emphasize what the biggest problem in exploring karst is, and what is most important when studying karst terrains for the purpose of creating reservoirs and constructing water engineering facilities, these would undoubtedly be the hydrogeological investigations with determination of rock permeability and the direction and type of groundwater flow. So, underground water circulation is the essence of karst. Water losses in cubic meters per second and devastating intrusions of water in tunnels and other underground works are only possible in karst conditions" (M. T. Luković, 1961).

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