ARTIFICIAL UNDERGROUND RESERVOIRS IN THE KARST EXPERIMENTAL AND PROJECT EXAMPLES

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ABSTRACT

Artificial underground storage can be realised by watertight geotechnical construction into the karstified rock massif, behind the spring, or on the surface in front of the spring. It is impossible to establish a universal model of geological structure preferable for artificial groundwater storage. The crucial parameters of artificial groundwater storage are: geological structure, i.e. the position of different hydrogeological units; recent stage of karst aquifer evolution, i.e. the parameters of base groundwater flows; the parameters of aquifer hydrogeological contours; storage capacity of karst aquifer; maximum possible underground backwater level and position of underground dam construction.

After few small scale experiments (plugging of individual underground karst channels) and long-term investigations and monitoring of a large karst aquifer the feasibility report for project Omla is finished. The underground dam Omla, near Dubrovnik, should be constructed to regulate the karst spring discharge (4-120 m$^3$/s). The grout curtain and channel plugging techniques should be used for construction of 100 m high underground dam. The power plant (60 MW) should be situated also underground.

INTRODUCTION

In spite of the effort to collect at the surface all disposable water in karst regions a huge quantity of water is out of any possible control and rational use.
Especially the water circulated at deep karst aquifers is uncollectable at the surface. Also, the retention capability of karst aquifers, generally speaking, is relatively low. It means that the transportation possibilities dominated, i.e. the aquifer discharge is often directly proportional to precipitation. Natural water storage capacity is mainly limited. In that case there is only one possibility for economical water management – artificial regulation of karst aquifer, i.e. the artificial groundwater storage at selected parts of geological karstified structures.

The experiments and analyses performed in karstified rock masses at different regions in the world show that an artificial underground storage can be a realistic way for technically and economically rational groundwater management.

An artificial underground reservoir is a part of an aquifer whose natural hydrogeological properties are geotechnically or hydrotechnically improved with goal to control the discharge regime of artificially stored water.

GENERAL UNDERGROUND RESERVOIR CLASSIFICATION

Generally the artificial underground reservoirs should be classified in three basic groups:

1. The first group includes underground reservoirs with storage space limited on one karst channel system.

2. In the second group are classified underground reservoirs comprising all types of porosity in a part of an aeration zone with fossilized karst channels.

3. The third type of underground storages is physically coupled to the surface storage reservoirs and they are located at a limited space in the reservoirs banks.

BASIC CONDITIONS FOR ARTIFICIAL UNDERGROUND STORAGE

It is impossible to establish a universal model of a hydrogeological structure preferable for underground water storage. Every karst aquifer is a unique hydrogeological entity, especially from the artificial storage water point of view. The basic geological conditions for underground reservoir construction are:

- characteristics of geological structure;
- existing storage of karst aquifer evolution process;
- hydrodynamic regime of aquifer base flow;
- characteristics of watershed boundaries, contours of aquifer and contours of underground storage space;
- way of aquifer discharge (one or more springs) and type of spring; and
- storage capacity and retardation capability of karst aquifer.

The following characteristics and parameters of the main conditions are important for carrying out the artificial underground reservoirs:
- position of underground impervious geotechnical structure;
- maximal possible underground backwater level; and
- storage capacity of underground reservoir area.

The most advantageous hydrogeological structure for artificial underground regulation and water conservation is an aquifer with one discharge point at the level of base karst flow.

It is especially preferable if the discharge point is located at the lithological boundary between karstified rock masses and impervious hydrogeological formations. The base underground flow (main water collecting and aquifer transporting) is favourable for good hydraulic connection, i.e. for a quick pressure propagation from the remote parts of the aquifer to the underground "dam" site. It is, also, very important to remove the newly established piezometric line from the discharge zone farther in the aquifer rock mass.

POSSIBLE CONCEPTS OF WATERTIGHT STRUCTURE

Depending on geomorphological, geostructural, hydrogeological and geotechnical features, five general concepts can be established for underground reservoir formation:

1. Surface dam in front of the main discharge zone.
2. Cut-off wall structure is preferable in aquifers with intergranular or fractured rock porosity.
3. Plugging of underground flows is suggested for water storing in individual karst channels.
4. Grout curtain is favourable to construction of a wide watertight screen connected with impervious rocks.
5. Combined underground geotechnical structure is composed of conduit flows plugging with localised cut-off walls and the grout curtain which is connected to imper-
vious hydrogeological formations.

**EXPERIMENTAL AND PROJECT EXAMPLES**

Three possible concepts of underground water storage and discharge regulation are analysed at the Dinaric karst region (East Herzegovina and Dubrovnik littoral):

(I) Plugging of karst channel which has a role of a natural aquifer overflow.

(II) Plugging of local karst aquifer base conduit flow for water storage in the free space of one cave system.

(III) Simultaneous regulation of circulation through the base flow as well as all over the active frontal aquifer cross-section. The optimal groundwater management of the aquifer water is the main goal of this concept. Beside the local plugging this concept includes the construction of geotechnical watertight barrier till the anticipated headwater level. Underground storage reservoir is not only the main karst conduit system because it includes all types of porosities in the part of the zone of dynamic aquifer reserves which is activated with storage process.

**First example**

The Obod estavelle (Fig. 1) is situated in the Fatničko polje at the tectonical contact (reverse fault) between the Upper Cretaceous limestone and the Eocene flysch sediments. The estavelle is natural aquifer overflow and its discharge varies between 0 and 60 m$^3$/s. At the outflow part of the channel a massive concrete plug was constructed, 10 m high and 3.5 wide on the average. The ultimate aim of plugging was to prevent the flooding of polje and to "press" the underground water to flow downstream with only partial discharge at the polje level. The plug was calculated for the pressure of 40 bar. After plugging, the first rainfall was extremely high, amounting to more than 200 mm/24 hours. The water pressure in underground karst channel system increased rapidly till 10.6 bar. A few tenths of new springs are formed 80-100 m above the plug level with total discharge of about 11 m$^3$/s. A local but strong earth shaking was the consequence of an extremely rapid filling of the aeration zone. The road at the hillside over the plugged estavelle has started sliding. At the distance of 250 to
Fig. 1 The Obod spring plugging
300 m along the hill slope above Oboj estavelle a lot of houses were damaged.

After blasting of a part of concrete plug (opening 1.3 x 1.3 m) the pressure decreased rapidly. During six hours after plug blasting all artificially stored water was discharged.

The expected effect of plugging (underground storage) was not achieved in the existing geological and hydrogeological conditions in the Fatnicko polje ("transit" erosion base level in the bifurcation area) with a hanging hydrogeological barrier which act as a retarder only when the aquifer is completely saturated. Under such hydrogeological conditions forming of an underground reservoir is not possible.

Second example

The Jedres spring at the altitude of 904 m is the discharge point of the local base karst flow. A small scale catchment area feeds the Jedres spring. The karst aquifer, including the base conduit flow and the spring zone, is developed in Eocene conglomerate with discharge varying between 1.0-350 l/s. After geological analyses, drilling procedure, piezometric monitoring and speleological investigations the part of the channel at about 60 m from the spring point was selected as the best location for plugging. The access adit is excavated till the space for plug construction and a part of natural karst channel is enlarged (Fig. 2). At the upstream part of the enlarged zone the concrete plug is constructed. The plug diameter is about 3 m and its thickness 1.5 m. Because of leakage water passing around the plug, grouting of the surrounding rock mass was performed.

Four steel tubes are installed through the plug structure: one tube for bottom outlet, two of them in the middle of the structure - for water consumption, and the fourth one at the upper part of the plug, which is a large diameter tube for the storage space inspection.

After several fillings of the reservoir space twelve meters of the storage water are determined as the maximum ground backwater level. During the filling procedure it has been established that the surrounding rock mass was watertight enough for the new water pressure stage.

The explained example indicates a possibility of
**Fig. 2** The Jedres spring plugging (horizontal and vertical presentation)

relatively unexpensive artificial karst channel transformation in the useful reservoir space, mostly with limited storage capacity.

**Ombla Project**

The large syphonal spring Ombla is formed at the tectonical contact between Mesozoic carbonate formations (allochtonous tectonic block) and impervious Eocene flysch sediments (autochtonous tectonic block) at the both sides of the spring zone hydrogeological flysch barrier is arising in shape of the letter "V" with Ombla spring at the lowest point. The spring zone is located at the altitude of 240 m, but the deepest part of the explored syphonal karst channel is at 25 meters below the sea level. The spring water yield varies between 4 and 120 m$^3$/s. The average annual discharge is 23 m$^3$/s. The surface of 600 km$^2$ was estimated to be the optimal Ombla catchment area. The maximum range of aquifer water table fluctuation is about 200 m (Fig. 3). The rate of water

![Fig. 3 Simplified cross-section through the Ombla spring aquifer](image)

table rise may sometimes attain 370 cm per hour, that is up to 89 m per day. Circulation through a system of karst channels and caves of great transmissivity indicates that this karst aquifer system functions under pressure. The correlation coefficient between the spring hydrograph and the water table fluctuation (in the piezometric borehole 4 km far from the spring) is very high - 0.976.

To collect the necessary data a great number of investigations have been performed: detail geological mapping, analyses of satellite images and low altitude aerial photographs, geoelectrical sounding and mapping of a large part of the catchment area, a lot of dye tests, deep drilling procedure, long-term water table monitoring and speleology with especially successful diving speleology.

The idea about an artificial underground storage was created on the base of the presented geostructural and hydrogeological parameters. A few different concepts have been analysed. A concept with "underground dam" just in the spring background was selected as the most realistic one. The general concept of the underground dam and the reservoir is presented on the figures 4 and 5.

By construction of an archlike underground structure all conduits and fractured aquifer systems should be cut and made inactive. The deepest part of the geotechnical structure should be constructed in the zone of the base flow conduits. The watertight structure will be connected with impervious hydrogeological lateral barriers at both sides by grouting. All plugged channels should be artificially connected with the penstock right behind this structure and through the underground dam with the powerhouse cavern (underground power plant). This concept has been analysed in detail and presented in the form of a feasibility study.

The main characteristics of Ombla underground storage and power plant are:

1. The underground dam structure should be 100 m high.
2. "Dam site" is selected 170-200 m far from the discharge zone in the karstified carbonate massif.
3. The archlike "underground dam" is adapted to hydrogeological structure.
4. The power plant installed capacity should be 60 MW.
Geological and geophysical investigations indicated the area of spreading and the shape of the reservoir. The contour lines of the base of karstification showed an approximate underground reservoir spreading. As a consequence of strong new tectonical movement (the rapid uplifting and rotation of aquifer structure block) the karstified zone at the deepest aquifer part became narrower with limited storage capacity. A few kilometres behind the spring zone a highly karstrified part of the aquifer is concentrated in the form of a narrow corridor with main conduits. The
Fig. 5 Generalised concept of Ombla underground dam
leakage from the reservoir space to the boundary aquifers is prevented by the base of karstification arising at both sides of the karstified corridor zone. The storage capacity is limited at the part of the reservoir below the altitude 60 m. A beneficial storage space for energy production is in the upper reservoir zone between the elevation of 60 m and the proposed headwater level (100 m above sea level). Under the worst hydrological conditions (dry period and horizontal piezometric line) the storage capacity will be 25-30 $\times 10^6$ m$^3$. The storage capacity of 5 m high prismatic aquifer unit in the above mentioned upper aquifer zone is three times larger than the capacity of an identical prism in the low laying part of the aquifer. This phenomenon is in accordance with very dynamic karst aquifer evolutionary process in the zone of the conduit flow concentration.

By speleological and diving speleological investigations a huge cave system is discovered at the spring zone. The syphonal channel and the large cave space right behind the spring outlet are especially important from the hydrogeological and geotechnical point of view. The large cave system volume is developed behind the watertight structure zone and should be a part of the water storage space. The downstream syphonal part of the main karst conduit, including a large cavern, will be a part of the bottom outlet as well as of the tailrace tunnel. The outlook of the spring zone and the scenery of the hillside above the spring will remain natural and the landscape authentic, without any man made structure except the tailrace tunnel entrance.

REFERENCES
