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Ombla hydropower plant – design for use of groundwater energy in karst

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Professional paper

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The water power potential of surface watercourses in Dinaric karst areas, spreading in a wide belt along Croatian coast, has for the most part already been put to practical use. However, water power benefits of a significant quantity of water accumulated in the karst underground of this vast area have not so far been adequately exploited. Based on extensive research, the design has been prepared for the Ombla hydropower plant whose specific feature is that all its structures are buried underground, while the water would come from an underground water storage, to be created by construction of an underground dam.

Key words:
ground water, karst terrain, underground dam, water power potential, underground water storage

Stručni rad

Tomislav Paviša, Zvonimir Sever

Hidroelektrana Ombla - projekt za energetsko iskorištenje podzemnih voda u kršu

Energetski potencijal površinskih vodotoka na krškom terenu dinarida, koji se u širokom pojasu proteže uz hrvatsku obalu, većim je dijelom iskorišten. Međutim, značajni dio voda koje se akumuliraju u krškom podzemlju ovog velikog prostora nije do danas adekvatno energetski vrednovan. Na osnovi rezultata opsežnih istraživanja izrađen je projekt HE Ombla čija je posebnost da su joj sve građevine smještene u podzemlju te da se koristi voda iz podzemne akumulacije, stvorene izgradnjom podzemne brane.

Ključne riječi:
podzemne vode, krški teren, podzemna brana, energetski potencijal, podzemna akumulacija

Fachbericht

Tomislav Paviša, Zvonimir Sever

Das Wasserkraftwerk Ombla - ein Projekt zur Energienutzung des Grundwassers im Karstgebiet

Energiepotenziale der Oberflächenwasserströme auf dem Karstgebiet der Dinariden, das sich weit entlang der kroatischen Küste ausbreitet, sind größtenteils ausgeschöpft. Ein bedeutender Teil der im Untergrund des Karstgebiets akkumulierten Gewässer ist jedoch bis heute hinsichtlich der Energienutzung nicht entsprechend ausgewertet. Aufgrund von Resultaten ausführlicher Untersuchungen ist das Projekt WKW Ombla entstanden. Es zeichnet sich insbesondere dadurch aus, dass es ausschließlich unterirdische Objekte umfasst und auf der Nutzung eines unterirdischen Stausees beruht, der durch den Bau eines unterirdischen Dammes entstand.

Schlüsselwörter:
Grundwasser, Karstgebiet, unterirdischer Damm, Energiepotenzial, unterirdischer Stausee

1. Introduction

The idea about building a specific multi-purpose hydropower facility at the Ombla is primarily dependent on the possibility of forming an underground water storage, which is why almost all studies have been oriented toward defining the underground water storage area and the underground dam zone. Investigation results, presented in a number of specialist studies [1-10], have revealed that a natural underground retarding basin exists in this area, that it discharges right at the Ombla source, and that it would be possible to form an underground storage area, which would enable rational management of vast quantities of water present in this area. After completion of the preliminary design and detailed design for the Ombla Hydropower Plant [14, 20], and especially after model testing using the hydraulic model of structures for the evacuation of flood waters [16], it became clear that the proposed structural solutions are technically achievable and sound, while the power-supply and economic analyses show that the project would be highly profitable.

The objective of this brief presentation of investigation results, revealing also the concept and design solution adopted for this hydropower plant, is to inform the interested parties about this specific project that would involve construction of a buried dam, and creation of an underground water storage right in the hinterland of a big karstic water source. The project would enable a significant production of electric energy from a renewable source, while at the same time the natural look of the surrounding area, and the environment in general, would be preserved. This would also improve water supply for the town of Dubrovnik as the use of the available pressure would enable transport of water to the water supply tank by gravity. The project would also eliminate current occasional water pollution incidents with an increase in turbidity [13].

Figure 1. Source of Ombla in Rijeka dubrovačka bay

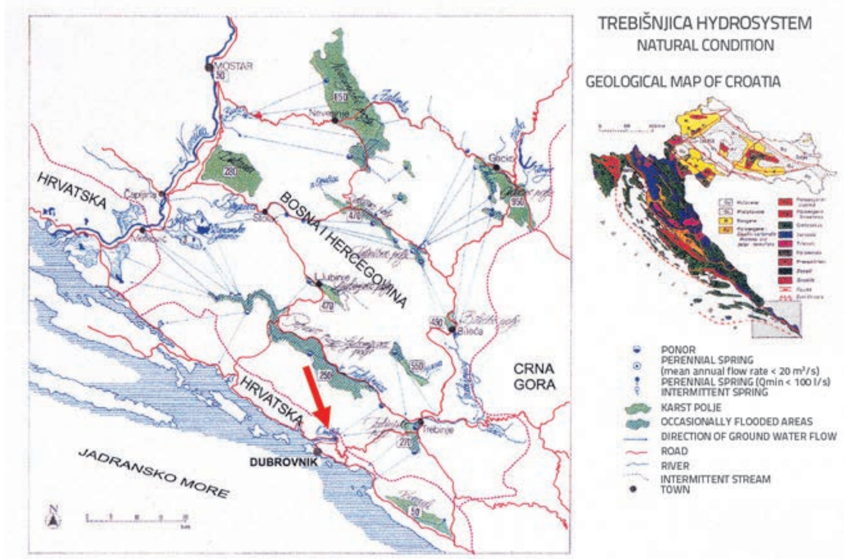

Figure 2. Trebišnjica Hydropower System and the Ombla spring (marked with arrow) – natural condition

2. Properties of drainage area

The Ombla spring is a highly abundant source of water situated in coastal karst. In its natural settings, prior to construction of the Trebišnjica River hydropower system, it functioned as a drainage system that used the shortest route to evacuate its own and tributary waters to the sea. From a wider perspective, this source belongs to the Trebišnjica River drainage basin which, by the abundance of its natural features, can be ranked among the most interesting karst areas in Europe (Figure 2).

2.1. Hydrological features

After construction of all components of the Trebišnjica hydropower system, the water from the indirect Ombla basin have been retained in reservoirs, and directed by tunnels toward the downstream hydropower plants: Trebinje I and II, Dubrovnik, and Čapljina. These anthropogenic interventions in space have caused changes in the natural discharge regimen of the Ombla spring. Long-term weather observations show that this area abounds in rainfalls which, according to annual average, range from 1400 mm in the coastal area to 2200 mm in the mountainous zone of the drainage area. The Ombla spring was

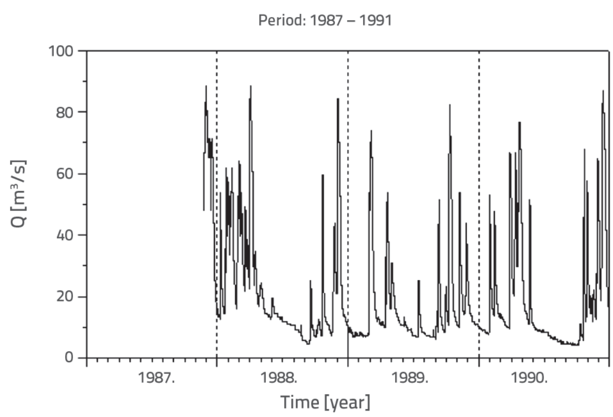

Figure 3. Typical hydrograph showing diurnal flow rates for the Ombla river – current situation

never reported to have dried up although the completely dry season may last for more than 90 days in this area.

Hydrological analyses [11] have revealed the current water regimen of the Ombla whose water actually comes from its own drainage area, which was created after completion of structures comprising the Trebišnjica hydropower system (Figure 3). The reduction of mean flow rate from Q = 34.2 m3/s to Q = 23.9 m3/s is due to elimination of water inflow from the indirect drainage area. At that, maximum flow rates remained unchanged, while the minimum flow rates actually increased. The current flow regimen is characterized by the following values:

$Qsr = 23{,}9\ m^3/s$, $Q\ 100\ max = 113{,}0\ m^3/s$, $Q\ 100\ min = 3{,}0\ m^3/s$

2.2. Hydrogeological properties

The terrain in the Ombla spring drainage area is mainly composed on limestones and dolomites originating from the Triassic, Jurassic, and Cretaceous periods. While limestones are highly impermeable, dolomites are weakly permeable formations that assume the hydrogeological role of an incomplete hydrogeological barrier that slows down and directs water flows in the underground. Eocene sediments are composed of a flysch complex dominated by clayey marls. The bottom of karst poljes and sinkholes is covered by Quaternary sediments. Basic structural and lithostratigraphic units are spread along the Dinarides, and elongated karst poljes are formed as a consequence of intensive neotectonic activity. The position of such poljes coincides with the spreading of basic geological structures. The main and the most represented lithostratigraphic unit is formed of weathered limestones (permeable rocks). Dolomites (weakly permeable to impermeable rocks) are much less represented, while flysch formations (impermeable barriers) are the least represented unit. In the direction of lower horizons, the surface water is drained into the underground via a number of greater or smaller ponors (swallow holes), the greatest capacity of which exceeds 50 m^3/s.

Changes in ground water levels are quite rapid (up to 100 m daily), and the total difference between minimum and maximum ground water levels may amount to as much as 200 m. Groundwater streams running from ponors toward the spring may be up to 30 km long. The velocity of groundwater streams flowing through the cave channels may vary, depending on hydrological conditions, from 2 to 50 cm/s [2]. All basic geological and hydrogeological factors that have influenced formation of this karst spring are presented on the enclosed hydrogeological map.

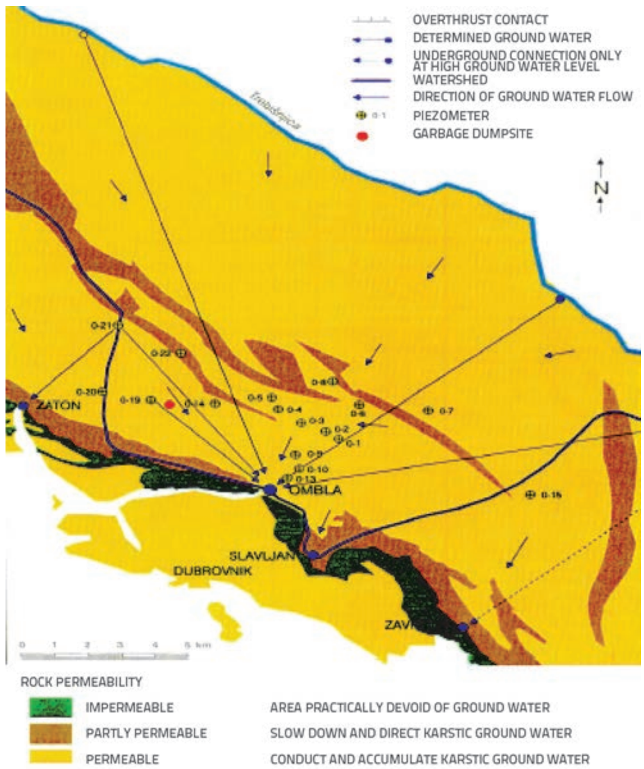

Figure 5. Part of the Ombla drainage area, position of piezometers, routes of underground streams

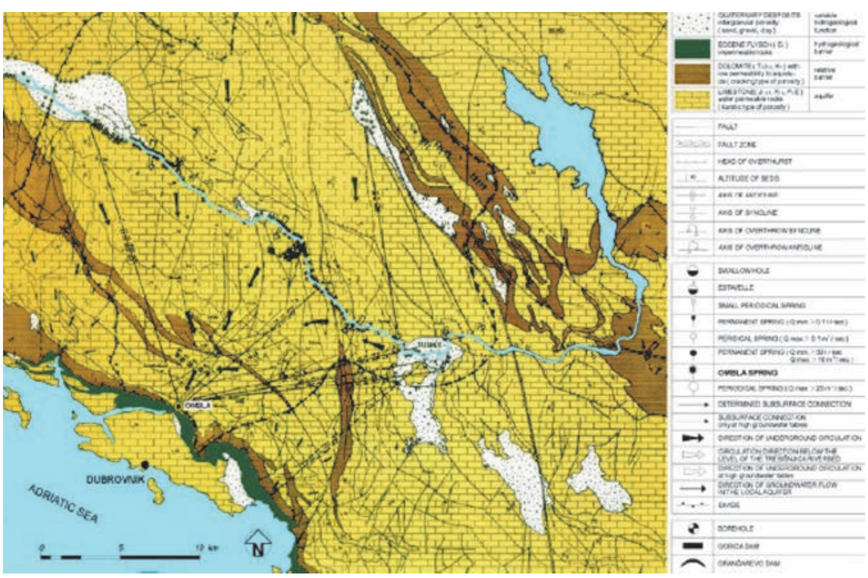

Figure 4. Hydrogeological map of Ombla drainage area

3. Investigation works

The fact that the fully dry season in the Ombla spring drainage basin may exceed 90 days and that the spring has never lost water despite such arid conditions shows that a natural retarding basin exists in the hinterland of this spring. As the analysis focusing on possibilities for forming an underground reservoir (water storage) is related to the need for gaining detailed information about hydrogeological properties of the terrain, i.e. about impermeability of the sides of the reservoir, most investigations have been directed toward the study of behaviour of the natural underground retarding basin in the Ombla spring hinterland. This retarding basin in the Ombla spring hinterland has occasionally been noted to become active. In line with this objective, detailed analyses of lithostratigraphic, hydrogeological [2] and neotectonic features [4] have been made in the area of the planned Ombla spring underground reservoir, and specifically in the zones of contact with drainage areas of neighbouring springs, i.e. Palata in Mali Zaton and Zavrelje near Mlin in Župa Dubrovačka. Twenty-two piezometric boreholes, each about 350 m in depth, were drilled in typical zones across the future reservoir, and hourly water level values are now continuously being registered. Hourly flow rates are also continuously registered at the Ombla spring, and at the neighbouring Palata and Zavrelje springs, which are thought to occasionally receive some waters from the Ombla spring drainage area. Daily precipitation values are registered at six rain gauge stations distributed over the entire drainage area. In order to define as accurately as possible the underground watershed of the Ombla and Palata (Zaton) drainage areas, the routes of underground streams were defined based on information collected from several typical boreholes (Figure 5) [7, 9]. The exploratory drift about 1100 m in length was

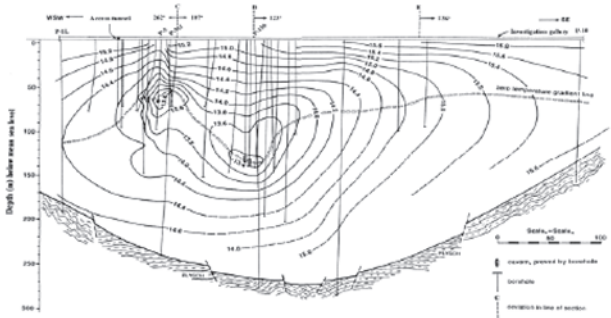

Figure 6. Weathering base, min i max groundwater levels

made in the zone of the future underground grout curtain, and thirty boreholes in the total length of 3.400 m were drilled along the bottom and along both abutments of the dam. The objective was to determine the zone with a greater rock mass weathering activity, and to locate all active and fossil cave channels. Quantitative data about the permeability of all layers

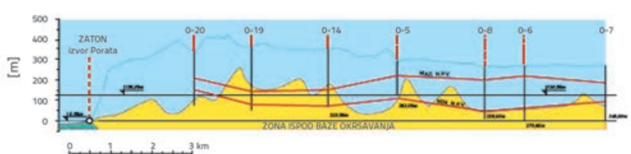

Figure 7. Carbonate and flysch complex boundary at slopes lateral to Ombla spring

Figure 8. Temperature field along the dam – position of the main cave inflow

within the studied zone were obtained by making permeability measurements along all boreholes.

The position of the main and secondary cave inflow was determined by thermometric measurements in boreholes distributed along the future dam site. The obtained temperature field (Figure 8) and permeability measurements clearly show the depth of greater weathering in the carbonate rock mass, i.e. the depth down to which grout curtain would have to be realized.

Structural relations in the zone of future structures/facilities, with fault zones (Figure 9 and Figure 10), were determined by means of detailed geological and structural tectonic mapping, through geophysical surveys, and through determination of boreholes made on the terrain surface on both sides of the spring and in the exploratory drift. The drilling has confirmed that the thickness of flysch in the substratum exceeds 350 m, and geophysical surveys have shown that the thickness of flysch in the substratum exceeds 950 m.

Figure 9. Structural relations in the spring area

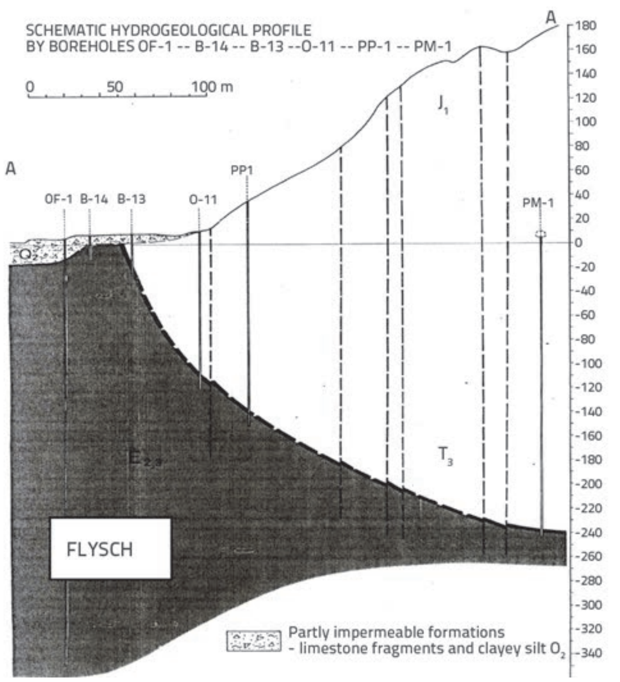

Figure 10. Structural relations in the spring (future dam site) area, cross section

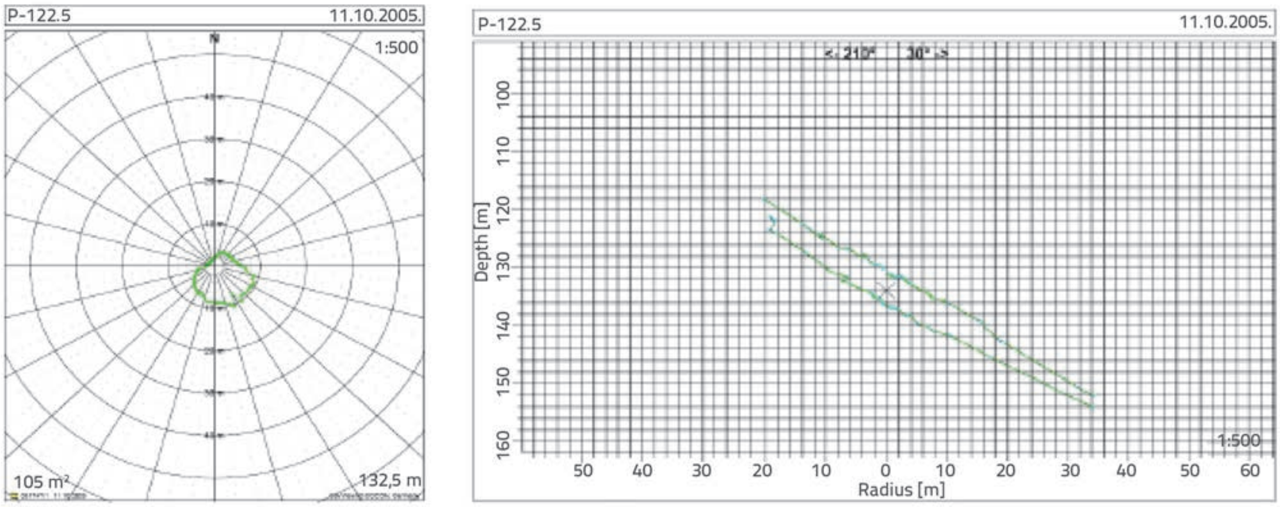

Figure 11. Horizontal and longitudinal section of the main cave inlet in the dam zone

The main inlet channel was surveyed using the ultrasound method in the grout curtain profile and upstream in the spring cave. The view of the main inlet channel as obtained with ultrasound sonar (Figure 11) is the result that is of high significance for defining the design solution for future construction of the concrete plug at the depth of 130 m, which is technically the most demanding intervention on the underground dam.

4. Underground reservoir

The current and future water level changes in the underground reservoir (water storage), and its emptying during impounding at the dam of the future grout curtain, are treated in an original and highly detailed way in the study entitled *Ombla Hydropower Plant – numerical model of the underground reservoir behaviour under natural and project-defined conditions* [12].

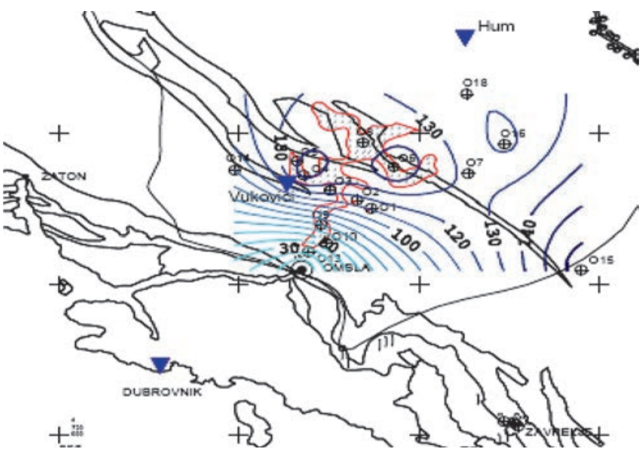

Figure 12. Flow pattern for high waters – natural condition

The basic study of the wider area of the natural underground retarding basin of the Ombla spring was conducted using the geoelectrical sounding method. The same method was applied during study of permeability of the left abutment of the Bileća reservoir. It is known that the Trebišnjica springs were flooded by construction of the Grančarevo Dam. Thus an underground storage about 70 m in height was created in the hinterland of these water abounding springs. A similar case of karst spring flooding occurred during construction of the Mratinje Dam, i.e. during creation of reservoir for the Piva HPP in the Republic of Montenegro.

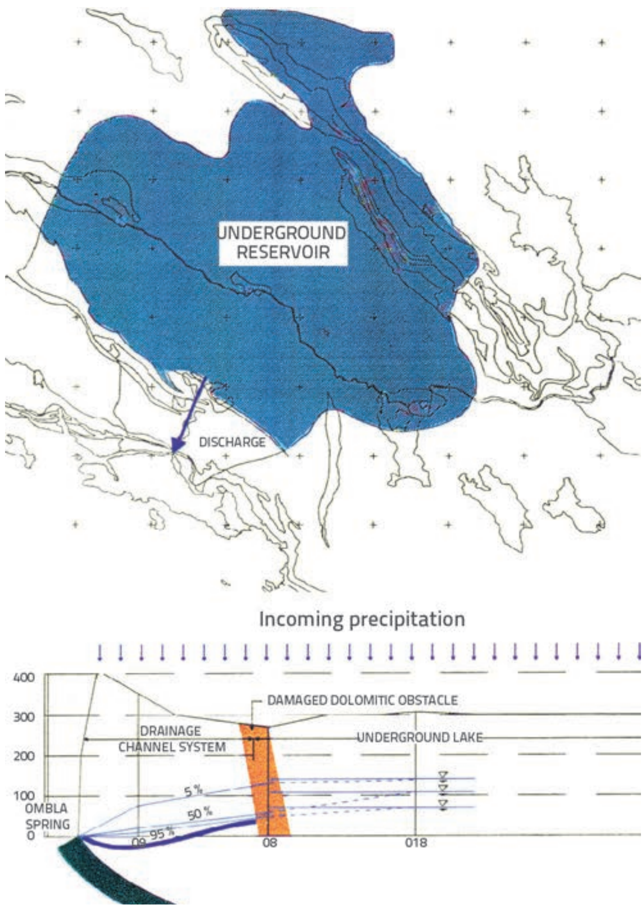

Figure 13. Schematic of underground retarding basin

The experience gained on these projects was extensively used during elaboration of the investigation works program for the Ombla Hydropower Plant. Thus the hydraulic model of the Ombla underground reservoir behaviour was created through analysis of structural relationships and tectonic damage in the zone of the incomplete underground dolomite barrier for the water coming from hinterland, through geolectrical sounding in the reservoir zone, and especially through creation of the flow pattern for low, medium and high waters (Figure 12) [12] as based on water level duration lines registered in piezometers. The basic hydraulic behaviour schema of the underground retarding basin is composed of two parts (Figure 13) [12]. The first part – located upstream of the underground dolomitic barrier – behaves as a reservoir that is emptied through the tectonically damaged dolomitic barrier. The second part – situated downstream of the underground dolomitic barrier – is much smaller by the area it occupies. This space is also filled with water after each rainfall but, due to effective permeability of the main drainage channel and the existence of secondary drainage systems, it empties quite rapidly. The flow is turbulent in the main and secondary channel-type drainage systems, while the flow is diffuse and laminar in the zones with joints and smaller cavities.

4.1. Water overflow toward neighbouring drainage areas – selection of maximum water level

The curve showing dependence between the water level in reservoir and a summary outflow, shown on an example of water evacuation from a reservoir through the bottom outlet and via the spillway on the dam crest (Figure 14) [3], is composed of two typical parts.

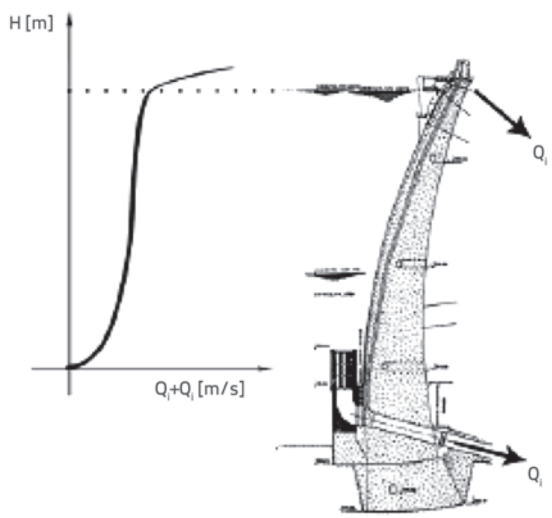

Figure 14. Curve showing dependence between water level in reservoir and summary outflows

The bottom part is characterized by the evacuation under pressure, while the top part shows that a sudden increase in flow occurred, i.e. that the spillway was activated. A similar form of the evacuation curve was defined by measuring changes in water level through piezometers installed at the Ombla.

The analysis of the relationship between the water level in typical piezometers O8 and O18 (Figure 15) and the summary flow of the Ombla and neighbouring Palata and Zavrelje springs (Figure 16) [3] confirmed the results of previous tests made to define the route of underground streams. It was demonstrated during these tests that under current natural conditions the water occasionally overflows toward Palata and Zavrelje. In fact, by water dyeing at Pridvorci ponor, it was established that during high waters the tracer occurs at the Ombla and Zavrelje, while the tracer occurs only at the Ombla at low waters [2].

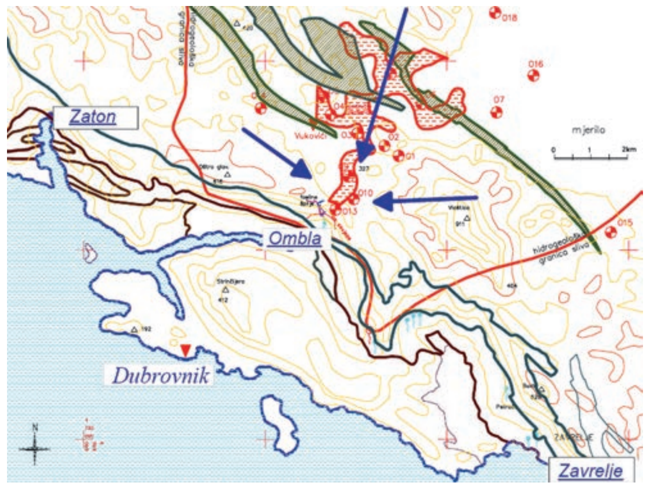

Figure 15. Position of borehole O8 in damaged underground dolomitic barrier zone and O18 in reservoir zone

Although the tracer was not determined at the Palata spring during all previous ponor dyeing activities conducted in the wider drainage area of Ombla, the overflow still occurs because the dye was registered at the Ombla (69.5 %) and Palata (3.5 %) as a result of dyeing at borehole O21 (cf. Figure 5). In fact, by pouring about 150 m^3, the water level in the borehole briefly attained the level of about 316 m a.s.l, but it soon dropped down and stabilised at the level of 135 m a.s.l. [9]. In order to check permeability of the right-side abutment in the direction of the Palata spring, under the dolomitic barrier, the dyeing was conducted from the borehole O19. the groundwater level attained the maximum of 145 m a.s.l. and the tracer occurred at the Ombla source only (cf. Figure 5). It should be noted that during this test the tracer was not registered at smaller springs (Dračevo selo and Prijevor), which are situated to the west of the Ombla at the contact between the flysch and carbonate formations at the level of about 65 m a.s.l. [9].
According to the graphical presentation of dependence between the summary flow of Ombla + Palata + Zavrelje and the ground water levels in piezometer O8 (situated in the zone of incomplete underground dolomitic barrier, cf. Figure 16) [3] it can easily be seen that the overflow from the Ombla drainage area toward the neighbouring drainage areas starts when the water level in this zone rises above the level of 150 m a.s.l. At that moment, the ground water level in piezometer O18 – situated upstream of the underground dolomitic barrier – attains the level of 175 m a.s.l in the zone of the underground retarding basin [3].

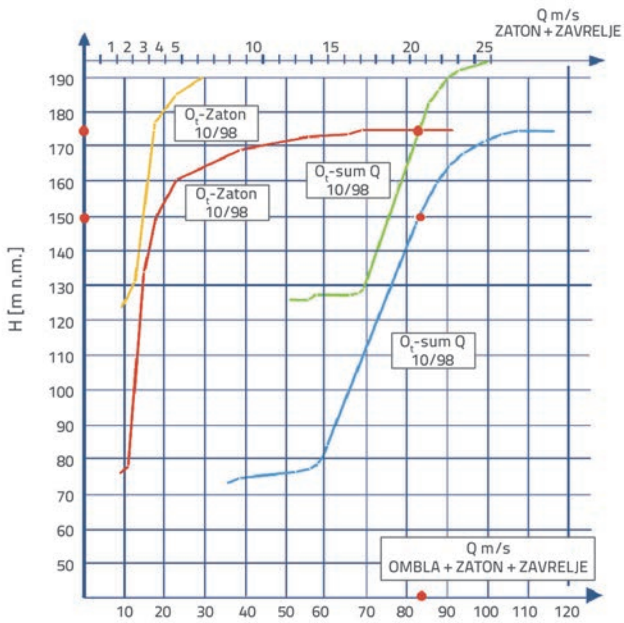

Figure 16. Summary flow of Ombla+Palata+Zavrelje and water levels in boreholes O8 and O18

Under current natural conditions, an average annual quantity of water flowing out of the Palata springs amounts to 19 hm^3, while it amounts to 14 hm^3 at Zavrelje (1989). According to Elektroprojekt data, this quantity amounts to 518 hm^3 for the Ombla spring. According to earlier and more recent Ombla spring flow data, this flow ranges from 483 to 575 hm3 (Figure 17). Measurement error for the Ombla spring ranges from 35 to 55 hm3 depending on the flow curve selected among those presented by various authors (Figure 17) [12].

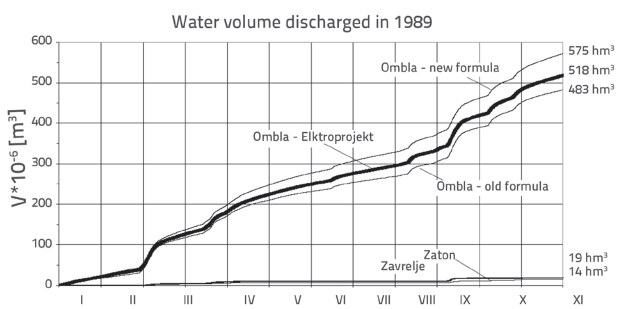

Figure 17. Flow rate registered in 1989 for the Ombla spring and neighbouring Zaton and Zavrelje springs

The water level of 130 m a.s.l. was selected as the maximum water level for the future hydropower plant based on the above mentioned conclusions that the impounding of the third level of cave channels supplying water to the Ombla starts when the water level exceeds the mentioned level, i.e. that conditions are then created for water overflow from the Ombla drainage area to the neighbouring areas and, in particular, that at that level cave channels are the best possible way for the evacuation of air from the underground during the reservoir impounding process, as the trapping of air could otherwise present difficulties.

4.2. Water discharge from reservoir at maximum water level

The behaviour of the underground reservoir changes significantly under conditions defined in the design. When water is raised to the level of 130 m a.s.l., the output hydrograph changes considerably, i.e. the maximum flow rate reduces and the water evacuation time increases, and hence the natural flow duration curve is transformed (Figure 18) [12]. Obviously, this also causes an increase in the water level in piezometers along the main channel system, beyond the maximum levels registered in natural conditions (Figure 19) [12].

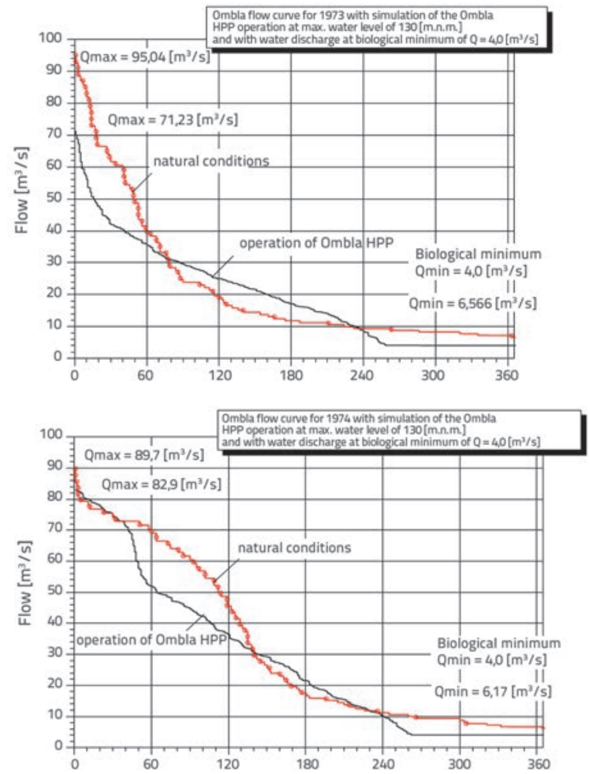

Figure 18. Duration curves for natural conditions and design conditions, for dry year and humid year

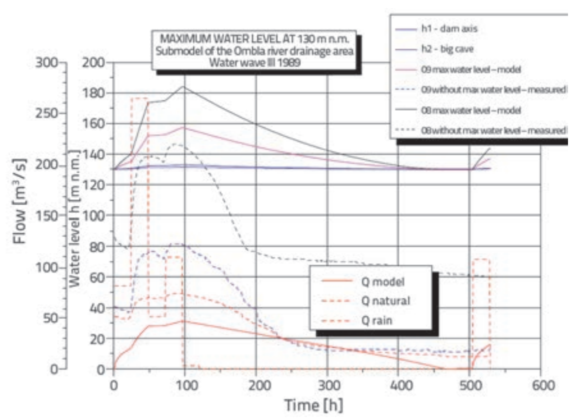

Figure 19. Piezometer levels at high water levels and maximum water level of 130 m a.s.l.

During the water wave registered in March 1989, the maximum flow rate amounted to 71 m^3/s in natural conditions, and the accumulated water discharged within 280 hours. In piezometer 08 the maximum water level amounted to 146 m a.s.l. It was established by simulation on numerical model that the maximum flow rate would amount to 45 m^3/s for the maximum water level of 130 m a.s.l. and for the water wave of similar characteristics. In this case the accumulated water would be discharged within approximately 450 hours. The maximum water level in piezometer 08 will reach the level of 180 m a.s.l. (Figure 18, Figure 20) [12] for the modelled effective porosity ranging from 0.5% at lower levels (approx. 70 m a.s.l.) to 0.1% at higher levels (above 130 m a.s.l, Figure 19). The results obtained are on the side of safety and it can be expected that the water level will be much lower, as many authors have shown that the effective porosity is much higher at higher levels (up to 3%).

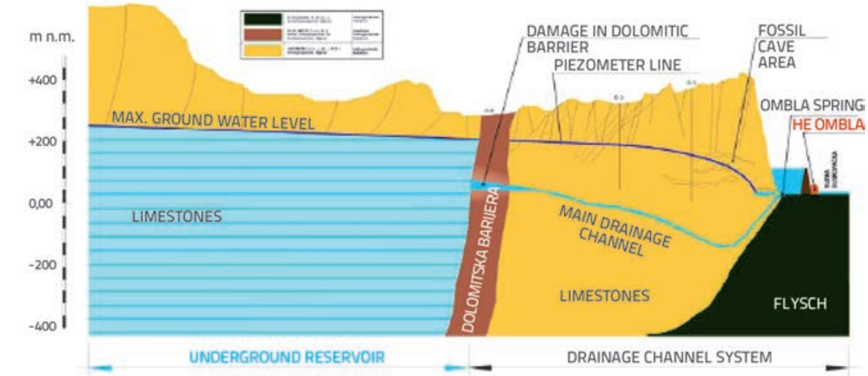

Figure 21. Schematic of Ombla spring with dam in Rijeka dubrovačka embayment

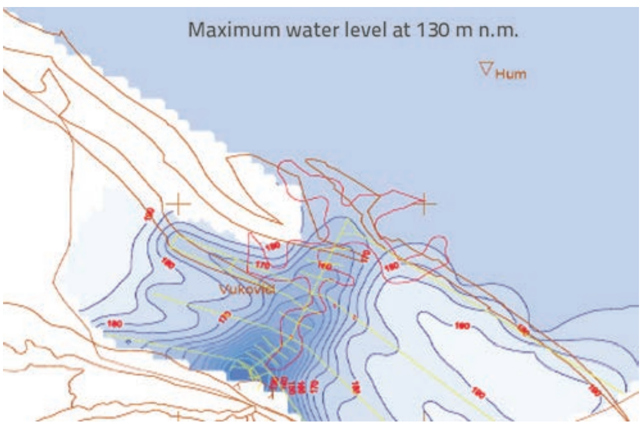

Figure 20. Water level in reservoir to the upstream and downstream of the underground dolomitic barrier once max. water level is reached

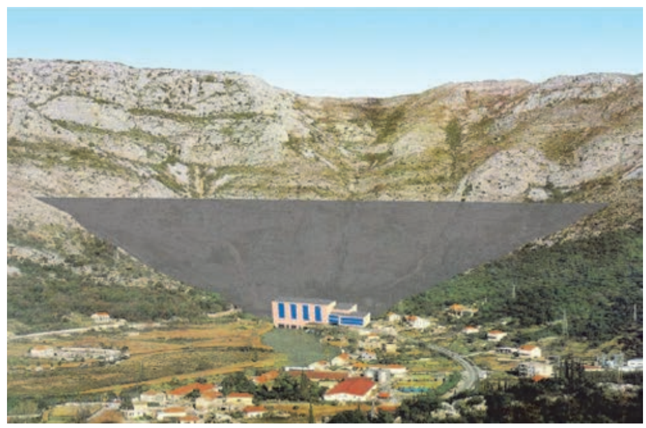

Figure 22. Ombla spring landscape with earthfill dam and HPP building – possible alternative solution

5. Design solution for Ombla hydropower plant

The project is based on the idea of creating an underground dam by building the grout curtain in the Ombla spring zone, using at that the natural rock massif as the dam body, and to ensure in this way the pressure that is required for commercial use [11, 14]. In other words, the water level would rise above the present level in the zone of the main channel and several secondary drainage channels, which are situated downstream of the underground dolomitic barrier. Thus this drainage zone would be converted into a part of a unique underground reservoir. In most parts of the year, the water level would be maintained in this reservoir at 130 m a.s.l. During the period of extreme droughts, when the minimum flow falls under Q = 4 m^3/s, the numerical model shows that the maximum water level will have to be gradually lowered to the minimum level of about 75 m a.s.l. [12]. When defining this technical solution, the main problem that had to be solved involved construction of a dam 130 m in height, without detrimental effects to natural environment. The Ombla spring area is characterized by an astounding landscape. Here we also have several protected monuments of leisure architecture. Construction of a traditional earthfill dam with an appropriate balancing reservoir would certainly be detrimental to such natural harmony (Figures 21 and 22) [14].

This is why the decision was made to place the dam into the underground and this by creating an impermeable barrier through construction of a grout curtaion in the underground, while using the natural mountain massif as dam body. Along its contour, the dam would lean onto the impermeable flysch barrier. The grout curtain would occupy an area of about 300,000 sq.m. and would be realized from three grouting galleries situated at the levels of 5, 60, and 134 m a.s.l., in the total length of about 3,500 m (Figures 23, 24, and 25). A technically and technologically complex activity during formation of the underground dam would be the construction of a plug in the underground natural inlet channel along the grout curtain, at the depth of about 130 m.

The positioning of the dam into the underground also called for underground positioning of all functional parts of the Ombla HPP. However, the exception was made for the power plant building

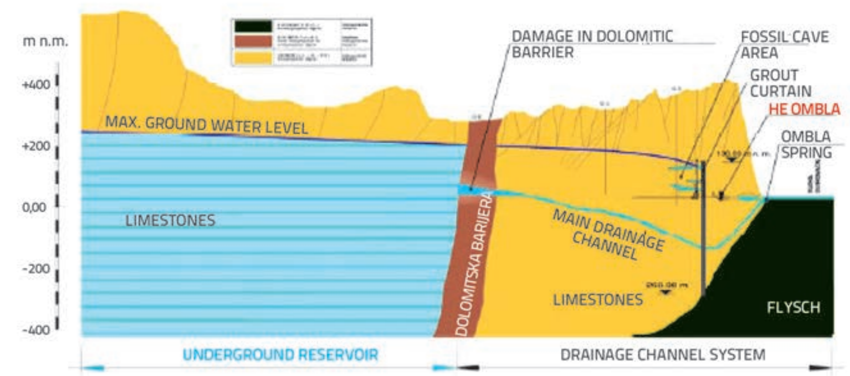

Figure 23. Schematic of Ombla spring with underground dam

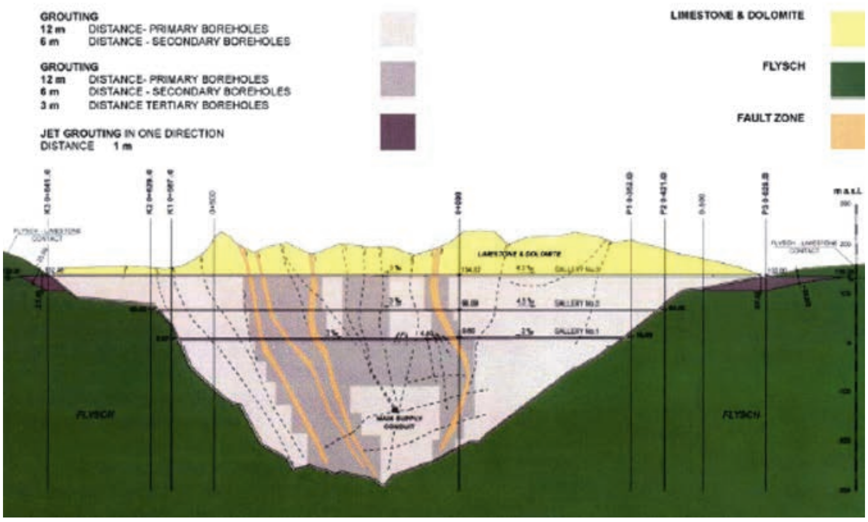

Figure 24. Cross-section of underground dam site

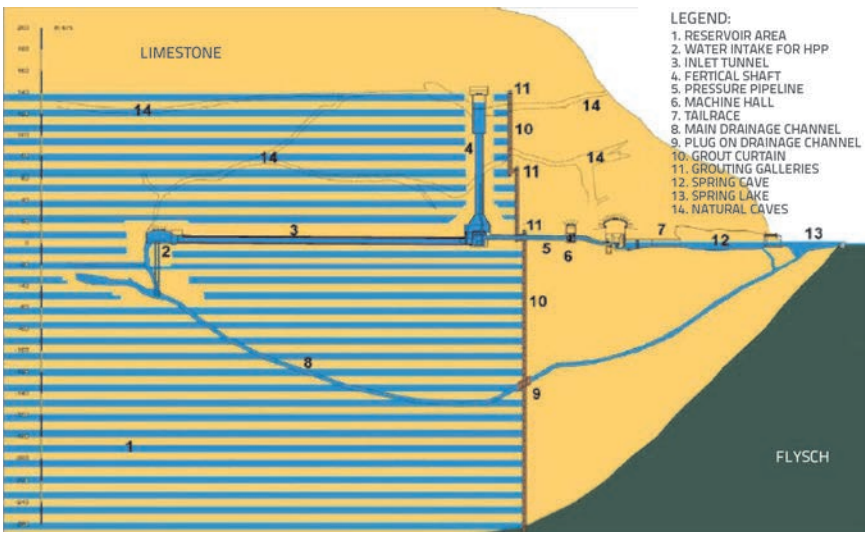

Figure 25. Ombla HPP – longitudinal profile through inlet tunnel and machine hall

which, by it volume and shape, can properly be integrated into natural surroundings. The natural harmony of the Ombla source will be fully preserved through implementation of this solution. In fact, the plant is fully hidden under the ground, while only the evacuation area at the main spring location can be seen, which visually corresponds to the current situation. The intake structure for the Ombla HPP is situated about 550 m from the entrance to the inlet tunnel of the power plant, in the natural cave located above the main natural headrace channel that currently supplies over 90% of the total water to the Ombla spring. The high pressure tunnel 250 m in length connects the intake structure to the vertical shaft. The tunnel providing access to the water intake runs in parallel with the tunnel, from the water intake to the vertical shaft.

The vertical shaft is situated within the reservoir and it is the central collection and distribution structure of the entire Ombla HPP system. It is the meeting point of the inlet tunnel, bottom outlet, pressure pipeline, and approach tunnel. One of its legs is connected to the tunnel supplying water to the town of Dubrovnik. The shaft is 136 m in height, and it varies from 5 to 10 m in diameter. By its purpose, it is the de-airing shaft enabling evacuation of air from the underground in case air bubbles become trapped in the underground. This shaft also receives overflowing waters and directs them toward the turbulent spillway. That is why the shaft is located at the contact between the inlet tunnel and pressure pipeline, and the turbulent spillway chute at its top part. To link all fossil caves at higher elevations of up to 130 m a.s.l. and to enable diversion of water for the water supply of Dubrovnik in the cave at 55 m a.s.l., the shaft is placed in such a way to enable connection of the fossil cave at various levels by the shortest possible horizontal links. In addition, the shaft will be used as the place where any tunnel can be temporarily cut off and its water diverted, so that it can be inspected or repaired during low water levels at the Ombla. The shaft will accommodate a gallery with gates from which individual tunnels can be cut off. During operation of the hydropower plant, these gates will be submerged. The gallery is linked to the approach tunnel, i.e. to its part situated within the reservoir behind the pressure gate, as presented in Section 6.

The water is carried via the pressure pipeline from the vertical shaft to turbines. The gate chamber with the butterfly gate is situated 120 m away from the vertical connection shaft. After the gate chamber, the pipeline divides into four branches and descends into the machine hall. The machine hall and the 110 kV switch yard are situated one facing the other in the same cavern 70 m in length, 18 m in width, and 30 m in height, and are separated by approach tunnel situated 126 m away from the tunnel entrance, which is at the same time the motor vehicle and pedestrian entrance for both structures. The machine hall accommodates four production units, two with Francis turbines for the nominal flow rate of Qi = 2x24 m^3/s and synchronous generators 2x30 MVA, and two smaller units for the nominal flow rate of Qi = 2x6 m^3/s and synchronous generators 2x8 MVA. The Ombla HPP will operate in a run-of-river mode. The total installed capacity of the plant is 68 MW, and the mean annual production in an average humidity year is 223 GWh. After passing through turbines and leaving the diffuser, the water is carried by the tailrace tunnel to the natural spring cave. The cave spreads down to the depth of about 60 m, it is about 40 m in width, and it ranges from 10 to 15 m in height. The water leaves the spring cave through the outlet structure and discharges into a spring lake and then via the spillway into the Rijeka dubrovačka.

The specific feature of this hydropower plant is the fact that the inlet tunnel is connected to the main cave channel at the point situated about 300 m to the upstream of the grout curtain profile. High waters are evacuated via bottom outlet with two cone-shaped gates and via the turbulent spillway at the dam crest. A specially devised solution has enabled the inlet tunnel and bottom outlet to act as the bypass tunnel during the construction works.

The bottom outlet spreads from the vertical shaft to Rijeka dubrovačka and, together with its stilling basin, it is a fully buried facility. In addition to its water discharge function, the bottom outlet also acts as a safety spillway, and serves for evacuation of water during construction of the Ombla hydropower plant. It is dimensioned in such a way that it can evacuate the water flow of 120 m^3/s corresponding to a 100-year return period. It consists of a circularly shaped tunnel measuring 4.0 m in diameter, main gate chamber with two Howel-bunger gates and one plate gate, stilling basin chamber, horse-shoe shaped tailrace tunnel, and overflow chamber next to the bank of Rijeka dubrovačka (Figure 26).

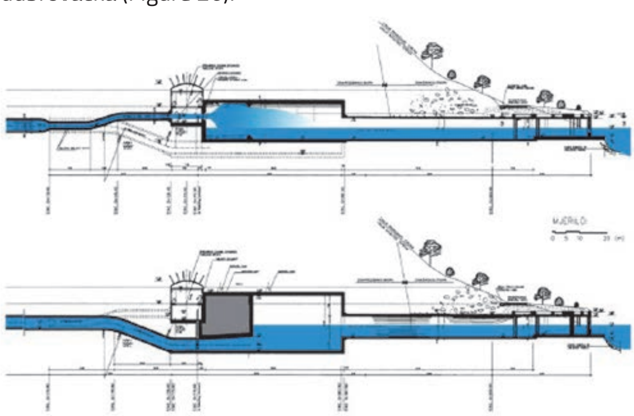

Figure 26. Bottom outlet – longitudinal profile

Because of complexity of hydraulic phenomena and relationships on this project, theoretical hydraulic calculations had to be complemented, after completion of preliminary design, with appropriate hydraulic model tests on a physical model [16] to enable proper preparation of the detailed design. In this respect, the connection had to be established between the shape of the cone shaped gate and dissipation of energy in the stilling basin chamber, so as to obtain the maximum damping of energy. It was also necessary to study flow in the tailrace tunnel and to optimize the shape of the bottom outlet chamber. Hydraulic model tests enabled the designer to get a more detailed insight into the hydraulic flow, which finally resulted in appropriate modifications and optimization, i.e. in the changes to the solution and shape of the facility (Figure 27).

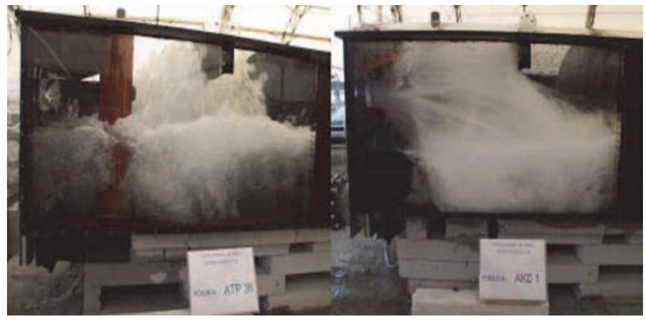

Figure 27. Testing bottom outlet on a physical model, plate gates and Howel-Bunger gates

The turbulent spillway is constructed in such a way that it receives water from the vertical shaft, and then it carries this water via the chute over the dam crest. The water is directed via a specially designed entrance section enabling creation of a turbulent flow to the vertical descending shaft, 130 m in height, which is aired along the entire height because of turbulent flow. Most energy is dissipated at the bottom of the shaft in the stilling basin and the water continues to flow through a shorter tailrace. The water flow is operated with a free water face, which enables good aeration and, ultimately, the water is discharged into the spring cave area. Conditions of flow in turbulent spillway also had to be checked on a hydraulic model [16]. The model testing objective was to obtain an uniform circular introduction of overflowing water into the spillway with the existence of a free air core. In addition, the most favourable form of walls in transitional section of the chute had to be determined in order to harmonize occurrence of seiches (standing waves) in the cross section of the exit, and also to harmonize the size and shape of the stilling basin in order to obtain a calm flow along the free water face in the tailrace (Figure 28).

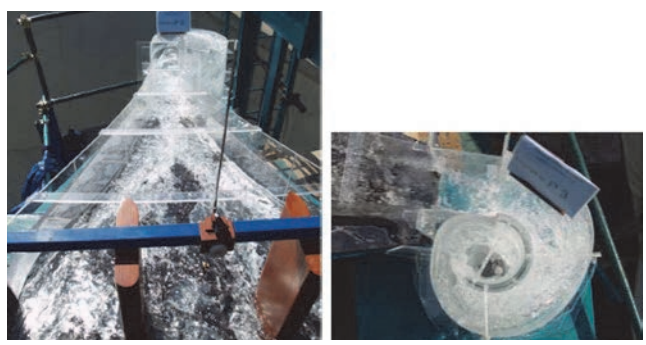

Figure 28 Testing turbulent spillway on physical model

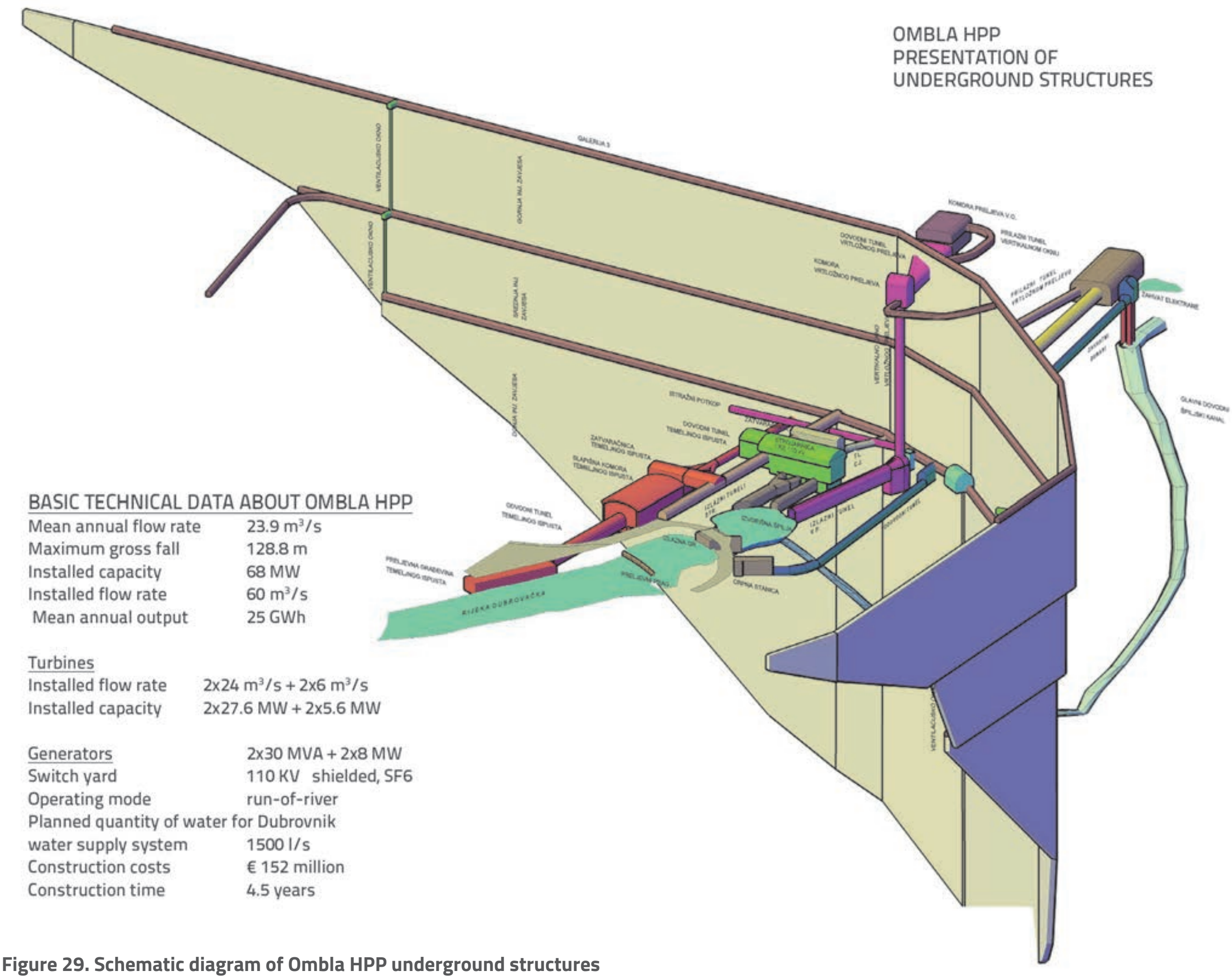

Figure 29. Schematic diagram of Ombla HPP underground structures

The pumping station of the existing water supply system of the town of Dubrovnik is located next to the spring lake. According to the Ombla HPP design, the Dubrovnik water supply system will be realized by collecting water from three points: from the natural cave about 500 m in the underground where the intake structure for the power plant will be located, from the vertical shaft at 55.0 m a.s.l., and from the present day spring lake, 1500 l/s in capacity. The schematic diagram of underground structures of the Ombla HPP is given in Figure 29.

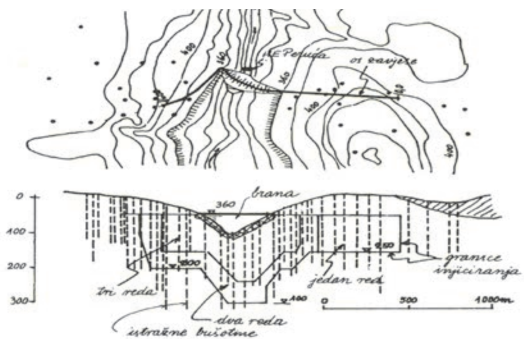

Figure 30. Plan view of Peruča surface dam with the route and longitudinal profile of grout curtain

6. Grout curtains in foundations of surface dams in dinaric karst

Examples of grout curtains successfully realized in foundations of above-surface dams erected in karst areas of Dinaric Alps (Figures 30 and 31, Table 1) [17] clearly show that the technology currently

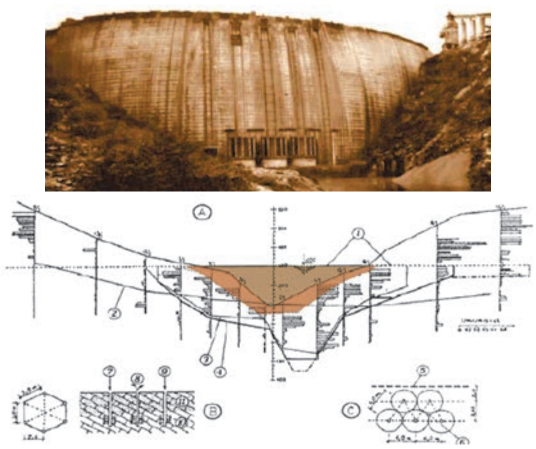

Figure 31. Grančarevo surface dam and underground dam (grout curtain) in its foundations

Table 1. Grout curtains of surface dams in Dinaric karst

Dam, height [m]	**Type**	**Geological composition of rock**	**Max. depth** [m]	**Grouted** [m]	[m/m²]	**Weight**	**Consumption of grout** [kg/m²]
Brane na kršu							
Liverovići, 49	BL	Limestone and dolomite	140	29.600	0,66	cpb	80
Peruča 65, desna lijeva prosječna	K	Cretaceous limestone	200	68.000 72.700 140.700	0,58 0,58 0,58	cbg 50/25/25 cg 25/75	176 248 210
Krupac, krila, zone	1 2 3	vapnenac i dolomit	42 30 25	4300 2400 4400	0,42 0,57 0,47	cpg 23/40/37	528 320 127
Široka ulica (bočna)	-	Limestone	75	18.200	0,35	cg 33/67	202
Gorica, 30	BG	Limestone	70	8700	0,46	cg 40/60	122
Grančarevo, 123	BL	Limestone, Jurassic	195	17.700	0,28	cg 33/67	49
Sklope, 78	K	Limestone and limestone breccia	120	55.700	0,59	cg 60/40	290
Rama, 100	K	Limestone and dolomite	200	32.600	0,38	cb 95/5	42
Špilje, 110	K	Limestone and schist	145	90.500	0,48	c	277
Letaj, 33	BL	Limestone	20	950	0,60	c	260*
Podgradina, 125	K	Eocene limestone and marl	65	7500	0,15	c/g 30/70	10
Kazaginac, 20	K	Cretaceous limestone	126	74.800	0,31	c/g 30/70	48
Kazaginac, bok		Cretaceous limestone	80	14.800	0,34	c/g 30/70	304
Metiljevica	-	Cretaceous limestone	67	7100	0,27	c/g 30/70	123
Poždrikoza	-	Cretaceous limestone	-	28.700	0,51	c/g 30/70	125
Sinjski ponor		Cretaceous limestone	-	31.600	0,25	c/g 30/70	139
Župica, 23	K	Limestone	185	41.720	0,34	c	34
Bokanjčko blato	-		32	11.000	0,22	c	90
Martinje, 220	BL	Limestone	278			c	

Table 2. Underground dams and reservoirs in karst on Japanese islands

Underground dams built in limestone rock in Japan							
Dam name	**Dam location**		**Built in**	**Height** [m]	**Length** [m]	**Reservoir size** [m³]	**Flow rate** [m³/dan]
Minafuku	Okinava	Gusukube	1979.	16,5	500	720.000	7000
Sunagawa	Okinava	Gusukube	1987. - 1994.	50	1677	9.500.000	24.000
Fukusako	Okinava	Gusukube	1993. - 2000.	27	1790	10.500.000	30.000
Kikai	Kagoshima	Kikai	1993. - 2002.	36	2190	1.681.000	
Komesu	Okinava	Itoman	1993. - 2003.	80	2489	3.457.000	89.000
Giza	Okinava	Gushikami	1998. - 2003.	51	955	389.000	1200
Kanjin	Okinava	Gushikava	1996. - 2003.	52	1088	158.000	

used for building grout curtains offers a very high level of safety with regard to prevention of water losses, and that grout curtains built in our karst conditions are both stable and long-lasting.

7. Underground dams worldwide

Underground dams with their underground reservoirs constructed so far in various parts of the world, most of them situated in karst areas, are best presented in paper [18] in which the Ombla underground dam is also mentioned. Underground dams constructed until 2003 on Japanese islands around Okinawa are presented in Table 2. These underground dams and their reservoirs were built for the water supply and irrigation purposes.

It is interesting to note that, even in this ground water utilisation concept, the position of the weathering zone base is used as the main result of hydrogeological studies, all in order to ensure proper impermeability at abutments (sides) of the underground reservoir.

8. Conclusion

The design of the Ombla hydropower plant constitutes a completely new approach to the use of water power for the production of electric energy. Such an approach can be implemented at the location of the Ombla spring due to its appropriate hydrogeological conditions that are typical for karst areas. The fact that the entire project is placed underground reduces the construction cost and, what is especially important, the surrounding natural landscape is not harmed by the project. The procedure described in the paper enables construction of complex structures, such as hydropower plants, in environmentally sensitive areas.

The results of very extensive and long-lasting research, and conclusions of many studies, clearly show that an underground reservoir can effectively be formed in the hinterland of the Ombla karst spring. Design solutions developed for individual structures of this project show that the idea about construction of an underground reservoir and power plant is technically feasible, and that the entire project is highly profitable. In addition, the current supply of water for the town of Dubrovnik will be improved through realization of the proposed development. The use of pumps is avoided because of the water level increase and, more importantly, present day problems related to an increased turbidity and occasional water pollution will be eliminated. Grout curtains, built in foundations of all surface dams in karst areas of Dinaric Alps (Peruča, Grančarevo, etc.) demonstrate in the best possible way that the proposed method is capable of ensuring watertightness of the Ombla underground dam.

Underground dams and reservoirs constructed so far in karst areas on Japanese islands clearly point to the current worldwide dam building trend and to the novel way of managing water resources, i.e. the new way for securing adequate quantities of water, which is increasingly lacking and in scarce supply all over the world. In this sense, the Ombla HPP project follows this trend as the first such project in the Mediterranean area. It should also be noted that Ombla is not the only locality in the Dinaric karst area of Croatia in which water from underground reservoirs can be used, which points to the presence of a considerable, albeit still unused, ground water potential in this area.

REFERENCES

[1] Energija iz kraškog podzemlja, HE Dubrovnik, 1989.
[2] Milanović, P. i dr.: HE Ombla, idejni projekt, geološki elaborat. Knjiga I-V, Energoprojekt, Beograd, 1989.
[3] Paviša, T.: Analiza ponašanja podzemne akumulacije Ombla u prirodnim uvjetima, Elektroprivreda Hrvatske, Dubrovnik, 1993.
[4] Prelogović, E., Buljan, R., Fritz, F.: HE Ombla, Strukturna istraživanja, Institut za geološka istraživanja, dokumentacija br. 111/94, Zagreb, 1994.
[5] Paviša, T.: Položaj glavnog špiljskog kanala i određivanje protoka, HEP Dubrovnik, 1994.
[6] Paviša, T.: Analiza ponašanja podzemne akumulacije u razvodnici prema Palati, 1995.
[7] Biondić, B., Pavičić, A.: HE Ombla, Ocjena maksimalne kote uspora podzemne akumulacije, Institut za geološka istraživanja, dokumentacija br. 109/95, Zagreb, 1995.
[8] Prelogović, E., Buljan, R.: HE Ombla, Lokacija pregrade i objekata - strukturni model, Institut za geološka istraživanja, br. 113/95, Zagreb, 1995.
[9] Renić, A.: HE Ombla, Izvještaj o rezultatima provedenog trasiranja tokova podzemne vode kroz bušotinu O19, Institut za geološka istraživanja, dokumentacija br. 32/96, Zagreb, 1996.
[10] Prelogović, E., Buljan, R.: HE Ombla, Strukturno-geološko kartiranje duž glavnog, desnog i lijevog tunela (pristupni tunel i galerije), Hidroinženjering, dokumentacije br. 11/96, Zagreb, 1996.
[11] Sever, Z. i dr.: HE Ombla, Idejni projekt, Hrvatska elektroprivreda, Elektroprojekt, Zagreb, 1998.
[12] Sever, Z.: HE Ombla - Glavni projekt, Elektroprojekt, Zagreb, 2011.
[13] Andročec, V., Babić, M.: HE Ombla, Rezultati modelskih ispitivanja organa za evakuaciju velikIh voda, IGH Zagreb, 2007.
[14] Izvješće o ispitivanju vode Omble, Zavod za javno zdravstvo grada Zagreba, 1997.
[15] Sever, Z.: HE Ombla, Idejni projekt - Otiješnjenje pregradnog mjesta, Elektroprojekt, Zagreb, 1996.
[16] Snimak glavnog špiljskog dovoda, SOCON Sonar Control Kavernenvermessung, Germany, 2005.
[17] Jović, V.: HE Ombla, Numerički model ponašanja podzemne akumulacije u prirodnim i projektom definiranim uvjetima, Aquarius engineering, Split, 1997.
[18] Nonveiller, E.: Injiciranje tla, Školska knjiga Zagreb, 1989.
[19] Ishida, S., Tsuchihara, T., Yoshimoto, S., Imaizumi, M.: Sustainable Use of Groundwater with Underground Dams, JARQ 45 (2011) 1, pp. 51 – 61, http://www.jircas.affrc.go.jp
[20] Geološki i hidrogeološki istražni radovi na širem području ''Grabovica'', Geoaqua Zagreb, 2008.