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Small Hydropower Plant Otočac Project †

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Abstract

A new small hydropower plant has been constructed in the city of Otočac, Croatia, on a branch of the existing Lika–Gacka channel. It operates with an average water head between 3 and 6 m and a rated discharge of 3 × 16 m^3/s, with a total installed capacity of 1.5 MW and an expected annual output of more than 7 GWh. SHPP Otočac consists of the following main components: water intake on the existing channel; gate structure on the existing channel or spillway structure; new headrace channel; the powerhouse structure with generating units; plateau with a control building; tailrace channel; access road; a 35 kV connection cable from the plant to the interconnection at the nearby substation.

Keywords: small hydropower plant; massive reinforced concrete structures; gate structure; powerhouse

1. Introduction

The small hydropower plant (SHPP) Otočac is constructed on a branch of the existing channel through which the Lika River flows into the Gacka River at the Šumečica junction in the town of Otočac, Croatia. It utilizes the hydropower potential of the Lika and Gacka rivers along the existing energy cascade from the Lika plateau to the Adriatic Sea. The average water head of the plant ranges from 3 to 6 m, while the rated discharge is 3 × 16 m^3/s [1]. The core of the power plant consists of submerged low-head generating units comprising variable-speed Kaplan turbines and permanent-magnet generators. The installed capacity of the plant is 3 × 0.5 = 1.5 MW, and the expected annual output exceeds 7 GWh of electric power [2].

The objective of this paper is to present the structural engineering challenges encountered in the design of SHPP Otočac and to summarize the design approaches and engineering lessons derived from their resolution. The principal engineering contribution lies in the integrated design of complex massive reinforced concrete hydraulic structures under combined hydraulic, groundwater, geotechnical, and seismic actions, including measures for controlling early-age cracking. Unlike a conventional small hydropower plant based on an independent dam–reservoir arrangement, SHPP Otočac is integrated into an existing water-conveyance and hydropower cascade system and utilizes a very low available head of approximately 3 to 6 m.

Check for updates

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2. Main Civil Structures of the SHPP Otočac

SHPP Otočac consists of the following civil engineering structures [3]:

1. Water intake on the existing channel;
2. Gate structure on the existing channel or spillway structure;
3. New headrace channel;
4. Powerhouse structure with generating units;
5. Tailrace channel;
6. Plateau with a control building;
7. Access road and 35 kV connection cable from the plant to the interconnection at the nearby substation.

Main structures are shown in Figure 1 and are marked according to previous numbering.

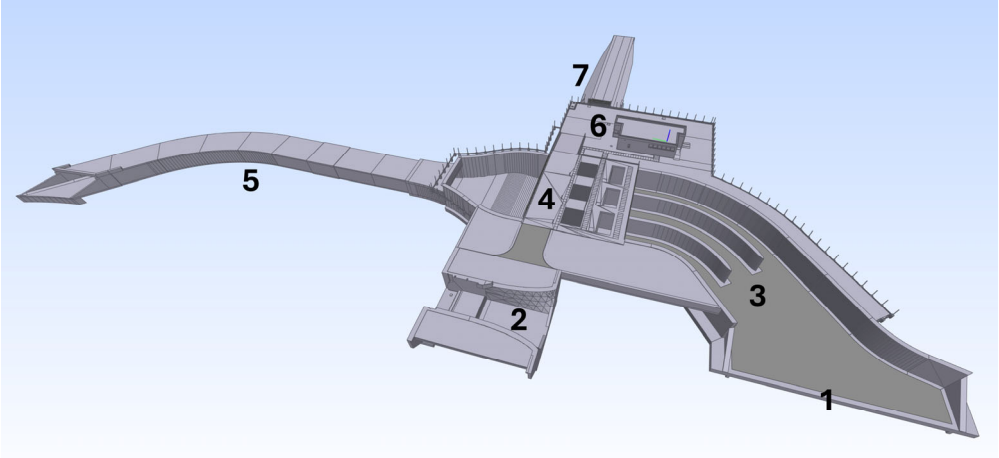


Figure 1. Layout of the main structures of the SHPP Otočac.

2.1. Water Intake on the Existing Channel and Gate Structure

The water intake is achieved by constructing a massive reinforced concrete (RC) gate structure with a spillway gate on the existing channel, which slows the water in the Lika–Gacka tunnel (channel).

The gate structure is planned upstream of the first cascade in the existing channel and consists of a spillway sill with a clear width of 8.0 m, on which a 2.50 m high flap gate is installed. During SHPP operation, all flow from the existing channel is directed into the new headrace channel. The gate structure or the spillway structure (depending on whether the flap gate is lifted or lowered) is a massive RC structure with a total length of 25.1 m, consisting of a 15.1 m long transition section and the 10.8 m long spillway structure itself, separated by an expansion joint. The transition section consists of a foundation slab of variable thickness (1.0–1.2 m), side walls arranged in plan along a curve (1.0 m thick on top) and cantilevered wing walls. The spillway structure consists of a foundation slab of variable cross-section (1.2–2.4–3.9 m), side walls (1.0 m thick) and wing walls with foundations [4]. The gate structure has shallow foundations and is shown in Figure 2.

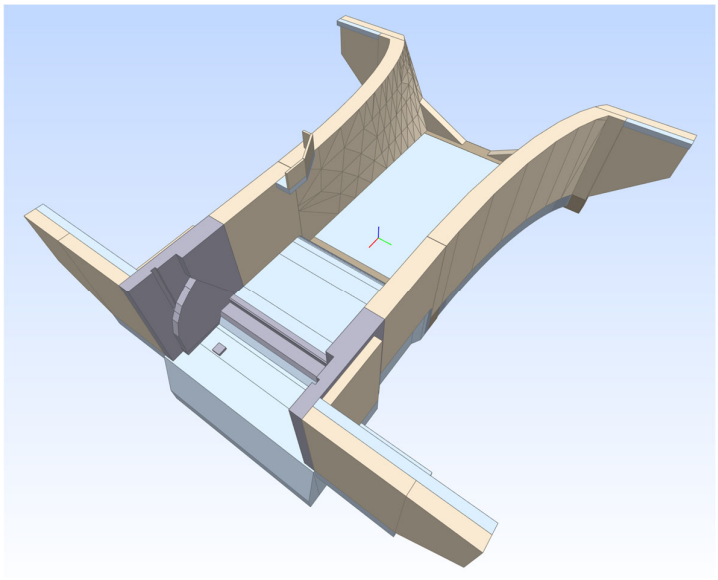


Figure 2. Gate structure or spillway structure.

2.2. New Headrace Channel

The new headrace channel conveys water from the existing channel to the generating units.

The headrace channel of SHPP is 63.0 m long, with an average width of approximately 25.0 m and a depth of about 6.00 m. In plan view, it consists of a straight section 33.55 m long, a curve with a radius of 25.5 m, and a final straight section 6.1 m long. The channel is formed by RC wing walls, side retaining walls, and internal RC dividing walls, providing a hydraulically favorable intake arrangement towards the generating units. The channel bottom is designed as stone embedded in concrete. Along the section from 30.5 m to 63 m, the channel is divided by internal walls into three parts: two side sections with a clear width of 7.5 m and a central section with a clear width of 8.0 m [4].

2.3. Powerhouse Structure with Generating Units

The powerhouse with generating units is a massive RC structure composed of the following interconnected elements: foundation slab; lateral walls; central walls; bridge slab, slab above the generating units, and transverse walls downstream of the units (spillway). The powerhouse structure is shown in Figures 3a,b and 4.

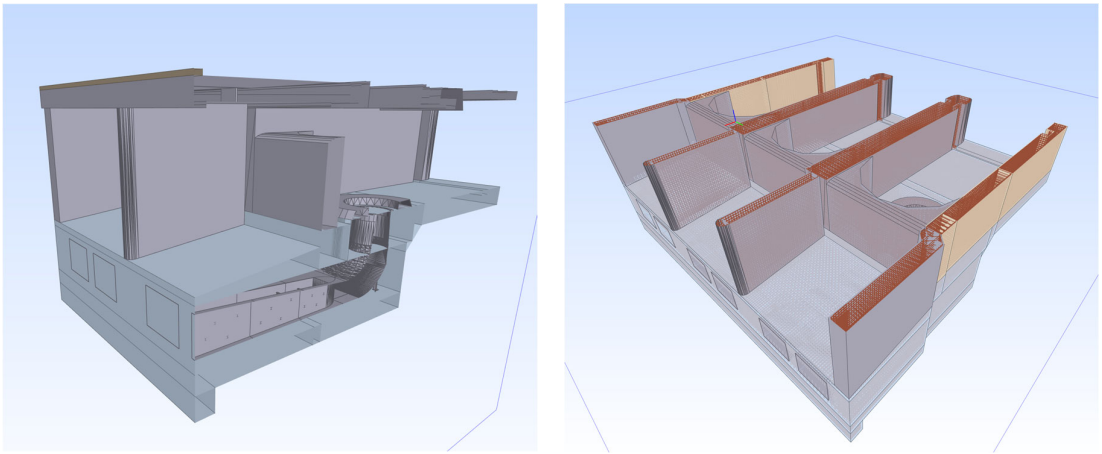
The intake section to the generating units is hydraulically favorably shaped to ensure a uniform water flow to each turbine. The discharge of water from the turbine into the tailwater is provided through a diffuser approximately 11.0 m long. The outlet cross-section of the diffuser has an area sufficient to ensure an outlet velocity lower than 1.0 m/s. The connection between the powerhouse with generating units and the tailwater is provided by the transition section of the tailrace channel.

The powerhouse with generating units has plan dimensions of 24.75 m × 29.00 m and a maximum height of 13.0 m. The maximum structural height of the powerhouse is 11.8 m, or 13.0 m at the downstream key below the foundation. The powerhouse is embedded into the existing ground, which is predominantly characterized as clay. The powerhouse structure has shallow foundations [4].

The powerhouse structure is composed of the following interconnected elements:

- Foundation slab—an RC slab 1.2 m thick, and 1.55 m thick below the diffuser.
- Lateral walls—RC walls up to the bridge slab with a full-height thickness of 1.0 m.

- Central walls—RC walls up to the bridge slab, with a full-height thickness of 2.0 m and 0.8 m thick below the bridge slab.
- Bridge slab—an RC bridge slab 0.8 m thick.
- Slab above the generating units—an RC slab above the generating units is 0.5 m thick.
- Transverse wall downstream of the generating units (spillway)—an RC wall behind the generating units, 0.8 m thick at its thinnest section, considered in the calculation as a wall of constant cross-section.
- Transverse beams—two RC beams with dimensions of 0.7/1.0 m—are formed along the cable channels at the top of the powerhouse.



(**a**) (**b**)

Figure 3. Powerhouse structure: (**a**) vertical section; (**b**) horizontal section.

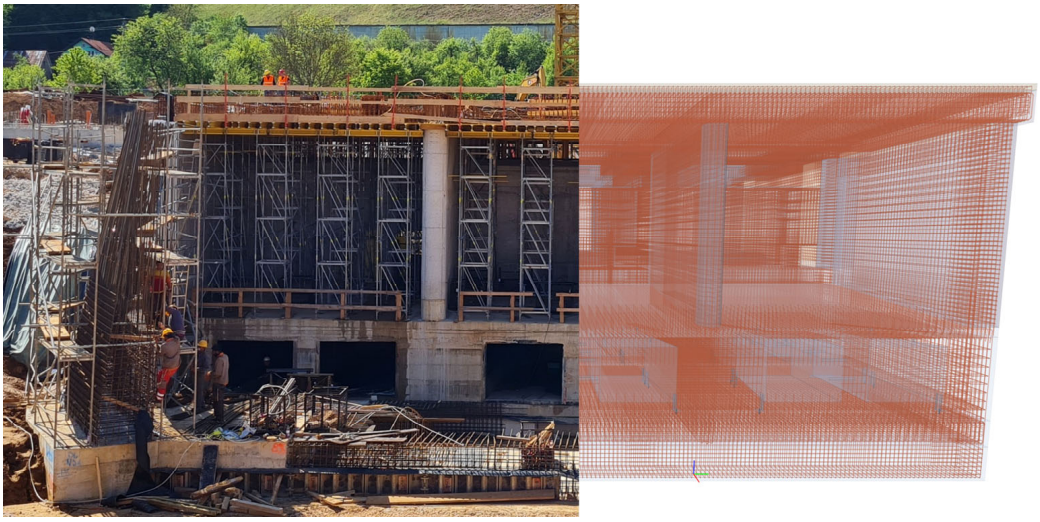


Figure 4. Construction of powerhouse structure and open channel transitional section.

2.4. Tailrace Channel

Water discharge from the generating units is provided through a tailrace channel connected to the existing Lika–Gacka channel downstream of the second cascade. The tailrace channel consists of three sections: open channel transitional section; closed channel section; connection between the new and existing channels.

The open channel transitional section (Figures 4 and 5) represents the connection between the powerhouse with generating units and the closed section of the tailrace channel (Figure 6), with a length of 35.85 m. This section is designed as an open rectangular profile with an initial

profile width of 26 m and a width of 8 m at the connection with the closed channel profile. The transition from one width to the other is formed by vertical RC walls, shaping a hydraulically favorable transition contour between the two profile widths. The transitional section is a geometrically complex structure, variable both in plan and in elevation. The maximum wall height is 10.25 m. The wall thickness increases from 0.6 m at the top, with an inclination of 10:1, to 1.53 m/1.35 m at the connection with the foundation slab [4].

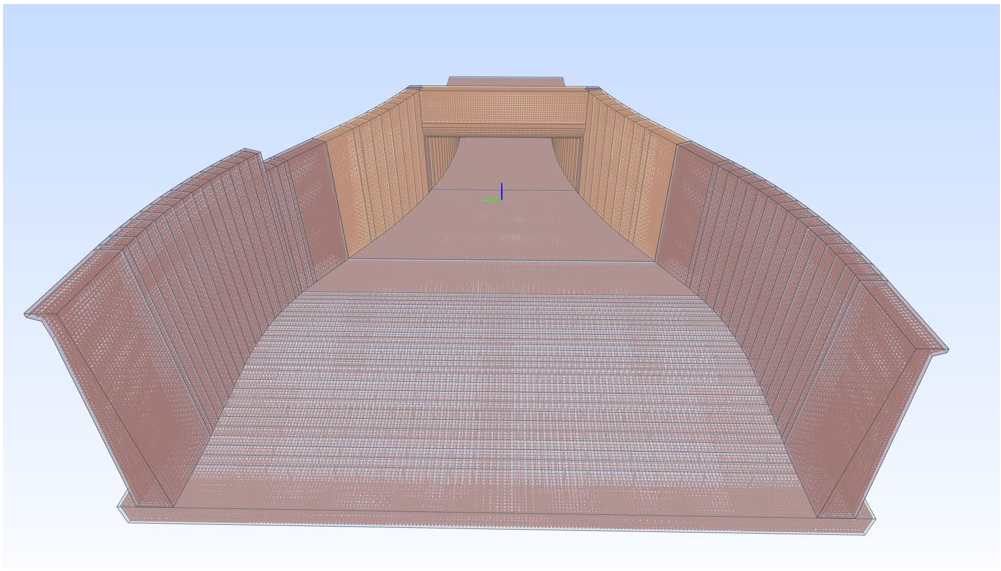


Figure 5. Open channel transitional section.

After the open channel section, the underground closed section begins. It consists of a lower foundation slab, walls and an upper slab 0.4 m thick. In cross-section, the RC frame has a clear opening 8.0 m wide and 4.0 m high. The bottom of the tailrace channel is designed with a slope of I = 0.000350, ensuring tranquil flow in the channel profile with a velocity of 2.0 m/s. The length of the closed channel section is approximately 111.0 m. All structures are backfilled with excavated material, i.e., clay, with proper compaction, and the tailrace channel has shallow foundations.

The connection between the new and the existing channels is provided by cutting a rectangular profile 8.0 m wide into the slope of the existing channel.

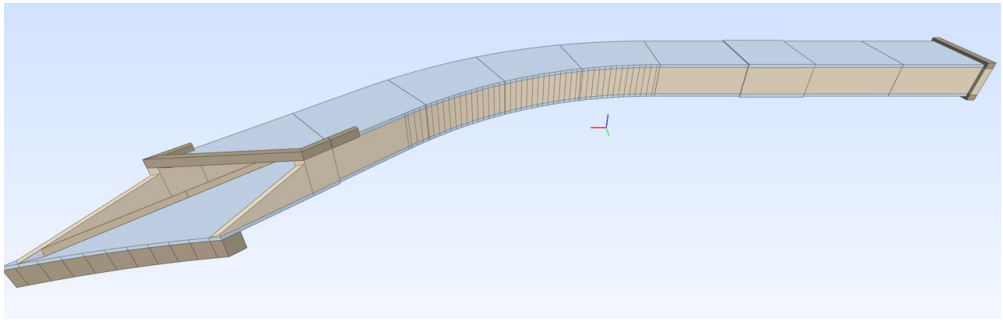


Figure 6. Closed section of the tailrace channel.

3. Design Approach

3.1. Global Stability Checks

Checks against uplift of RC structures were carried out in accordance with HRN EN 1997-1:2012 [5,6], which requires that the design value of destabilizing actions be less than

or equal to the sum of the design values of stabilizing, permanent vertical actions. The safety of the analyzed structures against uplift was verified for the most unfavorable case, in which the water inside the RC structure is suddenly emptied while the surrounding soil remains saturated with groundwater up to the ground surface. Results of checks against uplift for some main RC structures are shown in Table 1 below.

Table 1. Results for checks against uplift for main RC structures.

RC Structure	Design Value of Stabilizing Permanent Actions (kN)	Design Value of Destabilizing Actions (kN)	Safety Factor [1]
Gate structure	9360	6640	1.41 > 1.0
Powerhouse	85,157	60,012	1.42 > 1.0
Tailrace channel transitional section	19,655	14,207	1.38 > 1.0
Tailrace channel closed section	4610	3752	1.22 > 1.0

[1] Safety factor represents the ratio of design stabilizing/destabilizing values and does not represent the overall amount of safety because design values also include partial safety factors.

For structures retaining water, namely the powerhouse and gate structure and the retaining walls, global stability checks against sliding and overturning were carried out for both static and seismic actions. The most unfavorable case was verified, in which the flap gate is raised and retains water in the channel at the maximum water level, together with the corresponding seismic loading. The global stability verification was carried out in accordance with HRN EN 1997-1:2012 and HRN EN 1998-5:2011 [7], using Design Approach 3 (A2+M2+R3).

3.2. Design of Reinforced Concrete Structures

In the static analysis of all RC structures of the SHPP, the structural elements were designed for the ultimate limit state (ULS) using the permanent design combination, and for the serviceability limit state (SLS) with verification that concrete crack widths remain below 0.3 mm for the frequent combination in accordance with HRN EN 1992-1-1:2013 [8]. Additional calculations for the reinforcement required to control early-age cracking in massive RC structures were carried out in accordance with the BAW guidelines [9,10]. Representative ratios of installed B500B reinforcing steel in kg against installed C30/37 concrete in m3 for some main RC structures are shown in Table 2 below.

Table 2. Reinforcement/concrete ratio for main RC structures.

RC Structure	Reinforcement/Concrete Ratio (kg/m^3)
Gate structure	115
New headrace channel walls	85
Powerhouse structure	95
Tailrace channel transitional section	80
Tailrace channel closed section	175

Two calculation models were prepared: in one model, the embankment behind the structure is drained, i.e., without groundwater, while in the other model, the embankment is saturated, with groundwater up to the elevation of the surrounding terrain. In addition to preliminary manual calculations, FEA models were developed with adoption of some recommendations shown in [11] and usage of the following software packages for the following structures: SCIA Engineer 19.1 for powerhouse and gate structures; Sofistik 2020 for tailrace channel structures; Tower 7 for control building and GEO5 2021.66 Cantilever wall for headrace channel structures. Some of the calculation models are presented below

(Figure 7). Detailed design of RC structures was performed in Allplan 2020 software which proved to be particularly useful for complex structures with variable geometry. Detailed design 3D models are presented previously (Figures 1–6).

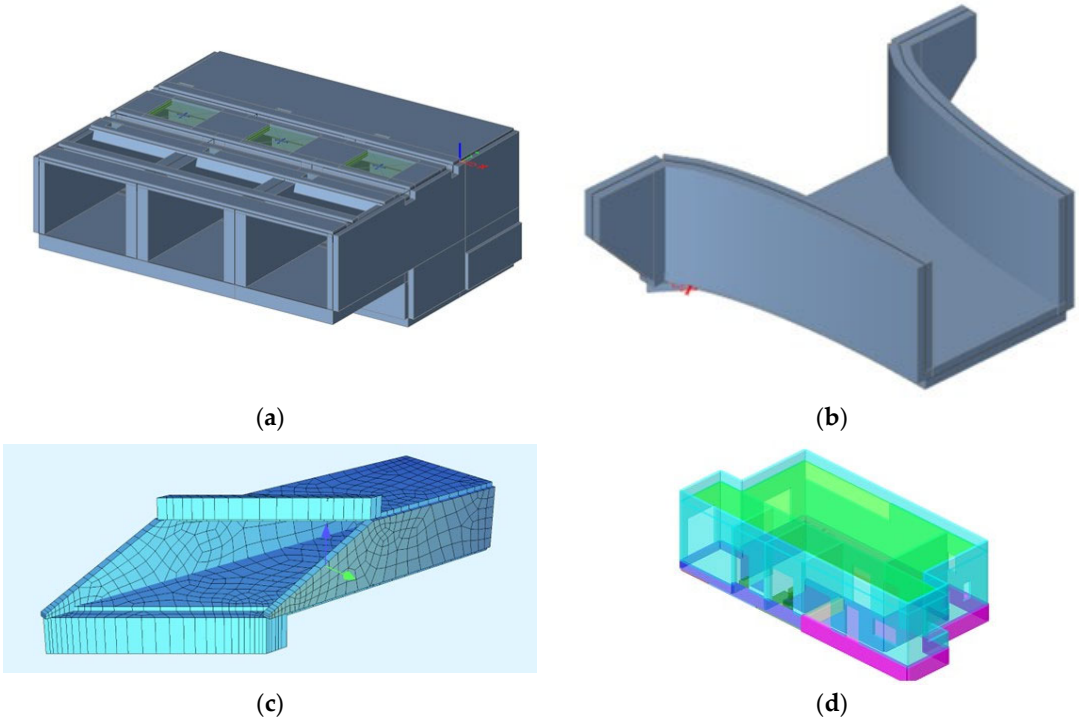


Figure 7. FEA calculation models: (**a**) Powerhouse structure; (**b**) Gate structure; (**c**) Tailrace channel; (**d**) Control building.

To avoid early-age cracking in massive RC structures, the following good practice recommendations and measures from [12,13] were prescribed in the main design [3]:

- Selection of a concrete mixture that will limit maximum concrete temperature to 65 °C and maximum temperature difference to 15 °C.
- Concrete pouring should only take place when the ambient temperature is above 5 °C and below 25 °C.
- It is necessary to maintain the concrete temperature at or above 10 °C for the first 72 h and limit the fresh concrete temperature at placement to max 25 °C.
- To control temperature in massive RC structures, temperature sensors must be placed at the bottom, middle, and top of the concrete element (in three layers), at each corner, and in the middle of the element layout; temperature must be monitored during the concrete curing period.
- Pouring should be avoided in windy conditions to prevent additional moisture evaporation through exposed surfaces of concrete elements.
- External curing should be adopted to reduce water evaporation from the surface of concrete elements. Fourteen-day curing is strongly recommended, but 7-day curing is minimum and essential for concrete. Suitable curing method includes curing with insulation, misting and wet blanket, which should be applied properly to fully cover the concrete surface.

4. Conclusions

The design phase of the SHPP Otočac project lasted for three years and included the preliminary design with the environmental impact assessment procedure, the main

design documentation for obtaining the construction permit and the detailed design with all necessary construction documentation. The construction of SHPP Otočac, including successful commissioning and testing, lasted for three years [14] with consumption of total 9395 m^3 of C30/37 concrete and 1017 t of B500B reinforcing steel. Figure 8 shows the finished project.

Finally, several engineering lessons learned from the SHPP Otočac project are summarized below:

- In verifying the global stability of RC structures against sliding and overturning in accordance with HRN EN 1997-1:2012 and HRN EN 1998-5:2011, the combination of maximum water levels (including groundwater) with the corresponding seismic loading is not clearly defined; therefore, the designer must make an informed judgment.
- The high demands regarding RC structure complex geometry at the design stage must be balanced against the selected contractor's capabilities during construction.
- Although the designer can prescribe good practice recommendations to avoid early-age cracking in massive RC structures, the implementation of specific measures is primarily the responsibility of the selected contractor.



Figure 8. SHPP Otočac.

Author Contributions: Section 1. Introduction, M.F., Section 2. Main Civil Structures of the SHPP Otočac, M.F., N.S., A.H. and D.T., Section 3. Design Approach, M.F., N.S., A.H. and D.T., Section 4. Conclusions, M.F. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

SHPP	Small Hydropower Plant
RC	Reinforced Concrete
FEA	Finite Element Analysis
BAW	Bundesanstalt für Wasserbau/Federal Waterways Engineering and Research Institute

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