Numerical study of the water discharge on a fish stepped passage at a low head dam

Cristian Bratanovici¹, Ioana - Alina Popescu-Busan¹, Gheorghe Lazar¹, Albert Titus Constantin¹, Serban-Vlad Nicoara¹
¹Politehnica University Timisoara, Romania
alina.popescu-busan@upt.ro

Abstract. Whereby the water course is considered a continuous system with hydrological connectivity – longitudinal, lateral, vertical – and variable in time, the design and implementation of barraging steps on water courses will have to follow the river dynamics and to respect the ecological concepts. Looking to diminish the negative impact on the environment, the promoted technical solution needs to consider a series of principles and criteria specific to the river basin for the conservation of nature and biodiversity. A specific river development assuming the accomplishment of a low head overflowing step ending with a water energy dissipater will have to be additionally endowed, according to nowadays legislation, with a corresponding fishway structure preserving the natural passing. The paper presents a numerical simulation of the water discharge transported by the fish stepped passage associated to the low head overflowing Livezeni Dam on Jiu River in Hunedoara County, Romania, considering the possible accidental high waters phenomenon given as a synthetic levels’ hydrograph. The hydraulic model looks to analyse the maximum discharges for the special structure and also to estimate the maximum values for water velocity in the strangled cross sections. As a consequent, the adjustment of the steps geometry or number can be studied in order to fulfil the nowadays regulation on the subject.

1. Introduction
Depending on the species of fish monitored on a water course, specific design conditions – maximum flow velocities and height of the thresholds – are required for planning a suitable fish passage that would ensure the ecologic preservation [1,2]. The water flow range along a passage structure should determine velocity values less than the fish sustaining speed on given sectors length and head, corresponding to the specific characteristics with respect to jumping distance and burst speed for each species [3]. The inlet area in the upstream and downstream passage structure must be determined according to the hydrological conditions existing in the reservoir and the natural place of aggregation of the fish. From the point of view of fish micro-habitat preferences, they tend to gather in the lake areas where water recirculation takes place [4]. In order to estimate the required depth of water along the fish passage, data from specialized studies on micro-habitat preferences of species found in the studied sector needs to be considered [5]. Although these data refer to the target species, it is important to note that these data were collected by field research conducted on natural areas of rivers, not on anthropogenic structures such as fish passages.

The low head water development of Livezeni - Bumbești [6] sector on Jiu River, Romania, was performed with the main purpose of hydropower harvesting. Once the investment is accomplished, it is...
assumed that it will supply an electric power value of about 259 GWh in a mean year. The sector under development is situated between Livezeni (south neighbourhood of Petroșani Town), from the West Jiu and Est Jiu Rivers joining section, and Valea Sadului (north neighbourhood of Bumbești-Jiu Town), along of the about 31 km length Jiu Gorges National Park. The Livezeni waterpower arrangement placed right at the gorges upstream entering is comprised of the following structures: the 45m wide overflow dam (Figure 1) expected to hold a water reservoir of 130000 m3 and equipped with three tainter + flap gates (12m wide by 9m height); the energy dissipater basin with tail block ramp; the right side hydropower water catchment with an underground silting basin; the headrace gallery of 6900 m length and 3.80 m diameter; the underground surge tank of 24 m height; the gate chamber housing a flap gate of large capacity; the steel penstock pipe of 142 m length and 2.95 m diameter; the right bank over-ground Dumitra Power Station accommodating the three Francis FVM 10.1-93 vertical axel hydropower equipment that discharge 36 m³/s in total at an installed power of 24.5 MW; the fish passage by the left bank of the retaining structure ensuring a downstream sanitary flow of 2.70 m³/s on Jiu River. The fish passage seems to be still on design stage following to be completed on the left side canal which was engaged as bypassing duct during the accomplishment of the main retaining structure. The water bypassing canal is 10 m wide and about 219 m long (Figure 2).

Figure 1. View of Livezeni water development on Jiu River, Romania
Figure 2. General view of the water bypassing canal (left) with a closer view in the area where the fish passage structure is to be accomplished (right) at Livezeni Dam on Jiu River

As thought by S.C. ISPH PROJECT DEVELOPMENT S.A. design company from Bucharest, the fish ladder passage is to be a reinforced concrete structure divided into three compartments as presented by Figure 3. The last compartment would work as a stilling and accommodation area for fish passing downstream to upstream, its lowest end being connected by a 2.50m wide opening (539.49mSL) to the fixed tail block ramp. The Figure also shows some detailed dimensions of the passage track along the upper and longest compartment, with the narrowing gaps indicated of about 0.33…0.34m in width. The optimisation study regarding this fish passage looks to develop a quality numerical modelling of the water discharge that would help in establishing the final designed geometry by considering the water velocities in the narrowed sections along the entire flow track with respect to the values admitted by the specific conditions in nowadays technical regulations.

Figure 3. 3D view of the fish passage geometry aside the Livezeni Dam (left) and a detailed plan view of a track sector along its upper largest compartment (right)

As long as the velocity limitations are not fulfilled (maximum admitted value goes to about 0.75 m/s, [5]), the designer should proceed either to alter the geometry of the already proposed elements or to consider an alteration on the passage configuration, with less or new structural elements. The planned
three-dimensional geometry as supplied in AutoCAD by the designing company was assimilated and processed under a suitable shape in order to clearly define the significant elements and so to be meshed for the numerical modelling.

The geometry of the main structural elements – walls and gaps – along the entire track defining the planned three-dimensional fish passage processed for developing the numerical model can be also comprehended from Figure 4.

\[ \text{Figure 4. The 3D fish passage structure developed on three compartments, as processed for numerical modelling} \]

The 1D flow modelling considers the multiple bent track as divided into rectilinear segments by cross-sections defined at the intersections of the three-dimensional structure with vertical planes. The numerical characteristics of the modelled geometric elements along the divided flow track are given by the cross-sections graphically obtained by processing in AutoCAD 3D the planned spatial structure, the general path view with the assigned cross-sections being presented by Figure 5.

\[ \text{Figure 5. General view of the multiple bent flow track along the fish passage at Livezeni Dam, divided into rectilinear segments by defined cross-sections} \]

2. General considerations regarding the flow numerical model development

The water discharge 1D numerical modelling for the planned fish passage at Livezeni Dam as unsteady (transitory) flow was performed by the help of HEC-RASv4.1 professional package software [7]. Following the meshing operation of the multiple bent flow track, there obtained 1142 rectilinear segments defined by some total of 1143 cross-sections of rectangular shape (as usually with the start reference on the top of the left side and the end point on the top of the right side each). The cross-views identification is considered as usual by a metric positioning growing as a real number from downstream towards upstream. This common procedure is quite useful for generating new intercalated cross-views by automatic linear interpolation between the original graphically produced cross-sections. The data base backing the fish passage geometry for its numerical modelling was stored in an EXCEL file as regarding the numerical location, the segmental lengths in a downstream sequence, and the defining coordinates for the cross-views (distances with respect to the left reference and structural levels). It was so prepared
the model defined by the plan view of the entire structure (describing the flor mean slope of about 2.504% for the first upper compartment, about 2.516% for the second middle one and respectively the horizontal flor for the third lowest compartment) and by the 1143 cross-views pointing out the flow geometrical shape with the considered roughness coefficient of the concrete bottom and walls. Finally, the 1D numerical model was developed by importing the prepared geometric data to HEC-RASv4.1 upon the described background view supplied by a Drawing Exchange Format file, as presented in Figure 6 with and without cross-views metric identification.

Figure 6. The HEC-RAS 1D numerical model of the fish passage at Livezeni Dam, with and without the metric identification of the flow path meshing cross-views

3. Numerical simulation and results presentation
The performed numerical modelling considers the water flow passing according to a non-permanent regime over three distinct stages. The first stage goes for the initially planned geometry of the fish passage as supplied by the designer. Along the second stage, there was considered that a tympan of 10cm thickness and about 50…110 cm rough height is set at each narrowing cross-section along the entire track. This tympan as a thin diaphragm wall determines both an over-spillway flow and a bottom-slot flow. Further on, following several geometrical optimization steps regarding the tympans height (altering the over and bottom flows in the narrowing cross-sections) the final proposed dimensions are considered along the third stage modelling. In the same time, an additional side gallery is considered along the third stage as an exterior path connected at the stilling bottom compartment of the fish passage (see Figure 9). Stage 1. The initially planned geometry is employed, for which the upstream water discharge of 0.25 m³/s and downstream energetic slope 0.0001575 are enforced as initial conditions. By adopting a levels hydrograph with the top limit of 552.00 mSL (as established by the operation conditions), the maximum discharge value on the fish passage is obtained. An additional overflow type of structure had to be modelled at the first compartment with the location and geometry revealed by Figure 7, in order to limit the passing water discharge.

Figure 7. Detailed view for the first compartment of fish passage numerical model indicating the location (left) and structural geometry (right) for the overflow retention type of structure
Stage 2. The initially planned geometry of the fish passage is altered by additional structural elements as tymphans (bridge type structures) over-modelled at each narrowing gap along the flow path [8]. Same initial conditions, 0.25 m³/s discharge assigned to the upstream end and 0.0001575 energetic slope attributed to the downstream cross-view, are enforced. Several analyses were performed as adjusting the tymphans height, meaning modifying the modelled over-spillway and bottom-slot flows, looking to reach maximum water velocities below the admitted value of 0.75 m/s. The optimum geometrical configuration of tymphans – slot height 22.5cm, tympan height 77.5cm, thin spillway height 100cm (Figure 8) – was then saved to be adopted as structural fish passage configuration for running the third stage.

Figure 8. Geometrical configuration of a current gap narrowing tympan (bridge type structure on “370.896”)

Stage 3. The optimised altered fish passage structure with respect to water velocity values is endowed with an additional side gallery connected to the bottom stilling compartment (the downstream “J-aval” joint in Figure 9) as it will come out further on.

Figure 9. The finally optimized 1D numerical model of the fish passage at Livezeni Dam
In order to control the maximum discharge value by the side gallery, a retaining type structure is modelled right after its upstream entering section of the side gallery (“59.308” metric ID), while a bridge type structure is considered at the downstream end of it in order to limit the water velocity at the confluence with the bottom stilling compartment. The enforced initial conditions are represented by the synthetic high-water levels hydrograph – symmetrically developed from the initial level of 551.60 mSL, rising along a period of one hour to the top level of 552.00 mSL and then decreasing along a second hour back to the same 551.60 mSL – the water discharge of 0.50 m$^3$/s attached to the upstream entering cross-view (“469.280” metric ID) and of 0.50 m$^3$/s at the side gallery catchment section (“59.308” metric ID), and respectively the energetic slope of 0.0001575 assigned to the downstream ending cross-view (“5.800” metric ID). The specific developing parameters – water levels, discharges and velocities – were revealed by performing the numerical simulations along the three distinct stages. Still, only the results of the first and third stages are further on synthetically presented. The time step analysis is $\Delta t = 1$ sec, while the reached results are set to be stored at every one minute. The significant graphically postprocessed results – longitudinal profiles and the correlated discharge-level time developments – reached by modelling the unsteady flow regime under the conditions given by stage 1 are presented by Figures 10 and 11. It came out that under the mentioned circumstances, the top water velocities in the narrowed cross-sections corresponding to an upstream level of 551.80 mSL reach a little above 6.6 m/s (top of Figure 10). Once the entering water level rises following the considered hydrograph, the top velocities became variant in-between about 8.75 and 9.63 m/s. In the same time, the top water discharge reaches about 1.46 m$^3$/s (as corresponding to the entering cross-sections “469.290” and “466.99” in Figure 11) which is attenuated downwards along the flowing path to a maximum value of about 1.25 m$^3$/s (as revealed at cross-section “5.80” in Figure 11, bottom). The important aspect is that the planned fish passage structure working under the given conditions does not fulfil the flowing requirements as stipulated by the nowadays regulations. Consequently, the structural configuration needs to be altered in order to reduce the passage discharge flow and the top velocity values (below the stipulated value of about 0.75 m/s). Since the bypassing structure was developed also to ensure the sanitary flow immediately downstream the Livezeni Dam, it comes as necessary to consider a complementary discharging path – the mentioned side gallery – that would raise the total passing discharge to the required sanitary value of about 2.70 m$^3$/s.

Figure 10. Water level profile under Stage 1 conditions at four relevant moments along the modelled period: the minute 20, 52, 62 and 95.
Figure 11. Water discharge and level time development for three characteristic cross-paths: the entering one “469.290”, the one attached to the overflow retention type structure “466.99” and the outgoing one “5.80”

As about the analysis of the optimised structural configuration (performed along the defined Stage 2 and endowed with the side gallery added element) prepared for Stage 3, the HEC-RAS numerical model can be considered as organised by three flowing paths: one from the upstream entering cross-view (identified as “469.290”) along the fish passage compartments down to the confluence point “J”, another from point “J” right to the model final outgoing cross-view (“5.80”), and a third one represented by the side gallery – specifically designed to frame up its discharge at about 2.40 m³/s – from its catchment element (“59.308”) to the confluence point “J”.

The post-processed obtained results would refer to water level (piezometric) longitudinal profiles along the considered three paths as an ensemble in correlation with the water velocity longitudinal development (Figure 12), and also in separate displays at several given moments (Figure 13 for the side gallery flow and Figure 14 for the entire fish passage structure flow). There are also presented here (Figure 15) the correlated water discharge-level time developments in some specific cross-sections: the upstream entering “469.290”, the side gallery entering “59.308”, the side gallery retaining structure “58.100”, the side gallery bridge structure “1.300”, the downstream bridge structure “74.629” and the outgoing “5.80”.
Figure 12. Water level profile under the Stage 3 conditions along the three paths ensemble in correlation with the water velocity longitudinal development.

Figure 13. Water level profile under the Stage 3 conditions along the side gallery discharging path at the specific time moment of minute 50, in correlation with the water velocity longitudinal development.

Figure 14. Water level profile under the Stage 3 conditions along the fish passage path in correlation with the water velocity longitudinal development at several specific time moments along the modelled hydrograph time spreading: minute 3, minute 31, minute 55, minute 82 and minute 120.
Figure 15. Water discharge and level time development for six characteristic cross-paths on the optimized fish passage structure under the Stage 3 conditions: the entering “469.290”, the side gallery entering “59.308”, the retaining structure type on the side gallery “58.100”, the bridge structure type on the side gallery “1.300”, the bridge structure type on the fish passage “74.629” and the outgoing “5.80”

4. Conclusions
As studying the flow transition through the altered structure representing the fish passage at Livezeni Dam on Jiu River under a frequent upstream levels hydrograph, one can ascertain that there would happen a slow regime along the entire modelled stepped path, the maximum water velocities in the narrowed sections reaching below the fish adequate value of 0.75 m/s.

There need to be mentioned the two exceptions with respect to the top water velocity even if the overvalues – a maximum value of about 0.83 m/s – are not substantial: the cross-sections “74.576” and “70.036” framing the downwards connection section between the second and third compartments modelling a sharp drop of 1.40 m (as given by the bottom mat difference from 540.89 to 539.49 mSL). This exception top overvalues were dropped at the mentioned level only after additional adjustments performed sequentially upon the model at this linking segment, regarding the tympan dimensions – overspillway and bottom-slot – for the two bridge type structures. The final geometry was established as
with slot / tympan / spillway heights 0.20 / 0.52 / 1.28 m for structure “74.629” and 0.20 / 0.70 / 1.10 m for structure “70.086”, while the opening of the first structure was increased from 0.34 to 0.44 m.

As about the transited water flow, the graphical representation of the numerical model output shows that the maximum discharge under the given circumstances would be of about 0.283 m$^3$/s by the fish-passage structure and of about 2.246 m$^3$/s by the side gallery. The maximum discharge at the downstream outgoing section reaches about 2.70 m$^3$/s, value that fulfils the required sanitary prescriptions on the developed river sector. Furthermore, by considering the outcome of the numerically performed optimisation study regarding the fish-passage structure at Livezeni Dam on Jiu River, one might count the possibility of fitting a micro-hydropower equipment towards the end of the side gallery, planning to employ a relatively constant 2.20 m$^3$/s discharge over a rough drop of about 12 m in order to reach an installed power of about 195 kW.

References
[1] ROM. GOV., “ORDINUL Ministerului Mediului si Dezvoltarii Durabile / ORDER of the Ministry of Environment and Sustainable Development No.1.163 /16.07.2007” (In Romanian).
[2] M. Nistorescu, A. Doba, M. Țibîrnac, A.A. Nagy, D. Cosmoiu, G.M. Berchi, and C. Ilinca, “Ghid de bune practici în vederea planificării și implementării investițiilor din sectorul microhidrocentrale / Well performance guide regarding investments planning and implementation in the subject of micro-hydropower stations”, Edited by “Nature 2000 and Sustainable Development in Romania” Organization and “Milvus Group” association, Bucharest, 2016 (In Romanian).
[3] G. Marmulla and R.L. Welcomme, “Fish Passes - Design, Dimensions and Monitoring, Food and Agriculture Organization of the United Nations / Deutscher Verband für Wasserwirtschaft und Kulturbau”, Rome, 2002.
[4] M. Larinier, “Upstream and Downstream Fish Passage Experience in France. Fish Migration and Fish Bypasses”, November, 127-145, 1998.
[5] S. Borlea, I. Sîrbu, S. Stănescu, A. Doba, and M. Nistorescu, “Studiu ihtiologic pentru fundamentarea ecologică a execuţiei unei Scări de peşti în dreptul barajului de la Livezeni, sector Livezeni – Bumbeşti al râului Jiu / Ichthyology study regarding the ecological substantiation for the accomplishment of a fish-passage aside of Livezeni Dam on Livezeni – Bumbești sector of Jiu River”, Bucharest, 2017 (In Romanian).
[6] ISPH SA, “Amenajarea hidroenergetică a râului Jiu pe sectorul Livezeni – Bumbeşti / The hydropower arrangement of Jiu River on Livezeni – Bumbești sector”. SC Hidroconstrucţia SA, Bucharest, 2016 (In Romanian).
[7] G.W. Brunner, “HEC–RAS 4.1 River Analysis System, Hydraulic Reference Manual”, US Army Corps of Engineers, 2002.
[8] V.F. Pîrăianu, and C. Ilinca, “Practical Solutions for Small Hydro Power Plant Design”, 18th European Concurrent Engineering Conference (ECEC 2012) and the 8th Future Business Technology Conference (FUBUTEC), Bucharest, România, pp 59-62, 2012.